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Lean Construction in Crisis Times: ***Responding to the Post-Pandemic AEC Industry Challenges***

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A NOTE FROM THE CONFERENCE CHAIR

While our IGLC community was trying to catch up with how the reshaping of the manufacturing by the advent of the "fourth industrial revolution" or industry 4.0 would impact the architecture-engineering-construction (AEC) industry, an even bigger and unprecedented economic and social disruption caused by the outbreak of the COVID-19 pandemic in 2020, posed new and unimaginable challenges leading to a world that is going through its biggest transformation in every single aspect of our society in almost a century.

Countries responded to the COVID-19 pandemic by taking unprecedented steps such as making large amounts of money available to fund rescue measures such as tax cuts, extended unemployment benefits, mortgage holidays, and liquidity for small and medium-sized businesses. And some of the millions of persons that suddenly started working remotely during the pandemic, have taken the unprecedented opportunity to shift their lives in a new direction expecting not having to go back to the office again. This has also shifted the traditional way of working in the AEC industry towards one that enable the e-office and e-collaboration among project teams.

Back in 2020, the 28th IGLC conference already setup (i.e., auditoriums, catering, hotel reservations, audiovisual equipment) to be carried out in Cusco, Peru had to be surprisingly cancelled due to the COVID-19 worldwide lockdown and traveling restrictions imposed throughout the word in March 2020. Iris Tommelein[1] and her P2SL group at UC Berkeley jointly with Emmanuel Danie[2] from University of Wolverhampton, raised to the occasion making the IGLC community statement "annual conferences are the main activity of the IGLC, and their locations rotate amongst the continents" to become charged with a new meaning, having by the first time a completely online IGLC conference in 2020. The 28th IGLC online conference organized by the P2SL at Berkeley replaced the originally planned in person conference to be held in Cusco, Peru in July 2020.

Building on top of the pioneering experience provided by UC Berkeley, this year's 29th IGLC full online conference has been entirely organized by the Peruvian university: "Pontificia Universidad Católica del Perú" under the leadership of Professors Dr Danny Murguia and Dr Xavier Brioso, and with the senior advice of Professors Dr Luis Fernando Alarcon from Catholic University of Chile and Dr Vicente Gonzalez from University of Auckland.

In this year's conference, we had 98 papers' presentations, 9 Summer School presentations, 2 keynote speakers, and a Gregory Howell Lean Game Session. All the papers and presentation slides are available online at iglc.net.

With the conviction that we shall emerge from this COVID-19 pandemic with a healthier respect for the environment and our common humanity, Dr Flores inaugurated the conference with the keynote presentation: "Trust, emotionality, relationships, and productivity - some reflections for the construction industry". And Dr Guilherme Luz Tortorella provided the closing keynote presentation "Integrating Industry 4.0 into Lean".

These IGLC29 conference proceedings do not only contain the records of the conference, but they will carry within themselves the story of the challenges and opportunities brought

[1] Director, Project Production Systems Laboratory (P2SL) at UC Berkeley
[2] Senior Lecturer in Construction Management, University of Wolverhampton

up by the COVID-19 pandemic to our IGLC community as well as to the broader Lean Construction community.

Finally, we would like to thank to all the members of the 2020 28th IGLC conference organizing committee that was not possible to be carried out in person in Cusco, Peru neither during 2020 nor during 2021, special thanks to Carlos Lepesqueur for his efforts and leadership on the organization of a conference that did not happen and that we still hope to happen in the new world of hope that has started to arise.

Lima 14th of July 2021

Leonardo Rischmoller, Conference Chair IGLC29

A NOTE FROM THE ORGANIZERS

On behalf of the Division of Civil Engineering at the Pontifical Catholic University of Peru (PUCP) and our research group GETEC, we are delighted to have organized the IGLC29 with the theme: "Lean Construction in Crisis Times: Responding to the Post-Pandemic AEC Industry Challenges". It is even more special to hold this event during the celebration of the bicentenary of Peru's proclamation of independence. In the conference logo, we have included the *"parihuana"*, an Andean bird of red and white colors that is said to have inspired Don Jose de San Martin in the design of our flag. This bird's flight represents our flag waving in the sky.

Lean Construction arrived in Peru in the mid-90s thanks to the late Dr Virgilio Guio Castillo, alumni PUCP and a former professor of our department. He was a member of the IGLC community since its early years. Professor Guio authored the first Lean Construction research in Peru (published in the IGLC1997) and wrote a seminal book on construction productivity. His legacy has inspired a generation of practitioners and academics in the construction industry. 24 years have passed now, and we can say that Lean Construction is a fundamental element of the Peruvian construction industry, although more research and implementation is needed to improve maturity and performance. On the academic side, PUCP's undergraduate and graduate Civil Engineering programs include Lean Construction, and their integration with BIM, ICTs and digital transformation. Organizing the IGLC29 reinforces our commitment to teaching and researching Construction Management based on value generation, waste elimination, and the integration of Lean with emerging systems and technologies; underpinned by respect to people and collaborative planning. This is aligned with our mission to educate better citizens with solid ethic principles.

This conference would have not been possible without the support of numerous people. First, we would like to thank PUCP's Events Team under the leadership of Patricia Harman. The graphic design, registration, webpage and the logistics was possible thanks to the hard work of Violeta Antón. Also, we would like to thank Zofia K. Rybkowski for organizing the Greg Howell Lean Game Sessions. The game sessions facilitators are as follows: Ming Shan Ng (Charmaine) and Daniel M. Hall (TVD for digital fabrication); Ganesh Devkar, Georgie Jacob, Nimish Sharma and Shaurya Bhatnagar (TVD simulation); Colin Milberg (Batch, Pull, Balance); Iris D. Tommelein (Mistakeproofing); Rajeswari Obulam (5S Puzzle); and Cynthia Tsao (Parades of Trades®). We would also like to thank Paz Arroyo and Ergo Pikas for excellently organizing the IGLC PhD Summer School under the theme "Novelty and Usefulness to Deliver Relevant Lean Construction Management Research". We would like to thank our research assistants for their support in the editorial process. The editorial plagiarism check was possible thanks to the work of Claudia Calderon-Hernandez. Compiling the proceedings and ensuring the quality of final papers was possible thanks to the work of Ema Perea. Finally, we would like to thank Alonso Urbina for drafting the conference program. We hope you enjoy the conference.

Lima 14th of July 2021

Danny Murguia and Xavier Brioso, Organizing Committee IGLC-29

PREFACE

The Annual Conference of the International Group for Lean Construction (IGLC), the main IGLC activity, has run without interruption since its inception in 1993. The IGLC represents a network of practitioners and academics from architecture, engineering and construction (AEC) who are passionate about Lean Construction and feel that the AEC industry has to be radically revamped so that it can respond to the global challenges ahead. The IGLC goal is to meet customer demands more effectively and to dramatically enhance the AEC process and product during the delivery of a project. In this regard, the IGLC has been developing new principles and methods tailored to the AEC industry that reflect a fundamental transformation in product development and production management. Originally, the IGLC began a progressive adoption of Lean Production principles and methods that proved to be very successful in the manufacturing domain. The IGLC emphasises the development of theory because the paucity of solid production management theory is an impediment to progress in the AEC industry. Today, Lean Construction has evolved and matured as a production management theory for construction in its own right embodying not only management and production aspects, but also other areas, such as human and social aspects of projects, the synergies between Lean and Digital Technology (IT), and the relationship between Lean and Sustainability.

The venues for the IGLC conference have alternated between the five continents, even though last year and this year conferences were organized in online format due to the pandemic times we are living in. The 29th Annual IGLC Conference was organised by the Pontificia Universidad Católica del Perú, with the main theme being "Lean Construction in Crisis Times: Responding to the Post-Pandemic AEC Industry Challenges". This conference will be bringing together a large number of practitioners and academics who will present their research and industry findings.

One hundred and twelve full papers were initially submitted to the conference. International experts (academics and practitioners) volunteered their time to review and assess the submitted papers through a double-blind peer review process. The final decision on papers' acceptance was jointly made by the track chairs and the scientific chairs based on these assessments. Finally, 98 papers were accepted from 23 countries, which is an excellent outcome for the first online IGLC conference run in Peru (the second held in this country). The papers have been organised into ten tracks: Contract and Cost Management; Enabling Lean with Information Technology; Lean Theory; People Culture and Change; Product Development and Design Management; Production Planning and Control; Production System Design; Safety, Quality and Green-Lean; Supply Chain Management and Off-Site Construction, and Learning and Teaching Lean. A summary of the submitted and accepted papers by track is shown in Table 1.

Table 1. Papers submitted and accepted to IGLC-29.

Track	**Papers Submitted**	**Papers Accepted**
Contract and Cost Management	6	5
Enabling Lean with IT	4	3
Lean & BIM	7	6
Lean Theory	10	9
People Culture & Change	26	23

Product Development & Design Management	8	6
Production Planning & Control	18	18
Production System Design	8	5
Safety, Quality & Green-Lean	5	5
Supply Chain Management and Off-Site Construction	7	7
Learning & Teaching Lean	13	11
Total	**112**	**98**

This year's conference considered two categories of papers, research and industry papers. Note that industry papers represent contributions that follow the general structure of a research paper but have an emphasis on the practical and industry side of Lean Construction, such as Lean transformation of construction organisations or implementation of Lean tools in projects.

Table 2 shows a summary of the accepted papers sorted by country. We would like to thank the international experts for reviewing these 98 papers. Their efforts helped to ensure the papers accepted for the conference and incorporated in the proceedings were of a high standard. We would also like to thank the authors for addressing the reviewers' comments. This guaranteed that the best possible papers were considered to be published in this year's conference.

Table 2. Papers accepted by country to IGLC-29.

Country[a]	**Papers Accepted**
Brazil	14
Peru	14
United States of America	11
Finland	8
United Kingdom	8
Norway	7
Germany	5
Denmark	5
Chile	4
Canada	3
India	3
Ireland	3
Luxembourg	2
New Zealand	2
Netherlands	1
South Africa	1
China	1
Australia	1
Lebanon	1
South Korea	1
Mexico	1
Switzerland	1
Italy	1
Total	**98**

[a]Country of the first author's institution

Finally, we would like to acknowledge the area track chairs for their assistance in the editorial process and for all their invaluable and hard work “behind the scenes”. The track chairs are as follows: Yong-Woo Kim (Contract and Cost Management), Olli Seppänen (Enabling Lean with Information Technology), Carlos Formoso (Lean Theory), James Smith (People Culture and Change), Dani Dietz (Product Development and Design Management), Farook Hamzeh (Production Planning and Control), Frode Drevland (Production System Design), Laura Florez (Safety, Quality and Green-Lean), Emmanuel Daniel (Supply Chain Management and Off-Site Construction), and Zofia Rybkowski (Learning and Teaching Lean).

Lima 14th of July 2021

Luis F. Alarcón and Vicente A. González, Editors and Scientific Chairs IGLC-29

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DEVELOPMENT OF TARGET COST FOR A HIGH-PERFORMANCE BUILDING

Atle Engebø[1], Olav Torp[2], and Ola Lædre[3]

ABSTRACT

Target costing aims at making both cost and value to drivers for design. Still, few have studied how this is done in a high-performance building project, where a set of parameters beyond the typical cost, schedule, and quality parameters are optimised. Here we explore how a construction project team collaborated to reach the owner's allowable cost during design using observations and document study. The findings show that the owner should precisely describe expectations before starting Target Value Design. If not, the owner will get disengaged or develop suspicion towards provided cost estimates. Furthermore, we argue that the typical development of expected cost can inhibit a high-performing design team. The expected cost typically starts at the owner's allowable cost, increases drastically during design, and has to be substantially reduced. The consequence is that a high-performing team's mood moves from optimism towards realism and eventually into a realm where challenges occur. The domain where challenges arise is when the project team must substantially reduce the expected cost to reach an acceptable level. To remain high-performing throughout, the project team should avoid a drastic increase in expected cost in the initial stages.

KEYWORDS

Target cost, Target Value Design, collaboration, team development.

INTRODUCTION

A project delivery method, as defined by Miller et al. (2000), is "a system for organizing and financing design, construction, operations and maintenance activities that facilitates the delivery of a goods or service". Previously, traditional project delivery methods such as design-bid-build and construction management at risk were a preferred choice for project owners. The latest years, collaborative project delivery methods with early contractor involvement (Lloyd-Walker and Walker, 2015; Fischer et al., 2017; Engebø et al., 2020b; Wondimu et al., 2020) and Target Value Design (TVD) (Ballard and Reiser, 2004; Ballard and Pennanen, 2013; Do et al., 2015) have received increased attention. Successful application of TVD in construction has been reported (e. g. Ballard and Reiser, 2004; Ballard and Pennanen, 2013; Denerolle, 2013) However, some TVD projects experience final costs that exceed target costs (Ballard et al., 2015; Tillman et al., 2017).

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For successful application, realistic performance requirements and target cost should be set before conceptual design (Tanaka, 1990).

In Target Costing, the cost is estimated directly from the owner's requirements before design rather than from a design offered to satisfy those requirements (Pennanen and Ballard 2008). According to (Ballard, 2006; Ballard, 2007), the target cost can equal the owner's allowable cost set in the project business plan before hiring the contractor, or it can equal the expected cost defined by the project team. The expected cost would be the facility's cost, with a determined performance, if provided at current best practice. The contractor's target cost (target selling price) is often set right below or at the allowable cost, while if the project team defines the expected cost, the owner often sets the target cost at the expected cost.

Current best practice refers to a situation where the project team participants set target costs that are stretch goals and share risk and reward with the owner. If setting target cost equal to the owner's allowable cost, the project team must assess if the requirements can be met when taking acceptable risk. The owner can combine a mutually agreed target cost with risk and reward sharing. Some researchers claim that the target cost should be lower than the allowable cost for both project alliancing and Integrated Project Delivery (Sakal, 2005; Fischer et al., 2017). Torp (2019) has studied how public agencies in Norway set cost targets. In Norway, both the Norwegian Public Roads Administration and Statsbygg (the Norwegian government's principal advisor in construction and property affairs) use steering targets lower than the allowable cost. The target cost can change during design, and in some projects, the owner has an option to fund design before making a Go/No Go decision for the actual construction. Applications of collaborative project delivery methods with TVD are not much studied in Norway, so this paper answers the following research questions:

1. How is target cost set on a high-performance building project?
2. How does expected cost develop through the collaborative phase?
3. How can a collaborative delivery method contribute to development of expected cost?

LITERATURE REVIEW

The project delivery method dictates how the project team engages, methods used, and how different actors get involved. Regardless of the project delivery method, the design is conducted by a multi-disciplinary team of designers seeking to fulfill the project owners' requirements. This paper is limited to so-called collaborative project delivery that seeks to integrate and align the actors in an early stage, i.e., already in the planning phase (Fischer et al., 2017). This sort of collaboration is challenging as the team assembled is both multi-disciplinary and inter-organisational. Another distinction is that the planning phase typically involves a high degree of uncertainty and an equally high degree of flexibility (Knotten et al., 2017).

THE CONCEPT: TARGET COSTING AND TARGET VALUE DESIGN

The method of target costing stems from Japanese Manufacturing companies and may be described as a management technique aimed at reducing life-cycle costs of new products, while ensuring quality, reliability, and other consumer requirements, by examining all possible ideas for cost reduction at the product planning, research and development, and the prototyping phases of production (Kato, 1993).

Guilding et al. (2000) refer to Target Costing as a practice that seeks to satisfy a customer need by setting a reasonable target cost is for that need. Target costing is implemented primarily during the development and design phases of the manufacturing process as a system designed to improve an organization's services and related processes through cost optimization (Sobotka et al., 2007). An often-used approach in traditional Design-build is a fixed-price contract. A more 'innovative' approach is the cost-plus approach, where the owner pays all of the project's audited costs plus some fee. The fee may be fixed, an incentive, or an award fee (Griffis and Butler, 1988). A difference between cost-plus with incentives for cost reduction and target cost is that cost-plus reduces cost by lowering performance, quality, and profit.

In contrast, design and customer input guides cost reduction in target cost. Cost-plus can, for example, leads to squeezing of the sub-contractors. Suppose target cost is reduced below allowable cost by pressing the sub-contractors' overhead, rather than changing the scope of design or customer input. In that case, this undercuts any motivation for the sub-contractors to lower the total cost (Nicolini et al., 2000). Instead, the object of target costing is to identify the production cost of a product so that, when sold, it generates the desired profit margins (Cooper, 2001). Consequently, the project team should emphasise proper cost management throughout the whole design process. The process should be centered around identifying the allowable cost at which the contractor can produce the product with a predefined and acceptable overhead. Then breaking the target cost down and have the suppliers find ways to deliver the components at the set target cost while still making a profit margin (Cooper, 1997; Cooper and Slagmulder, 1999).

Target Value Design (TVD) is a management practice in which the design and construction are steered towards the project constraints while maximizing customer value (Ballard, 2011). TVD can be implemented through various project delivery methods, and research suggests that TDV can be applied to projects of all sizes (Do et al., 2014). TVD was adopted from Target Costing (TC). Target Value Design focuses on setting targets, design to targets and builds to targets (Zimina et al., 2012). The allowable cost is a cost the customer finds acceptable; i.e., they are willing and able to pay that amount and are assured that they will receive in return what they want. The project owner sets allowable costs, and the expected cost is estimated several times during design and construction, as output from the cost model, estimated by the project team.

THE PROCESS: THE RELATIONAL SIDE – INTEGRATED TEAM

This paper concentrates on the design stage, as this phase is crucial for defining the project's value. Yet how the process is run varies vastly from project to project; for example, value engineering (VE) revolves around searching for alternative components that fulfill the component's function by an alternative method. The concept is centered around function analysis to identify low-cost products without reducing quality but remove unnecessary costs and improving design through workshops that focus on high-cost areas concerning the particular design (Palmer et al., 1996).

In collaborative project delivery methods with Early Contractor Involvement (ECI), the early stages of the project are centered around the notion of integrated design. Work is organised around multidisciplinary teams, whose members are often co-located to favour collaboration and innovation (Forgues et al., 2008). A way of organising the design is by engaging all involved representatives concurrently (Concurrent Engineering) and where all life cycle stages of the product are considered simultaneously, from the conceptual stage through to the detailed design stage (Love and Gunasekaran, 1997).

A key element to this approach is that one needs the multidisciplinary team to perform from an early stage and onward. Tuckman's model suggests that groups progress through four classified stages (Tuckman, 1965). Tuckman later revised his model, adding a fifth stage called adjourning (Tuckman and Jensen, 1977). The starting point called forming is constituted by orientation, testing, and establishing dependency. The second stage is storming, where conflict and polarization around interpersonal issues occur and serve as resistance to group influence and task requirements. In norming stage, this resistance is overcome, and the group feeling and cohesiveness develop, new standards evolve, and new roles are adopted. Lastly, the performing stage is reached in which the interpersonal structure becomes the tool of task activities. Roles become flexible and functional, and group energy is channelled into the task (Tuckman, 1965; Tuckman and Jensen, 1977). To contextualise, teamwork is one of the most critical features in the success of a good design process and to fulfill the project owners' requirements (Freire and Alarcón, 2002). Thus, using a framework such as the Tuckman model as a lens to understand how teams develop during a design process could be valuable in discussing group dynamics in the context of Target Value Design.

While the model is broadly accepted within various fields, providing a breadth of application for viewing different practical settings, contemporary sources have noted that the model does not sufficiently recognise the complexity of group dynamics or the many specialised areas of group development. Group dynamics also includes leadership, motivation and rewards, and external factors such as organizational roles, resource allocation, and external stakeholders' pressure (Bonebright, 2010).

METHODOLOGY

The empirical findings stem from an observational study and a document study of the design phase, the so-called contract phase 1, of a high-performance building located in Trondheim, Norway. The findings are merged with insight gained from a thematic literature review on Target Costing, Target Value Design, and Group Development.

The studied high-performance building is a Zero Emission Building (ZEB) Laboratory in Norway. This 4 stories high building contains approximately 2000 m², where a set of parameters beyond the typical cost, schedule and quality is optimised. When finished, it will be a full-scale laboratory where the users are exposed to different temperatures, air qualities, moisture levels, luminosities etc. The first reason for selecting this high-performance building is that the complexity made it challenging to estimate expected cost and define cost targets. The second reason is that experiences from collaborative project delivery methods with TVD are easier to transfer from complex to non-complex projects than the other way around.

To collect data, the main author observed the weekly full-day ICE-sessions (from 08:30-15:00) where the owner and the contractor-led project team participated for nearly half a year. The observations were part of a larger research project on collaborative project delivery methods in construction projects. The data presented in this paper are observations that resulted in a dataset of more than hundred pages of fieldnotes.

Normally, around twenty people attended the weekly ICE-sessions. The project team included five participants from the contractor (Project manager, Estimation manager, Design manager, BIM-coordinator, and one assistant), seven from the owner (Project manager, Project coordinator, Laboratory-representative, user-representative, and three ZEB-experts), three from the architect (Head-architect, assistant-architect, and LCA-Expert), and four from the sub-contractors (HVAC, Automation, Construction, and Electrician). The project team was informed about the intentions of the observations, and after a couple of weeks the presence of the observer felt natural.

Also, the researchers had access to a webserver with project documentation, including contracts and project specifications. Documents describing the development of expected cost during the design and from a discourse between the owner and the contractor regarding how they described Target Value Design were of particular interest. However, the study did not implement any specific tool for reporting the change in moods of the project team. Thus, the description of how the team developed through the design phase represents the perception and analysis of the empirical evidence collected by the observing researcher.

FINDINGS AND DISCUSSION

We have studied a project that used a two-step model where the first step started with the owner contracting a contractor together with an architect, consultants, and subcontractors to a development phase (contract phase 1). The development phase usually has a preliminary target price and an option for a turnkey contract with a target price in step two (contract phase 2), provided that the parties manage to develop an adequate project. The first contract was a Norwegian Standard contract (NS 8402: For consultancy commissions with remuneration based on actual time taken) supplemented with a "Partnering Agreement" drafted and signed by all parties involved. The first contract regulated the schematic design, where the contractor continuously updated the expected cost. The project team was assembled through a start-up seminar from the contract signing and subsequently worked together through 22 weekly Integrated Concurrent Engineering Sessions and workshops.

The case (The ZEB laboratory) was a "high-performance building" (HPB) with a set of ambitions beyond the typical cost, schedule, and quality parameters. The challenge was to design a building that fulfilled the particular demands: (1) to achieve ZEB-COM level (simulated in a 60 years perspective), (2) to have separate control and measurement systems, one for ordinary operation and one for research, (3) design flexible energy and climatization systems, (4) design flexible workspaces, (5) build a façade that enabled rebuilding and adaption, for example to future climate changes (Time et al., 2019).

HOW TARGET COST IS SET IN A HIGH-PERFORMANCE BUILDING PROJECT

The project's complexity made the owner opt for a collaborative project delivery method where key actors' were involvement early on and put together in a high-performance team that could provide technical solutions and innovations to produce the full-scale laboratory facility. Through the project delivery method, the owner emphasised relational aspects instead of just transactional. However, as the owner loosened up transactional regulations, the need for trust, shared goals, and follow-up by management increased (Engebø et al., 2020a). The project team started with just the ambitions laid out by the owner and the predefined allowable cost. The parties had to agree on a schematic design with an expected cost at- or below the allowable cost to proceed to the second phase. Thus, after phase 1, the owner had an option (but not an obligation) to procure the project team for detailed design and construction (contract phase 2) using a Norwegian Standard Design-Build contract (NS 8407: for design and build contracts).

The allowable cost was set at 127 million NOK by the three funding parties (a university, a research organisation, and the Norwegian Research Council). Thus, throughout phase one, the project team evaluated the expected cost against the design. The challenge was to develop the design, adding value for the customer while at the same time keeping the expected cost down. The project team developed the design in the ICE sessions. The sessions were designed to optimise iteration between the sub-contractors (technical specialists), the architect, the contractor, and the owner. Typical design iterations started with the architect presenting the current BIM model before the sub-contractors gave technical feedback, and the main contractor considered consequences for the expected cost. After sessions in the plenum, the team continued work in thematic groups (indoor design, outdoor design, and technical).

HOW EXPECTED COST DEVELOPS THROUGH THE COLLABORATIVE PHASE

Initially, the ICE-sessions proved to be a suitable means for balancing the design and managing the expected cost. The sub-contractors, the architect, and the owner representatives discussed, decided, and changed solutions in the ICE sessions. However, a transparent estimation of consequences for the expected cost was more challenging to incorporate. Using the previous ICE-session inputs, the contractor estimated and updated the expected cost before the next ICE session. This practice led the owner to perceive the estimation of consequences for expected cost like a "black box" as they only saw the input (design iteration in an ICE session) and output (updated costs in the next ICE session). In other words, the owner had little or no insight into the contractor's actual cost-estimation process, as illustrated in figure 1.

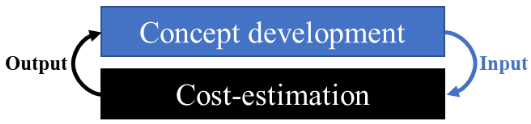

Figure 1: The cost estimation process seen from the owner perspective.

In theory, this should not be a problem as the participants meet jointly to reveal and revise their estimates before presenting an itemised list to the complete project team, including the owner. Although the owner attended those meetings and had access to the books (open book), it was not transparent how the contractor calculated the numbers and what they included. Therefore, the owner wanted to review the cost estimate. The contractor's hourly rates, material prices, and calculated overhead were of particular interest. The same was valid for the sub-contractors contingencies and overhead and whether the main contractor had added an overhead. The owner suspected that the contractor added overhead or contingencies onto the detailed cost items, and overhead included in the expected cost. The owner meant that the contractors should only include overhead once and not in "several layers.".

The degree of detail and the accuracy of the expected cost will typically increase as the schematic design progresses, as decisions are made, and more information is known. The contractor estimated the expected cost continuously during schematic design, and stretch-goals were built into the target cost to provide an incentive for cost savings when the owner and main contractor signed the design and build contract. The owner was decisive on the ambitions related to ZEB-COM, separate control, measurement systems, etc., and had to accept a reduced number of total square meters in the building during the iterations in schematic design. This way, the owner and contractor could agree on a target cost – as it should be according to TVD – lower than allowable cost (AC).

Figure 2 shows how the estimated expected cost developed through phase 1 of the case project. At the start of the schematic design, Positivism roamed. As the contractor started developing the project and assessing all the uncertainties, the expected cost surged (Expected Cost 1). Viewing the initial stages in the light of Tuckman's model, we can see the expected cost escalate through the forming and storming stages as the team has a positive attitude and at the same time seeks to avoid conflicts or themes that create tensions ("positivism roams"). At some point in the collaboration, realism takes hold of the project team as the project team reached the norming and performing stages. At this point (expected cost 2), the target cost has further increased because the contractor changed the estimation technique from rough element calculation to more detailed item calculation. It was unclear whether the increase in expected cost was caused by too-low initial pricing of the elements or the project team had added other qualities(too much emphasise on value-adding during the initial stages of the collaboration). The change in estimation technique also caused the owner to lose track since the estimates became detailed and too extensive for outsiders to comprehend. The subsequent cost reduction led by the owner and contractor seemed to remind the sub-contractors of a process that focuses on lowering specifications, reducing quality, which undercuts any motivation to lower the total cost (Nicolini et al., 2000). They felt that the main contractor tried to squeeze their profits in front of the owner. Therefore, the lowering of expected cost below allowable cost was an inhibitor to collaboration for the sub-contractors.

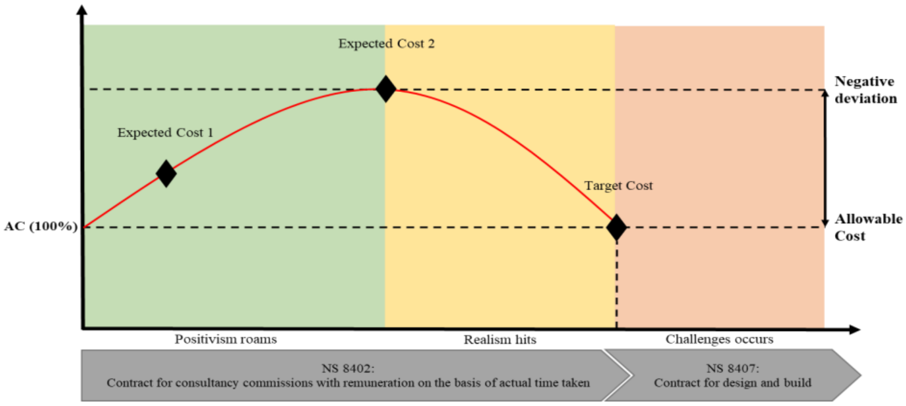

Figure 2: Conceptual presentation of the expected cost development.

Towards the end of the first phase, the expected cost travelled downward towards the allowable cost. The project team had to move away from concentrating on value-adding in the design towards strict cost-cutting instead. The contractor and the owner agreed upon a Target Cost that both parties could live with (but neither were utterly content with). The parties then signed the contract for phase 2 (detailed design & construction). Even though the owner and contractor agreed on a target cost after cost-cutting, they still seemed to have different perceptions of what was included and which party was responsible for the uncertainty. The total overhead included in the target cost was 15 %, and they added a risk contingency of approximately 1 % to the individual cost items. Consequently, despite a pleasant first part of the collaboration, the different perceptions of the target cost may cause problems during phase 2 (challenges occur).

HOW A COLLABORATIVE DELIVERY METHOD CONTRIBUTES TO DEVELOPMENT OF EXPECTED COST

Regarding the third research question – about how TVD can contribute to developing target cost – the owner and main contractor agreed on a target cost developed during the collaborative schematic design after a halting TVD process. As described in the literature, a potential downside of traditional design and build contracts is that the design concentrates on cost reduction by reducing performance, quality, and profit – not with design and customer input – and that undercuts any motivation for the subcontractors to lower the total cost (Nicolini et al., 2000). This cost-cutting by pure reduction of performance, quality, and profit is unwanted in TVD. Instead, the collaboration should result in innovative solutions for materials and systems that reduce costs while maintaining functions according to the owner's initial specifications. Furthermore, practicing open-book was supposed to support TVD, but the practice deviated from the theory. While the project team shared both model updates and cost estimate updates in the Big Room meetings, the contractor estimated expected costs between the ICE sessions.

Consequently, it became challenging for the owner to evaluate the estimate's basis and unclear if, for example, the estimates were reduced by lowering performance or as a result of design or customer input. The owner was given weekly summaries and spreadsheet overviews, but the owner had to physically access the contractor's computers located at their headquarter for detailed insight. The owner had been able to access estimates, neither on the web-hotel nor physically. This lack of transparency might catalyse the need for reviewing the build-up of the cost estimate. Additionally, the sub-contractors delivered their estimations to the main contractor, who included them in the owner's summaries. As documented in a similar case study, unclear descriptions of how the open book is practiced represent a potential weakness (Larssen et al., 2019).

Lean practitioners on both the owner and contractor sides should be aware that teams do evolve over time and that this development could affect the target value design process. However, one lesson is that the actors - to avoid relational challenges - must agree on both the scope and the target price before they enter the implementation phase.

CONCLUSIONS

This paper reports from the design process (contract phase 1) of a high-performance building. A contractor-led project team collaborated with the owner to reach a target cost corresponding to the owner's allowed cost. The team consisted of the main contractor, the architect, and sub-contractors. The team got a set of ambitions from the owner beyond the typical cost, schedule, quality parameters, developed design, and the corresponding expected cost. In phase 2, the owner and main contractor will sign a design and build contract based on the schematic design and the set target cost.

The development of the expected cost is illustrated in Figure 3. It derailed from the allowable cost quite early, in a realm of positivism where the actors introduced innovative technical solutions to add as much value as possible to the high-performance building. Seeing this in light of how teams develop, we can say that the team went from optimism (forming and storming) towards realism (norming and performing) when the project team put a more considerable emphasis on the expected cost. The managers changed from supporting playfulness towards stressing costs and assessing risks resulting in disagreements in the team, which corresponds well with the norming stage.

Target Value Design's benefits could have increased in the investigated case if the owner had communicated the ambitions more precisely. When the project team started to reduce expected cost 2 to a level corresponding to the owner's allowable cost, the mood changed from positivism to realism. The owner wanted to review the expected cost, while the contractor and the sub-contractors had to remove overhead and risk contingencies they felt entitled to. When the mood changed, the collaboration in the high-performing team of specialists cooled down.

This paper's contribution is the illustration of how the expected cost and the mood of the actors developed. More studies are needed to make sure that cost reduction in TVD projects is achieved by design and customer input and not by reducing performance, quality and profit.

REFERENCES

Ballard, G. 2006. "Rethinking Project Definition in Terms of Target Costing". *14th Annual Conference of the International Group for Lean Construction*, 2006/01/01 Santiago, Chile. Santiago, Chile, 77-89.

Ballard, G. 2007. Target costing in the construction industry. *Presentation in P2SL 2007 Conference.* Berkeley, California.

Ballard, G. 2011. "Target value design: current benchmark". *Lean Construction Journal*, 6**,** 79-84.

Ballard, G., Dilsworth, B., Do, D., Low, W., Mobley, J., Phillips, P., Reed, D., Sargent, Z., Tillmann, P. & Wood, N. 2015. "How to make shared risk and reward sustainable". *Proc. 23rd Ann. Conf. of the Int'l. Group for Lean Construction*. 257-266.

Ballard, G. & Pennanen, A. 2013. "Conceptual estimating and target costing". *Proc. 21th Annual Conference of the International Group for Lean Construction (IGLC)*, 2013/07/31 Fortaleza, Brazil. 31-2.

Ballard, G. & Reiser, P. 2004. "The St. Olaf College Fieldhouse Project: a case study in designing to target cost". *Proc. 12th Annual Conference of the International Group for Lean Construction (IGLC)*, 2014/08/03 Helsingør, Denmark. 234-249.

Bonebright, D. 2010. "40 years of storming: a historical review of Tuckman's model of small group development". *Human Resource Development International*, 13**,** 111-120.

Cooper, R. 1997. *Target costing and value engineering*, New York, Routledge. doi.org/10.1201/9780203737378.

Cooper, R. & Slagmulder, R. 1999. "Develop profitable new products with target costing". *MIT Sloan Management Review*, 40**,** 23.

Denerolle, S. 2013. *The application of Target Value Design to the design phase of 3 hospital projects*, Project Production Systems Laboratory, University of California, Berkeley

Do, D., Ballard, G. & Tillmann, P. 2015. Application of Target Value Design in the Design and Construction of the UHS Temecula Valley Hospital: part 1 of 5. University of California, Berkeley: Project Production Systems Laboratory. 231-245.

Do, D., Chen, C., Ballard, G. & Tommelein, I. D. 2014. "Target value design as a method for controlling project cost overruns". *Proc. 22nd Annual Conference of the International Group for Lean Construction (IGLC)*, Oslo, Norway. 171-181.

Engebø, A., Klakegg Ole, J., Lohne, J. & Lædre, O. 2020a. "A collaborative project delivery method for design of a high-performance building". *International Journal of Managing Projects in Business*.

Engebø, A., Lædre, O., Young, B., Larssen, P. F., Lohne, J. & Klakegg, O. J. 2020b. "Collaborative project delivery methods: a scoping review". *Journal of Civil Engineering and Management*, 26**,** 278-303.

Fischer, M., Ashcraft, H. W., Reed, D. & Khanzode, A. 2017. *Integrating Project Delivery: A Simple Framework for Putting IPD into Action*, Wiley Online Library.

Forgues, D., Koskela, L. & Lejeune, A. 2008. "Breaking Socio-Cognitive Barriers to Value Generation in Integrated Teams". *Proc. 16th Annual Conference of the International Group for Lean Construction (IGLC)*, 2008/07/16 Manchester, UK. Manchester, UK, 435-446.

Freire, J. & Alarcón, L. F. 2002. "Achieving Lean Design Process: Improvement Methodology". *Journal of Construction Engineering and Management,* 128**,** 248-256.
Griffis, F. H. & Butler, F. M. 1988. "Case for cost-plus contracting". *Journal of Construction Engineering and Management,* 114**,** 83-94.
Guilding, C., Cravens, K. S. & Tayles, M. 2000. "An international comparison of strategic management accounting practices". *Management Accounting Research,* 11.
Kato, Y. 1993. "Target costing support systems: lessons from leading Japanese companies". *Management Accounting Research,* 4**,** 33-47.
Knotten, V., Lædre, O. & Hansen, G. K. 2017. "Building design management – key success factors". *Architectural Engineering and Design Management,* 13**,** 479-493.
Larssen, P. F., Engebø, A., Lædre, O. & Klakegg, O. J. 2019. "Contracts and Culture in a Partnering Project". *10th Nordic Conference on Construction Economics and Organization* Talinn, Estonia. Emerald Publishing Limited, 49-57.
Lloyd-Walker, B. & Walker, D. 2015. *Collaborative project procurement arrangements,* Project Management Institute.
Love, P. E. D. & Gunasekaran, A. 1997. "Concurrent Engineering in the Construction Industry". *Concurrent Engineering,* 5**,** 155-162.
Nicolini, D., Tomkins, C., Holti, R., Oldman, A. & Smalley, M. 2000. "Can Target Costing and Whole Life Costing be Applied in the Construction Industry?: Evidence from Two Case Studies". *British Journal of Management,* 11**,** 303-324.
Palmer, A., Kelly, J. & Male, S. 1996. "Holistic Appraisal of Value Engineering in Construction in United States". *Journal of Construction Engineering and Management,* 122**,** 324-328.
Sakal, M. W. 2005. "Project alliancing: a relational contracting mechanism for dynamic projects". *Lean Construction Journal,* 2**,** 67-79.
Sobotka, A., Czarnigowska, A. & Skibniewski, M. J. 2007. "Target costing in public construction projects". *Proc. 9th International Conference Modern Building Materials, Structures and Techniques,* Vilnius, Latvia. 16-18.
Tanaka, M. 1990. "Topics in target costing in Japanese companies". *Genka Keisan,(Special Issue),* 28**,** 43-65.
Tillman, P., Do, D. & Ballard, G. 2017. "A Case Study on the Success Factors of Target Value Design". *Proc. 25th Annual Conference of the International Group for Lean Construction (IGLC),* 2017/07/9 Heraklion, Greece. 9-12.
Time, B., Engebø, A., Christensen, M., Dalby, O. & Kvande, T. 2019. "The design process for achievement of an office living laboratory with a ZEB standard". *IOP Conference Series: Earth and Environmental Science,* 352**,** 012053.
Torp, O. 2019. "How Stochastic Cost Estimates Could Be Applied in Relation to Target Value Design". *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*, 2019/07/03 Dublin, Ireland. Dublin, Ireland, 595-606.
Tuckman, B. W. 1965. "Developmental sequence in small groups". *Psychological bulletin,* 63**,** 384-399.
Tuckman, B. W. & Jensen, M. A. C. 1977. "Stages of small-group development revisited". *Group & Organization Studies,* 2**,** 419-427.
Wondimu, P. A., Klakegg, O. J. & Lædre, O. 2020. "Early contractor involvement (ECI): ways to do it in public projects". *Journal of Public Procurement*.
Zimina, D., Ballard, G. & Pasquire, C. 2012. "Target value design: using collaboration and a lean approach to reduce construction cost". *Construction Management and Economics,* 30**,** 383-398.

Dragone, I.S., Biotto, C.N., and Serra, S.M.B. (2021). "Evaluation of Lean Principles in Building Maintenance Management." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 13–22, doi.org/10.24928/2021/0151, online at iglc.net.

EVALUATION OF LEAN PRINCIPLES IN BUILDING MAINTENANCE MANAGEMENT

Isabela S. Dragone[1], Clarissa N. Biotto[2], and Sheyla M. B. Serra[3]

ABSTRACT

Buildings do not usually receive the necessary maintenance during their use, which may cause serious accidents. Building maintenance is essential for ensuring the project's planned performance, safety, and functionality during the phase of use and occupation, which are ensured by the maintenance management. However, with the increasing complexity of buildings, the traditional maintenance management methods have become outdated. The lean mentality is shown as a viable alternative since it is possible to apply it in building maintenance through its principles and practices. The research strategy adopted was the case study carried out in a building maintenance company. A lean maintenance checklist was created, composed of 46 practices grouped in the five lean principles, which support identifying the level of lean maintenance deployed in the activities and processes of building maintenance management adopted by the company.

KEYWORDS

Lean construction, lean maintenance, building maintenance management, construction industry.

INTRODUCTION

Buildings must have adequate conditions for use, necessary maintenance to prevent accidents caused by failures or wear of use/operation, and ensure its conservation and satisfactory performance throughout its useful life (Carlino, 2012).

There are three stages in the life cycle of buildings, as suggested by Lessa and Souza (2010). The first stage is related to study and to plan activities, such as viability, studies, and design documentation development. The second encompasses the activities related to the execution of the construction and assembly of buildings, and the third is the stage of use, operation, and maintenance.

Akcamete, Akinci and Garrett (2010) point out that the largest share of expenses within the building's life cycle occurs in the last stage, representing approximately 60% of all the costs involved. Furthermore, these authors indicate that corrective maintenance, which acts after the deterioration mechanism occurs, corresponds to this cost's more significant portion. The consequences of the lack of building maintenance, or its inadequate application, entails risks in its users' safety, no guarantee of the building

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lifespan, and high repair costs that could be avoided. According to the Brazilian Institute of Assessments and Engineering Expertise of São Paulo - IBAPE /SP (2015), more than 60% of buildings' accidents are caused by failures in maintenance and use.

In this context, maintenance management is responsible for planning, controlling, and executing building maintenance. However, the traditional management methods are no longer indicated, as they have not followed the evolution of buildings, which tend to have larger dimensions, especially vertically, besides existing more complex equipment and technologies that serve an increasing number of users (Abreu, Calado, and Requeijo, 2016). Thus, the importance of having more efficient maintenance has been demonstrated through recent studies that try to relate lean thinking with maintenance strategies, as claim Mostafa and Soltan (2014).

The lean philosophy aims to reduce activities or services that do not add value to the customer (user), and despite its initial development in the industrial environment, it can be applied in the service sector. Hence, it emerges the focus on lean maintenance, which still lacks studies on the drivers and barriers of implementation and its benefits for the building maintenance sector.

Therefore, through a case study, this paper proposes to identify the lean maintenance management principles and practices used by a company responsible for the building maintenance and in which conditions they are applied.

LITERATURE REVIEW

BUILDING MAINTENANCE MANAGEMENT

To ensure that the buildings and systems meet their functional capability,requirements and users' safety, it is necessary to apply a set of conservation or recovery activities, called maintenance (ABNT NBR 5674, 2012). It ensures that the building complies with standards and laws (Abreu, Calado, and Requeijo, 2016). The maintenance system is the "set of procedures organised to manage maintenance services". It aims to preserve the building's original characteristics and prevent its loss of performance defined in the design, resulting from the degradation of its systems, elements, and components (NBR 5674 ABNT, 2012).

The usual functions of the building maintenance management are preparation of plans, procedures, and routines of maintenance, operation of equipment and building facilities, manage works, documentation of the building and related equipment, human and material resources, contracts of external service providers, and prepare maintenance budget ensuring rationalisation and cost control (NBR 5674 ABNT, 2012; Abreu, Calado and Requeijo, 2016). In addition, the BMM must perform preventive, corrective and routine maintenance activities (NBR 5674 ABNT, 2012).

LEAN PRINCIPLES AND WASTE IN MAINTENANCE MANAGEMENT

The five lean principles proposed by Jones and Womack (1996) are the same in maintenance aspects (Davies and Greenough, 2010, Mostafa, Dumrak, and Soltan, 2015). Moreover, Pinto (2013) describes these five principles from the lean maintenance perspective as:

1. Identify the value: what the customer expects with maintenance, zero breakdowns, zero accidents, zero costs, sustained increase in efficiency in operations, among others;
2. Map the value stream: identify which are the steps within maintenance that deliver value to the customer;

3. Create a continuous flow of value: improving information, material and people flows in order to accelerate value creation processes by eliminating waste;
4. Establish pull: perform tasks only when necessary within the management of reserve materials, supplier management, and communication;
5. Seek perfection: encourage maintenance employees to improve performance with the adoption of systematic tools and methodologies that promote proactive practices and attitudes towards maintenance in order to eliminate activities that add time and cost;

Specifics actions should be taken to achieve the lean maintenance principles. For value definition, the organisational maintenance system must be define, including activities, planning, team, and training of those involved (Mostafa, Dumrak, and Solta, 2015). In identifying the value stream, the authors suggest mapping the maintenance value stream (current state), identifying waste in all activities and processes related to maintenance, and defining the performance measures of maintenance elements (Mostafa, Dumrak, and Solta, 2015).

In sequence, to create a continuous flow of value are the analysis of networks and waste practices, prioritisation of removing these, and documentation of gaps in the current state of maintenance management. Subsequently, it is recommended to reconfigure the value stream map (future state) with the selection of best lean practices, followed by the simulation and execution of lean maintenance that should have its overall effectiveness evaluated, thus configuring the step of applying the pull logic (Mostafa, Dumrak and Solta, 2015).

Finally, Mostafa, Dumrak, and Soltan (2015) suggest auditing lean maintenance results, creating standardisation of lean practices and procedures, developing teams and employees, and expanding lean practices to seek perfection in all processes.

Specifically for the maintenance of buildings, Abreu, Calado, and Requeijo (2016) propose applying lean philosophy in four phases/pillars based on the elimination of waste and the principles of continuous improvement (seeking perfection) definition/creation of value. The proposal of these authors, named Lean Building Maintenance (LBM), can be seen in

Figure 1.

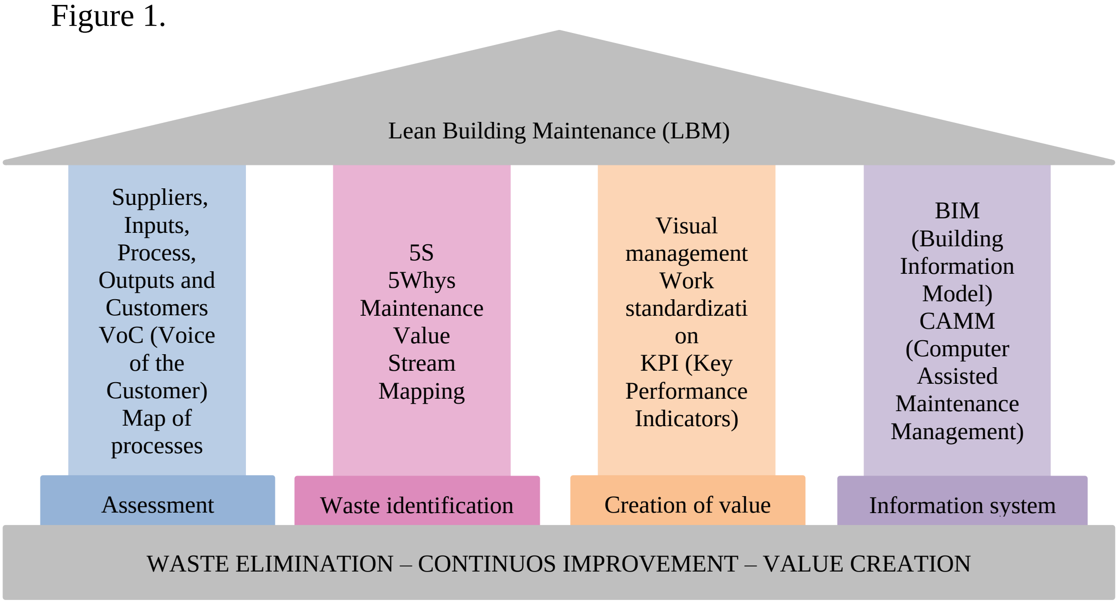

Figure 1: Lean Building Maintenance House (adapted from Abreu, Calado, and

Requeijo, 2016)

The first phase/pillar of Figure 1 aims to evaluate the organisation's state and knowledge to obtain the diagnosis of the most accurate current state possible. The second aims to identify waste, such as activities that do not add value to the organisation and suggest improvements. Thus, the actions of the first and second phase of this proposal include the actions related to the principles "1. Identify value", "2. Map the value stream", and "3. Create a continuous flow" from the previous proposal.

The third stage resembles the stage that addresses the fourth and fifth principles of the previous proposal, which are, respectively, "4. Establish pull" and "5. Seek perfection". In this stage, after applying suggested lean tools and practices, the objective is to expose the value creation to the organisation by measuring the impact of the implemented improvements and the elaboration of standardisation of practices.

Finally, the fourth stage/pillar aims to implement a computerised system to support decision-making and enable a more efficient administration of the volume of information required to manage activities.

To achieve the objective of each phase, the authors propose tools that are exposed in Figure 1 in their respective pillars.

THE 8 WASTES IN MAINTENANCE

The wastes within maintenance are proposed by different authors based on the original wastes defined by Ohno (1997). Within the bibliography, the proposals that most closely resemble each other are Pinto (2013), Clarke, Mulryan, and Liggan (2010), and Mostafa, Dumrak, and Soltan (2015). For Pinto (2013), the eight maintenance wastes are:

1. Unproductive work – performing activities that do not add value, such as unnecessarily performing preventive maintenance tasks or at intervals smaller than what is necessary;
2. Rework – incorrect performance of tasks that must be redone;
3. Waiting for resources – long periods of inactivity due to the lack of availability of materials, workforce, equipment, or information to accomplish the task;
4. Poor inventory management – not having or having excess material to perform the tasks;
5. Excessive transportation – an excessive movement of materials and information due to the unavailability of documentation and work orders and provision of resources away from work areas;
6. Waste by movement – loss of time in round trips due to the lack of an appropriate and unique place for the disposal of materials and documentation that are essential to the performance of maintenance services;
7. Ineffective data management – a collection of information that is not necessary, absence of vital data collection or inefficiency in data collection due to the lack of interconnection of this data with maintenance processes, e.g., with inspections;
8. Under utilisation of resources – an absence of the maximisation of resources is material or human, being the human exemplified by the non-use of such a skill set.

Clarke, Mulryan, and Liggan (2010) present the "incorrect application of machinery", which would be the incorrect operation of tools or choice of operational strategies that apply unnecessary maintenance services. Mostafa, Dumrak, and Soltan (2015) present in the "maintenance without the standard", as the operations are done as quickly as possible, without guidelines and standard procedures, eliminating the opportunity to perform a higher quality repair.

LEAN PRACTICES AND TOOLS

Lean tools represent applying the principles during this philosophy's implementation (Mostafa, Dumrak, and Soltan, 2015). Among the various existing tools, those that cover maintenance activities are: 5S; 5Whys; Total Production Management (TPM); *Kaizen*; *Poka-Yoke*; *Kanban;* Process Mapping (PM); Computerized Maintenance Management System (CMMS)/Computer-Aided Maintenance Management (CAMM); Just In Time; Failure Mode and Effect Analysis (FMEA); standardisation of procedures; Value Stream Mapping (VSM); Visual Management (Smith, 2004, Davies, Davies and Greenough, 2010, Mostafa, 2015, Abreu, Calado and Requeijo, 2016).

Building Information Model (BIM) can also help organisations manage maintenance information (Mostafa, Dumrak, and Soltan, 2015). Furthermore, PM differs from VSM by focusing on individual processes rather than material flows and product-related information. Also, the future state view of a Process Map is defined in noticeable improvements and does not consider lean principles such as VSM (Ferro, 2005).

RESEARCH METHOD

The research strategy adopted was the case study in a building maintenance company. It was developed a lean maintenance checklist for data collection with the study's participants.

DATA COLLECTION

The literature review was the basis for structuring the initial data collection tool, mainly NBR 5674 (ABNT, 2012) and lean principles. It was developed in joint with the participating company as a research protocol to diagnose their processes and understand the maintenance activities flow. Furthermore, the protocol inspired the tool for conducting qualitative exploratory research based on the method proposed by Toledo and Shiaishi (2009).

The final version of the checklist was divided into three parts: characterisation of the company and interviewees; identification of procedures, activities, tools, and practices used in maintenance management through lean maintenance principles (criteria). A set of best practices has been established for each principle of lean maintenance (criteria) based on the bibliographic review. This third part of the checklist (Table 1) contains 46 items to evaluate lean maintenance principles.

It is noteworthy to mention that the data collection was performed remotely through videoconferencing tools due to the social distance imposed by the Covid-19 pandemic. The application of the questionnaire had a duration of one and a half hours on average. The interviewee was the Maintenance Manager of the studied company, and it was not requested that he knew lean concepts.

DATA ANALYSIS METHOD

The data analysis was based on the method proposed by Saurin and Ferreira (2008), in which the criteria are analysed individually, qualitative, and quantitatively. Each lean principle, i.e., criterium, of the checklist had a total score resulted by the sum of each practices' scores. The researchers attributed the score according to the lean practice level in maintenance management (see Table 2).

Table 1: Checklist for the evaluation of lean maintenance principles in buildings

1	**Identify the value**
1.1	There is a maintenance plan
1.2	The maintenance plan is periodically reviewed
1.3	There is a standardised protocol/process for supplier management
1.4	Is there a system for identifying the opinion, need and preferences of the end customer (VoC)
1.5	Pre-site inspections are carried out periodically
1.6	End customers (users) are oriented on proper use and emergencies
1.7	Maintenance personnel are trained to learn about the philosophy, principles, and basic practices of lean maintenance
1.8	There is a computerised system for information management
2	**Map the value stream**
2.1	There is a map of maintenance processes
2.2	There is a map of the current state of the maintenance process
2.3	A team draws up the current state map with representatives from each part of the process
2.4	There are indicators for maintenance management
2.5	There are evaluation and review of the indicators of the
2.6	Area indicators and metrics are disseminated to all employees
2.7	The use of visual devices is disseminated for the sharing of information
2.8	There is a computerised system for information management
3	**Create continuous value flow**
3.1	There is a future state map, and action plans to implement it
3.2	A team with representatives from each part of the process analyses the map of the current state and elaborates the future state
3.3	Structured tools are used for analysis and waste solution, such as 5Whys, fishbone diagram, or brainstorming
3.4	There is an application of 5S or similar programs
3.5	There is a preference for preventive maintenance rather than corrective maintenance
3.6	There are operation sheets and standard routines to guide maintenance activities
3.7	There is a maintenance plan
3.8	There are specific locations for depositing materials and searching for information, and these favours the performance of the activities
3.9	The use of visual devices is disseminated for information sharing and visualisation of the process flow from start to finish
3.10	There is the autonomy of employees to perform their duties (no need for verification by the highest positions)
4.	**Establish pull**
4.1	There is a computerised system for information management
4.2	There are devices to pull process activities
4.3	There are devices to identify the removal of items from the process, such as materials and equipment
4.4	If kanban cards are used, the subsequent activity removes information from the preceding only in the quantities and in the necessary time
4.5	There are no large stocks
4.6	Supplier deliveries are pulled rather than pushed
4.7	Suppliers deliver in small batches and often
4.8	Devices for pulling material deliveries contain information about what is requested when to arrive, how much, and where it should be stored
4.9	There is an established partnership with suppliers
4.10	There is an established partnership with outsourced services when necessary
5	**Seek perfection**
5.1	There is an evaluation of the indicators of the area
5.2	Structured tools are used for analysis and troubleshooting, such as PDCA, 5Whys, 5W2H, fishbone diagram, or brainstorming
5.3	Action plans are drawn up for improvements
5.4	Senior management is involved with improvement programs
5.5	New implemented practices are expanded to other activities/processes
5.6	The improvements made are standardised
5.7	Employees participate in the development of standards to incorporate their experiences into them
5.8	The goals and indicators of the area are clearly defined and communicated to all involved
5.9	The goals of the area are clearly and objectively unfolded so that continuous improvement actions contribute to achieving them
5.10	Maintenance personnel are trained to learn about the philosophy, principles, and basic practices of lean maintenance

Table 2: Parameters for the evaluation of the lean maintenance practices

Parameters	Description of the level of application	Score
Does not apply (NA)	the practice is not applied due to the company's characteristics	0,0
Does not exist (NE)	the practice is not present in the company	0,0
Very weak application (VWA)	the practice has its use started recently in the company or is practised rarely or for a specific situation	2,5
Weak application (WA)	the practice is in use in the company but is applied in a few situations	5,0
Strong application (SA)	the practice is in use in the company and is applied to most situations	7,5
Very strong application (VSA)	the practice is already fully consolidated in the company and use	10,0

The following equation gives the scores for each lean maintenance principle: A is the number of applicable practices; B is the number of very weak application (VWA) practices; C is the number of weak application (WA) practices; D is the number of strong application (SA) practices, and E is the number of very strong application (VSA) practices.

$$Score = \frac{(Bx2{,}5) + (Cx5{,}0) + (Dx7{,}5) + (Ex10{,}0)}{A}$$

The Case Study Company

The case study was conducted in a maintenance management company located in São Paulo, Brazil. The company was identified in the Brazilian Association of Facilities' (ABRAFAC) register. It is a Brazilian firm founded in 1985, which operates in the industrial maintenance sector, facilities, administration, and logistics, having 35,000 employees in Brazil and Argentina and 300 customers, serving approximately 1500 units in Brazil and 1 in Argentina.

For each new client, a contract is drawn up according to their needs. For the case study, the maintenance company had a fixed maintenance team in the clients' facilities: they served three industrial buildings of approximately 78,000 sqm and ages from 5 to 25 years. The team consisted of nine employees: one maintenance supervisor, one planner, two electricians, one maintenance officer, one maintenance assistant, one refrigeration mechanic, one painter and one builder. In this case, the builder assists other employees and performs the inspection of equipment and systems.

RESULTS - COMPANY'S LEAN MAINTENANCE PRINCIPLES SCORE

The results of the application of the lean principles in building maintenance management are depicted in Figure 2 there is a score for the practices applied by the maintenance company. The average score of company for the principles is in chart 6 - Figure 2.

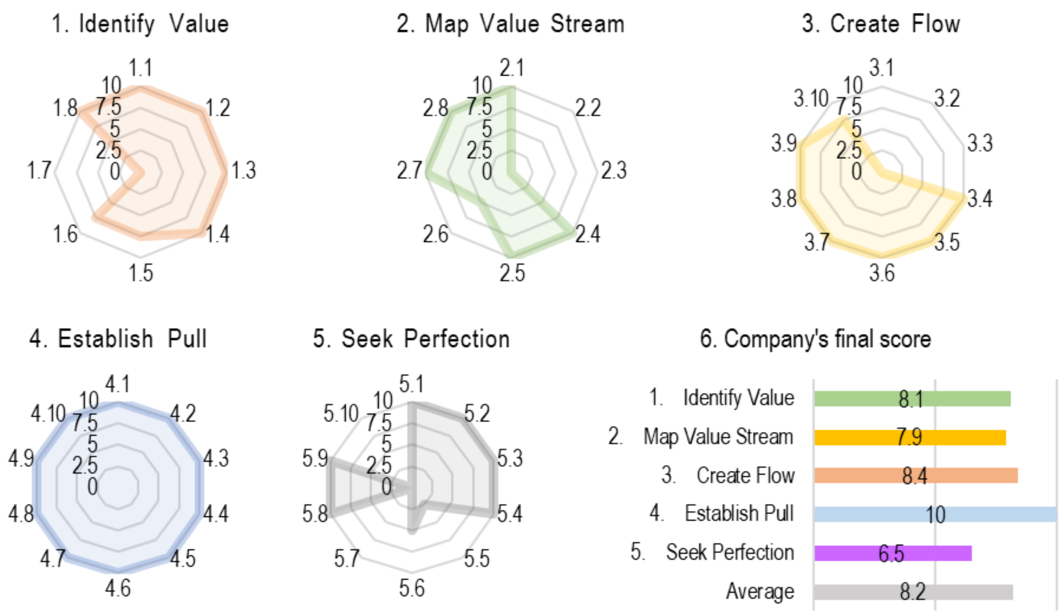

Figure 2: Charts 1 to 5 represent the company's scores in the application of lean principles. Chart 6 is the average score achieved for each principle.

In principle **"1. Define Value"** (note 8.1), the company highlighted the application of a customer's satisfaction survey with the periodicity of 6 months, evaluations of corrective work, which is also a metric for management, in addition to a frequent dialogue with the unit manager. These actions indicate a concern with the users' opinions, needs, and preferences. The first two practices are recorded in a computerised management system. It was also detected other relevant practices, such as the maintenance plan; standardised process for suppliers' management; building inspections; and users' guidance regarding the building's use and operation, including emergencies.

It has also been reported that clients invest in preventive maintenance and others who focus only on corrective maintenance. Others require verification of all services performed, making it difficult to flow activities. All these requirements are defined in advance in the contract and are the basis for the service provider's maintenance. In addition, it reveals an identification of the value coming from the contract since all customer/users' preferences are defined.

The principle **"2. Map the value stream"** (score 7.9) regards disseminating indicators and metrics. The indicators are essential to perform a critical and systemic analysis of the deployed building maintenance management and help identify waste. The company has the following indicators: productivity; the percentage of preventive maintenance execution; the number of orders in "backlog" (orders that were not performed); deviation scheduled vs executed correctives; and the service lead time per order. The tool suggested in the literature review, Value Stream Map, is not applied. However, the company uses the process map, which is disseminated visually by the computerised management system and accessed by all employees through mobile devices, such as smartphones or tablets.

The maintenance plan for each asset also contains standardised maintenance procedures. These procedures support creating a continuous flow of value according to Principle **"3. Create Flow"** (note 8,4). As a rule, imposed by the contractor, the company applies the 5S in the office and warehouse. In addition, the computerised system centralised the maintenance process information, being possible to verify the activities statuses. Also, employees have the autonomy to carry out their activities, and checks are required by the supervisor only when it interferes with safety or essential activities to production.

The principle **"4. Establish Pull"** reached the maximum score (10.0) since the computerised management system pulls the process activities, besides having a small inventory and partnership with suppliers and subcontractors. In addition, the computerised system records the requested materials by suppliers, their quantities, and the delivery dates.

The principle **"5. Seek perfection"** (score 6.8) has the lowest evaluation score. It is mainly due to employees' non-participation in the practice's standardisation and the lack of training on lean philosophy. However, other practices of this principle have been implemented, such as the PDCA and the Ishikawa diagram. An example of improvement was implementing the DDS (Daily Dialogue on Safety), reducing about 99% of accidents.

Due to the lack of training on lean philosophy, the non-participation of employees in the standardisation of practices, and the presentation of goals focused only on individual productivity, and it is evident that there is no involvement of all hierarchical levels in the continuous improvement.

In principles 2 and 5 (Map the value stream and Seek perfection), the deployed process map and indicators do not consider aspects of lean philosophy, such as *waste,* which would lead to continuous improvements.

In conclusion, it was verified that the company presented high marks for all the principles of lean maintenance despite not having any specific program of lean. The final score obtained by the company was impacted by the client preferences established in the contract, namely, the level of services quality, the types of maintenance to be performed, level of employees’ autonomy, application of 5S, among other requirements such as monthly presentations of five improvement proposals.

CONCLUSIONS

Despite the consensus regarding the importance of building maintenance, there are still many buildings in which it is neglected or misunderstood, resulting in risks to its users’ safety, no guarantee of the lifespan of the building, and high costs that could be avoided. Maintenance management is responsible for planning, controlling, and executing building maintenance, ensuring compliance with requirements.

Hence, a case study in a building maintenance and management company was carried out to evaluate its lean maintenance practices within its client. Results obtained through the application of a checklist showed that the maintenance management prioritises preventive and predictive maintenance activities and the application of many lean practices and tools, reaching grades between 6.8 and 10.0 and an average of 8.2 for the five lean maintenance principles. Furthermore, the average score was obtained after applying the checklist prepared with the best practices observed in the literature, demonstrating that the company can improve based on lean principles and technical standards for maintenance management.

Several requirements pointed out by NBR 5674 (ABNT, 2012) are framed as good practices of the lean maintenance principles, which contributed to the excellent average obtained. As the company is hired to do maintenance management, it became an expert and started to incorporate some lean practices due to the request and influence of customers/users in the implementation of contracts. This point of outsourcing the service can be considered as a positive impact to achieve a high score.

The organisational culture had also impacted positively on the results regarding the lean practices: the understanding of maintenance and the importance to perform different maintenance types; the application of 5S; the use of small inventories; the development of partnerships with suppliers and subcontractors. The isolated application of practices and tools does not guarantee the application of lean mentality since critical points such as the involvement of all employees in the improvement processes and the identification of waste and employees' training on lean were not applied in the case study.

Therefore, the lean mentality can help build maintenance management since it is implemented strategically, addressing its concepts and not only practices and tools. However, more important than its implementation is the attention paid to the normative requirements and recommendations of the bibliography for efficient building maintenance management.

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REFERENCES

Abreu, A., Calado, J., and Requeijo, J. 2016. "Buildings Lean Maintenance implementation model." *Open Engineering*, 6(1), 397-406.

Akcamete, A., Akinci, B., and Garrett, J.H. 2010. "Potential utilisation of building information models for planning maintenance activities." In Proc., The International Conference on Computing in Civil and Building Engineering. Nottingham: W Tizani.

Brazilian Association of Technical Standards (Associação Brasileira de Normas Técnicas - ABNT). 2012. *NBR 5674: Manutenção de Edifícios - Requisitos para o sistema de gestão de manutenção.* Rio de Janeiro: ABNT.

Brazilian Institute of Assessments and Engineering Expertise of São Paulo (Instituto Brasileiro de Avaliações e Perícias de Engenharia de São Paulo - IBAPE/SP). (Ed.2). 2015. "Inspeção Predial: a saúde dos edifícios". São Paulo, Brazil: IBAPE/SP.

Carlino, A.E. 2012. "Melhorias dos processos de manutenção em prédios públicos." *M.Sc. Thesis*, Master in Structures and Civil Construction, Federal University of São Carlos, São Carlos.

Clarke, G., Mulryan, G., and Liggan, P. 2010. "Lean Maintenance: a risk-based approach." *International Society for Pharmaceutical Engineering*, 30(5), 1-6.

Davies, C., and Greenough, R. M. 2010. "Measuring the effectiveness of lean thinking activities within maintenance." 9p. Available in: http://www.plant-maintenance.com/articles/Lean_Maintenance.pdf.

Ferro, J.R. 2005. "A essência da ferramenta Mapeamento do Fluxo de Valor." *Lean Institute Brasil*. Available in: https://www.lean.org.br/artigos/61/a-essencia-da-ferramenta-mapeamento-do-fluxo-de-valor.aspx.

Womack, J.P., and Jones, D.T. 1996 "Beyond Toyota: how to root out waste and pursue perfection." *Harvard Business Review*, 74(5), 140-172.

Lessa, A.K.M.D.C., and H.L. de Souza. (Ed.1). 2010. *Gestão da Manutenção Predial: uma aplicação prática*. Rio de Janeiro: Qualitymark.

Mostafa, S., Lee, S. H., Dumrak, J., Chileshe, N., and Soltan, H. 2015. "Lean thinking for a maintenance process." *Production and Manufacturing Research*, 3(1), 236-272.

Mostafa, S., Dumrak, J., and Soltan, H. 2015. "Lean maintenance roadmap." *Procedia Manufacturing*, 2, 434–444.

Mostafa, S., and Soltan, H. 2014. "Leanness and agility within maintenance process." *International Journal of Engineering Research & Technology*, 3(3), 553–555.

Ohno, T.O. 1997. *Sistema Toyota de Produção: além da produção em larga escala*. Porto Alegre: Bookman.

Pinto, J.P. 2013. *Manutenção Lean*. Lisbon: Lidel.

Saurin, T.A., and Ferreira, C.F. 2008. "Avaliação qualitativa da implantação de práticas da produção enxuta: estudo de caso em uma fábrica de máquinas agrícolas." *Gestão & Produção*, 15(3), 449–462.

Smith, R. 2004. "What is Lean maintenance? Elements that need to be in place for success." *Maintenance Technology*, 17(10), 15–21.

Toledo, L.A., and Shiaishi, G. de F. 2009. "Estudo de caso em pesquisas exploratórias qualitativas: um ensaio para a proposta de protocolo do estudo de caso." *Revista da FAE*, 12, 103–109.

Malvik, T.O., Kalsaas, B.T., Shabani, R., and Sandvik, K.O. (2021). "The Impact of BVP in a TVD Based Project Delivery" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 23–32, doi.org/10.24928/2021/0162, online at iglc.net.

THE IMPACT OF BVP IN A TVD BASED PROJECT DELIVERY

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ABSTRACT

Best Value Procurement (BVP) and Target Value Delivery (TVD) are registered to be increasingly applied in construction, and in some cases, also in the same project. The purpose of our paper is to address these two concepts theoretically and empirically to see if challenges occur when combining BVP and TVD. We deduce the proposition from a theoretical analysis: *Best Value Procurement (BVP) is inconsistent with the Target Value Delivery (TVD) approach.* We have examined a theoretical-oriented case study of a Norwegian highway construction project. Data was gathered by document analysis, direct observation, and semi-structured interviews. One finding was that BVP did not hinder the client from being a proactive actor and solution enabler in collaboration with the general contractor team. The study shows a lack of alignment of joint project development with a BVP and TVD structure. BVP has proved good results in projects using transactional contracts. However, in projects based on a relational contract, a more direct dialogical procurement approach may be more productive. The paper contributes to the literature by pinpointing conceptual and empirical counterproductive differences when combining BVP and TVD.

KEYWORDS

Best value procurement, Target Value Delivery, contradiction, decision-making.

INTRODUCTION

Best Value Procurement (BVP) is a procurement system based on the principle that the supplier (the Design-Build contractor and their team) is the expert relative to the client and thereby better suited to identify and handle project risk (Kashiwagi 2011). Target Value Delivery (TVD) emphasises the call for Lean Construction processes in target costing and value engineering. This comprises a management practice that drives the design and construction to deliver customer values within project constraints using costs and a value-driven design process instead of calculating the price after the design is completed, i.e., what value one can get for a given cost (Zimina et al. 2012). Such

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processes include Integrated Concurrent Engineering (ICE) and consensus decision-making with an orientation towards customer value delivery.

BVP and collaborative approaches have been presented as potential means to deal with increasingly large and complex projects in Norway (Malvik et al. 2021). However, there is a lack of a connection between the choice of procurement method and the level of integration it facilitates in the clarification and execution phase. Therefore, this paper aims to study the link between BVP and TVD and see if it is fruitful to combine the concepts.

We first address the method before we outline and discuss the concepts of BVP and TVD. We end the theoretical section by comparing the two concepts as a basis to create a research proposition. Then the case study is presented and discussed.

METHOD

This paper combines theory with empirical evidence to challenge and verify the applied theoretical informed proposition. A literature review and case study with mostly direct observations, interviews, and document analysis were used to gather information. The observations mainly were direct, but the researcher also had a participating role on some occasions. The case study approach was developed based on the method described by Yin (2018). Different sources lead to triangulation in practices and result in more data reliability (Gray 2013). The literature review aids in familiarising BVP, TVD, procurement procedures, delivery methods, and other related concepts and compliments the interviews from a technical perspective.

In the document analysis, project documents from the case study were reviewed, and essential information project details extracted. A public highway construction project in the design development phase was considered for this study.

An interview guide was designed for the interviews. Five main questions were asked with the guidance of the experienced authors. The interviews were directed by two authors with over 20 years of experience in the construction industry. Follow-up meetings were scheduled with interviewees to address any potential information gaps. The interviews were carried out as semi-structured roleplay exercises by experts in the roles of client project managers and winning contractors. The interviews each took approximately two hours. One of the authors has observed the project for almost one year, being part of its online engineering meetings and ICE sections, where three to five meetings have been observed weekly.

THEORETICAL BACKGROUND

BEST VALUE PROCUREMENT

BVP was developed by Kashiwagi and his research group at Arizona State University in the period 1991–2010 (Kashiwagi et al. 2012). The concept is claimed to be a paradigm change compared to the traditional Design-Bid-Build model. Kashiwagi also denotes the new approach Performance Information Procurement System (PIPS) regarding the underpinning of theoretical statements. The statements are denoted deductive logic and referred to as “Information Measurement Theory”. BVP/PIPS is a licensed technology from Arizona State University. However, it seems like the environment in the Netherlands later to a larger extent address Best Value Approach (BVA) or just Best Value (BV) in accordance with Kashiwagi's theory. The difference to BVP is that the execution phase, and not procurement phase, is in center of the approach[5].

BVP/PIPS was introduced into the Netherlands in 2005 by a large general contractor, Heijmans, and the method was modified to align with European procurement law. Following the introduction to the Netherlands, the methods have become known as BVP, at least in Europe (Kashiwagi et al. 2012).

One statement in the deductive logic is that client decisions increase the risk in construction projects organised as in Design-Bid-Build. In BVP, the basic idea is that the client should minimise risk in the whole project by selecting a vendor to meet this aim. Clients undertake risk reduction by choosing the expert vendor with experience to prevent and minimise risk for both parties. Best value is the best value with the lowest cost measured against the performance in line with the client's project goals. BVP is a process that helps clients choose the expert contractor by feeding necessary information on contractors' performances.

The Norwegian Agency for Public and Financial Management (DFØ) has produced a guide with five phases for BVP (DFØ 2021). The studied case relied on the process described in this guide (Figure 1).

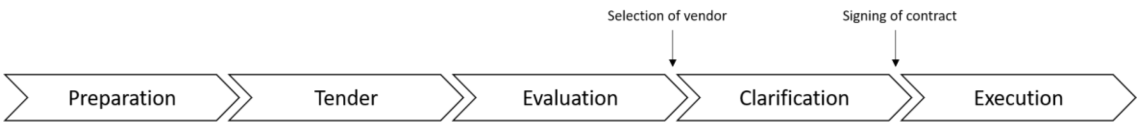

Figure 1: The BVP process, as described by DFØ (2021).

- The Preparation phase includes the presentation of functional requirements, primary goals, and pre-qualification.
- In the Tender phase, the selected vendors are preparing their offer using the required BVP template, and the client is providing the necessary common exchange of information. The template should include text about achievements, a risk assessment, and added value. Project objectives and the allowed cost are decided.
- During the Evaluation phase, all vendors are subject to individual interviews. After ranging the offer, the best vendor is invited to the Clarification phase.
- In the Clarification phase, the best vendor clarifies all risks and describes how to solve the task.
- During project Execution, engineering and construction are carried out using weekly risk reports. The expert vendor controls the project and practices management by risk minimisation.

TARGET VALUE DELIVERY (TVD)

The TVD concept has its roots in target costing, which was introduced in the early 1960s by companies in Japan. One of those companies referred by Cooper and Slagmulder (1997) was Toyota. These firms developed two specific cost management techniques to manage the cost of future products: target costing and value engineering.

Target costing deals with the practice of identifying the target cost of a product by subtracting the desired profit margin from the expected selling price; designing the

[5] Lecture June 15th 2021, in a DFØ-seminar, by Sander Groebe, Rijkswaterstaat, Ministerie van Infrastructuur en Waterstaat. His lecture was titled Best Value at RWS.

product so that it can be manufactured at the target cost; decomposing the target cost to component level, and using the target cost at this level as the basis for supplier negotiations. Value engineering is a multidisciplinary team effort to explore ways to increase functionality and quality and meet target costs. Functionality is multidimensional and includes both product and service issues. The objective of value engineering is not to minimise product cost but to maximise functionality within any target cost constraint.

Ballard (2011) replaced target costing in construction with target value design (TVD). Until then, target costing had been applied in construction for a considerable time. An example is the Cathedral Hill Hospital project which received considerable attention since it began in 2007 (e.g., Zimina et al. 2012). Later, Ballard (2020) argued that Target Value Delivery should be used instead of Target Value Design. The latter suggests that the mindset is limited to the design phase, while the former includes the whole delivery process. Zimina et al. (2012) argued that TVD applied in construction took the relevant features of target costing to fit the construction context. (Gomes Miron et al. 2015; Ballard 2020) argues that TVD is, like target costing, focused on cost mechanisms but pays more attention to generating value throughout a project.

A fundamental concept of TVD comes from value engineering and the search for alternative components, solutions, and functionality in product development. According to Azari et al. (2014), construction projects are becoming more complex, uncertain, and pushed to move faster. The authors emphasise the importance of relational contracting and Early Contractor Involvement (ECI) to cope with this.

In TVD, the owner defines the Allowable Cost (AC), i.e., how much the owner is willing to pay for the project. Next, the project team determines the Expected Cost (EC) based on the designed Bill of Quantities (BoQ) and related market prices. If the AC is greater or equal to the EC, the project can proceed. Then, the owner/client and contractor agree on a Target Cost (TC) for the project (Johansen et al. 2021). The objective is to drive down the EC during the project by implementing lean construction processes and TVD measures to reach the target cost. TVD projects have an incentive structure to support behaviours in sharing the risks and benefits of cost reduction. It is crucial for the owner and end-users that the final product's value is unaffected by the hunt for reduced work cost. This is why the concept deals with design-to-cost and design to the concrete project goals, which the client sets.

To cope with this, the TVD project approach highlights the importance of trust, collaboration, early involvement of contractors, cross-disciplinary problem-solving, and transparency (Do et al. 2014). Do et al. (2014) indicates from their research that TVD projects achieve 15–20% lower costs than traditional market bidding projects.

TARGET VALUE DELIVERY (TVD) VS BEST VALUE PROCUREMENT (BVP)

What TVD and BVP have in common is that both approaches have their point of departure in target cost; however, in BVP, the client budget price or maximum price is denoted. Value (for the client) in TVD is the maximum value delivered within the constraint of the target price, not the lowest cost. Value in BVP is conceived in a similar manner but may be more biased to the cost side. Both TVD and BVP measure value related to the specific project goals set by the client.

The differences become visible when we ask how value is achieved. In TVD, value is achieved by collaboration where the client, the designers, and contractors develop and execute the project together. The different experts join forces in mutual processes and joint decision making. In BVP, on the other hand, the expert contractor takes care of the execution on behalf of both the client and all the vendors in a transparent environment. Frequent risk reporting is part of this. The vendor takes care of the decisions when they are contracted. During the BVP Tender phase, there is no space for negotiation.

In the case study, the applied procurement method is BVP, and the TVD execution model includes an integrated phase of project development, including the client, designers, and contractors. The execution phase is organised around mutual decision processes and an open book approach. In other words, we deal with something that appears to be a contradiction between the procurement method and the development and execution model.

Following this, we have deduced that *Best Value Procurement (BVP) is not consistent with the Target Value Delivery (TVD) approach*. The proposition suggests that combining the concepts of BVP and TVD may lead to conflicting results, which will be addressed in the empirical analysis.

CASE STUDY

Characteristics of the case that has been investigated are presented in Table 1.

Table 1: Characteristics of the case study.

Case description	Highway case
Scope	32 km four-lane highway
Procurement method	Best Value Procurement
PDM (project development phase)	Integrated collaboration (inspired by IPD) with TVD and other LC principles
PDM (construction phase)	Design-Build with a target price
Contract size	$432 million
Planned construction start-finish	2021-2025 So
Position of the interviewees	Project managers from the client-side, winning contractors
Sources of data	Five interviews, one year of mainly direct observation with informal dialogues, document analysis

The project uses a collaborative Design-Build contract with a target price, outlined in Table 1. The project delivery method is inspired by Integrated Project Delivery (IPD), though one significant deviation is that the project uses a two-party agreement rather than a multi-party agreement. Otherwise, the PDM is like the IPD approach, and Lean Construction tools, including TVD, are used (Malvik et al. 2020). Figure 2 illustrates the project life cycle and the focus of the study.

Figure 2: The project life cycle with the study focus highlighted.

With project collaboration, a client's overall objective is to increase the project value; thus, the client understands TVD as a cornerstone in the collaborative approach. The client has named their Project Delivery Method (PDM) version "Integrated Collaboration." BVP is used as the preferred procurement method for the client. However, data indicate that the client is not considering the BVP process as more than a procurement procedure, and the project is therefore only modestly embracing the BVP process after the contract award. This means that the execution phase, the fifth phase in the theoretical BVP process (Figure 1), is given little attention in the project execution. Moreover, it is observed that the general contractor's project manager has expressed a strong work identity in the project and possesses an expert role.

In the highway case study examined here, the project development phase for stretches in the south and north parts are currently in the process of re-zonal planning. Detailed designs are being produced in the mid-zone, while early work has already started in defined minor parts. The construction contract for the complete project is expected to be signed in the middle of 2021. It is a current decisive project weight to close the gap between the target cost and bill of quantity (BoQ) based on expected cost.

The project's budget price was developed in three steps. First, the client made an estimate based on a top-down approach and a primary assumption of the road line during a corridor investigation. This estimate gave the client's available project budget. During BVP, all tendering contractors must agree on conducting the project within the client's available funds. The selected contractor confirmed this by signing the contract. This final target estimation was collectively established in the project development phase. If the target price rose above the client budget, the project closed, and the client must start the procurement process again.

The client had established guidelines for their involvement in the design development, which involved facilitating the process and applying a questioning technique. An example of this technique is "Which standard have you applied when engineering the local roads?", where one process revealed unnecessarily high standards for several secondary roads. According to the client, this was caused by a misinterpretation in the existing zoning plan for the highway's long mid-section. Another example is an ICE meeting that failed to include primary functions when selecting an alternative road intersection.

The design and engineering company has the lead in the project development phase and the parallel current detailed design phase for the road project's midsections. Two full-time design and engineering managers run the processes, except for cost calculations, where the general contractor and a subcontractor on road construction are the executives.

Client involvement

Data confirms that the client is actively involved in facilitating the processes to improve the workflow in design and engineering. The project has organised the most important decisions of which alternative solutions to select in meetings which are denoted as "ICE" (Integrated Concurrent Engineering), which relate to VDC (Virtual Design and Construction) terminology (Fischer et al. 2017). Concurrent Engineering is, however, a concept that was well-known long before VDC became a buzzword in construction (Love and Gunasekaran 1997). The denoted ICE meetings do not deal with Concurrent Engineering in the studied project but with decision-making on a tactical/operative level. For instance, when deciding on which type of bridge to apply in the crossing of a river.

A "rational" decision-making process is applied (Bazerman and Moore 2009), which can be outlined as 1, define the problem; 2, identify the criteria; 3, weight the criteria; 4, generate alternatives; 5, rate each alternative on each criterion; 6, compute the optimal solution. In the studied project, the problem is given. The alignment of the road requires, for example, a road intersection or a bridge. The problem is applied to a developed standardised set of criteria for the decisions in ICE meetings. This reflects the client's goal and value structure on environmental issues, cost, and other factors. Some political considerations related to the later processing of the zonal plan are included in the decision criteria set. Each criterion's weight is standardised in the applied decision model, but the rating is prepared and proposed by multidisciplinary groups to address the different customer values. The alternative options are, for the most part, developed by the designers. The final step of computing the optimal solution takes place in the ICE meeting where more than 30 people from all parties are gathered, and, based on the prepared material, the different values are evaluated. Such a meeting typically lasts for two hours or more, depending on the project complexity.

There are examples from the direct observations where the "best" alternative from the mutual ICE evaluation was later overruled by the clients. This happened during bridge type selection for a river crossing in an environment with significant terrain issues and concerns associated with wildlife and the natural environment. Data indicates that the client's primary reason to change the reached decision was that they believed the expert made the cheapest bridge more complicated than necessary and at a relatively overstated cost. A second example is the selection of an intersection between the planned new highway and another national road. The quality of the preparation of the ICE meeting decision missed out on having the intersection's primary function as one of the decision criteria. Hence, it was a good reason to revise the decision; the client took the lead in the traffic analysis to select a new type of intersection. This decision was later changed again because of the involvement by the local authority, which was unsatisfied by how the second choice dealt with local interests. The third alternative to be launched in the zonal plan is a compromise between the first two.

From the empirical data outlined above, we can see that the general contractor's expert role did not entirely hinder the client's involvement in following client interests on a relatively detailed level. Limited trust can be interpreted as the reason for client intervention in the bridge example above. The two examples addressed are, however, not generalizable in the project.

Cost estimation issues

We have tried to approach the question of "How deep is the collaboration?". First, it should be noted as a contextual factor that the client was a lean organisation with limited resources to go deep into all issues. The designers developed and submitted BoQ and detailed cost suggestions. The general contractor was responsible for the final cost estimate based on the maturity level in question. The client did not take part in the estimation. We can regard this as an example where the general contractor and their team are considered the experts, as in the BVP framework. An experience from the client perspective, it is difficult to achieve the necessary transparency in this crucial part of the TVD process. Transparency is understood as the communication of issues that gives simple access to decision-relevant information. It is not about keeping information secret. The lack of crucial information does not allow all forces to pull in the same direction to benefit the project.

BoQ cost and output estimation are presented in an aggregated format that is difficult to unpack and identify which elements contribute to its cost. The presentation format is not according to the concept of target costing, which distributes the target cost into elements and the cost numbers for subcontractors. Closing the gap between target cost and expected cost addresses the most critical contributing elements of cost and gives a basis for closer inspection and achieve a target cost basis for negotiation with subcontractors. Based on the client's questions, the calculations improved because operational risk and opportunities were identified.

Deviations between project expectations

Our data indicate that the most significant challenge with BVP is found in the interface between procurement and the collaborative project development phases. The Clarification phase (Figure 1) does not open for negotiation. Following the framework, the general contractor's team explained how they planned to solve the requirements and deliver the project values to the client team. According to a client respondent, the contractor's team expectations were "close, but no cigar" in meeting the client's project expectations. The respondent thought they could clarify more when the contract was signed, but then the project organisation changed pace and proceeded with the development at once.

Moreover, the general contractor team appeared to be locked into the execution model, which they, with earnest effort, had prepared for the clarification phase. A client respondent asked rhetorically in an interview, "expert in what – to build roads or the collaborative processes?" Learning points for the client for future projects of this kind are that they should be more explicit in how they want to have the processes and that BVP is not an acceptable procurement method for projects with a joint project development phase. Negotiations are still necessary at this phase, is the argument.

The client expressed the understanding that "we are the change agent" who should provide the processes. Regarding the change agent role, it is argued that it is not enough to gather highly qualified engineers and believe project development will occur. It is not sufficient for the client to express their wish to apply TVD or Last Planner approaches and expect every contractor to understand the processes. In these self-critical reflections, the Norwegian, and perhaps global markets, are not trained to handle collaborative value-creating processes, which were, and still are, the ambition in this project. The client addresses the importance of clear responsibility and ownership for the different processes.

DISCUSSION AND CONCLUSION

There is undoubtedly significant space for improvement in the management of the design and engineering processes regarding applying the principles inspired by Lean Construction. However, it is incredibly challenging to manage these complex and iterative processes in a time-compressed context. Nevertheless, the general impression is that the performance is at least state of the art. This is also indicated by the client, who has expressed that the project development process in the studied project is superior to other highway projects in their portfolio. We will address these processes in more detail in future work.

The general contractor company and its subcontractor participate in the design development regarding buildability and construction preparation. However, based on the ideas underpinning collaborative project development and TVD, we expected a more proactive role from the contractor in the project development phase than was observed.

The project was obliged to apply BVP, and this paper's proposition addresses how this might give unproductive confinement in the execution. In the case study, we found that BVP did not hinder the client in being a proactive actor or a solution enabler in collaboration with the general contractor team. However, BVP was not found to enable deep collaboration. Some of the challenges outlined may have been caused by a lack of experience and training by client and contractor in collaborative value-creation processes. That is also the case for the revealed lack of transparency around the BoQ and cost estimation processes which is crucial to produce adequate decision-oriented information for joint decision-making to align with target cost and BoQ cost calculations at different maturity levels as the project development phase proceeds.

The most crucial challenge with BVP for projects with a development phase based on target cost and value engineering is finding the "best" expert since the procurement method does not allow for negotiations. Hence, the clarification phase turns out to be a monologue. From the client's perspective, it was driven by the limited opportunity to clarify and contribute to how the TVD-process should be conducted. BVP's idea of selecting a Design-Build expert based only on their technical skills contrasts with promoting a collaborative dialogue with the client during the execution of a TVD process where soft communication skills would be more productive.

The BVP process is based on the idea that there is an imbalance between client and contractor, where the contractor is considered the expert. In reality, it might be the case that the client is superior to the contractor in some domains of expertise. In the collaborative project approach, the client and contractor are seen as equal partners, allowing for more client involvement. Still, some of the empirical findings highlighted suggest that the contractor, seen as the "expert," felt strong ownership to their "concept" described in the BVP process and was reluctant to consider any concept change.

On the other hand, the client felt that a lack of openness and clarification of the project requirements made them accept decisions that, in their eyes, did not sufficiently fulfil the project requirements. This shows at least two good examples of how the BVP process led to inefficient use of the TVD practice; impatience to start the work immediately after contract-signing resulted in a lack of further clarification to agree on optimal and uniform solutions, and the fact that the contractor is seen as the "expert" in the BVP process did not act in accordance with the collaborative nature of the TVD practice.

BVP has proved good results in projects using transactional contracts where limitations and clarification of responsibility and risk between a DB contractor and the client is crucial (Rivera 2017; Kashiwagi et al. 2019). However, in projects using a relational contract, a more direct dialogical procurement approach might be more productive.

The study is limited in external validity, which was not the main aim, but rather as an example and generalisation in terms of theory. The paper's outcome is a generalisation of a theoretical proposition believed to be true, which, according to Yin (2018), is a justification for conducting a single-case study. The reliability is regarded to be satisfied as it should be quite adequate for other researchers to reach the same result given similar data and theory.

The paper contributes to the literature by pinpointing conceptual and empirical counterproductive differences when combining BVP and TVD, which poorly aligned. In that sense, the proposition and theory are confirmed.

REFERENCES

Azari, R., Kim, Y.-W., Ballard, G., and Cho, S.-K. "Starting from scratch: a new project delivery paradigm." *Proc., Construction Research Congress 2014: Construction in a Global Network*, 2276-2285.

Ballard, G. (2020). "Target Value Delivery." *Lean Construction: Core Concepts and New Frontiers*, Routledge, 148.

Bazerman, M., and Moore, D. (2009). "Improving decision making." *Judgement in managerial decision making*, 179-199.

Cooper, R., and Slagmulder, R. (1997). "Factors influencing the target costing process: Lessons from Japanese practice." Citeseer.

DFØ (2021). "Veileder i prestasjonsinnkjøp - Best Value Procurement (BVP)." https://www.anskaffelser.no/verktoy/veiledere/veileder-i-prestasjonsinnkjop-best-value-procurement-bvp.

Do, D., Chen, C., Ballard, G., and Tommelein, I. (2014). "Target value design as a method for controlling project cost overruns." *International Group for Lean Construction*, 22.

Fischer, M., Ashcraft, H. W., Reed, D., and Khanzode, A. (2017). *Integrating project delivery*, Wiley Online Library.

Gomes Miron, L., Kaushik, A., and Koskela, L. (2015). "Target value design: The challenge of value generation."

Gray, D. E. (2013). *Doing research in the real world*, Sage.

Johansen, A., Engebø, A., Torp, O., and Kalsaas, B. T. (2021). "Development of target cost – By the owner or together with Contractors - Target Value Design." *Procedia Computer Science*, 181, 1171-1178.

Kashiwagi, D. (2011). "Best Value Procurement/Performance Information Procurement System Development." *Journal for the Advancement of Performance Information and Value*, 3(1), 12-12.

Kashiwagi, D., Kashiwagi, J., Smithwick, J., and Kashiwagi, I. "Changing the paradigm." *Proc., Proceedings of the 5th International Public Procurement Conference*, 1074-1095.

Kashiwagi, J., Rivera, A., and Taba, M. (2019). "A Private Organization Utilizes the Best Value Approach on an Enterprise Resource Planning System." *Journal for the Advancement of Performance Information and Value*, 11(1), 62-79.

Love, P. E., and Gunasekaran, A. (1997). "Concurrent engineering in the construction industry." *Concurrent Engineering*, 5(2), 155-162.

Malvik, T. O., Engebø, A., Wondimu, P. A., Johansen, A., and Kalsaas, B. T. "Comparing Road Construction Projects Against an IPD Standard." *Proc., 28th Annual Conference of the International Group for Lean Construction, IGLC 2020*.

Malvik, T. O., Wondimu, P., Kalsaas, B. T., and Johansen, A. (2021). "Various Approaches to Early Contractor Involvement in Relational Contracts." *Procedia Computer Science*, 181, 1162-1170.

Rivera, A. O. (2017). "Shifting from Management to Leadership: A Procurement Model Adaptation to Project Management." Arizona State University.

Yin, R. K. (2018). *Case study research and applications : design and methods*, SAGE, Los Angeles.

Zimina, D., Ballard, G., and Pasquire, C. (2012). "Target value design: using collaboration and a lean approach to reduce construction cost." *Construction Management and Economics*, 30(5), 383-398.

Alves, T.C.L., Martinez, M., Liu, M., and Scala, N.M. (2021). "Project Delivery Contract Language, Schedules, and Collaboration." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 33–42, doi.org/10.24928/2021/0168, online at iglc.net.

PROJECT DELIVERY CONTRACT LANGUAGE, SCHEDULES, AND COLLABORATION

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ABSTRACT

The construction industry has developed a variety of project delivery methods, contractual arrangements, and scheduling methods in order to facilitate collaboration of stakeholders to maximize project performance. It is critical to investigate how project delivery methods and contractual arrangements might influence collaboration during scheduling practice. Understanding this influence can help managers choose/adapt available project delivery methods to their needs and develop strategies to enforce collaboration when they plan for future projects. This research reviewed contractual language in project delivery methods from the perspective of how those methods accommodate stakeholders' collaboration. Twenty-six professionals were also interviewed to reveal their insights on how contractual arrangements influence collaborative scheduling practices. Contract clauses were identified and categorized based on their level of supporting compliance or collaboration. Finally, the results from the interviews were compared and contrasted with the analysis of contracts for cross validation. Results show that schedules are commonly used as contractual documents, and a need exists to improve contractual arrangements to address the lack of application of collective knowledge to develop, review, and validate schedules for construction projects regardless of the delivery method used.

KEYWORDS

Collaboration, transactional, relational, language, schedules.

INTRODUCTION

Delivery methods, or delivery systems, are forms of organizing different parties and their contractual relationships in order to deliver construction projects. Historically, the delivery of projects was concentrated in the hands of a single entity who worked as the master builder and was in charge of multiple aspects of the project, including but not limited to, design, construction, logistics, scheduling, contracting labor, and identifying the need for specialized trades. This original form of organizing to build projects

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constructed the Egyptian pyramids, the European cathedrals, and the infrastructure and roads that linked the Roman Empire and Inca civilization.

However, as trades developed and formed guilds and professions became more specialized from design to construction, the need to organize the work of multiple trades became a profession of its own and required more time spent on construction management. The role of the master builder was split into at least that of a designer, a builder, and a manager; after the Industrial Revolution started in the 18th century and accelerated over the 19th century, the role of trades unfortunately started being viewed as expendable, having less and less to do with the overall planning of construction project activities and more focus on putting work in place (Mulligan and Knutson 2000).

In this environment, the traditional delivery method of having separate entities in charge of different tasks and parts of the project emerged, giving way to the Design-Bid-Build (DBB) delivery method, to which other methods are compared against (Sweet et al. 2015). The form is used by different delivery methods to organize project stakeholders, define their rights and responsibilities, impact how parties work together, and determine whether they are more or less collaborative, ultimately impacting project performance (El Asmar et al. 2013). Previous research has shown that the language in contracts tends to be more prescriptive, transactional, and devoid of words that allude to collaboration and related practices in more traditional delivery methods that use dyadic contracts, whereas the language is more relational and collaborative in delivery methods with multi-party contracts (Willis and Alves 2019).

This study builds on previous research about contract language and centers its investigation on the development and implementation of schedules. The research objective is to study how the language in different project delivery methods and contractual arrangements influence scheduling practice and collaboration among stakeholders. The authors documented reports from practice, collected via interviews, and contractual language for different delivery methods, using a review of available contracts. The working hypothesis of this study is that more traditional delivery methods based on dyadic contractual relationships in general provide few to no opportunities or incentives for people to collaborate, whereas more collaborative and multi-party contracts have more specific language calling for the development of collaborative schedules. This paper is structured with a literature review that informed the research and discussion of results, followed by the research method, the analysis of results, and conclusions.

DELIVERY METHODS, SCHEDULE PRACTICES, AND HOW THEY ADDRESS COLLABORATION

This section presents an overview of delivery methods as they relate to this study, focusing both on the methods used in contract analysis that were also discussed by interviewees and on common schedule practices.

DELIVERY METHODS

The focus of this study centers on the first four delivery methods described below and three more that were mentioned during the interviews. A brief description of each is provided to support the discussion presented (Sweet et al. 2015).

Design-Bid-Build (DBB) represents the traditional delivery method where an owner initially hires a designer to design the project, later putting the project out for bid once it is designed, and finally hiring the contractor who usually offers the lowest price to build the project. While in DBB, the design continues to be developed via submittals after its award (Pestana et al. 2012). Designers and builders do not work together and are separated by the existence of separate contracts with the owner or between the general contractor and the specialized trades, who are hired sequentially and have no input on the design and little, if no, input on the project schedule.

Construction Management at Risk (CMAR) is used when the owner retains the services of the general contractor as a construction manager (CMgr) to manage the project starting from the design stage and provide advice during the preconstruction phase. Later, the CMgr hires additional trades to build the job as needed. The CMgr and the designer might work with additional trades providing support via design-assist contracts, as described below, and start collaborating on schedule development.

Design-Build (DB) consists of a more collaborative delivery method; the DB, and more recently the progressive DB, brings the architect and the general contractor together on a single contract at the start, when they are awarded the project as a team. In some cases, the DB team might choose to have trade partners working with them from the inception of the project; this will depend on how the request for proposals is structured by the owner. This will set the tone in terms of how much collaboration will happen between the parties involved from the start of the project. Moreover, DB contracts usually spell out specific methods to support schedule collaboration (Willis and Alves 2019).

Integrated Project Delivery (IPD) is the more recent of the delivery methods discussed here. IPD projects rely on multi-party contracts where the owner and the parties involved are signatories of a single contract and share risks and rewards. The agreement spells out commercial and organizational terms, which are present in contracts for other delivery methods, as well as the operating terms. The operating terms in IPD contracts are based on Lean Construction methods, tools, and tenets as espoused in the IGLC and professional literature promoted by industry organizations (Darrington et al. 2009, LCI 2021). Thus, schedule collaboration is present from the project's inception.

Construction Management (CM) is commonly employed in an environment where the owner holds multiple prime contracts and hires a construction manager to oversee activities. The CMgr in this case represents the owner but is not at risk for the project's performance.

Engineer-Procure-Construct (EPC) are often used in the oil and gas, chemical, and petrochemical industries and somewhat resemble the organization of the DB method. This might be because a single entity, with a diverse skillset to perform multiple tasks, is in charge of engineering the project, procuring its components, and building it or building via alliances between different companies like in DB.

Design-Assist (DA) involves specialized organizations providing expertise on an as-needed basis as the design is developed. Designers and contractors hired on a DA-basis might not be part of the team that will ultimately build the project. They provide solutions that might end up being built by others.

While other delivery methods and variations of the ones presented herein are available, the scope of this study is limited to these methods which are prevalent in the construction industry in the United States where the study was developed.

SCHEDULE PRACTICES

Considering the delivery methods discussed and how their organization and related contractual relationships impact collaboration, the way schedules and their development are treated varies across the methods reviewed.

Given the prevalence of DBB in construction in the United States and around the world, methods and tools that support the mechanisms outlined in DBB contracts have been at the forefront of construction engineering management (CEM) research for 70+ years, with the critical path method (CPM) extensively required in contracts as the method of choice to generate schedules, dominating this body of knowledge and practice (Olivieri et al. 2019). Exceptions considering the use of line of balance to schedule projects like the Empire State Building (Willis and Friedman 1998) as well as other efforts to bring it to the forefront of scheduling construction projects in the mid- to late 20^{th} century are also found. The longstanding CEM literature on schedule development and management is packed with the development of algorithms to support generation of schedules, the use of schedules to address claims, and the definition of metrics to manage schedules (e.g., earned value method).

The IGLC community started offering alternatives to the use of CPM schedules to manage construction projects starting from the early 1990s, based on the seminal work of Glenn Ballard and Greg Howell with the Last Planner System (LPS) (Howell and Ballard 1994, Ballard 2000), and later of others building on LPS-related work (Gonzalez et al. 2009; Viana et al. 2011; Hamzeh et al. 2015), line of balance (Kemmer et al. 2008), and takt planning (Frandson et al. 2013), to name a few. The line of work adopted by the IGLC community is very much centered on the idea promoted by the LPS that construction projects are socio-technical systems and need to be treated as such where the social part, involving interactions between project participants and their engagement, is as important as the technical solutions they are developing (Ballard and Tommelein 2016).

RESEARCH METHOD

This section describes how the study unfolded, including the details of the interview process and the analysis of contracts.

INTERVIEWS

Interviews of one or two industry practitioners at a time were usually conducted using Zoom or WebEx, with a few face-to-face ones, by researchers who documented statements provided by the interviewees. Three principal investigators were involved in the study, along with two graduate students. One of the researchers participated in all interviews, and at least two of these five researchers were present on any interview call. The transcripts would later be provided to the interviewees for review and validationas well as to allow them to provide additional comments if they had any. Out of a longer list of questions included in the interview, the following two are discussed in this paper: (1) What type of contract/delivery method was used between different stakeholders – owner, contractors, managers, subcontractors? (e.g., design-build, design-bid-build, construction manager at risk); and (2) Can you indicate any contractual arrangements and/or requirements that might influence how planning for this project is carried out? (e.g., LEED certification of the project, use of pull planning sessions, use of target value design during the design phase, and specific cost targets shared during construction.). Interviews were conducted from August 2019 through February 2020. In total, 26 professionals were interviewed in 24 interviews. Interviewees had a combined 604 years of experience, with a minimum of 5 years and a maximum of 50 years, and included owners (11), contractors (7), consultants (6), specialty contractor (1), and supplier (1). The interviews, which also included additional questions about schedule collaboration, lasted from 30 to 70 minutes.

CONTRACT ANALYSIS

The authors' interest in reviewing contracts to explain how schedules are addressed and developed in different delivery methods started with a comment by a practitioner regarding some contractual rules regarding schedules which stifle collaboration: some owners give contractors two weeks to provide and commit to a full schedule once the award is made and that leaves little time for them to collaboratively develop schedules when trade partners are not yet on board. With that in mind, the authors analyzed a group of contracts, previously collected by the first author and her students, and singled out the schedule-related clauses.

Once the clauses were identified, they were categorized as schedule-related clauses supporting one of the three purposes: compliance either in terms of (1) supporting owner requirements, (2) supporting government requirements, or (3) supporting collaboration. Clauses that supported compliance were further categorized as contractual responsibilities and obligations related to providing a schedule for the purposes of time and progress (master schedule), payment (schedule of values), submittals (design), services (consultant's work), materials and equipment (procurement), and dispute resolution processes. The analysis is grounded on a collaborative scheduling maturity model (CII 2021) which, amongst other areas, considers three levels of maturity when addressing the development and implementation of collaborative schedules. An excerpt of the model is shown in Table 1.

Table 1: Maturity Levels and Questions Considered During the Analysis (CII 2021)

Question	Maturity Level		
	Bronze	Silver	Gold
Schedule created primarily…	To define contractual expectations & responsibilities but not used.	To define contractual expectations & responsibilities but was not used by entire project team.	To enable strong project management communication and collaboration throughout project team.
Stakeholders	Were not involved early enough or considered in schedule creation.	Were involved early enough but not all appropriate and necessary.	Were appropriate and involved early enough in creating the schedule.
There were…	Little to no use of scheduling tools and methods utilized company wide (beyond scheduling software, ex. P6).	Use of additional tools/methods to support collaboration during schedule development.	Frequent updates of the schedule across the project; living, integrated document with appropriate tools and methods used (ex. LPS, BIM, 4D, AWP Takt Planning).

A total of 10 DBB, 9 CM/CMAR, 9 DB, and 10 IPD contracts (agreements) and related documents (e.g., general conditions, appendixes) were analyzed. The root "schedul" was searched in all contracts, and results were organized in Excel spreadsheets. The hypothesis defined for this part of the study was that schedules and the scheduling task are treated in static and prescriptive ways by less collaborative delivery methods and in more dynamic ways by collaborative delivery methods.

RESULTS

This section presents the results obtained from the interviews and contract analysis, previously described, and concludes with a cross-analysis of the two approaches used.

INTERVIEWS

Table 2 indicates the different delivery methods employed in the projects which were used by the interviewees for the interviews; the absense of IPD projects is noted. It should be noted that the first line lists the most common mentions made by interviewees, whereas the other lines include additional comments made about the various forms in which the projects they worked on were delivered. The third comment is insightful as the interviewee points to the importance of working to impart changes on alternative delivery methods that are more prevalent as a means to change the industry. As shown in Table 2, owners adopt different arrangements to procure and award contracts and that impacts how teams are assembled and work together. Delivery methods are also less defined than usually documented in the literature and adapted to cater to the needs of different projects and owner organizations.

Table 2: Delivery Methods, Contract Types, and Some Variations Used for the Projects Discussed During the Interviews

Delivery Methods (As Reported)
Design-Bid-Build, Design-Build, Construction Management at Risk, “pure” Construction Management Design-Assist, Engineering-Procure-Construct.
Engineering and construction firms invoice the owner for the work completed. Invoicing based on hourly rate+profit. Cost plus work is defined in work packages and then build.
Most are Design Build and CM at risk. DB is responsible for a little less than 40% in a dollar basis of all non-residential construction in the United States, and CM at risk is around that too. Try not to focus on IPD only to get the desired collaborative behaviors because that’s not where the change will occur most quickly.
Oil and gas, LNG plants, and offshore platforms – Lump Sum. Now it is more global projects, including chemical plants, refineries, and long pipelines; cost reimbursable projects. In reality the owner works mostly with EPC, sometimes EP and the C separate, and the owner does some procurement for long lead items. In a few cases they do engineering internally.
EP-C. They have an engineering and procurement contractor and a separate reimbursable contract for the contractor.
The owner acts as program manager and contracts out to contractors directly. Also has 18 internal crews. Contract out installation. The owner holds four design contracts with four firms. Use blanket contracts valid for 3 years and bid every three years. Scorecard used to weight items related to quality, safety record, cost, previous projects, and use best value.
Alliance engineers and alliance contractors. The engineers had one contract, and the builders had a separate contract.
Owner has a construction management group, also involved from the beginning. Estimating and project controls in-house.

Considering the diverse types of methods used by the interviewees to deliver projects, Table 3 summarizes some of the answers given in terms of any contractual arrangements that might have influenced how they planned the project and developed their schedules, linking them to the levels outlined in Table 1 (maturity model excerpt). Interviewees’ comments were edited to shorten long passages as they described arrangements but reflect their experiences and perceptions regarding the topic of collaborative schedules. Not all interviewees answered this question in its entirety, and some did not know the details of the contracts in place. Some noteworthy comments address the fact that people do not know how to work collaboratively to develop schedules, owners do not care about how the project will get built, use of schedules with differing levels of enforcement depending on the contract payment type (i.e., lump sum/fixed price, reimbursable), and vague or completely absent languange regarding schedules and milestones. On the bright side, some interviewees pointed to specific language being added to their contracts requiring the development of collaborative schedules.

Table 3: Examples of Contractual Arrangements Described in the Interviews

Purpose /Maturity Level	Example (related delivery method(s) used as reference by interviewees indicated in parenthesis)
Collaboration /Gold	The contract delivery is design-build which requires a certain level of collaboration. They have pull-planner/LPS verbiage which is something that he introduced in the contracts they have in <location>. Generically, contract says something like: the team members have to allocate two hours per week for pull planning. Even so, the foremen's meeting is centered around planning and identifying road-blocks. During the meetings they look at the plan "did you make it or not"? The scheduler or whoever is taking notes then captures the reasons for non-completion and adds to a report. (Design-Build)
Owner Requirements /Gold	They have some standard legal language added to the subcontractors' documents to follow how they plan. Sometimes they indicate the software and equipment requirements (e.g. iPads) to make things work. (Design-build with some variations; DB for the most part, mostly variations with collaborative contracts like IPDs)
Collaboration /Silver	40-50% of the projects have some kind of language requiring LPS practices in the contract, some very minor language. Two of their clients are including wording in contracts in terms of just-in-time deliveries, participation of foremen in weekly work plans, and the number of hours required for participation. Some contracts require that specific people participate in the weekly work plan. (Primarily CM at Risk and pure CM)
Collaboration /Silver	There is an addendum in the trade partners' contracts with the GC which requires the trade partners to participate in and support collaborative planning meetings at medium- and short-term levels. Not at the long term, because these are not IPD projects. Trade partners were complaining of having to do too much work by attending these meetings; now this is required in contracts. (For the most part CM at Risk)
Owner Requirements /Silver	Advanced work packaging was mandated. Prioritize certain systems in certain dates, and the owner was pretty harsh if these were not met. (EPC)
Owner Requirements /Bronze	Surprising how few projects put anything in contracts regarding collaborative schedules and how few projects talk about collaborative scheduling formally in the project. Lots of teams doing progressive design build, but out of 10 teams they had one team doing it right for collaboration and 2-3 were nibbling on it. People don't know how to work differently, collaboratively. (Primarily design-build, but also DBB, and CM at Risk)
Owner Requirements /Bronze	For any owner that requires a detailed CPM schedule in the beginning of the project, 30,000-40,000 activities very detailed with attached dates that will not materialize. Why plan with that level of detail? It is insane. If it is a DB team and they don't have all trades engaged, they can put the overall sequence of work together but not get into too much detail. Have a CM and an architect in the room to establish an environment of collaboration. (Most are Design Build and CM at risk)
Owner Requirements /Bronze	A lot of projects require the P6 schedule, and they want a contractual schedule. The owner doesn't really care how you'll get it done and let you think about the means and methods. (Design-Build)
Owner Requirements /Silver	In the past, they had some schedule language that was vague and didn't mean much. The owner could not hold anyone accountable, and they have reviewed it. They focused on refining planning and scheduling language in contracts to outline need for hours and estimates, really making sure contractors are holding to change order process that can get earned value information needed on weekly basis. […] The contractors know they have a level of expectation from the schedule department, and in the documentations, they state the expectations that the contractor has to participate. In the letter of intent or bridge funding, the needs are outlined in these documents. (EPC)
Owner Requirements /Bronze	Weaker area, they do not really build schedules or put milestones in their purchase orders. There are planned execution levels, and contractors are penalized if they are not completing activities per plans. Contractors are required to develop and provide the schedule weekly. No milestones are put in the contracts; the only lever is that they baseline an expected execution index, i.e., number of activities completed divided by number of activities planned. (CM Multi-prime – Owner as primary manager)
Owner Requirements /Bronze	Did not have anything in the contract; there was an incentive-based contract based on cost. In this case, there was already confidence that the GC would give the best schedule. (Design-Build)

CONTRACT ANALYSIS

The clauses investigated mostly fell onto the lowest tier (bronze) of the maturity model displayed in Table 1, with a focus on compliance, and little to no mention of collaborative efforts or additional tools and methods to support the scheduling effort. These clauses were found in all analyzed delivery methods, as all contracts have commercial terms which use the schedule as a reference for multiple types of responsibilities and obligations, indicated in the categorization previously mentioned. Examples of content in such clauses include:

- The contractor shall prepare/present/review the <progress, payment, submittal, inspection, etc.> schedule to the owner.
- The contractor/architect shall review <progress, payment, submittal, inspection, etc.> schedule for compliance/conformance.
- Mentions of the schedule milestones and phases plus related obligations about the development of work, payments, inspections, and/or excused/inexcusable days.

Clauses that supported collaboration could have fallen in any of the previous designations for compliance, but they had one main difference: the clauses clearly called for collaboration with other project participants to provide input to develop schedules beyond simply complying with the requirement of turning in documents as a requirement or an obligation. The clauses would fall towards the Silver and Gold categories of the maturity model presented in Table 1. The schedule would be developed in a more participatory environment including at a minimum the owner, the architect, and the general contractor, with different tools and methods to support its development in a more dynamic type of environment. In this case, the schedule is not recognized solely as a compliance document (static); instead it evolves as participants join the project and give input to its constant development (dynamic). Some examples that illustrate these clauses include mentions to:

- Parties shall jointly develop the schedule, the target cost, project goals, and definitions.
- The core group shall engage in <specific tasks> and meet regularly.
- The team shall employ pull planning to develop the schedule, collaboratively developing weekly work plans that are used to track progress.
- Constructability and work structuring are part of the process of collaboratively designing the project and planning its execution (which impacts work packages and the flow of activities in the schedules).
- Activities and processes from multiple stakeholders are included in the schedule and submitted for review, validation, and approval by the core group.

The contracts for DB and IPD projects displayed a higher frequency of clauses that called for collaborative schedule development, whereas these clauses were virtually absent in the DBB contracts and somewhat present in the CM/CMAR contracts. DB and IPD contracts are also specific in terms of what additional methods and tools are to be used to promote schedule collaboration.

CROSS-ANALYSIS AND DISCUSSION

Results from the interviews (Table 3), when compared and contrasted with the analysis of contracts, offer some insights in terms of the relationship between delivery methods, schedule development, and collaboration. The analysis of contracts offers support to the hypothesis that schedules and the scheduling task are treated in somewhat static and prescriptive ways by less collaborative delivery methods and in more dynamic ways by collaborative delivery methods, as defined by the maturity model excerpt shared in Table 1. However, when the interview results are considered, interviewees shared a wide range of possibilities (categorized in different maturity levels) related to schedule development, regardless of the delivery methods used as reference for the interviews. Moreover, some interviewees indicated awareness of contractual clauses and how they support the development of collaborative schedules, whereas others pointed out to additional work to be done in this area. Some contracts, as reported, appeared to be entirely silent about schedule collaboration.

In general terms, based on the contract analysis, schedules are still very much viewed as documents that need to be produced and submitted to the owner in order to address compliance to the contract and serve as a baseline for progress and payment monitoring. Additionally, opportunities are missed when contracts are mostly focused on project management and do not explicitly call for the use of collaborative practices to develop and execute schedules in practice to also support production management (Olivieri et al. 2019). The lack of use of the collective knowledge and experience of teams to develop, review, and validate schedules is lost and remains an area that needs to be addressed in modern construction projects.

CONCLUSIONS

This study interviewed practitioners and reviewed contracts associated with project delivery methods to understand how the language associated with these methods might help to facilitate schedule collaboration among stakeholders. Interviewees indicated a broad range of ways (categorized in different maturity levels) in which contracts for different delivery methods address or are silent in terms of how to promote collaboration as schedules are developed. Within this group, there was no clear indication that, for instance, DB projects had more specific language about schedule collaboration. Conversely, the contract analysis revealed that DB and IPD projects did in fact display a higher frequency of clauses that called for collaborative schedule development, whereas these clauses were virtually absent in the DBB contracts and somewhat present in the CM/CMAR contracts. This contrast between what was observed during the interviews and the contract analysis might indicate that participants have the freedom to decide how to develop and implement their schedules on a more ad-hoc fashion, which might or might not lead to collaborative work. The authors are not advocating for any specific language related to schedule collaboration to be added to the contracts. However, leaving this area silent, or not providing grounds to encourage collaboration, might continue to contribute to the use of schedules as compliance documents with their development by isolated professionals without the support of the collective knowledge available in projects.

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REFERENCES

Ballard, H.G. (2000). *The last planner system of production control*. Thesis (Doctor of Philosophy), School of Civil Engineering, University of Birmingham.

Ballard, G. and Tommelein, I. (2016). *Current Process Benchmark for the Last Planner System.* Project Production Systems Laboratory (P2SL), University of California Berkeley, CA. Available at p2sl.berkeley.edu.

Construction Industry Institute [CII] (2021). *Breaking through to Collaborative Scheduling: Approaches and Obstacles. Final Report 362*. The University of Texas at Austin, Texas. 135pp.

Darrington, J., Dunne, D., and Lichtig, W. (2009). “Organization, Operating System, and Commercial Terms.” *Managing Integrated Project Delivery.* CMAA, McLean, Virginia, 10-47.

El Asmar, M., Hanna, A.S., and Loh, W. (2013). “Quantifying Performance for the Integrated Project Delivery System as compared to Established Delivery Systems.” *J. Constr. Eng. Manage.*, ASCE. 139(11): 04013012.

Frandson, A., Berghede, K., and Tommelein, I.D., (2013). Takt time planning for construction of exterior cladding. *Proc. 21th Annual Conference of the International Group for Lean Construction*. Fortaleza, Brazil. pp. 527-536.

Gonzalez, V. , Alarcon, L. F. , Maturana, S. , Mundaca, F., and Bustamante, J. A. (2009). “Rational Commitment Model: Improving Planning Reliability and Project Performance.” Proc. 17th Annual Conference of the International Group for Lean Construction.Taipei, Taiwan, pp 207-218.

Hamzeh, F., Kankoul, E., and Rouhana, C. (2015). *“How can ‘tasks made ready’ during lookahead planning impact reliable workflow and project duration?”* Construction Management and Economics, 33 (4), 243–258.

Howell, G. and Ballard, G. (1994). *“Implementing Lean Construction: Reducing Inflow Variation.”* Proc. 2nd Annual Conference of the International Group for Lean Construction (IGLC-2), Santiago, Chile.

Kemmer, S.L., Heineck, L.F.M., and Alves, T.C.L. (2008). “Using the line-of-balance for production system design.” *Proc. 16th Annual Conference of the International Group for Lean Construction*. Manchester. pp.299-308.

LCI (2021). Lean Construction Institute. https://www.leanconstruction.org/.

Mulligan, D.E., and Knutson, K. (2004). Construction and Culture: A Built Environment. Champaign, IL. 2nd Ed.

Olivieri, H., Seppänen, O., Alves, T., Scala, N., Liu, M., and Granja, A.D. (2019). "A survey comparing Critical Path Method, Last Planner System, and Location-Based techniques." *J. Constr. Eng. and Manage.*, ASCE. 145(12): 04019077.

Pestana, A.C.V.M.F., Alves, T. C.L., and Barbosa, A. (2012). “Application of Lean Construction Concepts to Manage the Submittal Process in AEC Projects.” *Journal of Management in Engineering*, ASCE, 30(4): 05014006.

Sweet, J., Schneier, M.M., and Wentz, B. (2015). *Construction Law for Design Professionals, Construction Managers, and Contractors*. Cengage Learning: Stamford, CT.

Viana, D. D. , Formoso, C. T., and Isatto, E. L. (2011). “Modelling the Network of Commitments in the Last Planner System” *Proc. 19th Annual Conference of the International Group for Lean Construction (IGLC).* Lima, Peru.

Willis, D. and Alves, T. C. L. (2019). “Contracting for Collaboration in Construction.” Proc. 27th Annual C of the International Group for Lean Construction (IGLC). Dublin, Ireland. pp 809-818.

Willis, C, and Friedman, D. (1998). *Building the Empire State Building*. New York: W.W. Norton & Company.

Koskela, L. and Ballard, G. (2021). "Shifting the Focus of Discussion: From Cost (Under)estimation to Cost Reduction." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 43–52, doi.org/10.24928/2021/0177, online at iglc.net.

SHIFTING THE FOCUS OF DISCUSSION: FROM COST (UNDER)ESTIMATION TO COST REDUCTION

Lauri Koskela[1] and Glenn Ballard[2]

ABSTRACT

In the last five years, two fierce academic debates have emerged in connection to cost planning in infrastructure projects – a domain which usually is not known as raising passions. The topic debated is alleged – or recommended – underestimation of project costs. Flyvbjerg has promoted the view that cost overruns in transport infrastructure projects are caused by initial cost underestimation, due intentional strategic misrepresentation on the part of project promoters. Love and his co-authors have attacked on Flyvbjerg's views, claiming that such cost overruns are primarily caused by natural, evolutionary scope changes. In turn, Flyvbjerg has objected the earlier suggestion of Hirschman to underestimate project costs, for getting the project started and for unleashing the creativity needed achieve the budget. Both debates have created several rounds of papers.

In this presentation, we contend that in these debates, the focus is partially misplaced, and the conceptualisation of cost planning too narrow. We argue that the primary focus of cost management should be on cost reduction, rather than on cost estimation. We contend that cost formation is a process controlled by man: costs inflate if they are allowed to do so; costs are reduced with will, effort and apt conceptual and methodological knowledge.

For justifying this argument, it is helpful to consider the underlying inferences in cost management. Deduction of total costs from the costs of components is a common inference in cost management. Induction of cost estimates from prior cost data is likewise very common. Reasoning backwards, in terms of regressive or abductive reasoning, is also used. Regressive reasoning answers to the question: How much can we get when using a given sum of money? Abductive reasoning answers to the question: How can we creatively reduce the costs?

The common conceptualization of cost management as cost estimation leads to a situation where deduction and induction are given a privileged or exclusive role as types of reasoning, thus overlooking regressive and abductive reasoning. We recommend applying regressive and abductive reasoning actively as means towards controlling and reducing costs.

KEYWORDS

Cost estimation, cost management, inference types.

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INTRODUCTION

Since the seminal paper (Flyvbjerg, Holm and Buhl 2002), Flyvbjerg has contended, in a stream of publications, that in transport infrastructure projects, costs are underestimated due to strategic misrepresentation, in simple terms, lying. Recently, Love and Ahiaga-Dagbui (2018) forcefully attacked the views by Flyvbjerg and his collaborators, comparing them to fake news. This criticism addresses several technical aspects of the empirical study by Flyvbjerg and his colleagues, and, most importantly, the claim that cost underestimation can best be explained by strategic misrepresentation. In turn, Love and Ahiaga-Dagbui (2018) forward an explanation related to evolutionary scope changes for cost underestimation.

In turn, Flyvbjerg (2016) recently critically discussed the idea of a Hiding Hand, originally proposed by Hirschman (1967). The Hiding Hand refers to underestimating a project's cost or difficulties for inducing creative action. For Flyvbjerg, this equates to actively recommending the very root cause for cost overruns, on which he has been trying to shed critical light.

These debates are useful, not only for creating the possibility of clarifying the topics of disagreements, but also as they lay bare strands of theoretical arguments in mainstream cost management. We contend that there are considerable gaps in the arguments by the parties. Namely, although the explanations of the parties refer to phenomena that certainly exist in connection to transportation (and other) projects, more important explanations are missing. Our main argument, inspired by Ohno (2012), is that cost formation should be seen as a process controlled by man – human agency plays a role in cost management, which thus should be classified as a technical science. This implies that cost reduction should be seen as the main task of cost management, rather than cost estimation. For justifying these arguments, we discuss the underlying inferences in cost management: deduction, induction, abduction and regression.

The paper is structured as follows. The next section presents a short summary of the two debates as well as our critical evaluation of them. Subsequently, a theoretical view of cost management, when understood as a technical discipline, and in terms of reasoning, is presented. Based on this wider conceptualization, cost management is discussed and new avenues for it are proposed. A section on conclusions completes the paper.

THE TWO DEBATES

In the following, the basic arguments on project failure of the parties in the two debates are briefly outlined, along with countermeasures suggested.

THE DEBATE BETWEEN FLYVBJERG AND LOVE

According to Flyvbjerg et al. (2018), "[t]he root cause of cost overrun is human bias, psychological and political". This bias, called planning fallacy, manifests itself either through delusion, in the form of optimism bias, or through deception, in the form of strategic misrepresentation or lying. As the primary countermeasure to these root causes of cost overruns, Flyvbjerg (2008) offers reference class forecasting (making cost estimates based on the costs of similar recent projects).

In turn, Love pinpoints changing conditions, requirements, and scope as the reasons for cost overruns (Love & al. 2019). Basically, he proposes better cost estimating as a solution to the cost overrun problem, and mentions BIM as a promising tool in this regard.

THE DEBATE ON HIRSCHMAN'S VIEWS

Based on his studies on development projects, Hirschman (1967) suggests underestimating a project's cost or difficulties (or overestimating benefits) for inducing creative action. For him, underestimating is the solution in view of the uncontrollability of the necessary creativity in the realization of the project, and a means for getting projects started. He explains the rationale behind the concept of Hiding Hand as follows (Hirschman 1967):

> We may be dealing here with a general principle of action. Creativity always comes as a surprise to us; therefore we can never count on it and we dare not believe in it until it has happened. In other words, we would not consciously engage upon tasks whose success clearly requires that creativity be forthcoming. Hence, the only way in which we can bring our creative resources fully into play is by misjudging the nature of the task, by presenting it to ourselves as more routine, simple, undemanding of genuine creativity than it will turn out to be. Or, put differently: since we necessarily underestimate our creativity it is desirable that we underestimate to a roughly similar extent the difficulties of the tasks we face, so as to be tricked by these two offsetting underestimates into undertaking tasks which we can, but otherwise would not dare, tackle.

These suggestions by Hirschman are of course diametrically opposed to the views of Flyvbjerg. Based on an empirical, quantitative analysis, Flyvbjerg (2016) claims that Hirschman's Hiding Hand can be identified only in a fifth of projects, the rest rather having cost overruns and benefit shortfalls, and strongly rejects the notion of the Hiding Hand (see also (Flyvbjerg & Sunstein 2016, Flyvbjerg 2018b). In turn, Flyvbjerg's claims have triggered several papers defending Hirschman (e.g. Ika 2018, Lepenies 2018, Kreiner 2020).

CRITICAL EVALUATION

We contend that in the discussion between Love and Flyvbjerg, there is a fundamental misconception around cost management. Namely, there is the failure to acknowledge the role of human agency in cost management. One important aspect of human agency is revealed in the saying by Ohno (2012): "*Costs do not exist to be calculated. Costs exist to be reduced*." Just calculating or predicting costs implies a natural science approach to the phenomena causing costs: they are out there and we as external observers examine them. This is the attitude of a quantity surveyor or an economist to cost. The former profession emerged to safeguard clients from unscrupulous builders, and quantity surveyors' viewpoint has been external to the construction process from the outset. The economist looks at production as a black box, and by force is outside that.

The other attitude, subscribed by Ohno, is the engineering (or technical) attitude: costs are both starting points and outcomes from our designing and planning and controlling. We can influence them. Note that this attitude embraces the natural science approach to costs: we still need to predict costs.

What would then a technical approach to cost management be in the case of projects? An infrastructure project consists of design and construction stages; project costs show partially different characteristics in these two stages. In the design stage, costs depend on the efforts of designers to take the budgeted costs to be a starting point of design and to go creatively (through abduction) beyond the solutions that are well-known. Both

Flyvbjerg and Love seem to fail to account for such deliberate efforts towards cost reduction. In the construction stage, there are avoidable and unavoidable costs; the amount of avoidable costs (cost for waste[3]) is dependent on appropriate leadership as well as managerial effort and effective managerial methods. Again, both Flyvbjerg and Love largely fail to account for avoidable costs.

Regarding then Hirschman, he accepts the role of human agency (and thus the technical attitude), especially in the sense of creativity, but views that it is incontrollable and is only triggered when the situation needs that. We consider this to be a too narrow and constraining view on creativity.

For justifying and expanding our arguments for the sake of cost management as a technical discipline, it is helpful to consider the major ways of controlling and reducing costs, as well their underlying inferences.

COST MANAGEMENT AS COST REDUCTION: THE METHODS TO CONTROL AND REDUCE COSTS

What then does this technical approach to costs embrace (besides cost prediction that of course remains to be a necessary step)? There are at least four methods to control and reduce costs:

- Steering design and construction towards allowed costs.
- Encouraging, in design and construction, more intense search of the best solutions.
- Encouraging creativity for finding novel, less costly options.
- Applying waste reduction for diminished costs.

These four methods are explained in the following.

STEERING

The question is about taking the cost target to be a requirement in design, rather than an outcome. Surely, in almost all design, there is an element of steering towards acceptable costs, but traditionally the decision cycle has been too long to be effective, leading to (too) late attempts of cost reduction.

MORE INTENSE SEARCH

A second viewpoint is based on considerations related to economics. The axiomatic assumption in economics is that economic actors are optimizing in their decisions. However, as advanced by Simon (1990), this is an unrealistic assumption, for several reasons, especially because of bounded rationality and search costs for finding the optimum; in practice people “satisfice”, select a satisfactory option. Thus, a gap (usually) remains between the selected option and the optimal option (should it be possible to determine it). It may be possible to narrow down this gap, and thus the question is about avoidable costs.

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[3] Accuracy of cost estimates is not the main topic of this paper. However, it is appropriate to state in passing that cost predictions are inaccurate also because there is a failure to predict the amount of waste costs, especially when the mainstream approach denies their existence (except in gregarious cases) and has no or little understanding on what is causing waste and how to reduce waste. The occurrence of waste is often emergent and varies from project to project. Flyvbjerg and Love fail to orderly conceptualize the phenomenon of waste.

Encouraging Creativity

A third viewpoint is related to creativity. Through creativity, novel (in the situation) solutions, possibly providing cost advantages, can be achieved.

Reducing Waste

The occurrence of waste is ubiquitous and significant in construction. In this situation, related avoidable costs provide a major source of cost reduction opportunities.

Discussion

The fundamental misconception of cost management as a natural science discipline leads to a situation where prediction of costs is given the dominant or exclusive role, and the ways of controlling and reducing costs are sidelined. In practice, predicting, controlling and reducing costs are realized through different types of inferences, and for the sake of a complete analysis, it is necessary to discuss them.

INFERENCES USED IN COST MANAGEMENT

For identifying the dominant inferences used in cost management, it is appropriate to start from the typical information needs occurring in relation to costs. These can be expressed through questions. We contend that for a client there are three questions of immediate interest in relation to cost:

1. Given a scope or design, how much will it cost?
2. Given a cost (or price), what will I get?
3. Given a difference between the estimated cost and the cost that can be afforded, how can the project be realized?

Note that there is an additional, fourth question in the background:

1. Given recent realized costs, which cost data should I use for my project?

In the field of pedagogy, it is common to distinguish inferential questions from other question types (Zucker et al. 2010). The criterion of an inferential question is that an inference is needed for responding to it. All the mentioned four questions are inferential, and remarkably, a particular inference type is respectively employed:

1. This is a deductive inference, proceeding forward, from number of things and activities and their unit costs (or prices) to total costs.
2. Regressive inferences are opposite to deductive inferences, they proceed backwards. A client may assess that a business case allows a certain amount of money to be used for a construction project. How many square meters and at which quality level can then be afforded?
3. In turn, abductive inferences are creative. Their starting point is a problem seemingly without a solution. However, a creative abduction provides an insight that solves the problem. This kind of situation emerges, say, if the cost of an existing product needs to be reduced by 20 % due to competitive pressures.
4. Inductive inferences are used for determining the unit costs in cost management. These inferences are based on observation of costs in the relevant marketplaces.

In the following, these inference types, as they occur in cost management, are examined in more detail.

DEDUCTIVE INFERENCES

Deduction can be defined as follows (Baker 2017): “A deduction is any sequence of statements each of which is derived from some initial set of statements (the premises) or from a prior statement in the sequence.” Deduction equals thus reasoning forward.

A deductive inference in construction cost management is typically of the form: The building will incorporate x tonnes of steel, with a price y per tonne, thus the total cost of steel will be xy. A deductive inference is thus used for prediction of the cost.

What is thus critical is (1) that all causes of costs (materials, activities, overheads) have been correctly identified and determined (in product and work breakdown structure) regarding their numerical value, and (2) that the unit cost is correct (with no systematic bias). Unfortunately, there are potential problems regarding both critical issues.

Regarding “all causes of costs”, there are several reasons why some causes are not identified or known in early stages of a project. The tendency of scope creep has been discussed in the literature (Kuprenas & Nasr 2003). During the project, new activities may emerge as necessary, or activities turn out to be more difficult that assumed. However, perhaps a dominating question may be that a part of cost is caused by non-necessary activities (or materials, etc.), leading thus to avoidable cost. The prediction of the widely varying occurrence of waste is in practice impossible.

The correctness of the unit cost is discussed below.

REGRESSIVE INFERENCES

Regressive inferences are similar to deductive inferences in being based on causality, but proceed in opposite direction, backward from outcomes to causes, while deduction proceeds forward, from causes to outcomes. Besides direction, there is another essential difference: the deductive inference is objective, each cause by necessity produces its pre-determined outcome. Instead, as several causes may produce the same outcome, a regressive inference is often selective, that is, there is a subjective selection among different known causes.

Regressive inferences are the main ingredient of design (Pikas 2019), and through them, the means-ends chain from requirements to the smallest element designed is created. From the viewpoint of cost management, regressive inferences are thus related to steering towards cost targets, and to extending the range of options for the sake of improved decisions (that is, pushing to the optimum in terms what is generally known, rather than creating new alternatives) - Empirical research shows that experienced designers tend to gravitate towards solution conjectures related to their prior experience (Cross 2004).

Regressive inferences, being counterparts to deductive inferences in opposite direction, have the same critical issues as the latter.

A further function for regressive inferences is in finding the root cause for waste.

ABDUCTIVE INFERENCES

Abduction was defined by the American philosopher and scientist Peirce (1934) as the only type of inference that produces new ideas. Although abduction has mostly been addressed in the context of scientific inventions, it has also been recognised as a key inference in design (Koskela, Paavola & Kroll 2018). In the design (or planning) context, an abductive inference leads to a solution that goes beyond being habitual or being selected, purportedly as the best, among existing, generally known options. Rather, an abductive solution shows novelty in the context. In the context of cost management, an abductive inference does not seek to predict or estimate a cost of a thing or process, but rather to find a thing or process with such novelty that it can be realized with reduced cost.

INDUCTIVE INFERENCES

A classical definition of induction is as follows by Hume (Ambrose 1947): "instances of which we have had no experience resemble those of which we have had experience". A typical inductive inference in cost management is as follows: Something has cost in the past, in same circumstances, x, let us assume that this will be the case in the future. - Also predicted inflation may be an induction.

Inductions on cost may be on different levels, from elemental level (cost of a type of material or work) to the project level. At the elemental level, there are commercial databases on average cost of different types of material and work, based on induction. At the project level, the question is about reference class cost prediction (Flyvbjerg 2008).

However, there is a major problem in relation to cost induction. Namely, any observed cost (per unit) may have a share of avoidable cost but its amount is usually not visible. For example, Koskenvesa & al. (2010) report that the Finnish productivity data for different types of construction work, as presented in a national, continuously updated database, contain a considerable share of waste time, which then migrates, as accepted waste, into schedules, task durations, contracts and cost estimations.

RELATION OF INFERENCE TYPES TO THE DIFFERENT METHODS OF TECHNICAL APPROACH TO COST MANAGEMENT

Now, we are in the position of presenting an overview on the inference types used by each method of the technical approach to cost management (Table 1): regressive and abductive inferences are in the central position, while deductive and inductive inferences are used as supporting types of reasoning (except in cost prediction).

Table 1. Methods and their inference types in the technical approach to cost management.

Method in the technical approach to cost management	Primary inference types	Secondary inference types
Cost prediction	Deductive and inductive inferences	-
Steering	Regressive inferences	Deductive and inductive inferences
Better decision-making	Regressive and deductive inferences	Inductive inferences
Creativity	Abductive inferences	Deductive and inductive inferences
Waste elimination	Regressive inferences (for finding the root causes for waste)	Deductive and inductive inferences

HOW TO GET THE TECHNICAL APPROACH TO COST MANAGEMENT REALIZED?

Up to recent times, the fragmented and siloed organizing of construction projects made it difficult to use the technical approach to cost management. Along with influences from other sectors, organizational innovations and maturation of digitised construction, new related practices and methods have emerged, such as Target Value Design (TVD), Set-based Design, Choosing by Advantages, etc., which can be used as part of cost management in the technical sense. In view of space limitations, only the two central inferences in the technical approach to cost management are commented in the following.

REGRESSIVE INFERENCES

Regression in steering to targets may seem straightforward, but actually already conceptual estimating/target setting prior to design requires a careful and systematic approach. One possibility is to identify different functions to be performed in the building, and to use prior statistical data (cost per function) for setting the target cost. A simple variant of this is the unit method (Kirkham 2014), where one functional unit is used for costing (say beds in a hospital ward). Another option is provided by the method described in (Pennanen, Ballard & Haahtela 2011), which is based on a software structured to transform the voice of the customer into a constructable Building Information Model. This BIM constructs all the quantities and costs of the building components before the design starts, basing on the client's needs. However, it has no visual read-out because the intention is to allow designers to be constrained only by functionalities, capacities and target cost, and to otherwise have free rein to deliver architectural and other soft qualities.

Furthermore, regression can reveal the need for abduction when conflicts between design criteria must be resolved, because otherwise the project purpose is unachieveable. A weaker sense of "must be resolved" also exists when project objectives that are not essential to its fundamental purpose can only delivered through invention (Ballard, et al., 2020).

All in all, our knowledge on the current state and developments opportunities of regression is still scant.

ABDUCTIVE INFERENCES

Abduction may be the most powerful type of inference. However, the challenge is that it cannot be conducted in a deliberate manner – there is hardly a recipe for abduction. Nevertheless, researchers have come up with factors which are encouraging or discouraging creativity – and thus abduction (the two first columns in Table 2).

Table 2. Factors influencing creativity and corresponding features in TVD

Factor influencing creativity	Explanation of the factor	Corresponding feature in the TVD practice
Progress principle	Making progress in meaningful work leads to intrinsic motivation and further to creativity (Amabile & Pratt 2016).	The progress towards the target cost is prominently visible.
Intrinsic and extrinsic motivators	Intrinsic motivation is conducive to creativity; controlling extrinsic motivation is detrimental to creativity but informational and enabling extrinsic motivation can be conducive (Amabile & Pratt 2016).	Intrinsic motivation is provided through progress, and such extrinsic motivators as the gain/pain sharing mechanism and the clear targets may act in a synergistic manner.
Work environment	Clear organizational goals, value placed on innovation, sufficient time, clear project goals and autonomy in how to meet project goals, etc. are related to creativity (Amabile & Pratt 2016).	Many of the stated work environment factors may exist in an TVD environment. Especially, cost reductions are expected to occur over the project duration, and thus there is sufficient time.
Collaboration and discussion	Participative decision-making, collaboration (Amabile & Pratt 2016) and discussion (Koskela & Kroll 2019) stimulate creativity.	Both wide collaboration and one-to-one discussions are encouraged.
Affect	Positive relation between affect and creativity: positive mood leads to higher levels of creativity (Amabile & Pratt 2016).	Applied methods, like Last Planner, lead to positive mood (Arroyo & Lang 2018).

Further, in Table 2 it is examined how abductive inferences are being supported in the practices related to TVD. Even if creativity aspects as such have not been a starting point in the development of the TVD approach, an initial analysis shows the approach is surprisingly compatible with the suggestions of creativity research.

There are two creativity factors which are especially interesting from the viewpoint cost management, namely the influence of available time and collaboration. Amabile, Hadley and Kramer (2002) contend, based on extensive empirical studies, that time pressure discourages creativity (however less if the employees feel a sense of mission). Instead, one-to-one collaborations support creativity according to these authors. The role of verbalization, discussion and debate was found also by Koskela and Kroll (2020) as important underlying factors for abduction.

However, our knowledge on the current state and development opportunities of abduction in construction cost management, as well as more generally in construction management, is very modest, and thus there are fertile topics for research on offer.

CONCLUSIONS

The common natural science conceptualization of cost management, subscribed by Flyvbjerg and Love, leads to a situation where deduction and induction are given a privileged or exclusive role as types of reasoning in dealing with costs, thus overlooking regressive and abductive reasoning. In Hirschman's project management concept, creativity through abductive reasoning is acknowledged, but it is considered uncontrollable and not actively managed. We recommend applying regressive and abductive reasoning actively and systematically as means towards controlling and reducing costs. Also, we suggest that the mentioned forms of reasoning in construction cost management invite for fertile opportunities for descriptive and prescriptive research.

REFERENCES

Amabile, T. M., Hadley, C. N., & Kramer, S. J. (2002). "Creativity under the gun." *Harvard Business Review*, *80*, 52-63.

Amabile, T.M., & Pratt, M.G. (2016). "The dynamic componential model of creativity and innovation in organizations: Making progress, making meaning." *Research in organizational behavior*, *36*, 157-183.

Ambrose, A. (1947). "The problem of justifying inductive inference." *The Journal of Philosophy*, *44*(10), 253-272.

Arroyo, P., and Long, D. (2018). "Collaborative Design Decisions" In: *Proc. 26th Annual Conference of the International. Group for Lean Construction (IGLC), González, V.A. (ed.)*, Chennai, India, pp. 463–472. doi.org/10.24928/2018/0509.

Baker, A. (2017) "Non-Deductive Methods in Mathematics", *The Stanford Encyclopedia of Philosophy* (Winter 2017 Edition), Edward N. Zalta (ed.), URL https://plato.stanford.edu/archives/win2017/entries/mathematics-nondeductive/.

Ballard, G., Arroyo, P. and Chiu, S. (2020). "Conflicting Design Requirements". 2020 Lean in Design Forum *Lean Construction Institute*. Available at p2sl.berkeley.edu.

Cross, N. (2004). "Expertise in design: an overview." *Design studies*, *25*(5), 427-441.

Flyvbjerg, B. (2008). "Curbing optimism bias and strategic misrepresentation in planning: Reference class forecasting in practice." *European Planning Studies*, *16*(1), 3-21.

Flyvbjerg, B. (2016). "The fallacy of beneficial ignorance: A test of Hirschman's hiding hand." *World Development*, *84*, 176–189.

Flyvbjerg, B. (2018a). Critics don't understand behavioral science. Local Trans. Today, April 27, pp. 3–4, https://www.transportxtra.com/publications/local-transport-today/news/56703/in-depth-academics-clash-on-causes-of-transport-cost-overruns.

Flyvbjerg, B. (2018b). “Planning fallacy or hiding hand: Which is the better explanation?” *World Development*, *103*, 383–386.
Flyvbjerg, B. and Sunstein, C.R. (2016). “The principle of the malevolent hiding hand; or, the planning fallacy writ large.” *Social Research: An International Quarterly*, *83*(4), 979-1004.
Flyvbjerg, B., Ansar, A., Budzier, A., Buhl, S., Cantarelli, C., Garbuio, M., ... & van Wee, B. (2018). Five things you should know about cost overrun. *Transportation Research Part A: Policy and Practice*, *118*, 174-190.
Flyvbjerg, B., Holm, M. S., & Buhl, S. (2002). “Underestimating costs in public works projects: Error or lie?” *Journal of the American Planning Association*, *68*(3), 279-295.
Hirschman, A.O. (1967). “The principle of the hiding hand.” *The Public Interest*, *6*, 10-23.
Ika, L. A. (2018). “Beneficial or detrimental ignorance: The straw man fallacy of Flyvbjerg’s test of Hirschman’s hiding hand.” *World Development*, *103*, 369–382.
Kirkham, R. (2014). *Ferry and Brandon's cost planning of buildings*. John Wiley & Sons.
Koskela, L., Paavola, S., & Kroll, E. (2018). “The role of abduction in production of new ideas in design.” In *Advancements in the Philosophy of Design* (pp. 153-183). Springer, Cham.
Koskenvesa, A., Koskela, L., Tolonen, T. and Sahlsted, S. (2010). “Waste and labor productivity in production planning: case Finnish construction industry”, in: *18th Annual Conference of the International Group for Lean Construction*, Haifa, Israel.
Kreiner, K. (2020). “Conflicting notions of a project: The battle between Albert O. Hirschman and Bent Flyvbjerg.” *Project Management Journal*, *51*(4) 400-410.
Kuprenas, J. A., & Nasr, E. B. (2003). “Controlling design-phase scope creep.” *AACE International Transactions*, CS11-CS15.
Lepenies, P. H. (2018). “Statistical tests as a hindrance to understanding: What the controversy around the “Hiding Hand” reveals about research in the social sciences and conceals about project management.” *World Development*, *103*, 360–365.
Love, P.E.D. and Ahiaga-Dagbui. D.D. (2018). “De-bunking ‘fake news’ in a post-truth era: the plausible untruths of cost underestimation in transport infrastructure projects.” *Transport. Res. A: Policy and Practice*, *113*, pp. 357-368.
Love, P.E.D., Sing, M. C. P., Ika, L.A., & Newton, S. (2019). “The cost performance of transportation projects: The fallacy of the planning fallacy account.” *Transportation Research Part A: Policy and Practice*, *122*, 1–20.
Ohno, T. (2012). *Taiichi Ohno's Workplace Management: Special 100th Birthday Edition*, McGraw Hill Professional.
Peirce, C. S. (1934). “Abduction and Perceptual Judgments.” *Collected Papers of Charles Sanders Peirce, V (MA: Harvard University Press, 1935)*, 113-120.
Pennanen, A., Ballard, G., & Haahtela, Y. (2011). “Target costing and designing to targets in construction.” *Journal of Financial Management of Property and Construction*, *16* (1)52-63.
Pikas, E. (2019). *Causality and interpretation: integrating the technical and social aspects of design.* Doctoral dissertation. Aalto University.
Simon H.A. (1990). “Bounded Rationality.” In: Eatwell J., Milgate M., Newman P. (eds.) *Utility and Probability.* The New Palgrave. Palgrave Macmillan, London.
Zucker, T. A., Justice, L. M., Piasta, S. B., & Kaderavek, J. N. (2010). “Preschool teachers’ literal and inferential questions and children's responses during whole-class shared reading.” *Early Childhood Research Quarterly*, *25*(1), 65-83.

ENABLING LEAN WITH INFORMATION TECHNOLOGY

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LEAN CONSTRUCTION IN A SERIOUS GAME USING A MULTIPLAYER VIRTUAL REALITY ENVIRONMENT

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ABSTRACT

Whereas Lean Construction is a state-of-the-art practice in construction, associated simulation games in academic or professional education still rely on manual data input and analysis. Proposed is a digital learning platform that teaches the concept of lean construction using an active, hands-on serious gaming environment involving multiple players simultaneously in virtual reality. The novelty is to share rapid feedback with the participants while playing the game. Findings through testing demonstrate they benefit from the run-time data analysis and more effectively understand lean principles to eliminate waste, allow collaboration, and optimize quality in the value-added building chain.

KEYWORDS

Lean, education and training, multiplayer virtual reality, runtime data, serious gaming.

INTRODUCTION

Labor productivity in the construction sector has seen little growth over the past decades (Barbosa et al., 2017). To direct necessary change, many possible avenues exist. One is labor productivity-increasing measures. Several other directions range from more effective collaboration among project partners and new contracting options to project-level actions, e.g. using emerging technology that optimizes construction operations.

For years, leading construction companies have identified waste in human capital as a prime reason for low productivity in construction. For this specific purpose, simulation games are used to educate project personnel with better results than traditional lectures (Herrera et al., 2019). For example, lean construction principles can be learned in simulating the real-world experience in form of a hypothetical scenario in a serious game (defined as a purpose other than just fun).

While lean construction simulation games assist in the task of aligning the individual project personnel to teams well, for several reasons, they have not become part of a general best practice developed for the construction industry (CII, 1997). One main reason is, playing such simulation games is a resource-intensive task. It: (a) requires often one or a group of experienced lean expert/s with adequate training skills to convey the learning goals and measure accordingly the team's progress; (b) involves typically large scale physical models, which are difficult to set up on the day of training and transport; (c) requires quite some maintenance to replenish individual pieces that are being

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consumed during the playing, and (d) demand sometimes extensive travel from the trainer(s) or the model to perhaps even foreign countries. In brief, the overall investment in custom-made physical simulation models and their accompanying instructional material easily reaches 10,000€ or more. The demand for such models and trainers within an organization can exceed their availability or be too rare to justify the investment. This a reason why lean construction training is often offered by consultants. Not surprisingly, simulation games in lean construction have evolved over time. Benefiting from industry experience, academia has constantly pioneered their next versions.

This is the case here. The proposed concept envisions resolving some of the shortcomings. This paper (1) introduces lean construction principles, (2) reflects upon the use of simulation games in lean construction training, (3) provides the state-of-the-art specifically in multiplayer virtual reality (VR) and serious gaming environments, (4) introduces the design of the developed serious game in multiplayer VR, (5) shows early implementation and results, and (6) gives an outlook and the remaining crucial challenges.

BACKGROUND

LEAN CONSTRUCTION PRINCIPLES

Lean in construction was examined as early as 1992. Koskela (1992 and 2000) developed the Transformation-Flow-Value (TFV) theory and Seven Flows, saying that construction can be conceptualized with the transformation of resources and the creation of systematic value and continuous flow of materials and people. Lean production control theories have been emerging for the construction sector since then (von Heyl and Teizer, 2017).

One of the goals of applying lean to construction is to fully understand the dynamics of production, the effects of dependencies, and the variation that occurs along the supply and assembly chains for each project. Because the scope of the projects differs from every project, lean construction uses two major criteria (Aziz and Hafez, 2013): Planning: The defining criteria for success and producing strategies for achieving the end goal; control: The ability to control events so that they conform to the plan and also trigger learning and re-planning. This research seeks to reduce waste. Several lean principles can be applied.

The Flow principle is one of the core elements of Lean Thinking. Flow depends heavily on the quality management of activities. Avoiding rework related to quality deficiencies is essential for assuring that the flow of products is as planned. Another key factor within the flow is the visual transparency of work. Research has shown that visual controls in job sites observed a straight correlation between transparency and efficiency.

The Perfection principle is more of a focus on the learning aspect of Lean. One note of Lean Thinking is the continuous learning and improvement of techniques and methods. Therefore, establishing a systematic procedure to constantly learn and improve the standardisation of work is key by using quality systems and focusing on the characteristics that affect product performance (Cheng et al., 2012).

LEAN THINKING USING SIMULATION GAMES

Although Lean Thinking intended practical benefits, efficient training tools for lean construction are still emerging. In these, however, it is often humans that gather and assess data during the training event. Humans again are needed to interpret the results and transfer information to valuable knowledge that is finally applied in collaborative learning experiences. The chance for instructor/s to manipulate information in such settings is high.

Example: At least two rounds are played in simulation games. The first round does not and the second round follows lean principles. The performance of the participants in both is often compared. The assessment criteria seem strict: total playtime by minutes and seconds (recorded by a manual stopwatch), the number of completed sections (often rooms) by the entire team, the progress made by individual trade, and their number of defects created. While the participants are divided into carrying out trade-specific work tasks, each represents the trade they identify with the most, for example, being a: carpenter, plumber, or electrician. The instructor/s determine any of the potential quality issues based on a-priori set knowledge (previous events) at the end of each play round.

Existing simulation games are often criticized to lack realism, e.g., with construction being depicted by paper airplanes or in miniature format with alternative materials such as marbles or Lego (von Heyl 2015). Dallasega et al. (2020) implement VR in a simulation game, but the segment is still not realistic as the task of building Lego is just transferred to a virtual environment. Furthermore, most games lack data collection as this is handled manually by observers. This can potentially lead to biased data or few data being collected.

While quality issues are often not argued (the serious gaming environment is quite relaxed), as experienced in several runs of academic as well as professional simulation games, instructor/s often give participants the opportunity to take short breaks in the second round. While the clock is then stopped, the participants can re-assess and modify their performance just-in-time. This opportunity, however, is not given to the (same) participants in the first round. This causes two issues: (a) time recordings are not comparable and (b) lessons learned from playing the same simulation game twice (it would be too difficult to have a second, but different model available) improves naturally the performance criteria (participants' learning curve).

Therefore, it is believed that simulation games are tailored towards an expected outcome. Errors occur when the instructor/s presents quantitative data that actually should compare the participants' performance in both rounds objectively. However, it does not.

TRACKING METHODS FOR LEAN PURPOSES

Numerous promising methods exist that link technology to lean construction implementation as well as training. For example, Building Information Modeling (BIM)-based scheduling has been tied to scheduling (4D) in lean construction. Sacks et al. (2009 and 2010), in particular, and others (Mollasalehi, 2018; Singhal et. al., 2018; Fosse et al., 2017; Tillmann and Sargent, 2016; Dave et al., 2011, Teizer et al., 2017a) have shown from the earliest concepts to now applications in industry. Other studies (Cheng et al., 2010; Costin et al., 2015; von Heyl and Teizer, 2017; Teizer et al. 2017b; Li et al., 2017) have taken a further step and started integrating technology as an additional enabler for harmonizing the meaningful data sets which exist or can be generated within each of the three silos: BIM, Internet of Things, and Lean Construction. One could call this integration a 'Digital Twin' today, where continuous gathering of performed data on construction sites replenishes as-planned data. By doing so, it results in rapid, objective information that enables control over a project's progress, systematic analysis and forecasting, and communication for informed decision making among collaboratively working teams across all trades. However, while this has become possible in real life, higher education or training environments lack such use of technology.

A critical component for digitalizing simulation games in lean construction is the possibility of seamless data recording. This includes but is not limited to locating construction workers inside of a work environment (in real life) or participants in a lean construction simulation game (here: virtual). While a large body of work in the research literature exists on indoor location tracking – even in combination with BIM (Neges et al., 2017; Teizer et al. 2007; von Heyl and Demir, 2019), little of it can be used in lean construction simulation games (Teizer et al., 2020). None can be applied in multiplayer virtual learning environments meant for lean construction (Teizer et al., 2019; Golovina et al., 2019), because players typically traverse in virtuality only.

USE OF VIRTUAL REALITY IN CONSTRUCTION

Over the past years, the construction industry has increasingly adopted VR solutions (Zhang, et al., 2020). The solutions vary in use, for example, safety training (Golovina et al., 2019; Wolf et al. 2019; Bükrü et al., 2020, Solberg et al., 2020), workspace planning (Getuli et al., 2020), and project walkthroughs (Du et al., 2018). Since construction provides a collaborative environment, a virtual environment that imitates it would allow for better immersion and an experience more true to the construction environment. This could be achieved through a multiplayer virtual environment, which would enable a more realistic setting when compared to the real construction site.

VR is achieved through the implementation of computer technology. A range of commercially available systems have been created for this purpose such as headsets, treadmills, gloves, and controllers (even with forced feedback). These systems allow for the creation of an illusion of reality, which is interactive. Immersive VR technologies, therefore, enable a user to enter a simulated environment with related activities.

In construction, this is usually a construction site scenario based on real-life situations. Michalos et al. (2018) proposed a method that enhances the design of workplaces and supports decision-making processes, through the collection and analysis of the position tracking of a worker. This is facilitated by an immersive realistic VR-simulated environment in which a worker can perform regular tasks. Using this data, the worker's movement and actions can be optimised, thus reducing costs and time concerning the actual physical implementation of the work (Getuli et al., 2020). Delgado et al. (2020) have studied the current research within Augmented Reality (AR) and VR for architecture, engineering, and construction. They have concluded that the adoption level of both AR and VR remains low within the construction sector.

MULTIPLAYER ENVIRONMENTS IN VR

This paper presents a multiplayer environment, meaning an environment where multiple people can be present at once. Multiplayer environments have not yet been fully explored within a construction VR environment. Only a few papers fully utilize the possibilities the multiplayer environment presents, i.e. Du et al. (2018) who utilize the multiplayer feature in walkthroughs for communication between the designer, contractor, and owner, and Zhao et al. (2020) who research manufacturing simulation with multiplayer functionality. Furthermore, in the scene created by Zhao et al. (2020), the participants do not occupy the same workspace but have dedicated spaces for themselves.

The research related to construction has not yet utilized use-time data collection which is possible to capture through VR as seen in other experiences (Golovina et al., 2019; Solberg et al., 2020). Furthermore, they do not explore multiplayer VR for collaborative work as the work on a construction site usually will be (incl. a site with multiple trades).

ROLE OF MULTIPLAYER VIRTUAL REALITY

While no multiplayer VR environments exist that are tailored for a lean construction simulation game, our vision is a hands-on learning in a classroom-style setting that enables active learning. This would follow (not replace) other existing, traditional learning styles, i.e., frontal teaching lectures using presentation slides or small, but very efficient game-plays (e.g., "airplane game"). By today, quite a few well-implemented efforts that teach the lean principles using such methods have entered higher education and consulting (Table 1). Many yet do not address parts of the aforementioned issues. While they are called lean simulation games, they follow the objectives of serious games.

Table 1: Examples of lean construction simulation games and categories they address

Category / Game	Building Information Modeling	Automated data collection and processing	Lean principles*	Virtual reality
Lean construction simulation game(s)**			X	
Leapcon (Sacks et al., 2007)			X	
RBL-PHP (Li et al., 2018)	(X)	X	X	
BIM-IoT-LC (Teizer et al., 2020)	(X)	X	X	
Multiplayer Serious Game for Lean Construction		X	X	X

* Addressing some of the corresponding lean principles: planning and control, standardization, pull production, wastes, kaizen, site organization, quality, and safety.
** Numerous variations of simulation games exist that are being used in construction or consulting organizations (with a focus on commercial building, manufacturing, and infrastructure).

METHOD

Multiple solutions exist both for multiplayer VR hardware- and software setup. There are several commercially available options for the headset a user wears to experience a VR scene, the controllers a user needs to traverse or interact with objects in a VR scene, and the computers themselves to power and process the setup. Furthermore, several solutions are present for designing and creating a VR game, and even for how to enable multiple participants to be in the same VR environment at once. All is a non-trivial effort, often compared to movie sets in the filming industry (Wolf et al. 2019). The full setup that was created in iterative development stages is seen in Figure 1.

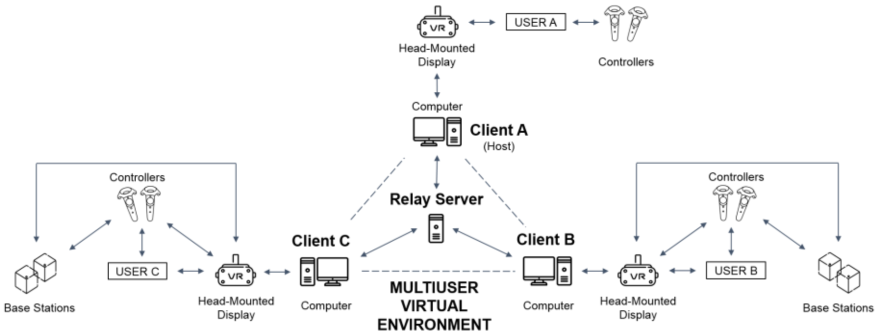

Figure 1: Multiplayer virtual environment for a serious game in lean training

DESIGN OF SCENARIO

The design includes two scenes (Figures 2a and 2c): A ‘messy’ scene, which does not follow lean initiatives, and a ‘lean’ scene where lean initiatives have been incorporated. Both are similar in layout, and at closer look small (but effectful for a participant) differences appear. In the first scene where lean initiatives are not present, the participants are confronted with several problems: (1) They have not been given a location sequence to follow, (2) they have not been instructed in the specific work, only what their task is, and (3) the workstations are not cleaned from obstructions. In the second scene lean initiatives are presented. A location sequence is given, all participants have training for their task, and according to Lean 5S principles all workstations are free from obstructions. Each round is designed to last under 30 minutes for reasons of learning effectiveness.

Each scene has three workstations and one panel area with a board used for instructions Figure 2b. When participants join the game, they are placed in the central part of the selected scene, in front of the (lean) instructions board. There it is possible to see both instructions for the tasks for the 3 trades (carpenter, plumber, and electrician) and their live work status. Latter is shown via cubes placed according to the workstation the trade is currently working in. The carpenter has to place 6 drywall sheets in 4 different sizes (Figure 3a-d). The plumber has to place 4 different pieces of pipes, 1 sink, and 1 toilet. The electrician has to place 2 lamps and 2 wires of the same kind. All the objects are part of automatic data collection which is used for the analysis of the game.

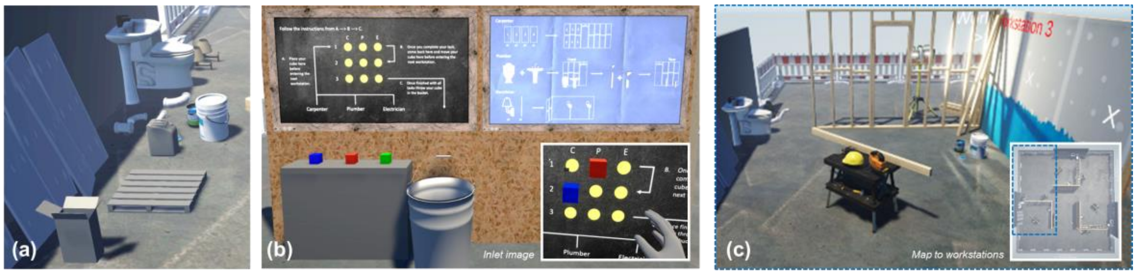

Figure 2: (a) Workstation in 'messy' state, (b) board with instructions (incl. display which workstation a trade occupies at a given time; assembly sequence of parts; small desk with 3 cubes indicating that trades are in a waiting position; bucket that trades use to throw their cube in after they completed all work tasks; the inlet image shows the live status of the display during a scene play), and (c) a workstation in its 'lean' state

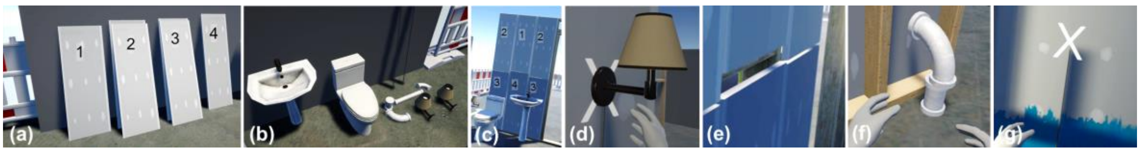

Figure 3: (a-b) Material sorted, (c-d) correctly installed by trades, (e-g) examples of observed quality issues, e.g. gaps in installed drywall sheets, misaligned pipe fitting, and lamp installation missing

HARDWARE SETUP

The research was conducted using two different types of VR headsets to display the possibility of cross-brand usability. The setup included two HTC Vive Pro Eye headsets (of which the eye-tracking functionality was not used) and one Oculus Quest 2 headset. The controllers being used were standard controllers shipped with the headsets and both the HTC Vive headsets were connected to two base stations respectively. All headsets were connected to computers, which were used as engines for running the game.

SOFTWARE SETUP

For the game engine, there are several options, amongst others Unity3D and Unreal Engine. Unity3D (version 2019.4.8f1) was used for the project and all scripts that enabled the game to run were written in C# as this is one of the two programming languages that Unity3D supports. For movement and interactions, the XR Interaction Toolkit (Unity, 2020) was used for the framework. This allowed for cross-brand experiences, which was necessary, because of the two different brands of headsets being used.

PUN 2 from Photon (Photon, 2020) is used as the integration that allows for the development of multiplayer experiences (the server connecting Clients A, B, and C). With Unity, the host will have complete control over the game, i.e. when he leaves the scene, the game will end. With Photon, the host is only seen as another client. This allows for greater performance, as fewer steps are required to transfer data between the clients.

This setup is especially useful as this allows participants to connect from anywhere and will work on networks that have restrictions regarding peer-to-peer connectivity. Furthermore, this setup allows for easy setup if the experiment is conducted in a different location, as it is not reliant on the IP addresses and without the need for reconfiguration.

DATA COLLECTION

For the experiences in VR, automatic data collection has been set up. This allows for quantitative analysis of the runs and makes it possible to see potential optimizations, which in the end could allow users to optimize the workflow on real construction projects. The data collection happens when interactions with objects happen. All interactions are recorded in a CSV file. The contents are shown in Table 2.

Table 2: Data types and their meaning

Data type	Timestamp	Object	Location	Action	Trade
Description	Time of action [hh:mm:ss]	Object interacted with [e.g., sink, pipe]	Location of interaction [WS1 to 3]	Type of action [Pick-up, Place]	Who interacted [Carpenter, Plumber, Electrician]

RESULTS

Similar to simulation games for lean construction involving a physical model, two rounds were played to be able to display the impact of lean when compared to experiencing a workplace without lean initiatives. The automatic data recording is being used in both scenes to be able to compare them afterward.

The first round took the 3 participants 12 minutes and 16 seconds to complete. They combined had 29 occasions of multiple material handlings, which refers to the number of times a participant had to handle an object more than needed. An example, is dropping material and picking it back up again, or relocating it to its final installation point. Even with the 29 steps of rework, there still were 5 quality issues observed during the first round. These were found upon inspecting the data that relates to quality issues (incorrectly placed objects trigger a counter). This later was verified by analysing additional video footage of cameras installed throughout the scene and the participants' field-of-view recordings. Examples of these quality issues can be seen in Figure 3e-g.

The second round took 6 min and 56 sec to complete and had 11 occasions of multiple material handling (62% decrease) and ended up with only 1 quality issue (80% decrease). This already shows an improvement between the two scenarios. Because of the automatic data collection, it is possible to look at data for every workspace and thereby examine why the lean round was significantly faster. Figure 4 shows the comparison.

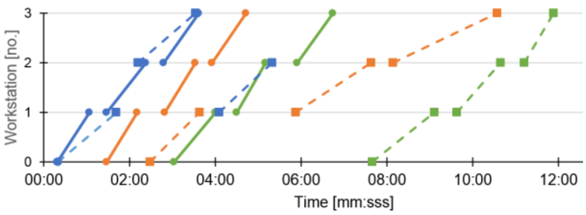

Figure 4: Location-based schedule of 'messy' (dashed) vs. 'lean' scene (solid lines)

The 'lean' version (solid lines) is faster than the non-lean ('messy') version (dashed lines). Overall, the duration is cut roughly into a bit more than half (57%). Another indication is the slope of the lines. When the slope is steep (vertical lines), the task is done faster. Here, especially the carpenter and the plumber (orange colour) performed faster. This can be due to several things, the most significant being the mess that needs to be cleaned before starting their work in the 'messy' scene. This could also be a reason why the electrician (green colour) did not have as much improvement as the other two trades, as the slope difference between the green solid lines and green dashed lines was not as significant as the other trades. This is because this trade did not need to move objects before starting the assigned task. Besides the slope, it is also seen that the carpenter went from workstations 1 to 3 directly instead of following the sequence: 1 to 2, and then to 3. This made the plumber wait after workspace 1 and thereby delaying the whole team.

The 'lean' scene was played as the last. This meant that all participants were already experienced in this environment, which also could affect the performance of the second round, both in terms of the time of completion but also in terms of quality as described earlier. Eventually, multiple different environments with various tasks will remedy such issues, or additional participants not used to either scene will be used for more objective comparison. These limitations can be uplifted, but should not diminish the benefits the developed serious game using a multiplayer virtual reality environment generated and once results are compared to existing simulation games used in lean construction training.

CONCLUSION

This research successfully developed a serious virtual reality (VR) multiplayer game to teach lean construction. The preliminary findings show high potential for use-time data collection for a thorough analysis of several lean principles, such as the flow principle and the perfection principle. The results also show how a VR experience can be used to teach lean principles in a more realistic environment than board or other lean simulation games and that it can help in decision-making processes by the use of data collection and analysis. The developed tool is more sensitive to the overall investment, and also allows for teaching these principles while participants are apart, e.g., under Covid-19 restrictions.

The study is one of the first attempts to examine multiplayer environments for construction. It has shown potential for improvement. For example, giving participants with little to no prior VR experience additional training or distinguishing the layout and tasks in the two rounds more. Future versions would also benefit from implementing additional lean principles (e.g., the pull principle where a warehouse functions as the central hub for the material). For data collection, it should be showcased if participants were helping each other with tasks. Their trajectory tracking should be recorded to further optimize the workflow through data analysis and presentation between the two game scenes. Using a larger sample size and video footage recorded of the participants outside of VR would allow for better data analysis, incl. which impact emotional reactions and mistakes of participants have when learning with VR. While a study of VR sickness was not part of the research scope, its limitation should be investigated in a future study. The same counts for protecting the participants' privacy rights. The individual analysis would then allow personalized feedback for their performance, as it is a training environment.

This game currently is limited to ten participants that join the server application. More tasks could be added and modelled in Unity3D to allow for more realistic workflows typical in construction. This, however, requires additional VR headsets and computers, which come at higher expenses. The investment may return value for other AEC purposes.

REFERENCES

Aziz, R. & Hafez, S. (2013). "Applying lean thinking in construction and performance improvement." Alexandria Eng. J. 52(4), 679–695, doi.org/10.1016/j.aej.2013.04.008.

Barbosa, F. (2017). "A Route to Higher Productivity." McKinsey&Company.

Bükrü, S., Wolf, M., Böhm, B., König, M., & Teizer, J. (2020). "Augmented Virtuality in Construction Safety Education and Training." EG-ICE, Berlin, Germany, 115-124.

Cheng, T., Yang, J., Teizer, J, & Vela, P.A. (2010). "Automated Construction Resource Location Tracking to Support the Analysis of Lean Principles." 18th IGLC, 643-653.

Cheng, T., Mantripragada, U., Teizer, J. & Vela, P.A. (2012). "Automated Trajectory and Path Planning Analysis Based on Ultra Wideband Data", Computing in Civil Engineering, 26(2), 151-160. doi.org/10.1061/(ASCE)CP.1943-5487.0000115.

Construction Industry Institute. (1997). "Team Alignment During Pre-Project Planning of Capital Facilities - RR113-12." The University of Texas at Austin.

Costin, A.M., Teizer, J., & Schoner, B. (2015). "RFID and BIM-enabled worker location tracking to support real-time building protocol and data visualization." Information Technologies in Construction (ITCON), 20, 495–517.

Dallasega, P., Revolti, A.,Sauer, P.C., Schulze, F. & Rauch, R. (2020). "BIM, Augmented and Virtual Reality Empowering Lean Construction Management: A Project Simulation Game." Pro. Manfct. 45:49–54. doi.org/10.1016/j.promfg.2020.04.059.

Du, J., Shi, Y., Zou, Z., Dong, Z. (2018). "CoVR: Cloud-Based Multiuser Virtual Reality Headset System for Project Communication of Remote Users." C. Eng. Mgmt., 144.

Delgado, J.M.D., Oyedele, L., Demian, P. & Beach, T. (2020). "A research agenda for augmented and virtual reality in architecture, engineering and construction." Adv. Eng. Inf., 45101122.

Dave, B., Boddy, S. & Koskela, L. (2011). "Visilean: Designing a production management system with Lean and BIM." 19th IGLC, Lima.

Fosse, R., Ballard, G. & Fischer, M. (2017). "Virtual Design and Construction: Aligning BIM and Lean in Practice". 25th IGLC. Heraklion, Greece, 499-506.

Golovina, O., Kazanci, C., Teizer, J. & König, M. (2019). "Using Serious Games in Virtual Reality for Automated Close Call and Contact Collision Analysis in Construction Safety." 36th ISARC, doi.org/10.22260/ISARC2019/0129.

Getuli, V., Capone, P., Bruttini, A. & Isaac, S. (2020). "BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach." Aut. in Constr., 114103160.

Herrera, Rodrigo F., Sanz, M. Amalia, Montalbán-Domingo, Laura, García-Segura, Tatiana & Pellicer, Eugenio. (2019). "Impact of Game-Based Learning on Understanding Lean Construction Principles", Sustainability, 11, 5294.

Koskela, L. (1992). "Application of the new Production Philosophy to Construction", CIFE Technical Report #72, CIFE, Stanford University.

Koskela, L. (2000). "An Exploration Towards a Production Theory and its Application to Construction", VTT, Finland.

Li, X., Shen, G.Q., Wu, P. & Fan, H. (2018). "RBL-PHP: simulation of lean construction and information technologies for prefabrication housing production", J. Mgmt. in Eng., 34(2), 4017053.

Michalos, G., Karvouniari, A., Dimitropoulos, N., Togias, T., et al. (2018). "Workplace analysis and design using virtual reality techniques." CIRP Annals. 67 (1), 141–144.

Mollasalehi, S., Aboumoemen, A.A., Rathnayake, A., Fleming, A., & Underwood, J. (2018). "Development of an Integrated BIM and Lean Maturity Model." 26th IGLC, 1217–1228.

Neges, M., Wolf, M., Propach, M., Teizer, J., Abramovici, M. (2017). "Improving Indoor Location Tracking Quality for Construction and Facility Management." 34th ISARC.

Photon. (2020) "Photon PUN" https://www.photonengine.com/pun (Jan. 20, 2021).

Unity Technologies. (2020). “Unity-XR Interaction Toolkit.” https://docs.unity3d.com/Manual/com.unity.xr.interaction.toolkit.html (Dec. 10, 2020).

Sacks, R., Esquenazi, A., & Goldin, M. (2007). “LEAPCON: Simulation of lean construction of high-rise apartment buildings.” J. Const. Eng. Mgmt., 133:7, 529–539.

Sacks, R., Dave, B., Koskela, L., & Owen, R. (2009). “Analysis Framework for the Interaction Between Lean Construction and Building Information Modeling.” 17th IGLC, 1-10.

Sacks, R. Radosavljevic, M., & Barak, R. (2010). “Requirements for building information modeling based lean production management systems for construction.” Aut. in Constr., 19(6), 641-655.

Singh, G.R. (2019). “Raywenderlich”. https://www.raywenderlich.com/1142814-introduction-to-multiplayer-games-with-unity-and-photon. (Jan. 19, 2021).

Singhal, N., & Ahuja, R. (2018). “Can BIM furnish Lean benefits - an Indian case study.” 26th IGLC, 90-100.

Solberg, A., Hognestad, J. K., Golovina, O., & Teizer, J. (2020). “Active Personalized Training of Construction Safety Using Run Time Data Collection in Virtual Reality.” 20th CONVR, pp. 19-30. Middlesbrough, UK: Teesside University Press.

Tillmann, P., & Sargent, Z. (2016). “Last Planner & BIM Integration: Lessons from a Continuous Improvement Effort.” 24th IGLC, Boston, 113-122.

Teizer, J., Lao, D., & Sofer, M. (2007). “Rapid Automated Monitoring of Construction Site Activities using Ultra-Wideband.” 24th ISARC, Cochin, India, 23-28.

Teizer, J., Melzner, J., Wolf, M., Golovina, O., & König, M. (2017a). “Automatisierte 4D-Bauablaufvisualisierung und Ist-Datenerfassung zur Planung und Steuerung von Bauprozessen. [Automating Lean Management]” Bauingenieur, Springer, 129-135.

Teizer, J., Wolf, M., Golovina, O., Perschewski, M., Neges, M., & König, M. (2017b). “Internet of Things (IoT) for Integrating Environmental and Localization Data in Building Information Modeling (BIM).” 34th ISARC, doi.org/10.22260/ISARC2017/0084.

Teizer, J., Wolf, M., & König, M. (2018). “Mixed Reality Anwendungen und ihr Einsatz in der Aus- und Weiterbildung kapitalintensiver Industrien.” [Mixed Reality in Construction Education] Bauingenieur, 73-82.

Teizer, J., Embers, S., Golovina, O., & Wolf, M. (2020). “A serious gaming approach to integrate BIM, IoT and Lean Construction in Construction Education.” Construction Research Congress 2020, Tempe, USA.

von Heyl, J. (2015). “Lean Simulation in Road Construction: Teaching of Basic Lean Principles”, 23rd IGLC, Perth, Australia, 403-412.

von Heyl, J. & Teizer, J. (2017). “Lean Production Controlling and Progress Tracking using Digital Methods.” LC3, Heraklion, Greece, 127-134.

von Heyl, J. & Demir, S.-T. (2019). “Digitalizing lean construction with building information modeling.” 27th IGLC, Dublin, Ireland, 843-852.

Wolf, M., Teizer, J., & Ruse, J.H. (2019). “Case Study on Mobile Virtual Reality Construction Training.” 36th ISARC, Banff, Canada.

Zhang, Y., Liu, H., Kang, S., & Al-Hussein, M. (2020) “Virtual reality applications for the built environment: Research trends and opportunities.” Aut. in Constr., 118103311.

Zhao, R., Aqlan, F., Elliott, L.J, & Baxter, E.J. (2020). “Multiplayer Physical and Virtual Reality Games for Team-based Manufacturing Simulation”. ASEE Conf., 1-2-34989.

Hua, D. and Schwartz, T., (2021). "LPS Implementation using physical and digital Visual Management-based tools: A case Study in Luxembourg" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 65–74, doi.org/10.24928/2021/0161, online at iglc.net.

LPS IMPLEMENTATION USING PHYSICAL AND DIGITAL VISUAL MANAGEMENT-BASED TOOLS: A CASE STUDY IN LUXEMBOURG

Duan Hua[1] and Thomas Schwartz[2]

ABSTRACT

The Work described in this paper presents the results of a lean construction research project. The objective was to evaluate the impact of Visual Management-based tools to improve Last Planner® System implementation in Luxembourg. To drive this project, a Design Science Research methodology has been used on two construction sites.

The first step of the research focuses on the use of physical supports to design visual management-based tools to implement LPS conversations. The results show a very positive impact as it tackles LPS implementation challenges (collaboration between trades, skills acquisition, change management) but also show that the workload to manage LPS conversation is a serious problem.

The second step of the research tackles this workload issue by digitizing the Visual Management-based tools designed in the first iteration. The results show a huge improvement for users allowing more efficient meetings, better access to data, improved use of LPS outputs to communicate between the client and the project management team and even more flexibility to respect COVID 19 sanitary rules.

The paper concludes with the limit of the digital solution which was used in this project. As it is not specially dedicated to LPS it lacks the possibility to calculate and simulate planning and production data.

KEYWORDS

Last Planner® System, digital, visual management, obeya.

INTRODUCTION

The Last Planner® System (LPS) is a method for planning and controlling production developed by Ballard and Howell (Ballard and Howell 1994) for the construction industry

It aims to reduce variability and uncertainty in the production workflow by planning, removing constraints and ensuring continuous improvement.

Recent decades have shown that the implementation of LPS is a real issue for construction companies (Porwal et al. 2010). Several challenges as, partial LPS implementation (Bhargav, 2015), lack of training (Fernandez, 2018), issue with change management (Tayeh, 2018) complexity to implement specific discussion, ie make ready

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plan (Ebb, 2018) have been reported without giving real operational solutions for LPS practitioners. This paper describes two separate instances of LPS implementation from past and ongoing projects and a presentation of operational tools tackling LPS implementation challenges. As LPS is closely associated with collaboration (Mosmann, 2015), transparency (Brady, 2014), operation tools based on visual management (Brady, 2014) will be presented and evaluated as they could bring an important support for LPS implementation by ensuring more structure and facilitate skills acquisition. In addition, it has been observed that LPS meetings are time consuming (Bassam 2018), to tackle this challenge, an IT based solution will be presented as it could easily provide extra support to facilitate LPS implementation. Evaluations of both implementations will be based on observations and users' feedbacks.

THE LAST PLANNER® SYSTEM

The Last Planner® System, developed by Ballard and Howell in 1992, focuses construction project management around planning and production control, rather than on directing and adjusting production (Daniel et al. 2015). This method improves collaboration between the different project stakeholders to reach the common goal by organizing / structuring collaboration around 5 conversations (Mossman 2015) with specific goals:

- Should: Master Schedule and Phase Schedule
- Can: Make Work Ready Plan
- Do: Weekly Work Plan
- Did: Percentage of Promises Completed and Continuous Improvement

Studies have reported the substantial benefits resulting from the implementation of the LPS in building construction (Alarcón et al., 2005), which could explain the increasing demand from construction stakeholders, building project owners and contractors. The main barriers to LPS implementation are related to a lack of both training (Fernandez, 2018) and time to implement change management, resulting in an insufficient acquisition of LPS skills from stakeholders. In addition, the complexity of the LPS method and the fact that meetings are considered a waste of time by most subcontractors in our study can result in a loss of interest from participants, drastically reducing the level of collaboration and the added value of the LPS method. This sometimes results in LPS ultimately being abandoned.

RESEARCH METHOD

Khan 2014, indicates that Design Science Research (DSR) can support the development of valid and reliable knowledge that can be used to create lean solutions to practical problems in the construction industry.

As already done by several lean construction publications, we used a Design Science Research (DSR)methodology both to develop new artefacts to solve issues we faced during our LPS implementation and to contribute to the theory of the LPS (Lukka, 2003).

The Design Science Research methodology (DSR) (Peffers, 2007) adopted for this research required the first five steps to be implemented in order to develop an LPS physical environment with 'paper artefacts' that tackles the problem we faced during past LPS implementations. We've used the DSRM method in a specific manner; we did not perform several iterations on the same problem. To provide practical results we carried out one iteration tackling a challenge based on literature review and a second one discovered during the evaluation phase of the first iteration. After the design, the implementation and the evaluation of our demonstrator on the field. The first iteration showed good results for the dynamics of the collaboration, but other additional practical problems appeared. We decided to solve those issues with an IT solution and a second iteration (Fig 1) on a different construction project. Those two iterations will be presented in this paper

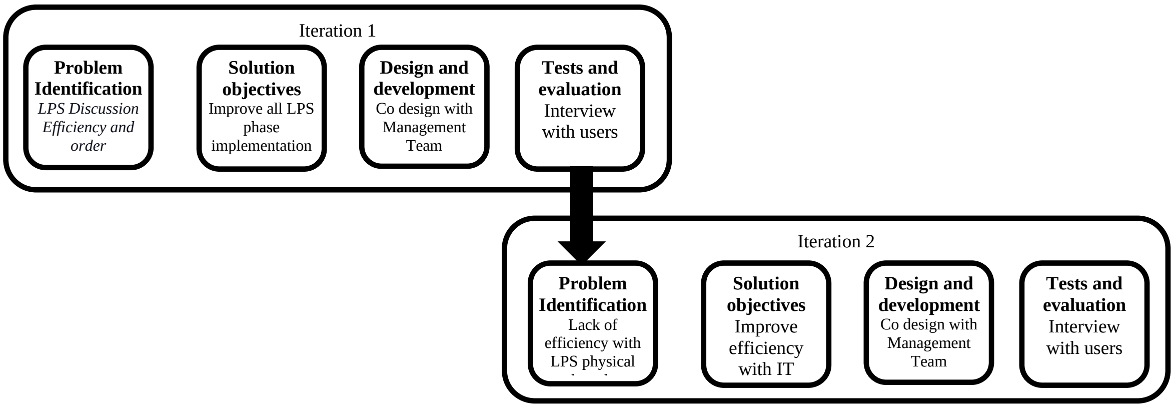

Figure1 Double iteration DSR Scheme

For each iteration, a first explanation on the context and the tools used will be done, then the identification of the practical problems and their impact on the LPS implementation and finally the solution developed and its evaluation on the field.

FIRST ITERATION

The first iteration of our research was requested by a building owner wanting to implement the Last Planner® System for a €10 million project that included all building trades. The project stakeholders had no experience with LPS. The project manager was highly experienced in using the classic method based on directing and adjusting (Cybernetic model). All subcontractors and the project manager were trained in LPS concepts and conversations, in the weekly meeting routine, and were trained to use the different physical tools supporting LPS implementation. Several evaluations were planned with the teams to adjust the process and tools according to user needs.

PROBLEM IDENTIFICATION AND MOTIVATION: LPS DISCUSSION EFFICIENCY AND ORDER

We decided to tackle two practical problems identified during past LPS implementations that were related to one or more LPS implementation challenges already identified in the literature. Mixing LPS discussions leading to partial implementation (Bhargav,2015) and improve Make Ready Discussion (Ebb 2018).

FIRST ISSUE ADDRESSED: MIXING LPS DISCUSSIONS

It has been observed that most LPS projects were characterized by a lack of training, and a lack of time to manage change. As a result, although users invest time in LPS, they still have a “This is how I ‘ve always done it” attitude, which results in managing LPS conversations in the wrong chronological order and mixing their objectives, thus leading to partial LPS implementation. As an example, contractors and subcontractors have the tendency to start the Make Work Ready Plan too early, extracting data directly from the Master Schedule before working on the Phase Schedule. Without robust information like detailed planning, work sequence or the agreement between subcontractors about consecutive tasks handoffs, investing time in preparing task soundness is highly unproductive, as non-priority tasks will be addressed, and work started too early will have to be done again. Furthermore, these digressions result in a global loss of efficiency, longer meetings that do not produce what is expected, a loss of interest in LPS as the objectives are not achieved, and the risk of giving up on LPS.

Solution Objective

Compensate lack of training, lack of implementation time available by improving the guiding capacity of supporting tools and improving the "learning by doing" effect provided by visual management (Tezel et al.2009)

Design and Development

The main element in this proposal for supporting LPS implementation was to guide users with a dedicated physical tool for each LPS conversation. Therefore, sticky note boards have been used to support the Master Schedule (MP) and Phase Schedule (PS) (Fig.2), Make Work Ready plan (MR) and Weekly Work Plan (WWP).

Each tool was designed to fit with each LPS conversation and its objectives with a specific time horizon (monthly for the MP, weekly for the PS and daily for the WWP) and a specific level of information granularity. This helped subcontractors to focus their exchanges during meetings, helped the LPS facilitator to avoid digression, and avoided describing a task in too much detail too early on or planning and preparing a task too late.

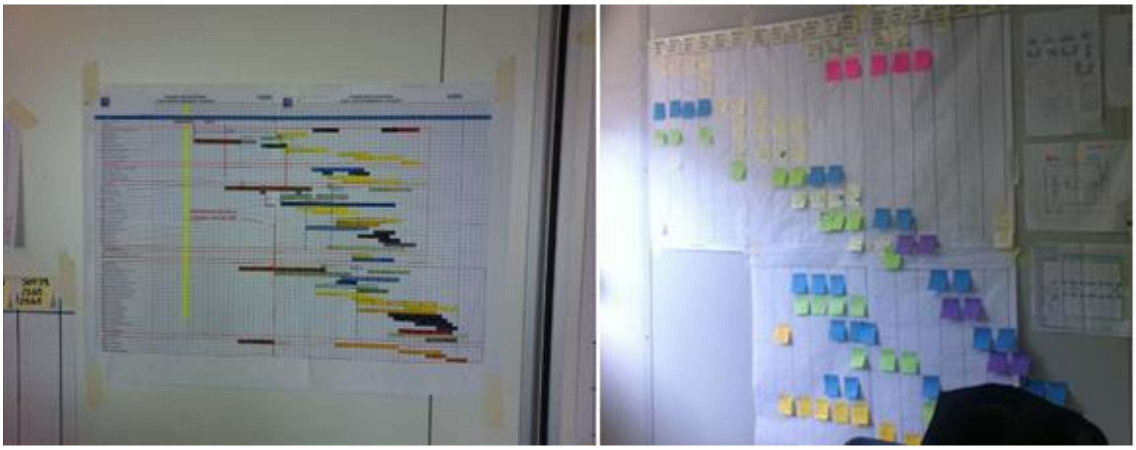

Figure 2: Master Schedule & Phase Schedule

Tests and Evaluation

According to observations during meetings and interviews with users, the implementation of a specific visual management-based tool for each conversation enabled the project team to improve its productivity and collaboration during LPS meetings and reduce meeting length by focusing only on the LPS conversation objectives. It also provided a structured routine to manage LPS meetings, and improved stakeholders' involvement and their ability to take responsibility, as well as their autonomy to fuel the meetings with data. The different tools supporting each LPS conversation and their specific design helped users to acquire LPS skills, which resulted in more discipline during the meetings.

SECOND ISSUE ADDRESSED: IMPROVE THE MAKE READY CONVERSATION

The second issue was the implementation of the Make Ready conversation as it induces the most important change (Ebbs, 2018) Indeed, for construction stakeholders, solving problems and removing constraints are common activities in a construction project. These used to be accomplished in an individual fire-fighting dynamic rather than in a planned and collaborative way as recommended in the LPS method. It is common to use Excel sheets (Figure 3) to identify and monitor constraints by providing key information like task description, localizations, comments, deadlines for removing the constraints, time horizon, and the person responsible for the constraint removal. However, we found that a simple list was not enough to help people collaborate in identifying constraints and monitoring constraint removal as it is difficult to identify work priorities and task "soundness"(Mossman 2015) issues according to the production horizon.

Task Operationalisation								Information			Ressources				Ready
N°	Task	Description	Zoning	Remark	Week	Date	Responsible	Plans	Validated Plans	Auhthoriza-tion	HR	materials	Equipment	Space	Y/N
130	Masonry	Joints for prefab wall	Stairs		35	29-aug	ASCO	V	V	V					
128	Masonry	Wall boiler room	LV +2		39	24-sept	ASCO	V	V	V	V	V	V	V	Y
112	Masonry	Concreting Elevator Inspection hatch	Roof	Inpection Hatch Protection	36	05-sept	ASCO	V	V	V	V				
127	Masonry	Closing wall roiler Room	Lv +2		36	09-sept	ASCO	V	V	V					
144	Masonry	Finalizing Coincreting disposal room	Basement -3		39	24-sept	ASCO	V	V	V	V				

Figure 3: Make Ready

Solution Objective

Improve the Make Ready implementation and Collaboration, Support Constraint removal with visual management control.

Design and Development

A design has been completed with project members to integrate visual management functions to simplify data display (Tezel et al 2009) and ensure learning by doing. This solution was based on a kanban board (Figure 4) to represent task soundness according to different constraint categories (Ballard and Tommelein 2016). Using visual control, this view enables the quick identification of priority tasks with a low level of soundness and short production horizon.

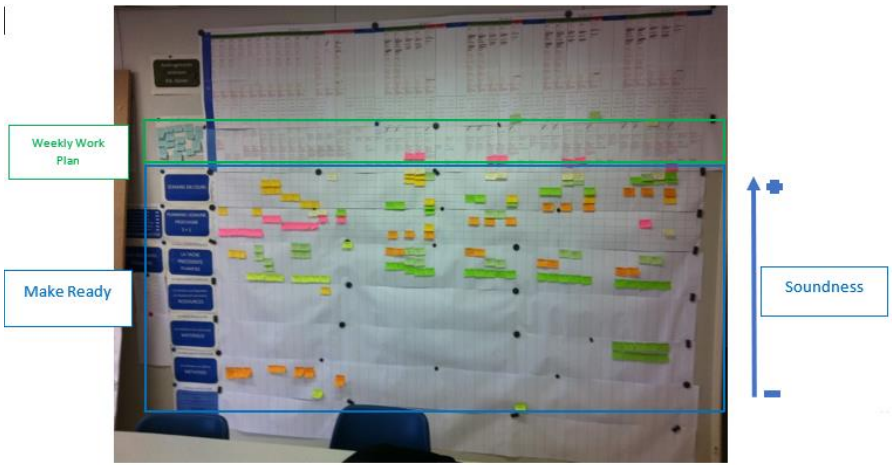

Figure 4: Visual Management-based Make Ready tool Linked to Weekly Work Plan

Tests and Evaluation

This tool helped improve the Make Ready conversation by using collective intelligence, and the combined experiences of all trades to define and deal with constraints according to shared resources (space and coactivity, crane time…), settle handoffs between trades, and define options and alternative ways of fulfilling tasks and improving commitment before production.

The final point was the time gain for project managers, as shared planning between several managers and autonomous subcontractors helped the project managers improve their added value by allowing them to focus their workload on anticipating problems and improving collaborative decision-making, rather than firefighting and solving administrative issues.

GENERAL EVALUATION

Despite the solutions implemented bringing huge benefits for LPS implementation, several problems were pointed out. The main problem was the time required to produce and update the different views for each conversation. Indeed, planning charts were filled with hundreds of sticky notes that needed to be written out and moved by hand one-by-one. In addition, all views needed to be updated by hand from Master Schedule to production plan and vice versa. The question of accessibility was also noted. In practice, physical boards are only accessible in the construction office containers. Furthermore, the use of the planning charts for reporting was complicated as photos were not always exploitable; handwriting also caused some readability issues. All these elements are serious hindrances for LPS implementation and led us to a second iteration with another construction project and a new team. Those challenges will be tackled in the second iteration.

SECOND ITERATION

Another collaboration project was defined with a general contractor wanting to implement LPS with physical and digital tools on several construction sites. This section will focus on the implementation of a digital visual management-based solution for a project entailing the renovation of an existing building in Luxembourg city centre. Although the project manager had a little experience in the LPS method, the construction manager and his assistant had no experience in LPS before the beginning of the project.

To support the skills acquisition of the project team, several training sessions were planned to transfer LPS concepts, tools and routines, alongside time dedicated to implementation support and coaching for the construction manager and the assistant, who was identified as the future LPS facilitator.

SOFTWARE SELECTION

Our Company selected software to support our work on visual management-based tools to improve LPS implementation according to our past experiences that led us to identify key issues.

PROBLEM IDENTIFICATION

Several problems were identified during our first iteration and were solved during this second iteration:

- **Reduce time wasted**

- **Improve information availability**
- **Synchronize all LPS views**
- **Gain space in construction office containers**

REDUCE TIME WASTED:

Whether for the Master Schedule or Phase Schedule, the initialization of this views requires testing several ways of representing information and formalizing different construction scenarios. Using physical boards for this can take a lot of time due to the number of sticky notes to handwrite and to move. It is sometimes the cause of a chart that no longer represents the reality in the field.

Solution Objective

Improve data production during meetings.

Design and Development

The software enables the users to:

- Copy/paste sticky notes that, after few weeks of work, are often the same or just a variation of old sticky notes.
- Adjust planning with the drag-and-drop function.
- Duplicate entire boards or sequences of work to create alternative scenarios.
- Copy data from a low-detail planning to a higher-detail one.

IMPROVE INFORMATION AVAILABILITY:

Each meeting requires the planning views to be updated based on considering the actual progress of work, changes requested by the client and provisional planning adjustments to respect milestones. Provisional planning updates must be part of the meeting minutes to allow each trade to prepare the next meeting with constraint identification, resource availability, etc. Taking pictures of plannings and send them is not ideal, therefore this solution request additional work to formalize the adjustments made during the meeting. This administrative Works takes time for the lean facilitator to complete, which creates a problem as he/she has less time to prepare and follow up the next meeting.

Solution Objective

Improve use of administrative time between meetings for all stakeholders.

Design and Development

The software enables users to export planning charts in a digital format, the project manager to share global planning charts with the client or the client’s project manager, and enables specific data to be shared with subcontractors, architects or engineers by sorting data so that it is assigned to a specific user. Furthermore, online access and user access management facilitate the access to planning charts for all stakeholders and allows subcontractors to update their work in the field with an app.

SYNCHRONIZE ALL LPS VIEWS :

Splitting planning information between several boards is one way to facilitate the structure of LPS conversations and avoid mixing discussions during meetings. However, being able to see / understand the impact of a change in a short-term plan over a more long-term view is crucial to respecting the final deadline. With physical boards displaying those LPS views, this link is only made by people, which brings more complexity in terms of ensuring coherence between high-level planning and short-term planning. More importantly, updating the Master Schedule with updated data from the field is a complex exercise. This information flow needs to be explicitly defined in the LPS. (Bhargav et al. 2015).

Solution Objective

Improve coherence between LPS conversation and its dedicated tools.

Design and Development

Synchronized and encapsulated sticky note functions enable the synchronization between views and the visualization of a correct level of information according to the LPS conversation. As an example, activities from the Phase Schedule (Figure 5) are described as more detailed tasks in the shorter-term planning horizon, the Look Ahead Plan. Those tasks are then used to facilitate the last planner's commitment in the Weekly Work Plan and are finally archived as soon as tasks are completed and validated (Figure 5). A visual signal is displayed on the Master Schedule every time a synchronized task is moved on the Phase Schedule and vice versa to invite the user to check the impact of a modification in the shorter or longer term.

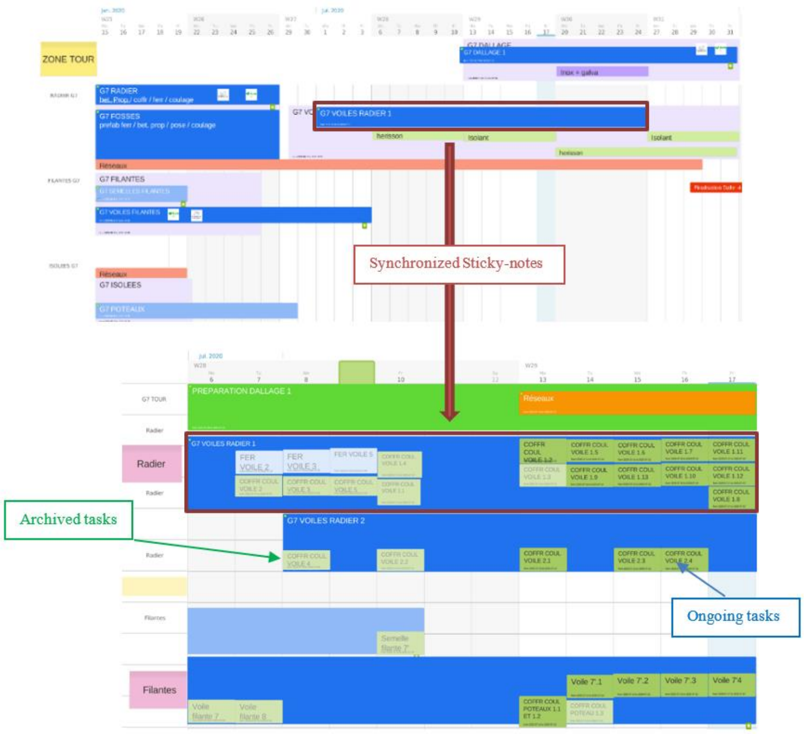

Figure 5: Phase Schedule to Look Ahead Plan to Weekly Work Plan

GAIN SPACE IN CONSTRUCTION OFFICE CONTAINERS

Using visual management requires a large surface to display information. Depending on the project complexity, a large wall area is required; even if the use of removal panels is possible, the area available to display visual devices is sometimes critical and has a recurring cost. In some cases, these recurring rental costs for extra construction office containers are a hindrance to visual management deployment. Also, to respect COVID-

19 sanitary measures, it is more complex to organize meetings using common supports and using sticky notes can be tricky.

Solution Proposed

Improve flexibility and LPS Implementation in the construction office containers.

Design and Development

Each specific view related to an LPS conversation can be displayed on a large touchscreen (+65”) which allows the reduction of the space requirement. It has been observed that the rental cost of the touchscreen was equivalent to the rental of an extra office. In addition, sometimes the number of office containers is limited.

Another important function is the online multi-user access. The software enables the different subcontractors to contribute to the same document during online meetings with their own IT device, ensuring the respect of COVID-19 sanitary measures and that meetings can be held remotely when mandatory.

GENERAL TESTS AND EVALUATION

According to the interviews with team members, the use of the software greatly improved efficiency both during and between meetings for all stakeholders. As many stakeholders, especially subcontractors, usually consider meeting a waste of time, gaining time during LPS meetings was a huge game-changer for LPS adoption, helping users to become more autonomous in LPS planning completion.

Furthermore, it provides the ability to instantly communicate planning charts with the client’s project manager after a meeting in order to share focused data. The limits of this kind of software, which is not especially designed for the last planner, is that the LPS facilitator must be experienced and be able to design views for LPS conversations.

CONCLUSION AND PERSPECTIVES

LPS implementation has often been observed as limited because of the low skills acquisition path from the LPS teams and incomplete or incorrect implementation. The reasons for this are a lack of training and time to implement change in an ongoing project, leading to a low return on investment for LPS meetings.

To respect LPS conversations, according to stakeholders feedbacks, it is confirmed that visual management-based tools are the perfect fit to transpose LPS structures and objectives, in order to improve learning by doing and collaboration, simplify LPS work and reduce the duration of LPS meetings. Nevertheless, LPS physical boards can be a serious hindrance to LPS implementation because of the workload related to sticky note management, the limited of the boards and the space required to hang physical boards.

Those limits can be removed with IT solutions. Therefore, IT associated with visual management is a perfect solution for improving LPS implementation. A highly adaptative software will support experienced LPS users in transposing their LPS routine digitally whereas non-experienced users will continue to need support and coaching from LPS experts.

However, IT solutions require more time and even more change management, it will also induce an initial investment and generates a theft issue because of the use of a touch screen.

Our next research will focus on more data-automatic analyses to provide more added value in the generation of scenarios and automatic Percentage of Promises Complete, as well as continuous improvement reporting. We will also focus on the change management process as a lot of construction stakeholders are still technology and change resistant.

REFERENCES

Ballard, G. and Howell, G., 1994. Implementing Lean Construction: Stabilizing Work Flow. Proc. 2nd Ann. Conf. of the Int'l. Group for Lean Construction, Pontificia Universidad Catolica de Chile, Santiago.

Ballard, G., and Howell, G., An Update on Last Planner, 2003, An Update on Last Planner. Lean Construction Institute.

Ballard G., and Tommelein, I., 2016, Current Process Benchmark for the Last Planner System. Available at p2sl.berkeley.edu.

Bhargav D., Juho-Pekka H., Koskela L., 2015, Exploring the recurrent problems in the last planner implementation on construction projects.

Brady, D. A., 2014, Using visual management to improve transparency in planning and control in construction, Doctoral dissertation, University of Salford.

Daniel, EI., Pasquire, C., and Dickens, G., 2015, Exploring the implementation of the last planner® System through IGLC community : Twenty one years of experience, in: Proc. 23th Ann Conf. of the International Group for Lean Construction, Perth, Australia.

Ebbs, P. J., and Pasquire, C. L, 2018, Make Ready Planning Using Flow Walks: A New Approach to Collaboratively Identifying Project Constraints. In: Proc. 26th Annual Conference of the International. Group for Lean Construction, Chennai, India.

Fernández-Solís J, Porwal V, Lavy S, 2018, Guidelines to Address Challenges Faced by Last Planner Users and Implementers at Organizational and Project Levels.

Khan S., Tzortzopoulos P., 2018, Using design research and action research to bridge the gap between theory and practice in lean construction research, In: Proc. 26th Annual Conference of the International. Group for Lean Construction, Chennai, India.

Lukka K., 2003, The constructive research approach, Case Study Research in Logistics.

Mossman A. 2015, Last Planner, Collaborative conversations for predictable design & construction delivery.

Peffers, K., Tuunanen, T., Rothenberger, M., Chatterjee, S., 2007, A design science research methodology for information systems research, Journal of Management Information Systems.

Porwal V., Fernández-Solís J., Lavy S., Rybkowski Z., 2010, Last planner system implementation challenges, In: Proc. 18th Annual Conference of the International. Group for Lean Construction, Haifa, Israel.

Tayeh, B.A, Al Hallaq, K., Al Faqawi1 A.H., Alaloul, W.S., and Kim, S.Y.,2018, Success Factors and Barriers of Last Planner System Implementation in the Gaza Strip Construction Industry, The Open Construction and Building Technology Journal.

Tezel, BA., Koskela, LJ., and Tzortzopoulos, P., 2009, The functions of visual management, available at https://usir.salford.ac.uk/10883/.

Salhab, D., Noueihed, K., Fayek, A., Hamzeh, F., and Ahuja, R. (2021). “A Framework for Implementing the Last Planner® System in a Virtual Environment.” *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 75–84, doi.org/10.24928/2021/0179, online at iglc.net.

A FRAMEWORK FOR IMPLEMENTING THE LAST PLANNER® SYSTEM IN A VIRTUAL ENVIRONMENT

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ABSTRACT

The Last Planner® system (LPS) has witnessed a major shift in implementation at the onset of Coronavirus disease 19 (COVID-19). Governed by maintaining social distancing and many other safety restrictions, some construction practices including LPS implementation are now taking place in the virtual environment. However, potential challenges and enablers of implementing LPS in such an environment are yet to be investigated. This paper presents a framework based on lean philosophy and aims at successful implementation of LPS in a virtual environment. The framework calls for embracing a strong lean culture in the virtual work environment. The study also seeks to outline the challenges and enablers of this implementation. The framework was tested on a construction project through an expert panel. Results show that the framework is promising, and that although COVID-19 inflicted many challenges, it also had some positive impacts on LPS implementation. The framework will help practitioners and managers adopt a systematic approach from initiation to implementation of LPS in a virtual environment.

KEYWORDS

Last Planner® System (LPS), challenges, enablers, COVID-19, virtual environment.

INTRODUCTION

The Last Planner® System (LPS) is a production planning and control system aimed at reducing variation and uncertainty in construction works (Hamzeh et. al, 2012). However, the global pandemic Coronavirus disease 19 (COVID-19 infectious disease) that surfaced in 2019 was not accounted for in any production system; and it was first perceived as an external condition for construction projects. This pandemic imposed hurdles on various aspects of businesses including the construction industry. Furthermore, the rapid spread of the virus and the unfamiliarity with its transmission mechanisms induced officials to

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issue restrictions such as limited person to person contact (Parr et. al, 2021). This led to the online communication platforms replacing the face-to-face meetings.

Knowing that the human workforce is at the base of designing and making in construction projects, the construction industry is facing many challenges to adapt to the new work conditions imposed by the current circumstances. Indeed, construction projects are achieved by the collaborative efforts of engineers, general contractors and trades, managers, workers, foreman, suppliers, etc. Particularly, the pillars of the LPS are planning work in greater details, developing the plans with the people who will perform the work, identifying and removing constraints ahead of time, making reliable promises, and learning from failures (Hamzeh et. al, 2012). Proper implementation of the aforementioned pillars has been successful on many projects. However, governed by maintaining social distancing, current LPS practices are yet to be explored. Many research studies addressed the challenges and enablers of implementing LPS in normal conditions. Nonetheless, no research study has been found to tackle the issue of implementing the LPS in a virtual environment. This study presents a framework to guide practitioners and companies in implementing LPS in a virtual environment based on lean philosophy. It also employs an expert panel questionnaire to assess the enablers and challenges currently faced by a company following a similar framework.

LITERATURE REVIEW

Various aspects of lean practices are tackled heavily in the literature, especially LPS. Challenges and enablers of implementing LPS are discussed by many researchers. Table 1 below summarizes challenges discussed by some researchers.

Furthermore, the literature highlights many endeavours that complement LPS implementation in the industry. Several researchers have proposed frameworks that target successful implementation of LPS. These frameworks act as guidelines that highlight critical factors for effective implementation and how to address them. Daniel and Pasquire (2017) developed the LPS-PCA approach for effective implementation of LPS on construction projects. The approach does not describe the LPS implementation methodology, but rather serves as a guide for clients, main contractors, or subcontractors to help identify and remove constraints that were proved to obstruct LPS success. Hamzeh (2011) conducted an action-based research on three construction projects implementing the LPS. The author came up with a framework describing 11 guiding principles for successful and sustainable implementation of LPS.

Nevertheless, the discussion about LPS frameworks and implementations is limited to implementation in casual conditions. Casual conditions refer to the absence of a pandemic that imposed restrictions on face-to-face meetings and overall business practices. Still there are some studies that addressed the impact of COVID-19 pandemic on the overall construction industry. For instance, according to a study conducted by Assaad and El-adaway (2021a), COVID-19 has affected four main areas within the construction projects: (1) workforce, (2) project and workplace concerns, (3) procurement and supply chain, and (4) contractual, legal, and insurance processes. Furthermore, due to the COVID-19 infection, the workers' absence from the site witnessed an increase (Franzese, 2020) and so did the provisional suspension of on-site work because of the 14 days quarantine (Piro, 2020). Moreover, there was a decrease in the overall project productivity and labor productivity due to widespread pandemic infections (Assaad and El-adaway, 2021b).

Consequently, this study presents a framework for successful implementation of LPS in a virtual environment given the current conditions and addresses the challenges faced by practitioners.

Table 1 Literature Review on Challenges to LPS Implementation

Researcher	Challenges to LPS Implementation
Viana et. al (2010)	Difficulty in adapting to the new culture Incompatible personnel qualifications Long time spent on planning issues Incomplete information High interdependence between different processes
Ballard et. al (2007)	Strong resistance to change Lack of leadership Lack of commitment from upper management Lack of active support due to top-down management
Hamzeh et. al (2016)	Different levels of understanding of Lean Construction philosophy Repetition of failures Non-collaborative development of the master schedule
Porwal et. al (2010)	Lack of training Lack of leadership Failure of management commitment/organizational climate Organizational inertia & resistance to change Stakeholder support Contracting and legal issues/contractual structure

METHODOLOGY

The research methodology adopted is Design Science Research. This methodology includes three main phases: problem identification, solution design, and evaluation (Offerman et. al, 2009). This study tackles the problem of implementing LPS in a virtual environment. The literature identified and classified general challenges of implementing LPS. However, no study has been found to tackle the challenges and enablers of implementing LPS in a virtual environment. As for the solution design, a framework that targets these challenges to achievement of full potential of LPS is developed. Lastly, the evaluation is performed through the assessment of enablers and challenges of implementing a similar framework. This is done by interviewing an expert panel of practitioners working on different construction projects. The practitioners work at the same company where they apply LPS in the current situation governed by safety restrictions on many aspects due to COVID-19. The company, which operates in the field of general contracting, selected a software that facilitates LPS implementation and is currently involved in six projects. The following section presents the suggested framework.

SUGGESTED FRAMEWORK

The challenges faced when implementing LPS may still be faced in a virtual environment. COVID-19 is a warning for people to rethink the current management methods and have the urgency to adopt a new workstyle that aims at improving productivity and reducing the impacts of possible contingency. Therefore, the suggested framework reintroduces different aspects of lean philosophy to pave the way for successful implementation of LPS. This framework is inspired by the framework developed by Hamzeh (2011); the framework was used as a starting point and amended as per the authors' research on the challenges of applying LPS in a virtual environment. Since LPS is based on collaboration and communication between different project stakeholders, the new framework facilitates LPS implementation catering to well-known challenges from previous experiences and the imposed novel challenges. The steps for implementing the framework are as follows.

1- Top Management Buy-in: The first step is of paramount importance; it is about the top-down management devoting a strong buy-in for the lean principles within its vision and embracing a lean culture. A lean culture implies one where everybody is encouraged to contribute to improvements in a collaborative environment. AlSehaimi et al. (2009) classified top management support as a critical success factor of LPS implementation; and it acts as a prerequisite for the following steps. They have the highest influence of change in the organization's systems and people. Managers usually resist abandoning the traditional practices they have adopted for years, and this is normal. Also, some will come with preconceived beliefs that a new system will not work. Accordingly, a mentality shift within the work environment should be achieved; it is challenging but not impossible. Presenting the advantages of lean construction through a small pilot study and more importantly showing that it works is a good strategy to achieve the shift.

2- Mid Management and Last Planners Buy-in: The second step is also of great importance. After the top management firmly believes in the need for LPS, they will encourage and convince the rest of the team (mid managers and last planners) to implement the method. It is expected to experience ramp up time adapting to the new system and moving people out of their comfort zone. However, providing a training where people are walked through the rational and the advantages of applying lean and last planner system eases this phase. In brief, the top management shall not push the system on the people, but rather highlight the effectiveness and the need of such a system. This will also build trust within the organization and enhance collaboration.

3- Creating a Cross Functional Team: "Work groups are the focal point for solving problems." (Liker, 2004). Creating a cross-functional team that brings together people from various trades and disciplines and investing in such a team is essential. Most of the improvements a company achieves could come from its people since they are the ones involved in various aspects and operations of the job. The team should have autonomy and freedom to suggest LPS implementation ideas. It is essential to have a lean expert on the team at this point to guide and oversee the whole process.

4- Providing LPS Training: The basis of the company's management approach needs to be one that integrates social systems with technical systems through training exceptional people (Liker, 2004). The lean expert should give a thorough and practical training on the principles and tools of LPS. It is crucial to build the discussion on the importance of embracing the long-term philosophy behind the lean culture, even at the expense of short-term financial goals; lean is way more than just tools and techniques (Liker, 2004). The training is a critical step in the overall process, it should not be pushed and forced on the team. The last planners should be highly involved as they will be the ones who will utilize the LPS tool mostly. Several online communication platforms that allow screen sharing can be used to achieve this. This way, the expert providing the training can share their screen with all participants. Furthermore, virtual lean simulations are becoming a popular approach for educating people more about different lean aspects.

5- Mapping the Planning Process Using Value Stream Mapping (VSM): After training the team, members will have a better idea of the current practices and can contribute towards process improvements more effectively. There might exist great but undiscovered opportunities for improvements in the operations of a company; using a simple visual mapping tool such as VSM assists in uncovering such opportunities. It allows pinpointing deficiencies and wastes in the current operations and stimulates participants to think of effective alternative solutions using a common language. Therefore, the current planning process should be mapped by the team where they give feedback on how to improve the process based on their experience. This exercise can also be done using commercial applications that allow users to draw charts and diagrams seamlessly. This is equivalent to the teams meeting in a room and mapping everything with sticky notes. All participants can contribute through adding the improvement ideas they have using such online tools.

6- Investigating Available Software: Although meeting in one room became unfeasible due to safety restrictions, the project participants can still conduct weekly work plans and other LPS requirements through an online software. Many software support LPS implementation; the software should serve the team in achieving their needs and should have a simple interface. Essential features should include managing weekly work plans (WWP) and PPC, constraints, and coordination between trades. The last planners should still be able to link the front-end planning (master schedule) with production planning (look-ahead and WWP) using the software or else the PPC would not be a reliable indicator of the project performance (Hamzeh et. al, 2012). It is recommended to have software companies present their product and explain its features to the whole team; and the team could ask for any clarification they have in mind. To make a decision, the team should give feedback on the pros and cons of each software with respect to how well the software fits their needs.

7- Choosing by Advantage (CBA) a Software: The evaluation technique to pick the software is CBA which is a subjective and collaborative decision-making technique. Several potential software alternatives should be initially specified. The team must decide on the factors they are interested in such as the ability to integrate with Primavera P6, daily coordination, task duration flexibility, etc. The process could be done using simple tools such as a spreadsheet. This will help the team come to a united decision on what fits them best. At this point, a technical expert from the software company chosen should join the team for the implementation of the software and adjust it as per what the team needs and not necessarily pushing what the software does.

8- Providing Training on the Software: The software will be the tool the last planners use to effectively implement the LPS. The software should not be a burden on the last planners because it is critical for them to have a new system supporting their work rather than hindering it. It is highly recommended to have a representative from the software company and have flexibility to adjust according to last planners' need when possible.

9- Preparing a Dashboard with Various Metrics: Although PPC is the most used metric in practice, there are many metrics that are essential and complement PPC. There is a significant gap between near-term planning and long-term planning (Hamzeh et al., 2019). A dashboard will serve as a tool to continuously monitor performance and uncover hidden problems on site. Also, it is as a proactive tool that will help projects stay on track.

10- Implementing a Pilot Study on a New Project/Project Phase: The implementation of LPS is easier and more effective when it is implemented at an early start of a project (AlSehaimi et al., 2009). This will help the team to set the foundations right and improve as they progress. People tend to be convinced more when they see tangible results. As mentioned earlier, seeing the advantages of the lean system and understanding that it works make the project participants aspire to adopt lean.

11- Developing a Standard Work Methodology: The team should be able to come up with a standardized work pattern on how things should be done (frequency of meetings, look-ahead planning window, daily huddles, etc.). The team should adopt the method and improve it as work progresses; they could go back to the mapping process to re-adjust it as per the needs if necessary. It is essential for the team to develop a checklist in each meeting to ensure that the objectives of the meetings are met. Also, it is important that all participants contribute during the online meetings.

12- Developing a Plan for Sustaining LPS: Having a plan for sustaining the LPS system and other lean practices is substantial. Failure to do so will impair all the efforts exerted in securing a lean environment for the current and future projects. LPS is sustained whenever the teams and the company realize the benefits and not just learn about them. Hamzeh (2009) stated that it is important to have a positive experience during initial LPS implementation. This is a significant factor for sustaining LPS since the last planners would pick up the pace on how to implement LPS and realize the benefits of it. Another contributing factor in this step is the top management. Sustaining LPS requires investing in tools such as the software, training workshops, experts… It also requires the company to embed LPS standards into the work methods and to have first run studies and trials to assess inefficiencies in the system.

The process aims at helping people challenge the status-quo and expand their knowledge. The human factor is highlighted in each step of the process and should be the driving factor of LPS implementation in any environment. If performed correctly, this will potentially increase the responsiveness of the organization which is a fundamental organizational trait in these turbulent times that the industry is passing through. The process is summarized in Figure 1.

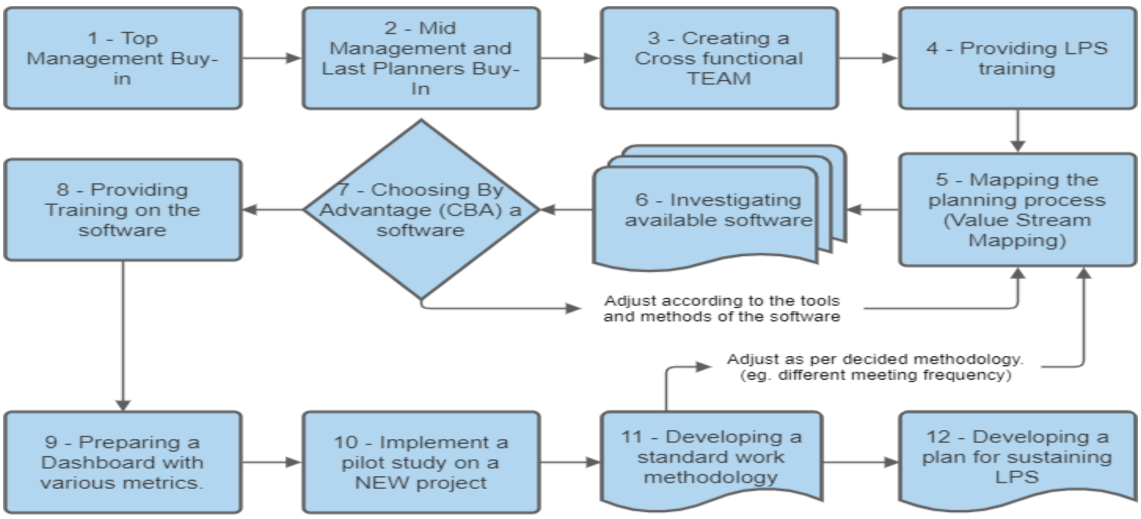

Figure 1 Flowchart of the Framework

APPLICATION OF FRAMEWORK RESULTS

A set of 14 questions related to implementation of LPS is prepared based on extensive literature review. These questions are addressed to three superintendents working on different projects but are from the same general contracting company. The 4th person represents an electrical trade company working with the contracting company.

Table 2: Expert Panel Questionnaire

Question	Sup. 1	Sup. 2	Sup. 3	Trade Partner
1-What is the level of engagement in the weekly planning meeting in a virtual environment?	Very High	Very High	High	High
2-What is the level of transparency between trades in a virtual environment?	Neither high nor low.	High	Neither high nor low.	Neither high nor low.
3-What trust level you have that the preceding trades will finish as promised?	High	High	High	High
4-How much do you rate team satisfaction in a virtual environment?	Very satisfied	Satisfied	Satisfied	Satisfied
5-What is the level of cooperation between the different trades within the virtual environment?	High	High	High	High
6-What is your level of awareness about the progress of different trades in a virtual environment?	Very High	Very High. It is easier to see the progress	Very High	Very High
7-It was difficult to move to online communication platforms.	Disagree	Agree; but got easier	Disagree	Disagree
8-The software used is comprehensive for LPS implementation and it covers all aspects of LPS.	Agree	Strongly agree	Agree	Strongly agree
9-The software can document failure reasons	Agree	Strongly agree	Agree	Strongly agree
10-Metrics used are enough for proper project control in a virtual environment.	Agree. PPC is enough	Neither agree nor disagree	Agree	Agree
11-LPS was implemented correctly.	Agree	Agree	Agree	Agree

The questions are aimed at understanding the practices, challenges, and enablers of implementing LPS in the current virtual environment. The first 11 questions are on a Likert scale; some have answers ranging from strongly disagree to strongly agree and others from very low/dissatisfied to very high/satisfied. These questions are summarized in Table 2. The rest of the questions are open-ended and discussed afterwards. Finally, to get input on the challenges from an upper management perspective, one of the company's senior managers was interviewed. The interview results are summarized at the end of this section. Note that the interviews were done with each person independently so that no one participant would influence the opinion of other participants.

12-How can you improve the LPS implementation and increase trust and transparency in your opinion in a virtual environment?

All superintendents endorse the idea that more practice is needed to improve the LPS implementation. This includes training and practice on effective use of online communication platforms and active engagement of all participants during meetings. The superintendents emphasized the importance of buy-in from trades, which would increase the transparency between them. This is realized through proper training, assigning the right responsibilities to the right people, having accountability, and trusting others' work.

13-What do you think can be done to get culture lean in a virtual environment?

Although it is recurring, the concept of training seems to be a part of the solution to many issues; and this sheds light on its importance. The experts emphasized the importance of project participants getting together as a team to learn more about LPS and lean construction in general. Through proper training, the participants will embrace the lean way of thinking. Consequently, this creates a clearer visibility about the status of the project and the proactive management needed to properly steer the work. Empowering the participants with a good understanding of the advantages of LPS and lean concepts has proven to be a very useful approach, said the experts.

14-What is the main challenge you are facing in implementing LPS in the virtual environment?

All superintendents state that the main challenges include having a positive buy-in from the trades, but this applies also to implementing LPS in normal conditions. The main challenge for all superintendents was the absence of face-to-face interaction between team members which is essential for establishing and maintaining trust and high morale.

The manager had a different view on the challenges of LPS implementation. The interview focused on the impact of moving into a virtual environment from a management perspective. He asserted the importance of face-to-face interaction in learning more about the team members and building trust in each one of them. Having said so, the lack of physical interaction constitutes the major issue in moving to online communication platforms. Additionally, as a manger, he highlighted the challenge of keeping the trades engaged and winning their buy-in and belief in the effectiveness of LPS. According to him, this requires senses other than verbiage; the body language and tactile factor is a prerequisite for the buy in. Moreover, he highlighted the effectiveness of using a software to steer parts of the project and adopting it as a tool to build transparency within teams. The software serves as a tool to highlight areas of improvement and real-time progress for all the last planners and managers. However, he believes that the software cannot be used to manage the whole aspects of the project. Being physically on site is inevitable for building trust among the teams. For these reasons, current restrictions make it difficult to achieve this buy-in, build the necessary trust, and implement LPS effectively on projects.

DISCUSSION

From a last planner's perspective, it could be noted that the virtual environment embraced LPS practices because the survey results show that people are encouraged to work on the LPS software, and they want to adopt LPS. However, from a management perspective, the challenges are more critical to deal with. This framework is promising in terms of fostering a successful LPS implementation. One drawback resulting from the shift to online communication platforms was spending time adapting to new technologies, but still it was not a major obstacle due to the fast-learning curve. Furthermore, sometimes people tend to be less engaged in online meetings where they get easily distracted away from their devices. Having the option to turn off the video and the microphone makes it easier to adopt such a behavior. On the other hand, contractors or stakeholders who are engaged in many projects found it way more effective to complete all their meetings online instead of wasting time commuting, moving from one site to another, and getting stuck in traffic. This does not eliminate the importance of conducting face-to-face meetings whenever possible.

This framework aims at spreading a culture of learning and cooperation, and it focuses on providing various types of training. Most importantly, the framework addresses the issue of maintaining physical separation, which has never been perceived an option for implementing LPS before COVID-19 hit. Moreover, the platform provides visual control over who fulfilled their promises, which in turn enforces commitment. Note that the company chose the specific LPS software based on its features that are compatible with the company's needs and capabilities, the participants' skills, and the project complexity.

CONCLUSIONS

The global COVID-19 pandemic modified the usual ways of running different businesses including construction projects, and it was not accounted for in any production system. Various restrictions arose as a response to the pandemic, encompassing mainly limited physical contact. This led to a shift in communication approaches from traditional-physical meetings to online communication platforms. Aside from the challenges that LPS implementation faces during normal conditions, its implementation holds the potential of new challenges after the newly emerged restrictions. This study aims at providing a framework for successful implementation of LPS in a virtual environment and seeks to assess the challenges and enablers of such implementation. The framework focuses on getting a strong buy-in for the lean system from all participants, providing LPS training, mapping the current process, choosing a suitable software to implement LPS, and implementing a pilot study along with other steps. The framework places great importance on providing a lean culture; one where each participant is valued as an effective member and is encouraged to contribute to improvements within the company. Evaluation of this framework was performed through an expert panel questionnaire with five practitioners applying a similar framework. The results showed that the practitioners found it effective switching from analogue mode to a virtual mode given that they adopted a similar approach explained in the framework. The challenges overcame were communication, collaboration, and technical challenges. However, from a management point of view, the main challenge that was still there is the absence of physical interaction which affected trust and buy-in; these are critical for proper management. Embracing a lean culture and facing these challenges with a lean mindset turned these challenges into opportunities; this was shown in the results of the interviews with the superintendents. The limitation of the study is that only five practitioners are interviewed. It is recommended for future studies to interview further practitioners from various trades and explore additional aspects of the virtual implementation.

REFERENCES

AlSehaimi, A. O., Tzortzopoulos, P., and Koskela, L. (2009). Last planner system: Experiences from pilot implementation in the Middle East.

Assaad, R., and El-adaway, I. H. (2021a). “Guidelines for Responding to COVID-19 Pandemic: Best Practices, Impacts, and Future Research Directions.” *J. Manage. Eng.*, 37(3) 06021001.

Assaad, R., and El-adaway, I. H. (2021b). “Impact of Dynamic Workforce and Workplace Variables on the Productivity of the Construction Industry: New Gross Construction Productivity Indicator.” J. Manage. Eng., 37(1) 04020092.

Ballard, G., Kim, Y.W., Jang, J.W., and Liu, M. (2007). “Road Map for Lean Implementation at the Project Level”, *Research Report*, Construction Industry Institute, The Univ. of Texas at Austin, Texas, USA, 426.

Daniel, E. I., and Pasquire, C. (2017). “Last Planner System Path Clearing Approach (LPS-PCA): an approach to guide; clients, main contractors and subcontractors in the implementation of the LPS.”

Franzese, N. P. 2020. “Potential Impacts of the Coronavirus Pandemic on Construction Projects.” Accessed February 20, 2021. https://www.natlawreview.com/article/potential-impacts-coronavirus-pandemic-construction-projects.

Hamzeh, F.R. (2011, July). “The lean journey: implementing the last planner system in construction.” In *Proc., 19th Annual Conf. of the International Group for Lean Construction, IGLC*, 13-15.

Hamzeh, F. (2009). “Improving Construction Workflow - The Role of Production Planning and Control.” *PhD Diss.*, Civil and Envir., Univ. of California, Berkeley.

Hamzeh, F., Ballard, G., and Tommelein, I. D. (2012). “Rethinking Look-ahead Planning to Optimize Construction Workflow.” *Lean Constr. J.*

Hamzeh, F., Kallassy, J., Lahoud, M., & Azar, R. (2016). The first extensive implementation of lean and LPS in Lebanon: results and reflections. In Proceedings of the 24th annual conference of the international group for lean construction, Boston, EE. UU.

Liker, J. K. (2004). Toyota way: 14 management principles from the world's greatest manufacturer. McGraw-Hill Education.

Offermann, P., Levina, O., Schönherr, M., and Bub, U. (2009, May). “Outline of a Design Science Research Process.” In *Proc. 4th International Conf. on Design Science Research in Information Systems and Technology*, 1-11.

Parr, S., Wolshon, B., Murray-Tuite, P., and Lomax, T. (2021). “Multistate Assessment of Roadway Travel, Social Separation, and COVID-19 Cases.” *J. Transport. Eng., Part A: Systems*, 147(5) 04021012.

Piro, J. (2020). “COVID-19 impact on the construction market.” Accesses February 20, 2021. https://www.gilbaneco.com/wp-content/uploads/COVID-19-Impact-To-Construction-March-2020-HQ.pdf.

Porwal, V., Fernández-Solís, J., Lavy, S., and Rybkowski, Z. K. (2010, July). “Last planner system implementation challenges.” In *Proc., 18th Annual Conf. of the International Group for Lean Construction, IGLC*, 548-54.

Viana, D.D., Mota, B., Formoso, C.T., Echeveste, M., Piexoto, M., and Rodrigues, C.L. (2010). “A Survey on the Last Planner System: Impacts and Difficulties for Implementation in Brazilian Companies”, In *Proc., the 18th Annual Conf. of the International Group for Lean Construction, IGLC*, 497- 507.

LEAN AND BIM

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ROLE OF A DIGITAL LAST PLANNER® SYSTEM TO ENSURING SAFE AND PRODUCTIVE WORKFORCE AND WORKFLOW IN COVID-19 PANDEMIC

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ABSTRACT

To cope with the dynamics of production, construction managers spend a significant amount of time organising the workforce, managing logistics and controlling the flow. Underestimating the process of workforce allocation and management could lead to serious productivity, safety, logistics, and coordination problems. To exacerbate this situation, the onset of the global Covid-19 pandemic has created a situation where unorganised workforce allocation and tracking could increase the health and safety risk for the project. The Last Planner® System (LPS) advocates and incorporates processes to sustain flow suggested in Lean Production theory. Hence, the complex job of creating the workforce-flow can potentially be simplified through the LPS proactive planning during lookahead discussions. The paper captures a case study where the same safety and productivity issues were heavily encountered in a project involving multiple trades (15+) and having hundreds of workers struggling in the pandemic situation. Implementing design Science approach, the team has discovered a digital workflow management system that exhibits significant improvement in coordination, control over productivity wastage and safe working environment.

This research utilised a digital LPS powered by real-time cloud-based system, capable of actively tracking the agreed workforce boosting productivity whilst keeping the workforce safe and secure.

KEYWORDS

Workforce flow planning, digital, Last Planner® System, production planning and tracking.

INTRODUCTION

BACKGROUND

Safety and safe working environments are an undivided part of construction projects, yet safety management practices are often treated as separate and isolated entity in construction management (Zhang et al., 2015). Project characteristics, and complexity

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has a significant impact on the logistics and system inhabitants. As the project complexity increases, the inherent risks with high levels of change and uncertainty are raised significantly in the project (Trinh & Feng, 2020). With these uncontrolled dynamics of project systems, the safety hazards become inherent in the project and hence resist the flow of project delivery and productivity inevitably (Sacks et al., 2005). The overall damage to the sector is more than it has been realised only in terms of cost and delays amongst all the stakeholders (Lingard & Rowlinson, 2005).

Over the period, countless efforts have been recorded to address the jobsite safety with people or technology (Emuze & Smallwood, 2013). In the recent development, researchers are pushing sensor-based networking systems, computer vison, Unmanned Aerial Vehicle (UAV) and Machine Learning technologies to aid the safety assurance on construction sites (Chen et al., 2019; Fang et al., 2020; Poh et al., 2018; Seo et al., 2015; Tixier et al., 2016; Yang et al., 2020; Zhang et al., 2013). Though the detection process of the safety hazards is getting efficient, the overall development is evidently going into reactive type of safety management rather than the proactive one (Teizer et al., 2010). It emerges that there is a serious need to have a balanced review of safety management that involves people, process, product, and technology combined.

This paper initially discusses the perception of safety and how it has been connected to the production management followed by the state of the art for the same. Additionally, the state of safety due to COVID-19 pandemic has also been realised through the paper that bring about the dire need of inventing an integrated workplace safety practices which is supported by digital LPS. A case-study has been presented to capture the effectiveness and efficiency of such resilient approach.

LITERATURE REVIEW

RELATION BETWEEN PRODUCTION MANAGEMENT AND SAFETY

The cognitive engineering paradigm in the research of safe working clearly states that the way groups of individuals interact with the work system has a definite impact on the safety (P. T. Mitropoulos, 2012). Hence, the way the production system is designed certainly has its implication on the overall safe working environment (Aslesen et al., 2013).

Since being suggested by several authors since the 90's, the majority of studies have investigated the integration of safety into production planning framework (Emuze & Smallwood, 2013). Though the full-scale realisation and implementation for the same is yet to be percolated through the roots of production planning (P. T. Mitropoulos, 2012) and evidently very few researchers have captured the real-life implementation and benefits for this (Emuze & Smallwood, 2013).

Many of the authors including (Ciribini & Rigamonti, 1999) and (Kartam, 1995) for instance, discussed the introduction of safety measures into construction plans, using CPM or line of balance planning techniques. The CPM approach has proven quite ineffective, since it is a top-down approach that does not take into consideration reality (Koskela et al., 2014). On the other hand, collaboration focused Lean thinking suggests that the efforts undertaken to implement occupational safety and health at jobsite can be an excellent starting point to identify waste and have positive impacts for controlling the disruptions in flow (Sacks et al., 2005). Hence, the tools and techniques supported by lean concepts and principles have clear synergy and advantage of making a production management system integrated into safe working practices. For instance, (Saurin et al.,

2002) has provided safety planning and control model (SPC) where the production practices are injected within the production long/short term planning and control.

STATE OF THE ART IN THE WORKFORCE SAFETY

New tools and systems that incorporate safety protocols in the planning practices are coming to fore in recent years. For example, an investigation from Denmark (Thomassen et al., 2003) highlighted that crews using the LPS reported 45 percent fewer accidents compared to traditional management systems. The primary reason behind the decrease in accident prone safety practices has been derived from the LPS' uncompromising attitude towards high-quality work and emphasis on cyclic-collaboration activities (P. Mitropoulos et al., 2005). Consequently, the working conditions and workflows are fortified and the element of unpredictability in tasks which are responsible for hazardous situations, interruptions in flow and improvised processes are reduced. Nevertheless, reducing task unpredictability is only one step on the way to a safer construction site. Also important is issue management and evolving/empowering the team to successfully recognize, swiftly raise, share, cope with & recover from hazardous situations and errors. (Aslesen et al., 2013) infer to the question yet to be answered: how we can integrate the function of error or safety management into practical production control and management.

Apart from LPS, line of balance has gained popularity in terms of maintaining the flow and promoting the safety for production. The location-based planning and line of balance combined approach is supportive for controlling process flow and operation flow simultaneously (Grau et al., 2019). The major focus here is the maintaining the flow of workforce in such a way that the safety hazards can be minimised in alignment with the process flow. Though the process-oriented safety planning appears rather effective, the implementation of the same has always been challenging with traditional approaches (Awada et al., 2016). However, combined with digitally enabled spatial awareness technologies that includes Building Information Modelling (BIM) and cloud computing, the performance of these tools in terms of managing safety can exponentially be increased (Zhang et al., 2013, 2015).

PROBLEM STATEMENT

The onset of the COVID-19 pandemic has forced production environments (especially in the construction domain) to become more sensitive regarding the safe working environment (Stiles et al., 2021; Wu & Wang, 2020).The arrival of the pandemic resulted in all industrial and social activities being temporarily suspended. To successfully reopen societal and industry social distancing measures had to be implemented to safeguard the population from disease transmission. These imposed regulations have evidently posed major disruption in the production systems by restricting team's collaboration capabilities and production workflows. More specifically, office teams are now forced to work remotely which has hampered active communication resulting into coordination issues ultimately affecting the production planning. Whereas the ground teams and their numbers are strictly limited making them struggle to achieve their productivity goals. The situation demands a system where the production disruption can be kept minimum.

RESEARCH METHODOLOGY

The researchers were involved in developing and managing the project LPS and the development of the existing digital LPS. The advent of the pandemic required another iteration for the LPS. Design science research method was used to develop the hybrid digital LPS that channels the safe and remote collaboration requirements through production management. In the case of such complex projects, on top of safety planning a unique spatial awareness is needed to proactively determine the safety hazards on the jobsite. In order to figure out the efficiency and effectiveness of the developed solution, pre and post covid safety and production planning situations have been analysed the presented. Overall, the case study encapsulates a model workforce planning for safe and proactive production planning and management practices that has been deployed implicitly the digital LPS.

CASE-STUDY

BACKGROUND

The study was carried out on a hyperscale data centre construction project. The project is an 86,000 square meter structure consisting of 8 single storey data halls and an administration building. The project commenced early in 2019 and is expected to be completed mid-2022. The project team has matured in lean production practices and had successfully implemented the same on similar data-centre projects.

During the early first quarter of 2020, the production team has been operating almost 46,264 operative hours and roughly 895 workforces at the site.

WHEN THE PANDEMIC HIT THE SITE

In March 2020 when the production was reaching its peak, all social and industrial activity was suspended by government to reduce spread of Covid-19. After getting site-based activities suspended with only works continuing related to design and procurement. Later, when the sites were re-opened, there were many regulatory restrictions which had been introduced causing listed challenges:

- Planning, Managing, controlling number of workforces in defined area and timeframe.
- Production coordination and discussions became more difficult due to remote working and work safety distancing.
- Ensuring the volume of work is getting delivered and simultaneously avoiding the safety risks.

FINDING THE SOLUTION

The team had taken up this challenge to build even more resilient and safe system of work to operate during a pandemic. This included introducing new way of visualising and analysing workforces, remote working where possible for site-based support management, additional shift patterns were introduced, and labour maximum occupancy levels were introduced on the project the maintain social distancing on the project.

In order to counter the collaboration challenges, the redeployed LPS was fully digitised which allows the teams to continue to prepare and manage the production plans despite the fragmentation of teams to mitigate Covid-19. Project based collaborative planning sessions were moved to digital meeting platforms (Microsoft™ Teams) which provided the collaborative space to work. This allowed remote working teams to come together to manage and sequence tasks. This was initially used to manage off site documentation and design work while on site activities were suspended.

As part of the return-to-work strategy the project needed to demonstrate how activities could be planned and executed while respecting social distancing. Labour management and forecasting was an important part of the return-to-work strategy. To manage this, maximum room occupancies were determined based on room areas to highlight allowable access to work areas. This was a further consideration for work planning process. Therefore, for tasks to be approved in the Last Planners sessions, information required was: Planned workforce, Location, Health & safety (Distancing Method statement etc.), Quality (Tech sub, checklist inspection schedule), Quantity and Duration.

The construction team had already deployed a digital LPS system called Visilean. The Visilean team worked with the project team to solve the post covid safety challenge. In order to achieve this, new interfaces were developed in VisiLean to a) input number of planned workers in each location, b) input maximum number of workers who can be accommodated in each location while maintaining minimum safe distance, c) report number of actual workers working at each location by using the app and d) visualise and report the total number of workers at each location. Tasks now had to be assigned the properties to allow them to be sequenced and scheduled in the look ahead meetings. There was a requirement to increase the reliance on visual management to connect remote teams. This resulted in a workforce management dashboard and BIM model viewer adaption of the software to allow teams to communicate and quantify resources and outputs with declared tasks. This provided clarity for teams to support effective communication.

PRODUCTION PLANNING

Production planning is a collaborative weekly process where meetings are held in collaborative 'Big Room'. This approach was replicated virtually to co-ordinate weekly work plans. These plans were developed on a digital platform where teams managed and co-ordinated their works (Figure 1). Preparations for the weekly workplans co-ordination meeting were held in advance and each work.

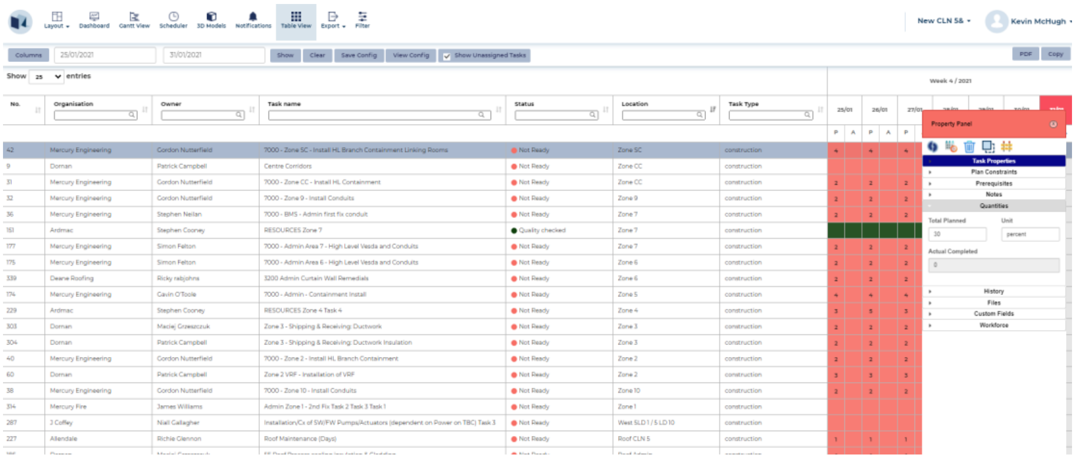

Figure 1: Digital weekly work plan

It was now needed to identify measure and control productivity while working remotely. This was done by preparing a continuity project in Visilean (Figure 2). Trade contractors were tasked to prepare and submit a 6 week look ahead for the remote working period. This resulted in more than 800 tasks being generated in the look ahead period. This assisted the team's ability to co-ordinate and manage project deliverables remotely. The teams were able to conduct package specific work plan reviews, weekly co-ordination meetings and 'Daily Activity Briefing's' (DAB's) catch up with the trade contractors while working remotely. Collaborating digitally facilitated teams to communicate and engage positively. Labour allocations were assigned based on progress updates to ensure work was available for the assigned resources. There was a focus on sequencing activities correctly to remove bottlenecks & ensure operatives can safely work together in an area.

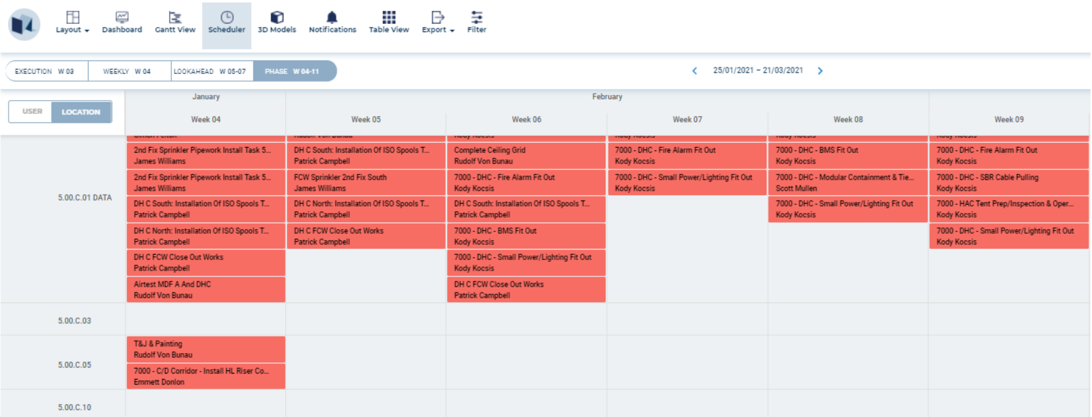

Figure 2: Digital pull plan session

With this structure in place the production management crew were able to maintain effective communication with the operation teams and work collectively to deliver value to the client. The teams were also able to demonstrate this by sharing the planned and actual production.

Production Control

The requirement to manage the production control system digitally was now essential to manage the development and delivery of weekly work plans. It was evident that during covid-19, the production process would need to be amended. to help forecast labour allocations. There was also an increased importance of resource forecasting and management. There was a requirement to measure planned and actual daily workforce and a requirement to control how they were deployed.

An amended project plan was developed to operate during the pandemic. This plan was resourced based on maximum project occupancy levels and was divided into shifts to mitigate bottlenecks and maintain productivity to achieve existing project milestones.

The resource loading of plans was required to plan works in each project area (Figure 3). All rooms were assigned a maximum allowable personnel capacity based on its floor area. This assisted the sequencing of works, where the teams could identify if they can complete the works in the original timeframe or introduce mitigation methods. Plans were communicated and controlled using DAB’s meeting that were held on the floorplate and hosted online to allow increased engagement and transparency. Tasks were updated daily with actual resource numbers assigned to tasks to ensure works have been accounted for. The workforce could then be managed efficiently by project supervisor and that no overcrowding of work areas occurred.

This led to a greater emphasis for the creation of weekly work plans. The previous study (McHugh et al., 2019) identified areas for improvement using PPC as a tool for measuring reliability the focus was on constraint removal & accurately sizing work for weekly outputs. There was also an increased focus on the quantities of work declared to allow to improve the predictability of completed sections of work. At the DAB’s meetings, the activities were declared by the supervisors and updated on the platform using the mobile application in the field to ensure all activities were identified. All work should have safety, design, logistics and personnel constraints removed before committing to weekly tasks. This facilitated supervisors to focus on site co-ordination which improved the quality of commitments a highlighted the interdependencies of trades in the field.

The use of the digital platform assisted the resource to be sequencing which improved the detail in the look ahead to process. Trade contractors could work on their look ahead plans with full visibility of current constrains and current look ahead plans. Trade contractors could then issue their look ahead plans in line with preceding works which could highlight risks and opportunities to the construction delivery programme. This level of preparation of look ahead planning, constraint analysis and quantified weekly work plans that were created in a digital platform was a rich source of information. This enabled teams to gather fully informed and prepared for weekly co-ordination meetings. This provided a greater level of detail for discussion to allow teams to manage a large volume of tasks in the weekly meeting.

The digitised LPS provided a greater connection between all levels of site management and operatives. The ability of trade contractors to manage their tasks and resources improved this connection. Risks were easily highlighted and mitigating works could be co-ordinated to manage at risks areas. Opportunities for improvement could be managed by bringing forward design coordination, procurement of materials and mobilising resources to match the improved production rates.

Location	Daily Limit	17/1 SUN	18/1 MON	19/1 TUE	20/1 WED	21/1 THU	22/1 FRI	23/1 SAT
5.00.M.15 ADMIN PLANTROOM Tasks	2	0	0	0	0	0	0	0
5.00.M.12 ELECTRICAL ROOM Tasks	2	0	0	6	6	6	6	0
5.00.M.09 S/R SECURITY Tasks	2	0	2	0	0	0	0	0
5.00.M.08 BOH ENTRY VESTIBULE Tasks	2	0	0	0	0	0	0	0
5.00.M.07 SECURITY OFFICE Tasks	2	0	0	0	0	0	0	0
5.00.M.06 SOC A/V Tasks	2	0	0	0	0	0	0	0
5.00.M.05 SECURITY STORAGE Tasks	2	0	0	0	0	0	0	0
5.00.M.04 SOC Tasks	2	0	0	0	0	0	0	0
5.00.M.01 BATTERY STORAGE Tasks	2	0	4	4	6	4	2	0
− Zone SC Tasks	-	0	4	4	4	4	4	0
5.00.M.02 HALLWAY Tasks	2	0	2	0	0	0	0	0
− Zone 2 Tasks	-	0	4	4	4	4	4	0

Figure 3: Workforce room occupancy management dashboard.

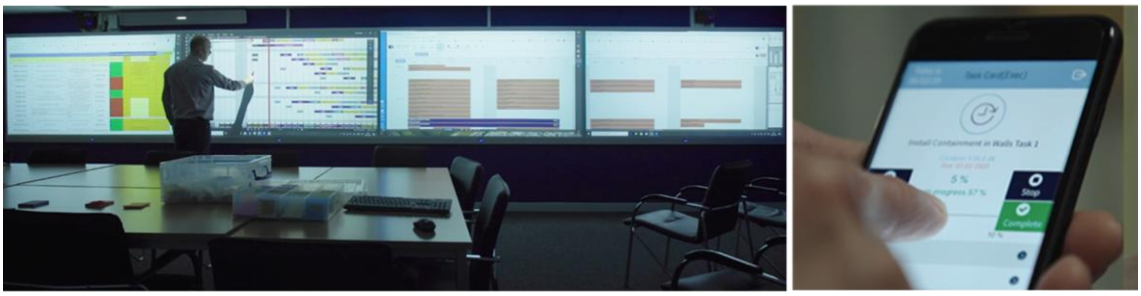

Figure 4: Digital workflow for managing the production environment.

The use of the mobile application (Figure 4) that provided greater control from the trade supervisors to manage works in the field. This also supported supervisors to identify works which were not fully identified in current weekly work plans that could be added to improve the detail of future submitted weekly work plans. The use of the mobile app in the field improved the accuracy of reporting and improved the quality of the collaboration which was based on the latest information from the field. The Dab's discussions were more informed and the high activity areas could be broken down into more manageable work zones. Management could then provide the support needed to maintain progress & ensure targeted areas were open for production free of constraints.

DISCUSSION

The daily workforce check-in at the DAB's is an essential component of the LPS. Trade contractors can confirm activities are in progress and highlight risks and opportunities related to their tasks. This provides an opportunity for improving the trade-to-trade handovers and increasing the quality of planned assignments. The quality of the information assigned to each activity facilitated greater coordination between project teams. Resources could be managed where social distancing could be achieved and improved interaction between trades improved the sequencing of subsequent works.

Digitising the weekly planning provided greater transparency between teams which increased the engagement with the production control system All trades had access to each other's plans and could review and discuss planned works and highlight dependencies and risks to each other. This provided greater information and allowed contractors to communicate effectively. This improved quality of information provided a safer working environment. The development and focus of labour resource reporting was identified as key constraint for operating during a pandemic. The authors developed a workforce management function in the existing digital LPS.

This update has established strong basis of discussion that has elevated safety discussion from operational to tactical level proceedings. Moreover, Production level safety discussions are now percolating to the ground level team in form of mandatory (digitally) prerequisites that cannot be missed reducing the scope of ambiguity.

OUTLINING THE FUTURE STATE

More and more projects will adapt lean construction techniques to improve project productivity and hance would be needing safe ways of effective collaboration. Ultimately, the ability to plan safety, collaborate, react, and manage production plans in the pandemic situation by more advance mediums i.e., using a combination of sensory and imagery data has become more vital to increase the spatial and situational awareness. In a nutshell, the objective is to reinforce the collaborations systems and channels with by enabling safe working planning and control platforms where teams can plan, assess, and ensure the safety proactively. By providing a strong link between fragmented project teams a greater awareness and understanding can be developed where teams can be more productive and increase the safety and quality of construction tasks.

CONCLUSION

The LPS has proven to be robust and provided a basis for improving the production control system for managing a construction project during the pandemic. A new constraint was recognised where personnel had to maintain safe working distance. Access and logistical measures were also put in place to increase the control of personnel and materials. The digitisation of the LPS allowed teams to fully integrate despite further fragmentation. Teams were no longer permitted to gather in a 'big room' to collaborate and socially interact with each other, or to come together at the workplace and interact at daily activity briefings. Digitising the LPS supported the team's ability to interact remotely and provided the social aspect that was reduced through social distancing by sharing all information on one platform, enhancing communication and collaboration. Digitising the LPS fully integrated project teams and improved the quality of the interactions. This can be further developed in a post pandemic world & add real value to construction production processes.

The digitised LPS will be used in future post pandemic operations. The greater connectivity between site & office-based personnel increased engagement with the LPS. Greater team visibility improved the quality of the WWP's. This improved the size & sequencing of planned works. This has provided a greater safety, quality, and more efficient assignments. An average 1100 operative working a cumulative of 57,000 operative hours recorded are being managed collaboratively using the Digital LPS.

REFERENCES

Aslesen, S., Sandberg, E., Stake, S., & Bølviken, T. (2013). Integrating safety analyses in production planning and control – a proposal. *Iglc-21*, *4*, 843–852.

Awada, M. A., Lakkis, B. S., Doughan, A. R., & Hamzeh, F. R. (2016). Influence of Lean Concepts on Safety in the Lebanese Construction Industry. *International Group for Lean Construction*, *11*, 63–72.

Chen, Y., Zhang, J., & Min, B. C. (2019). Applications of BIM and UAV to construction safety. *Proceedings, Annual Conference - Canadian Society for Civil Engineering*, *2019-June*, 1–7.

Ciribini, A., & Rigamonti, G. (1999). Time/Space chart drawings techniques for safety managemen. *Proceedings of International Conference of CIB Working Commission W99*, 25–32.

Emuze, F., & Smallwood, J. (2013). The integration of health and safety (H&S), lean and sustainability in construction: A literature review. *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*, *051*, 736–745.

Fang, W., Ding, L., Love, P. E. D., Luo, H., Li, H., Peña-Mora, F., Zhong, B., & Zhou, C. (2020). Computer vision applications in construction safety assurance. *Automation in Construction*, *110*(November 2019), 103013. doi.org/10.1016/j.autcon.2019.103013.

Grau, D., Abbaszadegan, A., & Assanair, R. (2019). Process versus operations workflow - Making the case for continuous monitoring of construction operations. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, *1*, 563–572. doi.org/10.24928/2019/0197.

Kartam, N. (1995). Integrating construction safety and health performance into CPM. *ASCE Construction Congress Proceedings*, *June*, 456–462.

Koskela, L., Howell, G., Pikas, E., & Dave, B. (2014). If CPM is so bad, why have we been using it so long? *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*, 27–37.

Lingard, H., & Rowlinson, S. (2005). Occupational Health and Safety in Construction Project Management. In H. Lingard & S. Rowlinson (Eds.), *Spon Press* (2005th ed.). Spon Press Taylor & Francis Group.

McHugh, K., Dave, B., & Craig, R. (2019). Integrated lean and BIM processes for modularised construction - A case study. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, 227–238. doi.org/10.24928/2019/0252.

Mitropoulos, P., Abdelhamid, T. S., & Howell, G. A. (2005). Systems Model of Construction Accident Causation. *Journal of Construction Engineering and Management*, *131*(7), 816–825. doi.org/10.1061/(ASCE)0733-9364(2005)131:7(816).

Mitropoulos, P. T. (2012). Production control and safety management as project safety determinants. *IGLC 2012 - 20th Conference of the International Group for Lean Construction*.

Poh, C. Q. X., Ubeynarayana, C. U., & Goh, Y. M. (2018). Safety leading indicators for construction sites: A machine learning approach. *Automation in Construction*, *93*(March), 375–386. doi.org/10.1016/j.autcon.2018.03.022.

Sacks, R., Rosenfeld, Y., & Rozenfeld, O. (2005). Lean scheduling for safety: Development of a time-dependent risk level model. *Proceedings of the 13th International Group for Lean Construction Annual Conference*, 513.

Saurin, T. A., Formoso, C. T., Cambraia, F. B., & Howell, G. (2002). A Cognitive Systems Engineering Perspective of Construction Safety. *Safety, Quality and Environmental Management Systems*.

Seo, J., Han, S., Lee, S., & Kim, H. (2015). Computer vision techniques for construction safety and health monitoring. *Advanced Engineering Informatics*, *29*(2), 239–251. doi.org/10.1016/j.aei.2015.02.001.

Stiles, S., Golightly, D., & Ryan, B. (2021). *Impact of COVID - 19 on health and safety in the construction sector*. *October 2020*. doi.org/10.1002/hfm.20882.

Teizer, J., Allread, B. S., Fullerton, C. E., & Hinze, J. (2010). Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. *Automation in Construction*, *19*(5), 630–640. doi.org/10.1016/j.autcon.2010.02.009.

Thomassen, M. A., Sander, D., Barnes, K. A., & Nielsen, A. (2003). Experience and results from implementing lean construction in a large Danish contracting firm. *Proceedings of 11th Annual Conference on Lean Construction*, 644–655.

Tixier, A. J. P., Hallowell, M. R., Rajagopalan, B., & Bowman, D. (2016). Application of machine learning to construction injury prediction. *Automation in Construction*, *69*, 102–114. doi.org/10.1016/j.autcon.2016.05.016.

Trinh, M. T., & Feng, Y. (2020). Impact of Project Complexity on Construction Safety Performance: Moderating Role of Resilient Safety Culture. *Journal of Construction Engineering and Management*, *146*(2), 04019103. doi.org/10.1061/(ASCE)CO.1943-7862.0001758.

Wu, X., & Wang, Y. (2020). *Research on the construction of government emergency management system under the "COVID-19"* *2*(4), 41–52. https://francis-press.com/uploads/papers/0dK9ppxTnlKZRmpGrTFgM6tWpKrzY2W41qQeacNz.pdf.

Yang, R. J., Gunarathna, C. L., McDermott, V., Lingard, H., Zhao, H., & Liu, C. (2020). Opportunities for improving construction health and safety using real-time H&S management innovations: a socio-technical-economic perspective. *International Journal of Construction Management*, *20*(5), 534–554. doi.org/10.1080/15623599.2018.1490866.

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015). BIM-based fall hazard identification and prevention in construction safety planning. *Safety Science*, *72*, 31–45. doi.org/10.1016/j.ssci.2014.08.001.

Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., & Venugopal, M. (2013). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction*, *29*, 183–195.

Schimanski C.P., Monizza G. P., and Matt D.T. (2021). “The Role of Common Data Environments as Enabler for Reliable Digital Lean Construction Management”. *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29), Alarcon, L.F. and González, V.A. (eds.),* Lima, Peru, pp. 97–106, doi.org/10.24928/2021/0110, online at iglc.net.

THE ROLE OF COMMON DATA ENVIRONMENTS AS ENABLER FOR RELIABE DIGITAL LEAN CONSTRUCTION MANAGEMENT

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ABSTRACT

Collaboration has always been a core element of Lean Construction. However, the current pandemic is changing the way collaborative environments can be created. Moving away from face-to-face discussions, concepts are needed that allow people to collaborate without meeting in person. Lean Construction methods implemented with digital technologies are a possible way to achieve this. Digital technologies in the built environment sector rely often on the Building Information Modelling (BIM) process. When information is managed and exchanged in a BIM process, Common Data Environments (CDE) as central information hubs come into play. How Lean concepts can make use of a standardized CDE workflow to access reliable information needed, e.g. for construction process planning, is yet to be addressed by the scientific community.

This paper outlines a concept for using CDE workflows together with a digital variant of the Last Planner® System that has been devised from a Design Science Research initiative. We hypothesize that this concept allows for achieving similar positive collaboration effects in remote planning sessions as in physical ones. First findings from a mock-up implementation of this concept in a Focus Group environment are presented and discussed in this paper.

KEYWORDS

Common data environment, BIM, Last Planner® System, lean construction, information management.

INTRODUCTION AND RELATED WORK

The current COVID-19 pandemic hinders people from meeting each other in person. This has surely an impact on how people collaborate with each other, which affects the global construction industry (CI) on a global scale. The CI is an industry, in which many different stakeholders need to collaborate to deliver projects. Improving collaboration is

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one important principle of Lean Construction Management (LCM) to increase productivity. Weak productivity has been reported for years in the construction industry (Dallasega et al. 2013; Matt et al. 2013). Ideas based on “Lean Thinking” aim at improving this status quo (Aziz and Hafez 2013). In addition to the deficient organization of how people work together, a poor degree of digitalization is often referred to as the main driver for weak productivity in the construction industry (Gbadamosi et al. 2019).

Whilst LCM focuses on improving how people work together, the process of Building Information Modeling (BIM) is considered the core of digitalization in the construction industry (EUBIM Task Group 2017). BIM can be defined as a process for creating, collecting and distributing information over the life cycle of a building (NBS 2016).

LCM and BIM are not independent (Bhatla and Leite 2012), but can even positively influence each other (Khan and Tzortzopoulos 2014). This also applies to workflow stabilization and production control in construction processes. In fact, information management, which is key to project delivery when BIM is used (ISO 19650-1 2018), is considered as crucial for successful production management (Von Heyl and Teizer 2017).

Digitalization can empower collaboration and teamwork across large distances all over the world. This has been demonstrated not least by the current pandemic, in which people have been forced to switch to home office models and digital co-working concepts very rapidly. The possibility of remote co-working through digitalization while preserving the positive effects of team collaboration does also play an important role for Lean Construction: More and more concepts to improve design and construction processes based on Lean philosophy, which are well-proven umpteen times in an "analog" implementation, such as the Last Planner® System (LPS) (Ballard 2000a), or Takt Planning (Haghsheno et al. 2016), are being implemented into software systems (usually cloud-based). Examples of such systems include LCM Digital® (Demir et al. 2019), VisiLean® (Dave et al. 2011) or BeaM! (Schimanski et al. 2020). This paper aims to address the question whether remotely applied Lean concepts through digital tools differ from non-digital application.

It is not uncommon for digital Lean Construction tools to be connected to the BIM approach. Linking BIM models to Lean Construction methods does intuitively make sense, since information inherently available in BIM models are often input parameters for applying these methods (e.g., material quantities for estimating activity durations within the pull planning sessions of the LPS). Moreover, in the literature there are also frequently cited references that emphasize the positive synergies of Lean and BIM (Sacks et al. 2010).

PROBLEM STATEMENT

The BIM-based and digital implementation of Lean methods such as the Last Planner® System opens up the possibility of holding collaborative planning sessions online via cloud systems and thus also across large distances. To this end, IT tools such as the BeaM! software prototype are already being put forward. The BeaM! prototype enables pull planning tailored for the LPS on digital touchboards. One of the challenges of BIM-supported pull planning of construction processes is that it must be always clearly identifiable which planning basis is being referred to. This means that it must always be unambiguously and reliably clear what state the information in the BIM model has and hence, what it may and may not be used for.

For this purpose, so-called Common Data Environments (CDE) are used in BIM projects. Preidel et al. (2017) define a CDE as a "central space for collecting, managing, evaluating and sharing information" and describe its importance for BIM-based collaboration processes. International standards differentiate between (i) the CDE workflow to account for the process perspective and (ii) CDE solutions that can be technological providers of the before mentioned “central space” (Kemp 2020). The CDE workflow may be implemented by multiple CDE solutions. The extent to which these considerations can be relevant for digital Lean Construction applications has not yet been addressed in the literature. The role of CDEs for applying BIM-supported Lean concepts is one of the issues being addressed in this paper.

Since this paper presents a concept for remote pull planning meetings via video conferencing tools, this study also investigates to what extent this technical medium impacts the human perception on efficiency in pull planning sessions. Efficiency here means how smoothly and thoroughly the digital, remote pull planning is carried out compared to a traditional in-situ pull planning.

RESEARCH METHODOLOGY

A prescriptive concept for digital, BIM-based and remote Lean Construction involving the BeaM! Production Management System is presented in this study (BeaM! is introduced in a separate section below). The development of BeaM! itself is part of a larger research project following the Design Science Research (DRS) approach and not within the scope of this paper. However, contributing to the evaluation of BeaM! in terms of practicability and in the face of the current pandemic situation, this paper examines the aspect of collaborative pull planning (as an essential element of BeaM!) from the point of view of remote applicability. The aim is to investigate whether a remotely applied, digital pull planning differs from a non-digital one. For this purpose, the Focus Group methodology is used. Focus Groups consist of rather few selected participants who are brought together to discuss and reveal novel perspectives on developments in early stages (Ereiba et al. 2004). Focus groups are usually guided by a moderator and prepared questions.

According to the DSR evaluation framework by Brocke and Sonnenberg (2012), Focus Groups provide for a valid method to evaluate the current development stage of BeaM! as a so-called "ex ante evaluation", since the final prototype has not yet been entirely constructed.

CONCEPT PROPOSAL

INFORMATION MANAGEMENT IN BIM PROJECTS

The ISO 19650 series is an international standard describing requirements and principles for information management in the built environment sector. When information management according to ISO 19650 is required in BIM projects, the utilization of a so-called Common Data Environment (CDE) for information exchange is recommended. In the CDE workflow, a so-called information container passes through various states, which are suggested in ISO 19650 as *Work-in-Progress (WIP)*, *Shared*, *Published* and *Archived* states. In addition, each information container should be assigned a "suitability" so that each stakeholder involved in the design process can clearly determine at any time for what the information may be used for. It is thus intuitively understandable that only *published* information containers – saying only complete, checked, reviewed, approved and finally authorized information - with suitability *for construction* should be used for construction execution. Even if in practice we are still a way off from this ideal, the CDE workflow can help to always reveal in a reliable and transparent way which design bases were used for construction or which design deliverables and approvals for execution are still missing.

BEAM! PRODUCTION MANAGEMENT SYSTEM

BeaM! is a Production Management System that conceptually takes up the Last Planner® System, adapts it and expands it to include aspects of BIM, agile project management according to Scrum as well as cost management. However, the integration of the LPS with BIM is the main focus on a conceptual level. The term "BeaM!" refers to both the conceptual considerations for a novel Production Management System and an IT-prototype that implements this Production Management System into a piece of software. The conceptual foundations for BeaM! are described in Schimanski et al. (2020). In principle, BeaM! aims at fully digitalizing the LPS process steps and supporting them by BIM. As an example, pull planning sessions for phase or look-ahead planning take place in front of a digital touchboard instead of at brown paper in the construction container. Another example is that quantity information for the determination of process and operation durations can be derived automatically from the linked BIM model objects, which are stored on a cloud-based model-server making use of open APIs.

In the current pandemic, this digital version represents a promising opportunity to conduct a full-fledged LPS involving all relevant Last Planners from distance using the nowadays well established video conferencing systems such as MS Teams®, Zoom® or Skype® (Wiederhold 2020). However, especially in planning meetings where the participants are not physically present in the same room, it is necessary that the planning basis, which in this case consists of the BIM models, is reliable and that each participant is clearly aware of the state and suitability of the information within the model. For this purpose, we propose to link a CDE workflow to the BeaM! Production Management System to foster remote application.

The prototypical implementation of BeaM! in an IT system is based on an architecture, where the process planning tool acts as a stand-alone web-application interacting with BIM models that are stored on a cloud-based model server. For the latter, the open source BIMserver.org project is used, where all Industry Foundation Classes (IFC) entities are available as Java classes (Beetz et al. 2010). The BIMserver itself represents a platform that could fulfill the requirements for a CDE solution (Preidel et al. 2017). The BeaM! process planning tool can retrieve quantity information of linked BIM objects. Linking does take place within in the BeaM! user interface.

The proposed concept for a resilient and ISO 19650 compliant digital Lean Construction Management (exemplified by a part of BeaM! as Production Management System and BIMserver as a CDE solution) is implemented and evaluated in a mock-up digital pull planning session. We chose pull planning, since it comprises the key-component of BeaM! for phase and lookahead planning.

CDE-BEAM! WORKFLOW AND MOCK-UP IMPLEMENTATION

The CDE-BeaM! workflow is shown in Figure 1.

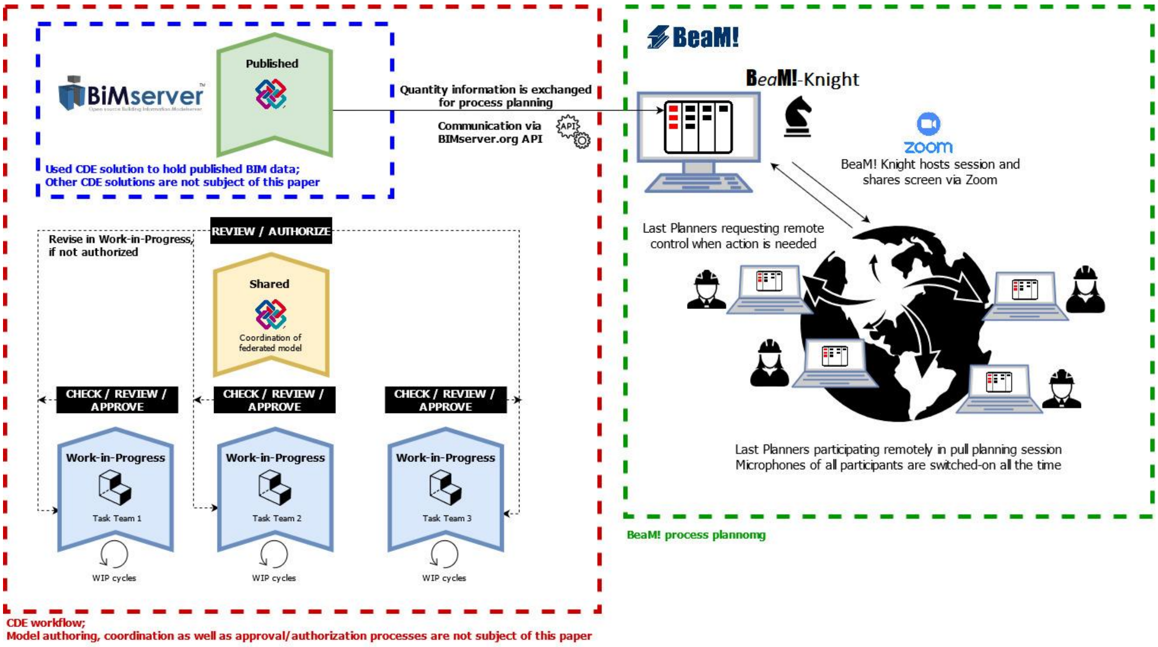

Figure 1: CDE-BeaM! Workflow

In line with the CDE workflow according to ISO 19650, the BIM models pass through various states until they finally reach the state of *published* and suitability *for execution*. The information up to this status flows through various quality gates (e.g. clash control of all involved discipline models).. All BIM models are exchanged in the vendor-neutral IFC file format. Only objects of BIM models in the state *published* with suitability *for execution* are used for pull planning within the BeaM! web application.

To conduct pull planning remotely, a video conference meeting via the Zoom® platform is hosted by the BeaM!-Knight, who comprises the moderating role in the BeaM! Production Management System. The participating Last Planners are invited to this conference via email link. The BeaM!-Knight shares his/her screen so that all participants see the same scene of the pull planning process at the same time. All participants have their microphones permanently switched on. Then, the activities and necessary discussions among the Last Planners for the planning of a phase or a process by means of pull planning can start: The Last Planners one by one request control of the screen. The BeaM! Knight provides the permission and only one Last Planner at a time can create new sticky notes and arrange them on the digital planning board. In this way, the process continues iteratively through the trades until a coordinated phase plan or look-ahead plan has been created and agreed on.

This concept was implemented with one Focus Group in a mock-up process planning scenario. The Focus Group consisted of a total of 5 participants working in the construction sector who took on the role of Last Planners. All of whom were either already familiar with the "traditional" application of LPS or received a training beforehand. The participants' task was to create a phase plan for the construction phase of a single-family house using the pull planning module of the BeaM! software prototype, following the phase scheduling rules as postulated by Ballard (2000b). The planning session was moderated by the BeaM!-Knight. The role of the BeaM!-Knight in this mock-up implementation was taken on by the first author of this paper. Figure 2 shows a screenshot taken during the phase planning in the Focus Group.

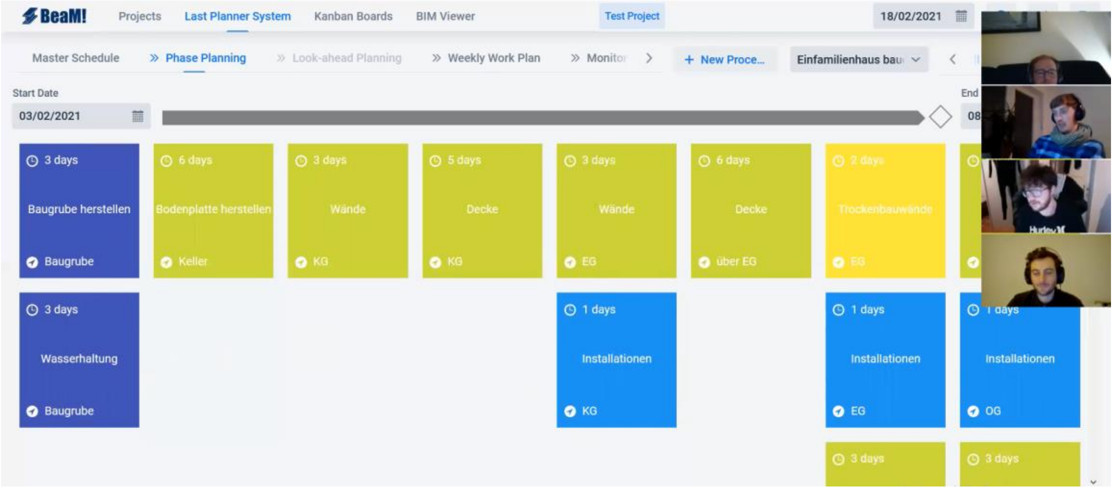

Figure 2: Screenshot taken during Focus Group mock-up Implementation

EVALUATION AND PRELIMINARY FINDINGS

The focus of evaluation in this paper is not the BeaM!-tool itself in terms of its applicability or potential benefit in practice (this will be addressed in a separate publication). This paper primarily aims at evaluating the usability of the BeaM!-tool while considering CDE workflow for enabling Lean Construction from a distance as presented in Figure 1. Consequently, the focus was laid on the pull planning aspects of the LPS and the questions directed to the participants were mainly addressing the perceived differences between digital and non-digital implementation as well as information reliability. The questions to the participants of the Focus Group during and after the session were formulated as:

- Were the type/quality of discussions in the digital pull planning sessions comparable to traditional sessions?
- Could hand-offs and prerequisites between trades appropriately be addressed?
- Were you able to gather all the information you needed?
- Were you able to share everything you wanted to share?
- Have you felt any limitations/improvements in communication?
- Did the CDE workflow increase confidence in the reliability of the design basis?
- Was the used video-conferencing system adequate?
- What did you like, what did you not like during the planning sessions?
- Could the digital, BIM-based LPS process completely replace the traditional one, what is missing to get there?
- Did this session tire you more than a face-to-face session would?

The questions were raised in the form of casual discussions in line with the recommendations of conducting Focus Groups in construction management research by Ereiba et al. (2004). No transcription of what was said to capture the group discussion was made, but a video recording of the session was taken. The feedback of the participants can be summarized to the statement that the digital conduction of pull planning following the proposed concept was generally well possible. The participants confirmed that elementary principles in the virtual remote session did not differ from the traditional way.

This was especially confirmed for crucial points such as asking for hand-offs relevant to one's own activity or transmitting one's own relevant information for the overall process.

However, it was found that on the one hand the online discussion in this setup was not quite as free, spontaneous, and intuitive, since only one Last Planner at a time could receive control over the screen. On the other hand, this forced the planning to take place in a more disciplined manner compared to the traditional way in which all Last Planners pin their sticky notes on the brown paper in an uncoordinated and simultaneous fashion. As a limitation in communication, it was reported that the always switched-on microphone meant that sometimes one did not capture who said what. Further, it was mentioned that the remote control of the shared screen was associated with minimal delays in cursor movements when arranging sticky notes, which somewhat disrupted the flow while using the application.

Confidence in the reliability of the information in the BIM model provided by the CDE workflow was generally rated as high. The used hardware and the proposed workflow were also assessed as positive, except for the above-mentioned limitation (cursor delay). What the participants liked about this session was the possibility to conduct a pull planning session very spontaneously and independent of location, as well as the digital availability of information, so that, for example, no one had to transfer information from paper-based sticky notes to an Excel spreadsheet afterwards. An increased fatigue compared to physical pull planning sessions could not be observed at the scheduled duration of one hour. For longer sessions, however, this was assessed as being indeed possible.

A complete replacement of physical pull planning sessions was not advocated by the participants, since some points could have been discussed even more naturally and directly in face-to-face discussions on-site or in construction containers. This was explained, among other things, by the fact that an ambience close to the construction site is generally considered to be inspiring for construction related planning activities. Nevertheless, the – in this study not-tested - variant of conducting pull planning in a physical environment but using digital touchboards and the BeaM! IT-tool instead of paper-based tools was evaluated as promising by all participants.

DISCUSSION & CONCLUSION

The findings of the Focus Group show that remote collaborative planning can be a useful addition or even alternative to the preferred physical sessions. The complete replacement was rejected, because the means of video-conferencing could not transport all subliminal and interpersonal elements of personal discussions. One fact contributing to this circumstance, namely that only one user can operate the digital planning board at a time, could be mitigated in the future by more sophisticated IT-systems that allow parallel working in real time, as e.g. proposed by Atencio et al. (2019).

On the methodological side, it has been shown that the new style of “digital” discussion gives the moderator, in this case the BeaM!-Knight, an even more important role in coordinating the planning session appropriately. To this end, a high degree of methodological competence and interpersonal sensitivity are required to maintain a fruitful discussion. The emphasis on a moderating role for the application of BeaM! is also important in comparison to other existing BIM-Lean software systems mentioned in the introduction. In particular, BeaM! is designed to entirely mimic the "traditional" pull planning in a digital way. Therefore, digital sticky notes exist that can be freely moved on a canvas. Quantity information can be retrieved from linked BIM objects. This functionality, which can speed up e.g. the estimation of operation durations, certainly needs guidance for the Last Planners by in first applications.

Regarding the conjunction of Lean Construction techniques with a CDE workflow in line with ISO 19650, the participants stated an increased trust in reliability and suitability of the BIM information.

In overall conclusion, it can be stated that this paper's findings indicate that parts of collaborative planning sessions within Lean Construction methods could be conducted completely digitally and remotely, without having a significant negative impact on the quality of the planning outcome. Surely, even in pandemic times with very restrictive lockdown periods, the physical presence of workers on construction sites is necessary to deliver projects. However, if the presented concept can help to ensure that production planning meetings can take place virtually with no-quality losses, then the number of meetings with high density of people in small rooms on construction sites (such as in construction containers) can be greatly reduced. With this, also the risk of infections on construction sites is reduced, since the indispensable physical presence of workers can usually be distributed over a larger (open-air) area.

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REFERENCES

Van Aken, J. E. (2004). “Management Research Based on the Paradigm of the Design Sciences: The Quest for Field-Tested and Grounded Technological Rules.” *Journal of Management Studies*, 41(2), 219–246.

Atencio, Y. P., Cabrera, M. I., and Huaman, L. A. (2019). “A Cooperative Drawing Tool to Improve Children’s Creativity.” *16th International Conference, CDVE 2019, Mallorca, Spain, October 6–9, 2019, Proceedings*, 162–171.

Aziz, R. F., and Hafez, S. M. (2013). “Applying lean thinking in construction and performance improvement.” *Alexandria Engineering Journal*, 52(4), 679–695.

Ballard, G. (2000a). “The Last Planner system of production control.” University of Birmingham.

Ballard, G. (2000b). “Phase Scheduling.” *Lean Construction Institute: White Paper No. 7*, 7, 1–3.

Beetz, J., van Berlo, L. A. H. M., de Laat, R., and van den Helm, P. (2010). “Bimserver.org - an Open Source IFC model server.” *27th International CIB W78 Conference, November 16-19, 2010, Cairo, Egypt*, 1–8.

Bhatla, A., and Leite, F. (2012). “Integration Framework of BIM with the Last Planner System.” *Proc. 20th Ann. Conf. of the Int’l. Group for Lean Construction*, International Group for Lean Construction, San Diego, 10.

Brocke, J., and Sonnenberg, C. (2012). “Evaluation Patterns for Design Science Research Artefacts.” *Communications in Computer and Information Science*, 286(Jan), 171–177.

Dallasega, P., Matt, D. T., and Krause, D. (2013). “Design of the Building Execution Process in SME Construction Networks.” *Second International Workshop on Design in Civil and Environmental Engineering*, 7–15.

Dave, B., Boddy, S., and Koskela, L. (2011). "Visilean: Designing a production management system with lean and BIM." *19th Annual Conference of the International Group for Lean Construction 2011, IGLC 2011*, 477–487.
Demir, S., von Heyl, J., and Demir, S. (2019). "Digitizing Lean Construction With." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*, 843–852.
Ereiba, Y. H., Glass, J., and Thorpe, T. (2004). "TBY Using Focus Groups in Construction Management Research." *20th Annual ARCOM Conference*, 1–3.
EUBIM Task Group. (2017). *Handbook for the introduction of Building Information Modelling by the European Public Sector*. EUBIM Task Group.
Gbadamosi, A.-Q., Oyedele, L., Mahamadu, A.-M., Kusimo, H., and Olawale, O. (2019). "The Role of Internet of Things in Delivering Smart Construction." *CIB World Building Congress*, (June), 17–21.
Haghsheno, S., Binninger, M., Dlouhy, J., and Sterlike, S. (2016). "History and Theoretical Foundations of Takt Planning and Takt Control." *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, 53–62.
Haghsheno, S., Budau, M. R.-D., and Russmann, E. (2020). "Collaboration Barometer – Development of a Tool for Measuring Collaboration During Design and Construction ." *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC)*, 323–336.
Hamzeh, F. R., El Samad, G., and Emdanat, S. (2019). "Advanced Metrics for Construction Planning." *Journal of Construction Engineering and Management, ASCE*, in press(11), 1–16.
von Heyl, J., and Teizer, J. (2017). "Lean production controlling and tracking using digital methods." *IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction*, 127–134.
ISO 19650-1. (2018). ISO 19650 - *Organization of information about construction works -- Information management using building information modelling - Part 1: Concepts and principles*. Multiple Publishers. Distributed through American National Standards Institute (ANSI).
Kemp, A. (2020). *Information management according to BS EN ISO 19650 - Guidance Part C Facilitating the common data environment (workflow and technical solutions)*. UK BIM Framework.
Khan, S., and Tzortzopoulos, P. (2014). "Effects of the interactions between lps and bim on workflow in two building design projects." *22nd Annual Conference of the International Group for Lean Construction, IGLC 2014*, 933–944.
Matt, D. T., Krause, D., and Rauch, R. (2013). "Adaptation of the value stream optimization approach to collaborative company networks in the construction industry." *Procedia CIRP*, Elsevier B.V., 12, 402–407.
Mollasalehi, S., Fleming, A., Talebi, S., and Underwood, J. (2016). "Development of an Experimental Waste Framework Based on Bim / Lean Concept in Construction Design." *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, International Group for Lean Construction, Boston, 193–202.
NBS. (2016). "What is Building Information Modelling (BIM)?" https://www.thenbs.com/knowledge/what-is-building-information-modelling-bim (Feb. 12, 2021).

Parn, E. A., and Edwards, D. (2019). "Cyber threats confronting the digital built environment: Common data environment vulnerabilities and block chain deterrence." *Engineering, Construction and Architectural Management*, 26(2), 245–266.

Preidel, C., Borrmann, A., Oberender, C., and Tretheway, M. (2017). "Seamless Integration of Common Data Environment Access into BIM Authoring Applications: the BIM Integration Framework." *eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2016: Proc.*

Sacks, R., Koskela, L., Dave, B. A., and Owen, R. (2010). "Interaction of Lean and Building Information Modeling in Construction." *Journal of Construction Engineering and Management*, 136(9), 968–980.

Schimanski, C. P., Monizza, G. P., Marcher, C., and Matt, D. T. (2020). "Development of a BIM-based production planning and control system for Lean Construction through advancement and integration of existing management techniques." *Frontiers of Engineering Management*.

Wiederhold, B. K. (2020). "Connecting through Technology during the Coronavirus Disease 2019 Pandemic: Avoiding 'zoom Fatigue.'" *Cyberpsychology, Behavior, and Social Networking*, 23(7), 437–438.

Mandujano, M.G., Alarcon, L.F., Dave, B. A., Mourgues, C., and Koskela, L. (2021). "Understanding the Interaction Between Virtual Design, Construction and Lean Construction." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 107–115, doi.org/10.24928/2021/0124, online at iglc.net.

UNDERSTANDING THE INTERACTION BETWEEN VIRTUAL DESIGN, CONSTRUCTION AND LEAN CONSTRUCTION

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ABSTRACT

There have been important advances regarding the synergies between Building Information Modeling (BIM) – as part of Virtual Design and Construction (VDC) – and Lean Construction. However, the literature does not fully explore the nature of these synergies nor the conceptual reasons behind them. This better understanding of these synergies would allow the Architecture, Engineering and Construction (AEC) industry to achieve better Lean and VDC implementations and would provide a stepping-stone for the academia to continue building on these synergies. This article presents a thorough literature review based on leading international journals, conference proceedings and books, to explore the synergies between Lean Construction and VDC, including BIM (product), process and organization modeling. As part of this review, the article tests mechanisms about interaction mechanisms, previously mentioned in the literature. The findings indicate that using the entire VDC framework, the positive interactions between Lean and VDC increased significantly with respect to the same analysis restricted to the interaction between Lean and BIM. Identifying these new interactions and interaction mechanisms can help the AEC industry take a more holistic approach and generate improvements in every project phase.

KEYWORDS

Lean construction, collaboration, BIM, VDC, synergy.

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INTRODUCTION

The major challenges facing the architecture, engineering, and construction (AEC) industry have created a new way of working, forcing companies to use new methodologies such as virtual design and construction (VDC) (Kunz and Fischer 2020). VDC is perceived as an approach that will help the AEC industry achieve better results by increasing the value of projects, reducing their costs, improving productivity, and creating other positive results (Lee et al. 2020). In a similar way, the Lean Construction philosophy can be used as a conceptual framework for VDC implementation because the impacts of VDC can be directly associated with Lean Construction principles (Alarcon et al. 2013). In view of this development, there is a growing need to make VDC users aware of Lean Construction principles, as well as a need to make Lean Construction users aware of the benefits of VDC (Mandujano 2019).

There have been important advances regarding the synergies between building information modeling (BIM), as part of virtual design and construction (VDC) and Lean Construction (Kunz and Fischer 2020; Mandujano 2017; Mandujano et al. 2016). Despite these advances, previous studies have been focused primarily on product modeling and Lean Construction synergies, leaving aside the process and organizational components. It is therefore important to understand a) the full extent of the synergies between VDC, including BIM (product), process and organization modeling, and Lean Construction; b) the nature of these synergies (i.e., how strong or weak, direct or indirect, etc.); and c) the reasons and conceptual explanations of why these synergies exist.

The remainder of this paper is structured as follows. Section 1 explains the difference between VDC and BIM. Section 2 reports the state of the art of VDC and Lean Construction. Section 3 presents the study's research method. Section 4 develops the interactions matrix. These new interactions complete the matrix proposed by Sacks et al. (2010) but also helps analyze the current VDC implementation from a Lean perspective and can help identify new VDC and Lean adoption strategies. Section 5 tests the four mechanisms proposed by Dave et al. (2013). Section 6 identifies the key gaps in the literature. Finally, in section 7 the conclusions and the implications for further research are outlined.

BACKGROUND

The literature is ambiguous about the differences between VDC and BIM. As a result, some companies have sold BIM as simply a software platform, setting aside the core of the methodology: collaborative work (Mandujano 2017). In this paper, we continue define VDC as mentioned by Kunz and Fischer (2011): "*The use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives*". Building Information Models (BIM) represent the form/scope of the *product*, which is a crucial but a partial representation of both the total perspective of a project and the information about a project represented in the VDC framework and a POP model (Alarcon et al. 2013). In this paper, we continue to define BIM as mentioned by Eastman et al. (2018): "*A digital database of a particular building that contains information about its objects*".

At the outset, it seems that the definition of BIM is slightly narrower and focuses on the production of a 3D virtual model that represents the physical reality, hence excluding the process element. On the other hand, VDC seems to focus on the overarching process, and takes BIM (or 3D modeling) as one of the tools and goes on to include 4D production, organizational and process modeling tools, and collaborative techniques as part of the approach. However, the authors would rather like to argue that this broader or inclusive definition is a somewhat modern development and the origins of the concept have deeper technological underpinnings. The authors would like to suggest that while the academia and industry have now realized the value of including people (organizational) and process aspects, there is a need to ensure that the chosen process model is based on sound foundation and has a potential to improve the core functions of the industry.

VDC involves much more than simply implementing new software; it is a new way of working (Mandujano et al. 2015). This requires a move away from traditional workflow, with all parties sharing and effectively working on a common pool of information (Mandujano et al. 2016). Lean implementation involves three components: product, organization and process (Kunz and Fischer 2011). The philosophy and culture of Lean and VDC principles have great synergies and share many main ideas (Alarcon et al. 2013). VDC eliminates waste but also improves workflow for many actors, even those who do not use VDC directly (Eastman et al. 2018). VDC encourages and provides a path for the sharing of information among the stakeholders. Although each approach can be carried out independently, to reach a higher potential, it is necessary to consider the culture, philosophy, and technology jointly. This makes the potential for VDC and Lean implementation greater than the sum of their parts, consequently improving project performance (Alarcon et al. 2013).

METHOD

The relevant articles published during the period from 2000 to 2020 were identified through a systematic search of many electronic databases. In order to limit this broad scope, we performed a keyword search in top journals as well databases and conference proceedings. The search was conducted using three keywords: BIM, VDC, and Lean. These keywords were chosen because we aimed to identify essential components of current literature reviews between VDC and Lean. The studies were divided according to their various methodologies: surveys/interviews, case studies, literature reviews, and implementation guides. The literature on VDC implementation covered many important aspects, including – but not limited to – its benefits and obstacles, synergies between Lean and VDC, its current status, implementation strategies, and the impacts of VDC in the AEC industry (Alarcon et al. 2013). A total of 300 articles that were reviewed in English and contained the selected keywords in their text or abstracts were retrieved through the database searches. Then, the abstracts of the retrieved articles were reviewed to determine whether they met these review’s inclusion criteria. The inclusion criteria included systematic integrated literature reviews that (a) used and described systematic search methods, (b) were relevant to VDC and Lean practices, and (c) included new interactions between VDC and Lean. Through this process, 250 articles were selected based on their abstracts. Then, the full text of all 250 articles was reviewed to determine whether they met the inclusion criteria. Finally, a total of 196 articles were selected and included in this literature review. The majority of these articles are from the Center for Integrated Facility Engineering (CIFE), Automation in Construction, and the Journal of Construction Engineering and Management. A substantial difference in the number of published articles can be observed between 2000 and 2020 (Figure 1). The authors found few articles published between 2000 and 2005. The greatest number of articles was published between the years 2020-2016.

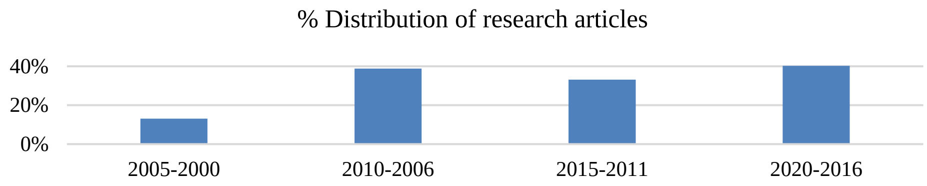

Figure 1: Distribution of research articles.

RESULTS

Using the information mentioned above, a matrix was developed (Table 1) showing 405 interactions between VDC and Lean, some of which, in one way or another, have been mentioned by Sacks et al. (2010) (including those referred to as 'not found yet' – the full list of interactions can be accessed at: www.maroconsulting.mx). The numbers within tables 1-2 represent types of interaction and if the same type of interaction was found in two papers it was counted once). We focused mostly on those VDC features most mentioned in our literature review to create the tables and matrix: Table 1 shows the frequency of occurrence of each interaction. The Lean principles were chosen based on Koskela (1992) and Sacks et al. (2010). The types of waste that VDC-Lean interaction could reduce and also the Lean techniques that the industry could apply in order to improve VDC adoption (Koskela 1992) were considered. The columns show the total occurrence for each VDC feature, and the rows show the totals for the lean principles. We can see that online communication product/ process (M) is the VDC feature most mentioned in our literature review. Followed by construction planning/ 4D modeling. Also, reduce time (d) and transparency (h) are the most mentioned lean principles allowed by VDC. The interactions more mentioned were: visualization of the design - reduce time, and online communication production/ process - reduce time. It is important to understand the relationship between Lean and VDC.

Dave et al. (2013) have presented four mechanisms to analyze how Lean and BIM relate to each other. In order to test these mechanisms, they were associated with the evidence from practice and/or research presented in the literature. We proposed that VDC allows for more interactions with Lean:

a) VDC contributes directly to Lean goals.
b) VDC enables Lean processes and contributes indirectly to Lean goals.
c) Auxiliary information systems, enabled by VDC, contribute directly and indirectly to Lean goals.
d) Lean processes facilitate the introduction of VDC.

Table 2 shows the frequency of the mechanisms vs. the frequency found in the literature carried on in our methodology about VDC. The hypothesis that, "BIM contributes directly to Lean goals." had the highest frequency within the analysis, followed by mechanisms 2, 3, and 4. In the fourth column, the hypothesis that, "VDC contributes directly to Lean goals" occurred with the highest frequency, followed by mechanisms b, c, and d. The results suggest that to achieve more synergies between Lean Construction and VDC, including BIM (product), process and organizational modeling, it is necessary to use the entire VDC framework. This allows more positive interactions between lean and VDC, versus a similar situation that only includes an interaction between Lean Construction and BIM.

Table 1: Frequency of interactions

	LEAN PRINCIPLES				PRINCIPLES FOR FLOW PROCESS DESIGN AND IMPROVEMENT												PROBLEM SOLVING		DEVELOPING PARTNERS	
					REDUCE THE NON VALUE- ACTIVITIES	CUSTOMER REQUIREMENTS	REDUCE VARIABILITY	REDUCE TIME	SIMPLIFY	FLEXIBILITY	STANDARDIZE	TRANSPARENCY	CONTROL THE PROCESS	BUILD CONTINUOUS IMPROVEME	BALANCE FLOW	BENCHMARK	GO AND SEE FOR YOURSELF	DECIDE BY CONSENSUS	CULTIVATE AN EXTENDED NETWORK	
ID	VDC/FEATURES	POP			a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	Total
A	VISUALIZATION OF THE DESIGN	X			11*	10	20	32	8	6	4	25	9	13	6	1	4	7	6	162
B	PRODUCTION OF CONSTRUCTION DOCUMENTS	X			15*	9	19	24*	9*	6	9	12	9	8	5	2	3	4	10	144
C	ANALYSIS OF DESIGN OPTIONS	X			8	9	5	9	4	3*	4*	7	3	3	2	1	2	7	4	71
D	SUPPLY CHAIN MANAGEMENT		X		4	2	3	7	3	2	2	2	3	1	2	1			2	34
E	DESIGN CHECKING	X			7	4	9	9	4	3	2	9	4	3	2	1	1	1	2	61
F	CODE REVIEWS		X			1		3	1		1	3	1	1		1	1		1	14
G	FORENSIC ANALYSIS		X			1		2	1	1	1	4								10
H	FACILITIES MANAGEMENT		X		2	1	2	3	3	1	2	6	3	2	1	1	1	1	1	30
I	QUANTITY TAKEOFF AND COST ESTIMATING/ 5D MODELING		X		4	5	6	14	3	2	2	4	2	2	1	1	1	1	1	49
J	CONSTRUCTION PLANNING / 4D MODELING		X		16	7	13	27	12	10	10	23	10	7	8	3	3	8	9	166
K	ORGANIZATIONAL MODELING			X	3		3	5	1	1	2	3	2	2	1	2	1	3	4	33
L	BUILDING PERFORMANCE ANALYSIS		X	X	5	2	2	7	3	3	3	9	3	4	2	4	2	2	2	53
M	ONLINE COMMUNICATION PRODUCT/PROCESS			X	8	5	12	32	9	6	5	22	6	11	6	2	5	14	24	167
Total					83	56	94	174	61	44	47	129	55	57	36	20	24	48	66	

Note: Considering space limitations to access to the full list, please visit: www.maroconsulting.mx. Numbers with * symbol represent negative interactions.

Table 2: VDC features vs. Lean principles

Hypothesis number	Hypothesis description	BIM	VDC
1, a	… contributes directly to Lean goals.	328	686
2, b	… enables Lean processes, which contributes indirectly to Lean goals.	310	653
3, c	Auxiliary information systems, enabled by… , contribute directly and indirectly to Lean goals.	306	580
4, d	Lean processes facilitate the adoption and use of…	253	468
1, a	… contributes directly to Lean goals.	328	686

DISCUSSION

This research distinguished between VDC and BIM. This step was crucial because in order to begin, it was necessary to clarify this ambiguity. Although significant advances have been made with regard to the synergies between BIM and Lean, there was a gap in extending these interactions throughout the VDC methodology (including BIM (product), process and organization modeling). After clarifying both concepts, 405 interactions between VDC and Lean were identified. These allow for the development of new VDC implementation strategies and also provide a broader picture that allows for the construction industry to implement more holistic and substantial improvements in every project phase. The new interactions found in the literature can help to complete the matrix proposed by Sacks et al. (2010) and create new implementation paths.

Some of the evidence found in this research includes:

- Co-locating the design and detailing teams such that detailers worked side-by-side, allowed them to construct designs virtually and resolve conflicts and issues immediately, further facilitating highly integrated project Delivery (e.g., Big Room).
- Extended networks that increase collaboration among firms are more effective at implementing models across organizations.
- 4D improves efficiency and safety. It can help identify bottlenecks, improve flow, and verify and validate process information.
- 5D models, which connect 3D models to a database for quantity take-off, support location-based planning and scheduling. These types of models make it easier to visualize quantities and integrate them into schedules and cash flows.
- With hyperlinks to drawings and documents, the way of obtaining information is standardized. The variability is reduced when you have direct links to the documents you need.

- As trust within any multi-organizational value network is considered crucial to collaboration, it is argued that companies trusting each other are more likely to share information in order to identify and manage inefficiencies and reduce costs.
- Multi-skilled resources: flexibility, process integration Optimization modeling algorithm - SIMAN code Off-site construction plant.

Our research showed that without the VDC framework, these interactions would be achieved to a lesser extent. This finding was supported by the previously discussed mechanisms (Table 2). The interactions most mentioned in the literature and practice were:

- Co-locating Visualization of the Design– Reduce Time (Ad);
- Online Communication Product/Process– Reduce Time (Md);
- Construction Planning/4D Modeling – Reduce Time (Jd);
- Visualization of the Design– Transparency (Ah);
- Online Communication Product/Process– Cultivate an Extended Network (Mo)
- Construction Planning/4D Modeling – Transparency (Jh);
- Production of Construction Documents – Reduce Time (Bd);
- Online Communication Product/Process– Transparency (Mh)

In fact, we can mention that the interactions listed above have a strong and direct impact between them. First, with the use of VDC the process as a whole becomes more efficient. The "Production of Construction Documents" becomes automatic, this allows to "Reduce Time" when documents are delivered (EEE). The use of "Construction Planning/4D Modeling" and "Cost Estimation/5D Modeling" help to reduce time and add value to projects. Moreover, the use of "Construction Planning/4D Modeling" improves the "Transparency" and "Reduce Time" in the project. Since the "4D Modeling" enables the visualization of the sequence of the project all issues are identify prior construction. This results in cost and time saving on site because of effective planning. VDC is a methodology based on technology, a clear example of this is the interactions "Online Communication Product/Process" – "Cultivate an Extended Network" and "Online Communication Product/Process" – "Reduce Time" and – "Transparency". The use of tools, such as iRoom onsite, plasma screen monitors, iPADs and or Tablet PC's loaded with the latest VDC model, allows for coordination and communication between all stakeholders. This level of visualization is high because it is close to the actual and most updated model version and is available to different levels of the hierarchy especially for onsite workers.

We cannot neglect the negative interactions found "where the use of VDC inhibits implementation of a lean principle (Sacks et al. 2010)".

- Production of Construction Documents – Reduce Non-Value Activities (Ba);
- Production of Construction Documents – Reduce Time (Bd);
- Production of Construction Documents – Simplicity (Be);
- Analysis of Design Options – Flexibility (Cf); and
- Analysis of Design Options – Standardize (Cg).

The negative interactions can be interpreted in several ways. While VDC allows a range of benefits throughout the entire project, the negative interactions are the result of keep seeing VDC just as a technology putting aside the collaborative view (processes and persons). An example of this is the interaction “Production of Construction Documents” and “Reduce Non-Value Adding Activities”. In many cases, the models that are sent from one entity to another contain many inconsistencies. Such inconsistencies create extra work during the production documents.

One key result is the interaction between “Production of Construction Documents” and “Reduce Time”. As mentioned before this interaction has a strong and direct impact, but when there is an abuse of the ease with which drawings can be generated can lead to more versions of drawings and as a consequence an increase time of processing. This result encourages caution when producing construction documents or analyzing design options. The ease with which “Production of Construction Documents” can be detailed creates a negative interaction with “Simplicity”. Too much detail in the construction documents increases complexity rather than simplicity. Finally, the interaction of “Analysis of Design Options” and “Flexibility” and “Standardize” are a clear example of the need to incorporate Lean throughout all VDC practice. Mandujano et al. (2016) found several types of waste within current VDC practice and suggested that if teams use Lean methods and focus on elimination of these types of waste (i.e., non-value added processing, motion (excess), inventory (excess), waiting and overproduction), teams can improve VDC practices dramatically and also suggests the use of protocols for sharing models, BIM libraries, meeting protocols or quality protocols in order to remove waste within VDC practice and, in our case, enhance or reverse the negative interactions.

CONCLUSION

This study contributes to provide a better understanding of the impact of simultaneous implementation of Lean Construction principles along with the VDC approach on various stages of construction projects. Identifying the interrelationship of lean principles with uses and actions performed through VDC provides a broader picture that allows the AEC industry to take a more holistic approach, which can help to obtain substantial improvements in every project phase, by increasing the effectiveness of the methods through a better alignment with relevant lean principles. The distinction between BIM and VDC definitions is also an important step in developing a better understanding of the methods and their associated management principles. By making this distinction clear, a significant number of new interactions between Lean Principles and VDC were found in the literature that can help to complete previous studies available in the literature and create new implementation paths in the future. Our research showed that without the VDC framework, these interactions would be achieved to a lesser extent. In order to support this, we tested the interaction mechanisms, previously mentioned in the literature. Future research should direct attention toward understanding the nature of these interactions in further detail and increasing the frequency of interactions between VDC and Lean. As previously mentioned, although VDC or Lean Principles initiatives can be carried out independently in order to reach a higher potential of these improvement efforts, it is necessary to consider the important synergies that their interactions offer. Only in this way companies and projects can take full advantage of all the benefits that VDC and Lean offer. Much remains to be done in the area of VDC and Lean, the AEC industry is constantly changing, and needs are becoming greater.

REFERENCES

Alarcon, L. F., Mandujano, M., and Mourgues, C. (2013). "Analysis of the implementation of VDC from a lean perspective: Literature review." *Proc., Proc. 21st*

Ann. Conf. of the Int'l. Group for Lean Construction, Int'l. Group for Lean Construction, Fortaleza, Brasil, 781-790.

Dave, B., Koskela, L., Kiviniemi, A., Tzortzopoulos, P., and Owen, R. (2013). "Implementing Lean in Construction: Lean Construction and BIM." CIRIA, London, UK.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2018). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*, John Wiley & Sons.

Koskela, L. (1992). *Application of the new production philosophy to construction*, Stanford university Stanford, CA.

Kunz, J., and Fischer, M. (2011). "Virtual design and construction: themes, case studies and implementation suggestions." *CIFE Working Paper #097*, Center for Integrated Facility Engineering, Stanford University, USA.

Kunz, J., and Fischer, M. (2020). "Virtual design and construction." *Construction Management and Economics*, 38(4), 355-363.

Lee, M., Cheah, W., Lau, S., Lee, X., Abdullahi, A., and Wong, S. "Evaluation of practicality of virtual design and construction (VDC) with 5D building information modelling (BIM) through a case study." *Proc., IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 012058.

Mandujano, M. (2017). "A Method To Identify Virtual Design And Construction Implementation Strategies From A Lean Construction Perspective." Degree of Doctor in Engineering Science., Pontificia Universidad Catolica De Chile Chile.

Mandujano, M. (2019). "Integration of Historic Building Information Modeling and Valuation Approaches for Managing Cultural Heritage Sites." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 1433-1444.

Mandujano, M., Alarcón, L., Kunz, J., and Mourgues, C. "Use of virtual design and construction, and its inefficiencies, from a lean thinking perspective." *Proc., Proceedings of the 23rd Annual Conference of the International Group for Lean Construction, Perth, Australia*.

Mandujano, M., Alarcón, L., Kunz, J., and Mourgues, C. (2016). "Identifying waste in virtual design and construction practice from a Lean Thinking perspective: A meta-analysis of the literature." *Revista de la Construcción*, 15(3), 107-118.

Sacks, R., Koskela, L., Dave, B. A., and Owen, R. (2010). "Interaction of lean and building information modeling in construction." *Journal of construction engineering and management*, 136(9), 968-980.

Pedo, B., Tezel, A., Koskela, L., Whitelock-Wainwright, A., Lenagan, D., and Nguyen, Q. A. (2021). "Lean contributions to BIM processes: the case of clash management in highways design." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 116–125, doi.org/10.24928/2021/0164, online at iglc.net.

LEAN CONTRIBUTIONS TO BIM PROCESSES: THE CASE OF CLASH MANAGEMENT IN HIGHWAYS DESIGN

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ABSTRACT

Managing design is still considered a challenge and few design and construction companies apply Lean and BIM in an integrated manner to support it. The interactions of Lean and BIM have been explored for more than 10 years. Despite this, most of the practical and theoretical discussions have focused on BIM capabilities' and features' contributions to Lean goals and techniques. Therefore, this paper aims to explore and discuss Lean contributions to BIM processes, which is still missing in the analysed context. Initial findings of an ongoing research project on exploring Lean and BIM synergies in the UK are presented. The investigation adopts case study as its research strategy, while exploring the potential implementation of Lean into the BIM-based clash management in highways design. The paper contributes to knowledge by determining how Lean could reduce waste and increase value of a clash detection and resolution process. The results indicate that Lean can contribute to the BIM processes, beyond the BIM capabilities and features, to support BIM process improvements. The wide range of intervention opportunities in BIM processes from a Lean perspective needs further investigation for Lean to have a firmer place in BIM discussions.

KEYWORDS

Lean and BIM, clash management, process, design management, waste.

INTRODUCTION

Lean production is a managerial philosophy, i.e. a combination of principles, tools and techniques, that emerged in the manufacturing sector and has been applied and adapted to construction since the 90s. It has been pointed out as an important approach to increase stakeholders' value, as well as to eliminate activities that do not add value (Womack et

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al. 1991); sharing the same principles with Lean construction, which is the reflection of Lean production on the construction industry. On the other hand, Building Information Modeling (BIM) is described as a process to design, construction and facilitity management, which can involve all project stakeholders (Hamdi and Leite 2012). Being the digital replica of a built asset, it is becoming a key product and process to support information management in project management in order to improve the project life cycle.

The literature has pointed out numerous synergies between BIM and Lean since 2010, enabling the industry to focus on the life cycle value (Dave et al. 2013; Sacks et al. 2010; Tzortzopoulos et al. 2020), even though they emerged as separate initiatives. According to Dave et al. (2013), there are four major mechanisms for how Lean and BIM interact: (i) BIM contributes to Lean goals, (ii) BIM enables Lean processes, (iii) auxiliary information systems, enabled by BIM, contribute to Lean, and (iv) Lean processes facilitate the introduction of BIM. However, investigations mostly focus on BIM's and auxiliary information systems' contributions to Lean techniques, and goals, which have been widely recognised in the literature and practice. For the design phase, the main focus of the current discussions is on how to solve specific design problems through the use of BIM based tools, such as clash detection, and how to facilitate the realisation of some Lean goals (Tzortzopoulos et al. 2020), not giving due regard to how Lean can contribute to BIM processes.

This paper reports findings of an ongoing Knowledge Transfer Partnership (KTP) with an infrastructure design and consultancy company, aiming to explore the integration of Lean and BIM. The aim of the paper is to investigate Lean contributions to BIM processes, over an illustrating case about clash management in highways design. BIM-related processes are still fragmented and wasteful, characterising the practical justification of the research, thus Lean can offer solutions. However, there are not enough investigations on Lean's contributions to BIM processes in the literature and practice, and this needs to be expanded. The synergetic interactions between Lean and BIM have been observed to exist, but at the moment, the highways sector does not seem to utilise them much, and in any case not in a systematic manner. Software issues have in the past prevented the adoption of Lean techniques for clash detection in Highways, an issue that does not exist in other disciplines such as Buildings. Also, related research has mostly focused on building projects, and it is not known whether the interactions would be the same in highway projects.

SYNERGIES OF LEAN AND BIM

The impacts of Lean and BIM are deep on their own when considering their separate applications; however, in addition to their parallel development, they also have synergistic impacts when implemented in integration (Sacks et al. 2010). Sacks et al. (2010) identified 52 positive interactions out of total 56 interactions between Lean and BIM. Significant positive interactions include: (i) reduction in design and construction work variability; (ii) reduction in design and construction cycle-times; and (iii) improved information flows and stakeholder engagement through visualisation of the product and process. By identifying those synergies, Sacks at al (2010) and Hamdi and Leite (2012) argue that the full potential of BIM and Lean can only be achieved through integrated approaches.

From the BIM to Lean aspect, it is important to highlight the opportunity and the need for information technologies to support Lean production management workflows (Tzortzopoulos et al. 2020), e.g. focusing on computer-assisted optimisation of process

(Schimanski et al. 2019). The use of BIM allows certain activities, which do not add value to the product and the process, to be automated or eliminated (Tezel and Aziz 2017).

The use of BIM as a way to enable effective Lean practices has been massively documented; however, the use of Lean for achieving improved levels of BIM adoption and processes has not been adequately explored (Mahalingam et al. 2015). This perspective outlines how Lean can support the implementation and continuous improvement of BIM. Practices such as colocation of stakeholders or implementation of big rooms for collaborative discussions and visualisation have been suggested as approaches to support BIM implementation through an improved coordination (Dave et al. 2013; Eastman et al. 2008).

Moreover, Lean has a potential to improve BIM processes and the literature has revealed new implementation opportunities in that regard. Uusitalo et al (2019) and Bhatla and Leite (2012) highlighted a lack of clarity on how to connect the different BIM concepts, e.g. level of detail, with Lean tools, such as the Last Planner® System (LPS), in order to develop correct and useful models. The use of the LPS as a BIM enabler has been also investigated by Mahalingam et al. (2015), who argue that more work can be developed in order to understand how other Lean tools can improve the information transfer within BIM-based projects. Process map and value stream analysis can impact the transparency of the processes (Klotz et al. 2008), and can also benefit BIM process improvements. BIM not only enables Lean goals, but it can also be enabled by Lean adoptions, such as collaboration and continuous improvement.

CLASH MANAGEMENT

Akponeware and Adamu (2017) highlighted that the detection of clashes has fascinated researchers for decades; however, the phase and time to detect a clash have progressively changed from a reactive activity, i.e. on-site activity, to a proactive activity in the preconstruction design phase. The clash detection or interference checking process refers to the practice of identifying clashes in a federated BIM model, which can be defined as waste in the production system (Tommelein and Gholami 2012). It is one of the many quality checks conducted by the design team before they release the product (Chahrour et al. 2021), and it is a “necessary non-value adding activity”. Design conflicts must be made visible, characterised, and have root causes identified, as a way to improve efficiencies and reduce wastes (Tommelein and Gholami 2012). Nevertheless, clash detection tools still generate huge amounts of irrelevant conflicts, which require time and resources to solve (Hartmann 2010).

The clash detection and resolution process involves identifying the conflicts in a 3D BIM environment, which is obtained by performing pair-wise comparison checks between a set of elements or disciplines (Radke et al. 2009). According to the ISO 19650-1 (2018), issues can be spatial, e.g. elements and services in the same space, or functional, e.g. materials not compatible with the regulations. Spatial clashes can be classified as “hard”, two objects are in the same space, “soft”, one object overlaps the operating or maintenance space of another object, or “time”, two objects are in the same place at the same time.

Coordination and clash detection improvements are included in the key reasons for BIM implementations (Akponeware and Adamu 2017); however, there are few investigations in clash management, apparently due to the mistaken idea that it is a simple and automated process. Few studies explored clash detection considering the process and investigating the root causes of clashes in building information models. Chahrour et al.

(2021) proposed a clash categorisation, considering the change impact and dependency on the stakeholders involved. Tommelein and Gholami (2012) identified the causes for hard and soft clashes, e.g. failing of design rules and design error. Thus, there is still a gap in the formalisation of the clash detection and resolution process, as most investigations focus on software tools instead of the process elements i.e. activity flows, required resources and underlying purposes, to support coordination.

RESEARCH METHOD

The paper presents the initial findings of an ongoing research project through a case study. The case study research method is typically chosen when the (i) type of research question posed is why and how, (ii) the investigator has no control over events, and (iii) there is a high degree of focus on contemporary events (Yin 2003). An empirical case study was carried out with an infrastructure design and consultancy company (company A) based in the UK. This investigation consisted of a critical analysis of the BIM processes at the company from a Lean perspective, aiming to understand how Lean principles and tools can be adopted to enable BIM use. Company A operates in the highways design and construction sector. The company was selected due to their willingness to participate in this research project, and also because it had previously adopted Lean and BIM practices to support design development and management. However, the Lean and BIM integrated implementation within the company was fragmented, lacked co-ordination and was still immature.

The scope of the analysis is restricted to one of highway design project, and thus the generalisability of the conclusions is limited. However, the clash detection and resolution process analysed in this paper was similar to the processes adopted in other projects within the company. The study was conducted in three stages: (i) understanding of the problem and the company's design processes, (ii) development and analysis of the clash detection and resolution process map in collaboration with company stakeholders, and (iii) analysis and reflection on the Lean contributions to the BIM processes. The main sources of evidence were: (i) workshops to refine the highways alignment and to develop the clash detection and resolution process in collaboration with the design and BIM leads (i.e. BIM managers and coordinators), and (ii) analysis of the existing design coordination documents (e.g. clash analysis report, clash resolution action plan, and lessons learned document), and existing process maps (e.g. overall and discipline-specific processes map). The workshops also enabled the discussions regarding improvement opportunities, whilst the document analysis supported the examination and evaluation of the current state and triggered suggestions for future state.

CASE STUDY ON CLASH MANAGEMENT - COMPANY A

DESCRIPTION OF THE CURRENT STATE

The starting point of this investigation was the understanding of the company's design process through three different levels of analysis: (i) overall process map of key design disciplines (level 1), (ii) discipline-specific processes connecting the stakeholders involved, i.e. highways alignment (level 2), and (iii) BIM sub-processes, detailing a process that required more attention, i.e. clash detection and resolution (level 3). Figure 1 shows the complexity associated with the design process and subprocesses. The highways discipline-specific process (level 2) was refined from previous developments and the clash detection and resolution process (level 3) was developed in the framework of this research through the workshops, not existing prior to this study.

The development of a specific highways scheme, which was part of a wider programme of schemes to improve connections in the UK, was used to conduct the clash management investigation through a retrospective analysis with the company staff. The clash management information was simplified for this paper, due to data confidentiality. In this work, clash management, i.e. detection and resolution, is described as an interactive process between the design and the BIM team in order to identify, classify, and resolve conflicts to achieve a minimum number of clashes. Navisworks was one of the main tools used to detect the clashes. A clash was defined by the company as spatial (hard and soft) or functional, following the ISO 19650 (2018) definitions.

The discussions with the company employees through the workshops showed that the teams carried out the clash management through an informal process, with no clear definition of responsibilities and sequence of activities. The key clash detection and resolution activities identified through workshops and document analysis are described as (Figure 1 – Level 3): (1) define and communicate the federation strategy, (2) generate models and prepare the disciplines for federation, (3) prepare the federated model and federate the discipline models, (4) perform clash detection on the federated model, (5) report the clashes and analyse issues detected, (6) publish the federated model, (7) organise and undertake regular design coordination meetings, (8) resolve issues detected by the clash detection, update and share the updated models, (9) update the clash register and issue a report (if required). Activities 2 and 8 were carried out by the design team, whereas the others were mostly related to the BIM team or in the interface between those stakeholders. The project analysis ran about 20 clash detection cycles.

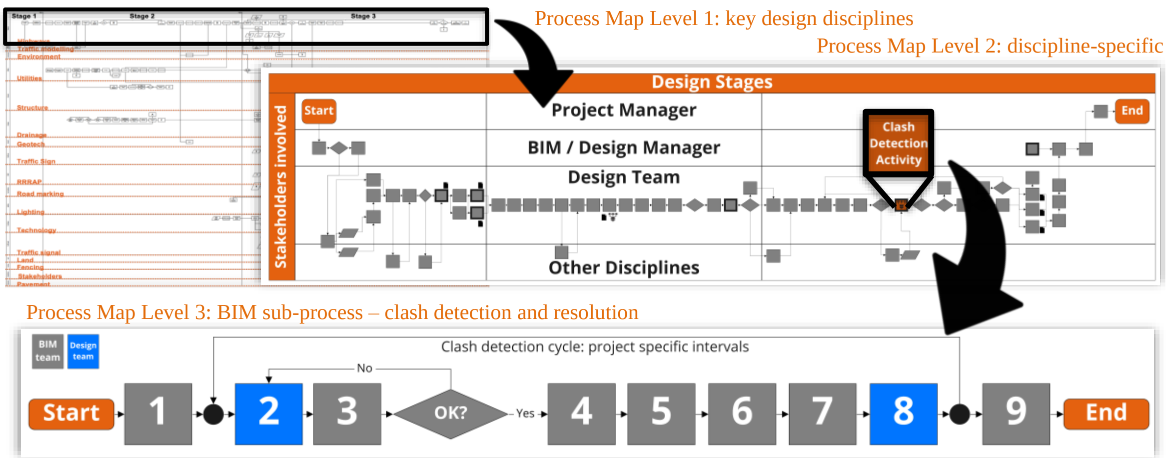

Figure 1: Company design process with different levels. The numbers in the boxes of the Process Map Level 3 refer to the clash detection and resolution activities carried out by the BIM (grey) and design (blue) teams.

The company adopted a silo-based approach to develop the discipline models before any federated model was created and any coordination was performed. The software used to undertake the design was also relatively new, also contributing to a huge inventory of clashes at the beginning of the clash detection process in the detail design stage. Approximately 8500 clashes were detected at the beginning of the process (Figure 2 shows the evolution of the number of clashes in the detail design stage). This approach has similar characteristics as the process of conflict identification in the pre-BIM era, in which drawings (digital or not) were manually compared to each other through an overlap of discipline drawings.

A clear target had been set by the client to achieve a fully clash-resolved BIM model before the submission of target price for the construction works. It resulted in the implementation of a multi-disciplinary management process for the BIM clash resolution. Key conflicts were discussed and resolved during coordination meetings, where the clashes identified in the federated model were displayed on a screen and the visualisation supported the discussion. A clash resolution action plan was also used to support the design coordination meetings (Figure 3). However, an effective record of clash occurrence was rarely developed, making it difficult to learn from the previous experience. Clash resolution action plans were reviewed and updated on a weekly or fortnightly basis and reported back to the client.

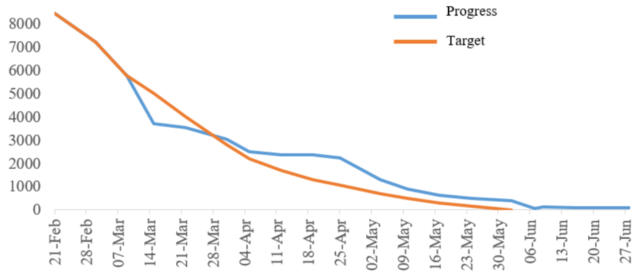

Figure 2: Evolution of the number of clashes.

Weekly or Fortnightly Cycle of Clash Detection (1 - n)											
Date:											
Prerequisites (discipline vs discipline)	Clash status							Clash Owner	Underlying Issue	Actions (current week)	Actions (next week)
	Sum of total	Sum of new	Sum of active	Sum of reviewed	Sum of approved	Sum of resolved (Closed)	Sum of Unresolved (Open)				

Figure 3: Clash resolution action plan.

ANALYSIS AND EVALUATION OF THE CURRENT STATE

The clash management activities were considered by the company as necessary non-value adding activities to coordinate all disciplines and to eliminate model conflicts, or even waste in the design process, especially when the activities relied on manual and time-consuming activities. There is no robust recording of efforts spent on the clash detection and resolution process. Approximately 27 BIM and design team members were involved in the process, including the clash owners (design leads), designers, BIM manager and coordinator, and design manager. However, the company staff pointed out that the workload related to BIM works had been underestimated due to lack of previous experience, and the resource requirement was significantly higher than the estimated.

The use of a federated BIM model enabled effective decision-making to solve conflicts with less rework, mostly due to the ability to visualise a consolidated model. Thus, the BIM process enabled collaborative decision-making among a multi-disciplinary design team. There was also an early involvement of the contractor in the process, including their support in the definition of the construction tolerances for clash detection. The high number of clashes required very close management to gain the client's confidence.

The key root causes for the inventory identified by the BIM leads were associated with (i) expected or intentional clashes, which can be resolved on site with minimal impact (allowable clashes that will support the construction stage) and can be related to the way the design was modelled (type I), (ii) design modelling errors which should be removed prior to construction stage, also related to the way it was modelled and the level of detail required (type II), (iii) minor errors of coordination between different disciplines (type III), and (iv) similar clashes that had not been grouped according to the disciplines at the beginning of the process (type IV). Due to the urgency associated with the design process, no root causes were analysed through a structured approach, even if the company has adopted a clash resolution action plan (Table 1). As a consequence, no actions were taken to prevent issues from recurring through a lessons learned exercise.

A clash-free federated model was required by the client contractually; however, it was labelled by the BIM leads as "unachievable". Construction tolerances were agreed with the construction company, considering 25% of the clashes were deliberately transferred to the construction company in order to communicate and raise awareness about specific conflicts (clash type I), e.g. safety barrier foundations and utilities were intentionally clashed, as a result of the way they were modelled, to inform the contractor of the location and to avoid placing the posts. The high number of clashes did not provide a realistic picture of the design maturity, so instead of reporting the number of clashes in BIM, the team could have reported the number of issues in BIM (e.g., resolving one issue could resolve hundreds of clashes), focusing on the design process and reducing the reliance on software. Also, due to technical issues, there was a need to repeatedly re-approve previously approved clashes following model updates.

SUGGESTIONS FOR THE FUTURE STATE

The clash detection and resolution activities should be performed systematically to maintain the accuracy of information and automate the activities that do not add value. It is fundamental that the company stakeholders understand where process inefficiencies are, so they are able to measure the value of BIM and Lean improvements. The formalisation through the process mapping exercise and analysis of the current process highlighted opportunities for improvements. Identifying improvements has enabled the company stakeholders to be conscious that even a simple activity, such as the definition of the federation strategy, and clash analysis and report, will require protocols for data structuring. The key activities of a clash detection and resolution process and identified improvement opportunities are presented in Figure 4 and Table 1.

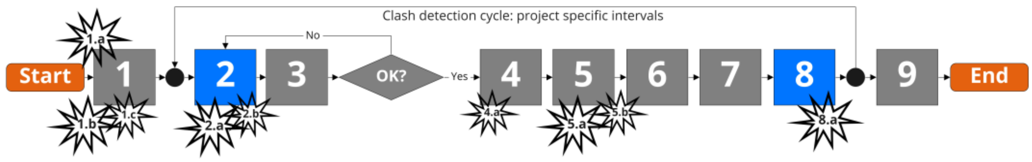

Figure 4: Improvement opportunities identified. The explosions represent the improvement opportunities and are further described in Table 1(second column). The numbers in the blue and grey boxes refer to the same activities as described in Figure 1 and Table 1 (first column).

The improvement opportunities were identified in collaboration with company members through workshops, as well as document analysis. The key improvement opportunities were refined during stage three, through analysis and reflection on the Lean contributions to the BIM processes. The key improvement opportunities are associated with the process itself, the structure and transfer of information, and the standardisation and automation of time-consuming activities. The use of process mapping technique (1.c in Table 1) can support the definition of clash management activities sequence, identifying how the information moves from one stage to another, also defining clash detection and resolution frequency and cycles for each project. It can increase the transparency and process visibility (Klotz et al. 2008).

The early definition of standards of clash detection prerequisites, tolerances, and methods (1.b), e.g. templates and guides, have the potential to support the definition of criteria for clashes, and to define standardised set of rules per clash detection software in early stages, grouping clashes appropriately and avoiding rework. The early identification of client requirements (1.a) can also be achieved through a clear definition in the BIM Execution Plan (BEP) at the start of the project, e.g. providing an early definition of clash detection levels of detail and tolerances required by the client.

Table 1: Key clash detection and resolution activities and potential improvement opportunities.

	Key activities	Potential improvement opportunities
1.	Define and communicate the federation strategy (defined by the BIM execution plan)	**1.a Early identification of client requirements** within a clear definition of the BIM Execution Plan (BEP) at the start of the project. **1.b** Develop **standards**, e.g. templates and guides, to support the definition of clash detection prerequisites, tolerances, and methods. **1.c** Use **process mapping technique** to increase transparency, defining clearly how the information moves from one stage to another, also clearly defining the clash detection and resolution frequency and cycles.
2.	Generate models and prepare disciplines for federation *(design team)*	**2.a One-piece flow** to handle the clashes one-by-one as they are detected. **2.b Mistake proofing** to support BIM models' compliance, consistency and accuracy, avoiding element omission or duplication.
3.	Prepare federated model and federate discipline models	-
4.	Perform clash detection on federated model	**4.a Improved process standardisation** and **automated approach** for manual and repetitive clash detection activities, e.g. grouping or filtering the clashes.
5.	Report the clashes and analyse issues detected	**5.a Flow management and control approach, digital visual management and A3 reporting** can be adopted to improve clash management through automated systems, defining an interactive way to find, report and analyse the clashes and to improve transparency. **5.b Systematic waste analysis** through root cause analysis and clear definition of a clash classification criteria, identifying and reporting issues instead of clashes.
6.	Publish the federated model	-
7.	Organise and undertake regular design coordination meetings	-
8.	Resolve issues detected by clash detection, update and share updated models *(design team)*	**8.a Continuous improvement** to facilitate the exchange of lessons learnt between projects, using **Lean problem-solving techniques.**
9.	Update clash register and issue a report (if required)	-

In this study, the Lean ideal of one-piece flow (2.a) was identified as a potential approach to support the improvement of clash management, as a way to handle the clashes one-by-one as they are detected, avoiding a huge inventory of conflicts and eradicating the clashes as soon as possible. This approach would require the adoption of a federated model in which different disciplines can work on different parts of the model simultaneously without generating clashes, using a common data environment solution, which follows three states (work in progress, shared, and published) to manage the information (British Standards Institution [ISO] 2018). A mistake proofing approach (2.b) can potentially support BIM models compliance, consistency and accuracy through automation during design development, avoiding element duplication or omission, and drawing attention when the issues occur. It can support a clash avoidance process, in which an effort to avoid coordination issues exist during the design process.

There was an over-reliance on the technology for resolving the conflicts and some negligence when it comes to investigating the process itself to improve it. Thus, identify and report issues instead of clashes can potentially encourage people to focus on their design effort and reduce the reliance on software in that regard, in order to avoid clashes in the first place. A further improvement opportunity identified is associated with the occurrence of repetitive manual operations to input data in a clash register and analyse it. It was estimated that 30% of time can be saved through automation and standardisation of clash detection activities (4.a), e.g. automatic grouping of clashes. For instance, systematic generation of information is the anticipated improvement from the automation of the clash register, in which information can be visually displayed and effectively support clash analysis through a greater information transparency (5.a). Actions could be taken by identifying the root cause of the most common issues through a systematic waste analysis (5.b). The use of Lean problem-solving and continuous improvement techniques can facilitate the exchange of lessons learned between projects (8.a).

FINAL CONSIDERATIONS

The formalisation and standardisation of BIM processes can increase the transparency of the process, as described by Klotz et al. (2008), making the improvement opportunities and wastes apparent. Clash detection and resolution is an important and justified process in a Lean project delivery (Tommelein and Gholami 2012). The main improvement areas identified are related to the early identification of requirements for clash managenent, process standardisation, automation of time-consuming activities, information transparency with Visual Management, systematic waste analysis and continuous improvement.

The investigation also emphasised federation strategy as an essential fundament at the beginning of the design process. It should consider (i) the clash detection prerequisites, tolerances, rules, and methods; (ii) frequency of cycles; and (iii) how the resolution of clashes will be carried out, considering the stakeholders, actions, and root causes. The key root causes identified in this exploration represent a first step in the improvement of the existing taxonomies (Chahrour et al. 2021; Tommelein and Gholami 2012). Also, the identification of "intentional clashes" in practice is worth mentioning and calls for further investigation. In addition, it is important to highlight that there is still an excessive trust in technology for resolving the clashes and some disregard in improving the process itself. A lack of process-focus is evident from the study.

The findings indicate that Lean can contribute to BIM processes, beyond BIM capabilities and features (see Figure 5), supporting BIM process improvements. Until BIM and Lean (particularly considering Lean support for BIM) are implemented jointly as a standard practice in the sector, researchers and practitioners are encouraged to disseminate lessons learned and case studies, demonstrating how Lean techniques can improve BIM processes and providing evidence for higher quality outputs. For the Lean community to have a firmer place in the BIM community and discussions, and to be able to claim a mutual synergy between Lean and BIM, the wide range of intervention opportunities in BIM processes from a Lean perspective should be investigated further through a more systematic approach.

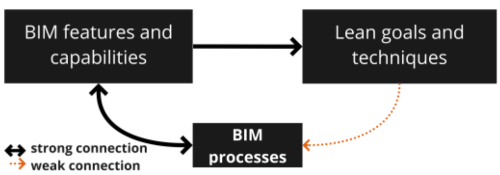

Figure 5: Lean goals and techniques contributions to BIM processes.

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REFERENCES

Akponeware, A. O., and Adamu, Z. A. (2017). "Clash detection or clash avoidance? An investigation into coordination problems in 3D BIM." *Buildings*, 7(3), 1–28.

Bhatla, A., and Leite, F. (2012). "Integration framework of BIM with the Last Planner System." *Proc. 20th Ann. Conf. Int. Group for Lean Construction.*

British Standards Institution (2018). "Organization and digitization of information about buildings and civil engineering works, including Building Information Modelling (BIM) - Information management using building information modelling." *Bs En Iso 19650-1:2018*, 1–46.

Chahrour, R., Hafeez, M. A., Ahmad, A. M., Sulieman, H. I., Dawood, H., Rodriguez-Trejo, S., Kassem, M., Naji, K. K., and Dawood, N. (2021). "Cost-benefit analysis of BIM-enabled design clash detection and resolution." *Constr. Manag. Econ.*, Routledge, 39(1), 55–72.

Dave, B., Koskela, L., Kiviniemi, A., Owen, R., and Tzortzopoulos, P. (2013). *Implementing Lean in construction: Lean construction and BIM*. CIRIA Guide C725.

Eastman,C.,Teicholz,P.,Sacks,R.,and Liston,K(2008).*BIM handbook:A guide to building information modeling for owners, managers, designers, engineers and contractors*.

Hamdi, O., and Leite, F. (2012). "BIM and Lean interactions from the BIM capability maturity model perspective: A case study." *Proc. 20th Ann. Conf. Int. Group for Lean Construction.*

Hartmann, T. (2010). "Detecting Design Conflicts Using Building Information Models : a Comparative Lab Experiment." *Proc. CIB W78 27th Int. Conf.*

Klotz, L., Horman, M., Bi, H. H., and Bechtel, J. (2008). "The impact of process mapping on transparency." *Int. J. Product. Perform. Manag.*, 57(8), 623–636.

Mahalingam, A., Yadav, A. K., and Varaprasad, J. (2015). "Investigating the Role of Lean Practices in Enabling BIM Adoption: Evidence from Two Indian Cases." *J. Constr. Eng. Manag.*, 141(7), 05015006.

Radke, A. M., Wallmark, T., and Tseng, M. M. (2009). "An automated approach for identification and resolution of spatial clashes in building design." *IEEE Int. Conf. on Ind. Eng. and Eng. Manag*.

Sacks, R., Koskela, L., Dave, A., and Owen, R. (2010). "Interaction of Lean and Building Information Modeling in Construction." *J. Constr. Eng. Manag.*, 136(9), 968–980.

Schimanski, C. P., Monizza, G. P., Marcher, C., and Matt, D. T. (2019). "Conceptual foundations for a new lean BIM-based production system in construction." *Proc. 27th Ann. Conf. Int. Group for Lean Construction*.

Tezel, A., and Aziz, Z. (2017). "From conventional to it based visual management: A conceptual discussion for lean construction." *J. Inf. Technol.*, 220–246.

Tommelein, I. D., and Gholami, S. (2012). "Root Causes of Clashes in BIM." *Proc. 20th Ann. Conf. Int. Group for Lean Construction.*

Tzortzopoulos, P., Kagioglou, M., and Koskela, L. (2020). *Lean Construction: Core Concepts and New Frontiers*. Routledge.

Uusitalo, P., Seppänen, O., Lappalainen, E., Peltokorpi, A., and Olivieri, H. (2019). "Applying level of detail in a BIM-based project: An overall process for lean design management." *Buildings*, 9(5), 1–13.

Womack, J. P., Jones, D. T., and Roos, D. (1991). *The machine that changed the world: The story of lean production*. Harper Collins.

Yin, R. K. (2003). *Case Study Research - Design and Methods*. Sage Publications, Inc. United States of America.

Veras de Carvalho, Y. M., Olimpio, L. C. M., Lima, M. G., Lima, M. M. X., and Barros Neto, J. P. (2021). "BIM and Visual Programming Language Supporting Project Constructability." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 126–135, doi.org/10.24928/2021/0199, online at iglc.net.

BIM AND VISUAL PROGRAMMING LANGUAGE SUPPORTING PROJECT CONSTRUCTABILITY

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ABSTRACT

Construction projects need to consider the multiplicity of constructive aspects on its development process via predefined parameters. Constructability is a concept that comprehends these features, and has a direct relationship with time, cost, and quality criteria. However, it is often neglected due the difficulty in measuring its indicators during project design process. Additionally, the indicators measurement is usually laborious, resulting in waste of resources during design stage. Recognizing this scenario, this research proposes a practical tool for designers and integrated with a design software. One of the steps of the model is the identification of project performance indicator's regarding its constructability. Following is the development of a programmable routine, created on Dynamo, used for the data collection from the BIM model. The indicators are updated in real time, granting project constructability evaluation during the modelling process. The alghorithm developed allows users to propose solutions that are almost impossible when using only a modeling software and that would require many operations. Some limitations that were identified are: the developed routines may not support unforeseen variations and since the model was built with a visual programming tool (Dynamo), it may have to undergo some adaptations for correct efficiency in other tools.

KEYWORDS

Constructability, visual programming, product development, lean construction.

INTRODUCTION

The design and execution processes in the construction industry are complex and fragmented (Vrijhoef and Koskela 2005). These two main disciplines are isolated in the traditional construction (Zhang et al. 2016). As a result, the designer makes decisions that

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directly impact on variables not previously covered, such as constructability, durability and client suitability whose consequences are suboptimal solutions and a great number of design and construction rework. (Alarcón and Mardones 1998).

Furthermore, the consideration of the constructive aspects in the design stage delivers significant benefits to cost, time, quality and safety in the quality of the construction process. In this context, emerges the importance of indicators. They are quantifiable representation of these aspects, giving support to the decision-making (Lantelme, 1994).

There are proposals and recommendations to quantify the efficiency of the design stage (Mascaro, 1985). However, evaluating projects in a quantitative way requires effort and time. The construction project simulation in a virtual environment by the combination of Building Information Modeling (BIM) and constructability concepts contributes to accomplish objectives in terms of time, cost and quality (Nascimento et al. 2017).

The use of BIM in the design process facilitates the development of automated verification of real-time model information and trade-offs can be more easily assessed, such as energy, functionality, aesthetics, and constructability through a fast and reliable process of using parameters and spatial relations between elements (Zhang et al. 2016). In this way, it is possible to predict the performance of the construction and assist decision making in the design phase. These processes can be transformed into programmable routines, allowing the evaluation of alternatives and project indicators (Nembrini, Samberger and Labelle, 2014). Currently, computational advancements, both at software and hardware levels, have enabled access to tools that automate the collection and processing of data for design evaluation (Lima, 2016).

Visual Programming Languages (VPL) are formal languages, based on images, defined by graphic objects consisting of nodes and connections (Singer and Borrmann, 2015). The VPLs are easily interpreted and understood because they comprise a visual logical arrangement, without the need of advanced knowledge in a given textual language. In the context of BIM, VPLs have become progressively important in dealing with geometric modelling processes (Kensek, 2015), thus, automating the information collection of a BIM model and the calculation of these indicators.

In the search for understanding constructive factors on contruction, organizations and scholars have discussed its concept. For CIRIA (1983) the constructability would be the dimension in which the design of a building supports the facility of construction, considering requirements of the concluded building. The meaning involves the integration of knowledge and constructive experience during the conception, planning, design and execution phases of the construction, aiming at simplifying the constructive operations through the awareness of the constructive technology to be adopted in the project (Mydin et al., 2011).

The goal of constructability is to improve the efficiency of construction processes by developing designs that consider execution aspects (Hon, Gairns, and Wilson, 1988). It benefits the cost, productivity and quality of the work (Dantas Filho, Angelim, Guedes, Silveira and Barros Neto, 2016). This is achieved by the increase of productivity, reduction of rework, intensive work, and satisfaction of stakeholders hence the constructive rationalization by improving construction process (Anquino and Melhado, 2002).

This procedure can be done by changing attributes in any of the designs, as in a structural design, for instance, which can promote a layout solution that results in less congestion in execution with higher tolerances and lower armour densities (Mydin et al., 2011). The degree of project simplification; the extent of the standardization adopted in the company; the executive sequence and interdependence between activities; accessibility to workspaces; and communication between project and work are some factors that can influence the constructability (Oliveira, Lantelme and Formoso, 1995).

Performance measurement systems are especially important in the construction industry (Bassioni., 2004). The first step starts with the selection of indicators. Indicators may have the role of clarify the performance of an organization, act in the control of a process, set goals, and act on motivating workers (Folan and Browne, 2005). Indicators are widely used in the measurement construction productivity, which is directly related to the constructive aspects of the projects. Being design-based, it is appropriate that the measurement of construction performance be concentrated in the design performances (Pekuri et al., 2011).

Spatial information is required for constructability analysis, where complex computations are obtained with the use of easily extracted data from the BIM model (Khemlani, 2004). Therefore, the BIM model facilitates design tests and activity sequencing to achieve better constructability (Zhang et al., 2016). However, the BIM design tools currently available do not provide model verifications tools. To solve this problem, an application can be developed ont this plataform, providing ease for a designer to validate this model according to the target rules (Zhang et al., 2013).

Model checkers based on automated rules include Revit, Navisworks, Solibri Model Checker (SMC), Express Data Manager (EDM) and FORNAX (Uhm et al., 2015). In these approaches the rules are implemented by software developers as procedural code embedded in the building code verification system (Eastman et al., 2009). The development of checking systems based on VPL is an approach that is being frequently used. Myers (1990), based on a survey of 50 visual programming languages, showed that a more visual style of programming can be easier to understand for non-programmers or novice programmers (Architects and Engineers normally fit into these categories).

In the context of BIM, VPLs have become progressively important to deal with geometric modeling processes, and several authors have researched the use of some type of VPL at some stage of their rule checking process. Ji and Leite (2018) applied VPL for checking crane plans and updating models. Khan et al. (2019) proposed a set of rule based alghoritms to asses excavation safety and generate protections. Ghannad et al (2019) uses VPL to propose a modularized structure for check BIM models compliance. Preidel and Borrmann (2016) introduce the Visual Code Checking Language (VCCL), which uses a graphical notation in order to represent the rules of a code.

This research proposes a tool that uses Visual Programming Language to create routines that extract data to calculate constructability metrics and evaluate building projects before the execution phase.

METHODOLOGY

The development of the project's constructability assessment tool was performed in five stages, presented in Figure 1. The first two stages of the model, that consists in the problem state and the literature review was presented in the introduction of this paper. The next three stages are described in the next sections.

Figure 1: Model Stages

METRICS AND INDICATORS

Starting from a broad search in the literature, a group of indicators which show relation with the principles of constructability were selected. The set of metrics represents the standardization of the project, the simplification of the parties, the interdependence between activities, and ease of access. As the indicators meet more than one of these principles, the categorization was performed by the system they comprise. The next step was the filtering processes, which take into account the projects' capability to use quantitative data that can be automated with the information available and its geometric elements information.

DEVELOPMENT OF ALGORITHM

A frame that allowed the automation of calculations using the model data was developed with the Autodesk® Revit (2020) and its interface with Dynamo (2.3). The choice of Autodesk® Revit was based on the researchers' familiarity and due Dynamo is the most frequent solution for this software. Next, a parametric approach analysis was established. That was done by prioritizing the evaluation of the parameters and information present in the elements of the model.

This approach leaded to a wider analysis since it demands lower computational cost. In order to make the calculation script as simple as possible, its main tasks were to read the model to collect data, then manipulate and use it to calculate the metrics and a compilation process into a worksheet, where the results were graphically displayed.

The final algorithm was implemented in the Dynamo Player, an interface within the Revit that allows the use of scripts without requiring VPL knowledge. This makes the proposed tool accessible to all types of users. It also allows calculations to be performed iteratively with user modifications, which can instantly assess the impact of changes.

APPLICATION OF THE MODEL

The projects that were analyzed have different geometric characteristics, and necessary information for the calculation of the indicators in key families and elements, justifying its selection. The first project (Figure 2) was a residential high standard building of a single tower with two garage floors, 15 typical floors and 1 roof. It has three apartments per floor, with approximately 90 m² each. The second project analyzed (Figure 3) had two towers with 22 floors each and 4 apartments per floor. Only one of the towers was selected, having apartments with 95m².

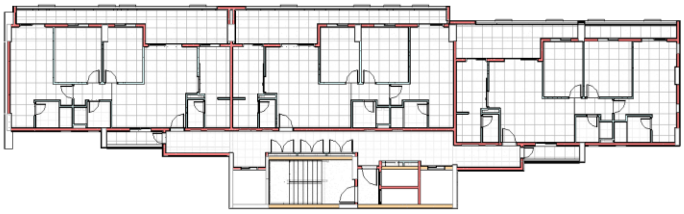

Figure 2: Project 1 Floor Plant

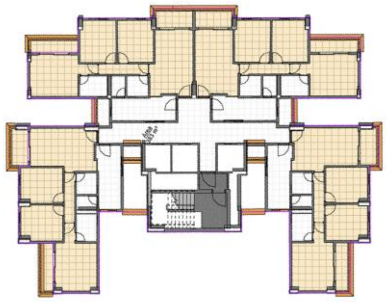

Figure 3: Project 2 Floor Plant

RESULTS

METRICS

The selection of metrics resulted in 11 items that support the measurement of the constructability of the project. These are presented in Table 1.

Table 1: Selected Constructability Metrics

	Name/Reference	Equation		Description
		ARCHITECTURAL		
1	Compactness Index Lantelme (1994) Mascaró (2010)	$CI = 2 * \frac{\sqrt{\pi * Farea}}{Fp}$	$Farea$:*floor area* Fp: *floor perimeter*	It represents the inverse relation of the geometric complexity of the perimeter of the pavement. The further from a square (0.84), the lower the index, and the lower the constructability
2	Wet Area Index Oliveira, Lantelme and Formoso (1995) Narloch (2015)	$WAI = Wa/Farea$	Wa:*wet Area*	Wet areas require more services due to waterproofing, testing and use of ceramics in masonry.
3	Wall Density Oliveira, Lantelme and Formoso (1995)	$WD = Farea/Wha$	Wha: *wall horizontal projection area*	The purpose of this metric is to verify the degree of optimization of the floor subdivisions
4	Facade Index Oliveira, Lantelme and Formoso (1995) Narloch (2015)	$FI = Farea/Fcarea$	$Fcarea$: *Facade area of the typical floor*	The vertical planes of the facades are more difficult and expensive to build. The indicator reveals the proportion of facades in relation to the typical floor plane of the building.
5	Frame Density Oliveira, Lantelme e Formoso (1995)	$DE = Farea/Wvarea$	$Wvarea$: *vertical walls area* $Farea$: *Frames area (doors and windows)*	Windows and doors frames require more services and increase constructive complexity
6	Frame Standard Index Oliveira, Lantelme e Formoso (1995)	$FS = Dfr/Frq$	Dfr: *Dissimilar frames* Frq: *Frames quantity*	The greater diversity of frames affects the complexity of the project, the purchase, the planning and the execution operation.
		STRUCTURAL		
7	Columns Density Index Jarkas (2010)	$CDi = Cpa/Cq$	CPa: *Columns Projection Area* CAQ: *Columns Adjusted Quantity*	Columns restrict movement in the worksite and increase foundation distribution.
8	Beams Density Index Jarkas (2010)	Se $Bl/Farea \leq 0.45$ (1) if not (2) $(1) BDi = Bl/(0.45 * Farea)$ or $(2) BDi = 2 - Bl/(0.45 * Farea)$	Bl: *Beams Length* $Farea$: *Floor Area*	This metric represents the efficiency of the project. The lower this value, the smaller the complexity of shapes and concreting services, also reducing interferences.
9	Columns Standard Index Jarkas (2010)	$CSi = DC/CQ$	DC: *Dissimilar Columns* CQ: *Columns Quantity*	This metric considers the complexity in the individuality of structural types, through the ratio of different pillars in their cross sections and the total number of pillars.
10	Beams Standard Index Jarkas (2010)	$BSi = DB/BQ$	DB: *Dissimilar Beams* BQ: *Beams Quantity*	This metric measures the complexity in the individuality of structural types, through the ratio of quantities of different beams in their cross sections and the total number of beams.
11	Floor Standard Index Jarkas (2010)	$FSi = \frac{DF}{FQ}$	DF: *Dissimilar Floors* FQ: *Floors Quantity*	This metric calculates the complexity in the individuality of structural types, through the relation of quantities of different slabs in their cross sections and the total number of slabs.

SCRIPT STRATEGIES

The structure developed results into a set of scripts (Figure 2), described next:

- *Parameter collection routine:* The node "Categories" is used to select the category of interest, and it feeds the node "All Elements of Category" that collects all the elements of the chosen category. It then source the "GetParameterValueByName" node which also needs the textual specification of the parameter to return a list of its values. This routine collects instance parameters, and if necessary it collects type parameters by the "ElementType" node applied first.
- *Filter script:* From the filtered list, it connects to a check node that returns a list of Booleans, along with the filtered list that feeds the "List.FilterByBoolMask" node which returns two new lists, one for the true and the other for the false tests.
- *Sum and Count Script:* The "Math.Sum" node receives a list of values and returns the cumulative sum. The "List.Count" node counts the number of values in a list.
- *Conditional Script:* The "If" node allows testing by condition, it needs to be fed with a test containing a boolean and the answers for a true and false function.
- *Calculation Script:* the implementation of specific equations through the "Code Block" node. It was used to calculate the indexes fed by the selected parameters.
- *Export Script:* The indexes values feeds the "List Create" node that binds them to a list, which is connected to the "Data.ExportExcel" node. To write the list to an Excel spreadsheet, it is necessary to supply the node with a row and column number, the name of the worksheet, the path of the file on the system, and a Boolean to allow the data to be overwritten. The program also allows to export via .csv file, implemented in the script.

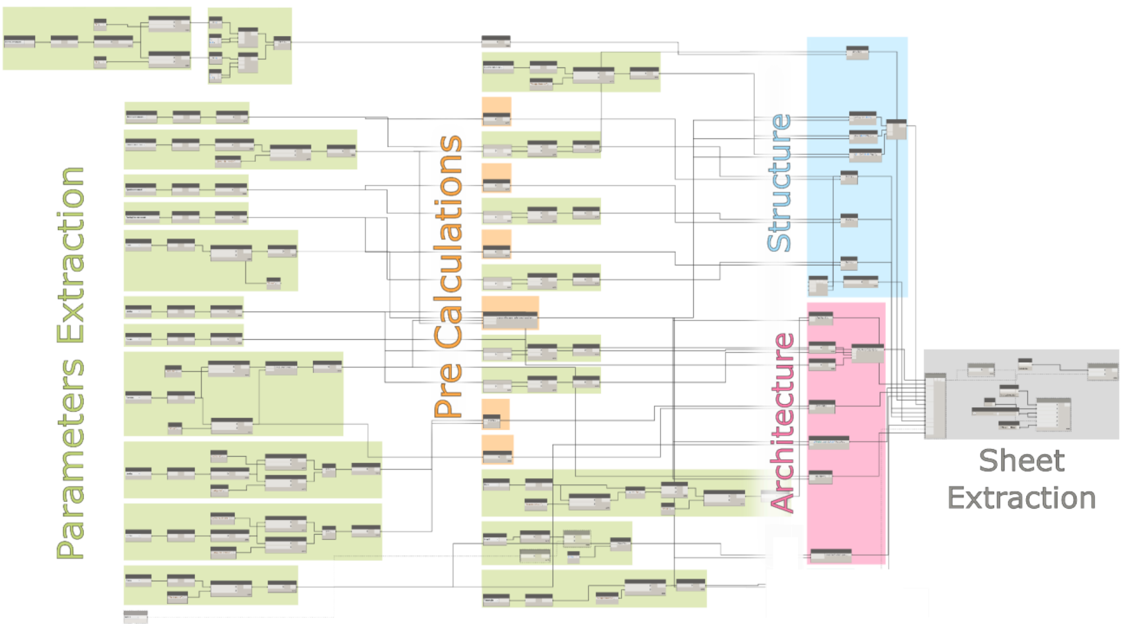

Figure 4: Scripts on Dynamo

APPLICATION

The application of the script presented in Figure 2 in the two projects resulted in the values of the constructability indexes found in Table 2. This table shows the direction in which the optimization takes place in the column named optimization. Then, when the arrow points upwards, it indicates that the higher the indicator for the project, the closer to the ideal this characteristic is. While when pointing downwards, it is closer to the ideal when the value is lower. Although the two projects present similar characteristics like the area, general dimensions and quality standard, the structural and architectural solutions are very particular, which could generate different constructability indicators.

By analyzing the solutions adopted in the design and the calculated metrics, it was possible to evaluate if the results match coherently with the logic of the equations proposed by authors in Table 1. Thus, the functionality of the script and its practicality was verified through automating the collection of information and calculations.

Starting from the first indicator, it was apparent that the first project Compactness Index, despite having a rectangular shape, has a higher value than the second project. This is because the second project has several recesses, obtaining a large perimeter. As presented by Mascaró (2010) both projects are far from the optimal value (0.84) that represents the shape of a square. This may adversely impact the cost and constructability of both projects, but factors such as constructive methods and builder experience should be taken into account.

The index of facades is related to compactness, and comprises the area of external walls on floor area. Thus, the first project has a proportionally smaller perimeter than the second, in turn, has more compartments, increasing the density of vertical planes. Both of these pieces of information were confirmed by a visual analysis of the models.

The wet area index of the first project was higher than the second. This is only due to the greater proportion of balconies in project 1. This index relates to the wet area, which implies services such as waterproofing, wich confered less constructability to project 1.

The indexes related to frames showed very different results. Project 1 has more frames per wall area, which decreases the constructability, but its frames vary less, which increases the constructability, compared to project 2. Therefore, the first project is better suited to the principle of standardization of design, while the second is better at simplifying the parts.

The structure indicators presented a considerable difference between the projects. Project 2 presented symmetry in the vertical direction and the structural solution adopted is more compact than that of project 1, which has no symmetry. In addition, the typology of the slabs of the projects were different: in the first, solid, and ribbed slabs in the second.

Considering the Structure, Project 2 presented good results in the Standard Indexes by having greater symmetry, reducing variations in the sections of the structural elements. The Density Indexes showed that the columns present less dissimilar values than the beams; this is due to the similarity of vertical loading. Project 1 has larger spans, adopting pre-stressed beams, which affected their structural indexes negatively. During the project design phase of Project 2, it could be assumed that the structure constructability was considered more important, while in Project 1 the shape of the building was more influential.

Table 2: Tool application results

N	Index	Optimization	Project 1	Project 2	Difference	%
			Architecture			
1	Compactness	↑	0,55	0,51	0,05	8,4%
2	Wet Area	↑	0,22	0,14	0,08	36,8%
3	Wall Density	↓	0,10	0,12	-0,01	-14,3%
4	Facade Indicator	↓	1,02	1,10	-0,08	-8,1%
5	Frame Density	↓	0,20	0,15	0,05	25,8%
6	Frame Standard	↑	0,26	0,18	0,09	33,3%
			Structure			
7	Columns Density	↓	0,30	0,23	0,07	23,0%
8	Beams Density	↓	0,83	0,54	0,29	35,2%
9	Columns Standard	↓	0,65	0,27	0,37	57,9%
10	Beams Standard	↓	0,29	0,13	0,16	55,5%
11	Floor Standard	↓	0,29	0,15	0,14	47,5%

CONCLUSION

As presented during the proposition, the collection and calculation procedures were performed with low effort, in a short period of time and the programming of the routine occurred in a fluid and fast way, proving the smoothness in its development. This feature allows users to propose solutions that are almost impossible when using only a modeling software and that would require many operations, without the ability to automate such processes. The interface warns of errors in the script, easing its construction, and promoting reliability to the execution.

It is verified that the designers must create the models considering the information necessary for the collection of data, following the standard to be adopted by the script. As an example, the area of wet floor was collected from the parameter of the floor with waterproofing, thus, for the extraction the models must have this information available in this parameter. It is recommended that designers promote the standardization of information allocation in models. Improving the programming, it is possible to develop flexible routines, with intelligent structures that identify in which parameters the desired information was allocated.

For this study, 11 indicators were chosen in scientific researches. These indicators have a relation with constructive aspects, in which the control of them should contribute to the improvement of the construction performance. However, the effects of the project constructability on the construction depend on several variables. It is advised that the designer should use a performance system incorporating this indicator, and promote the monitoring of the effects considering the criteria of the construction company, ensuring reliable results that take into account the specificities of the scenario. If properly validated, the construction company can create its own indicators that could be implemented in a script.

The proposal is shown as an easy-to-use tool for measuring indicators dynamically, assisting designers in project decisions due to the instant updating of values. The adoption of the tool in the construction should promote a necessary approximation between aspects of design and construction, reducing the communication deficiencies of these two disciplines, which generate executions with lower performances in terms of cost, time, quality and rework.

Some limitations were identified during the research. It is noteworthy the fact that the developed routines are governed by the initial definitions, and may not support unforeseen variations. The model was tested with a visual programming tool (Dynamo), and may have to undergo some adaptations for correct efficiency in other tools. Another difficulty is the need to use modeling standards to guarantee conformity in the model data. The possible use of a standardized library, with an object classification system, could be used to overcome this barrier.

Notwithstanding the low control in the literature review, the indicators have practical support and are directly related to the constructability. Additionally, the papers selected from which the indicators were extracted are from researchers with multiple studies applied in the respective area of their indicators. Although, is recognized a possibility of improving and expanding the research to meet other indicators, as well as proposing a general indicator comprising key indicators.

As a future research, it is suggested to measure the effects of the script application during a project, collecting information from the design and construction stages, electrical and plumbing data and understand how its implementation influences the design process.

REFERENCES

Alarcon, L. F. and Mardones, D. A. (1998). "Improving the design-construction interface." *6th Annual Conference of the International Group for Lean Construction*, Guarujá, Brazil, http://www.iglc.net/papers/details/34.

Anquino, J. P. R. and Melhado, S. B. (2002). "The importance of the design for production in the design process management in building construction." *10th Annual Conference of the International Group for Lean Construction*, C. T. Formoso and G. Ballard, eds., Gramado, Brazil, http://www.iglc.net/papers/details/170.

Bassioni, H. A., Price, A. D., and Hassan, T. M. (2004). "Performance measurement in construction." *Journal of management in engineering*, 20(2), 42–50.

Cândido, L. F., Lima, S. H. O., and Barros Neto, J. P. (2016). "Analysis of performance measurement systems in the construction industry" *Ambiente Construído*, 16(2), 189–208.

Dantas Filho, J. B. P., Angelim, B. M., Guedes, J. P., Silveira, S. S., and Barros Neto, J. P. (2016). "Constructability analysis of architecture–structure interface based on bim." *24th Annual Conference of the International Group for Lean Construction*, Boston, Massachusetts, USA, http://www.iglc.net/papers/details/1273.

Eastman, C., min Lee, J., suk Jeong, Y., and kook Lee, J. (2009). "Automatic rule-based checking of building designs."*Automation in Construction*, 18(8), 1011–1033.

Folan, P. and Browne, J. (2005). "A review of performance measurement: Towards performance management." *Computers in industry*, 56(7), 663–680.

Ghannad, P., Lee, Y.-C., Dimyadi, J., and Solihin, W. (2019). "Automated bim data validation integrating open-standard schema with visual programming language."Advanced Engineering Informatics, 40, 14–28

Jarkas, A. M. (2010). "Buildability factors affecting formwork labour productivity of building floors." *Canadian Journal of Civil Engineering*, 37(10), 1383–1394.

Kensek, K. (2015). "Visual programming for building information modeling: energy and shading analysis case studies." *Journal of Green Building*, 10(4), 28–43.

Khan, N., Ali, A. K., Skibniewski, M. J., Lee, D. Y., and Park, C. (2019). "Excavation safety modeling approach using bim and VPL."*Advances in Civil Engineering*, 2019.

Khemlani, L. (2004). "The ifc building model: A look under the hood." *AECbytes feature*, 1–10.

Lantelme, E. M. V. (1994). "Proposal for a system of quality and productivity indicators for civil construction." M.S. thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, http://hdl.handle.net/10183/163597.

Lima, M. M. X. (2016). "Metamodel for multi-performance integration in architectural design." Ph.D. thesis, Universidade Estadual de Campinas, Campinas, Brazil, http://repositorio.unicamp.br/jspui/handle/REPOSIP/305374.

Mascaró, J. L. (1985). *The cost of architectural decisions*. Nobel São Paulo.

Mydin, S. H., Zin, R. M., Abd Majid, M. Z., Zahidi, M., and Memon, A. H. (2011). "Buildability attributes at design phase in malaysian building construction." *International Journal of Sustainable Construction Engineering and Technology*, 2(1).

Narloch, T. B. et al. (2015). "Constructibility indicator model from the geometric analysis of the project." M.S. thesis, Universidade Federal de Santa Catarina, Florianópolis, Brazil, https://repositorio.ufsc.br/xmlui/handle/123456789/156886.

Nembrini, J., Samberger, S., and Labelle, G. (2014). "Parametric scripting for early design performance simulation." *Energy and Buildings*, 68, 786–798.

Oliveira, M., Lantelme, E. M. V., and Formoso, C. T. (1995). "System of quality and productivity indicators for civil construction: User manual." *SEBRAE/RS, Serviço de Apoio as Micro e Pequenas Empresas do Rio Grande do Sul. Porto Alegre*.

Pekuri, A., Haapasalo, H., and Herrala, M. (2011). "Productivity and performance management managerial practices in the construction industry." *International Journal of Performance Measurement*, 1(1), 39–58.

Preidel, C., Daum, S., and Borrmann, A. (2017). "Data retrieval from building information models based on visual programming." *Visualization in Engineering*, 5(1), 1–14.

Research, C. I. and Association, I. (1983). *CIRIA special publication*. CIRIA.

Singer, D., Borrmann, A., and Center, L. O. (2015). "A novel knowledge-based engineering approach for infrastructure design." *The Fourth International Conference on Soft Computing Technology in Civil, Structural and Environmental Engineering, Prague, Czech Republic*, Citeseer.

Solihin, W. (2004). "Lessons learned from experience of codechecking implementation". *BuildingSMART Conference*, Singapore, https://www.researchgate.net/publication/280599027_Lessons_learned_from_experience_of_code-checking_implementation_in_Singapore.

Uhm, M., Lee, G., Park, Y., Kim, S., Jung, J., and kook Lee, J. (2015). "Requirements for computational rule checking of requests for proposals (rfps) for building designs in south korea."Advanced Engineering Informatics, 29(3), 602–615.

Vrijhoef, R. and Koskela, L. (2005). "A critical review of construction as a project-based industry: identifying paths towards a project-independent approach to construction". *Proceedings CIB Combining Forces. June, Helsinki. Forthcoming*, 13–24.

Zhang, S., Teizer, J., Lee, J.-K., Eastman, C. M., and Venugopal, M. (2013). "Building information modeling (bim) and safety: Automatic safety checking of construction models and schedules."Automation in Construction, 29, 183–195.

Zhang, C., Zayed, T., Hijazi, W., Alkass, S., et al. (2016). "Quantitative assessment of building constructability using bim and 4d simulation." *Open journal of civil engineering*, 6(03), 442.

Chuquín, F., Chuquín, C., and Saire, R. (2021). "Lean and BIM Interaction in a High Rise Building." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 136–144, doi.org/10.24928/2021/0208, online at iglc.net.

LEAN AND BIM INTERACTION IN A HIGH RISE BUILDING

Frank Chuquín[1], Cristhian Chuquín[2], and Romina Saire[3]

ABSTRACT

Lean Design has been spreading its use in the AEC industry along with the emergence of Building Information Modelling (BIM).Those two methodologies; Lean and BIM are being implemented first independently and then together. as new means to deliver more efficient projects.

This paper researches some tools of Lean and BIM that permit a positive interaction by focusing on a case study related to a high rise building for residential use. Those tools are; from Lean Construction, set based design and value stream mapping. From BIM were used a 3D model and Integrated Concurrent Engineering (ICE) sessions. Also, the paper describes the interaction between those tools in the design phase and its impact in the construction stage.

KEYWORDS

Lean design, BIM, set based design, value stream, ice session.

INTRODUCTION

The construction industry in general is categorized as low productivity and riddled with inefficiencies. The construction sector is seen as one of the industries in which it uses intensive labor resources that open the doors to innovation and the implementation of new methodologies. According to Ghio V.(2000) in Lima the productivity levels were 27.9% of productive work, 36.3% of contributory work and 35.9% of non-contributory work. Later, in 2005 Morales N. and Galeas J. (2006) found this number slightly different: 30.4% of productive works, 44.2% of contributory works and 25.4% of non-contributory works. Then, the emergence of Lean Construction and Building Information Modeling as two innovative methodologies to address issues (productivity, inefficiencies) was gaining more adopters in the AEC industry on a global scale.

Lean concepts have been applied in the construction arena since the early 90s. Lean Construction is a new manner to deliver projects and a different manner of management. According to Koskela (2000), Lean Construction is "a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value". In Peru, Lean 'Construction was implemented first in the

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operation phase by using Last Planner® System (LPS), but little by little the Peruvian AEC community started implementing Lean Project Delivery System (LPDS) and in particular Lean Design through the use of different tools such as set based design, target value design and value stream mapping in the design phase.

In Peru, BIM started its implementation in 2010 and according to Murguia (2017) it was found that 24.5% of Peruvian projects implement BIM. Nevertheless, it is useful to keep in mind that not only technology is the necessary element in order to reach a successful implementation, but also processes, organizations and people. Also, Eastman et al.(2008) points out that BIM impacts the role and process of design in three different manners: the way conceptual design can be performed, the use of BIM for design and analysis of building systems and finally its use in developing construction-level information. In particular, the use of 3D models as a manner to influence conceptual design is also a way to improve visualization between different stakeholders.

Each of one, Lean Design and Building Information Modeling can be implemented independently as it was at the outset of using one of them. Sacks et al.(2010) states that Lean is “a conceptual approach to project and construction management and BIM is a transformative innovation technology”. Nevertheless, the synergy that can be created by implementing both of them in the same project has been analyzed in different researches. Zhang et al.(2017) states that the interaction of BIM with Lean Design establishes better communication in the work team. Consequently the quality of coordination and efficiency in project design is increased. . Moreover, based on a study of the interaction between Lean Design and BIM in 64 projects, Herrera et al.(2021) concluded that the tool with the most interaction and positive impact on Lean design processes is the BIM tool "Integrated concurrent session".

LITERATURE REVIEW

LEAN CONSTRUCTION

It is a methodology based on the application of the principles of the Toyota production systems as it was stated by Sacks et al. (2010). Lean looks for the reduction of waste and variability while increasing value to the customer linked to a continuous improvement in each process. But nothing all the above can be reached if there is a lack of commitment and accountability. Moreover, Lean construction put at the center the respect for people which for Seed et al. (2018) play a pivotal role in the implementation of Lean Construction.

LEAN DESIGN

It is part of the Lean Project Delivery System (LPDS) which comprises five stages. Lean Design comes after project definition and before lean supply, lean assembly and use. Lean design comprises three processes: design concepts, process design and product design. LPDS aims to create a strong relationship between the roles of designers and builders.

SET BASED DESIGN

It is a tool of Lean Design in which the objective is to generate sets, different alternatives or solutions in order to evaluate them and to choose the most optimal according to the conditions of satisfaction or criteria. According to Hill et al. (2016) multiple options must be explored with the aim to choose an informed decision at the right time considering the last responsible moment. Each set of alternatives must be investigated and it is imperative to collect important information in order to support a decision.

VALUE STREAM MAPPING

This tool permits to map the generation of value, waste and countermeasures when it is analyzed in a particular process. According to Seed et al.(2018) "a value stream mapping includes both material and information flows, decision points, handoffs and interaction between systems". This tool encourages teams to evaluate the entire value stream by evaluating the value of each step and optimize the entire process through value stream mapping. This tool gives the opportunity of understanding the actual state of the process, this requires the input of all participants in the process.

BUILDING INFORMATION MODELLING (BIM)

According to the National Building information Modeling Standard (NBIMS), BIM is "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle". Moreover, Eastman et al. (2008) defines BIM as "a modelling technology and associated set of processes to produce, communicate, and analyze building models". Those building models (digital representation through parametric objects) are composed by components that contain data in a consistent, non redundant,and coordinated manner.

INTEGRATED CONCURRENT SESSION (ICE)

Eastman et al. (2008) pointed out that ICE session is a collaborative work that involves different stakeholders such as: design team, engineering-technical specialists and consultants. The same authors states that ICE is "a special integration event consisting of three elements: product and project performance metrics, BIM + simulation, and process design. It is a problem-solving technique that looks for speeding up solutions considering different points of view.This design reviews are set in an I-room where stakeholders discuss aspects of the design on large screens. Moreover, by including ICE sessions in the design schedule when important decisions are made, it is possible to accelerate the evaluation of different alternatives.

PROBLEM

It is unknown to what extent those interactions between Lean principles and BIM functionalities create relevant positive or negative interactions that can be clearly understandable in terms of benefits and cost for practitioners in the AEC industry. According to Sacks et al.(2010) there are 56 interactions between Lean principles and BIM functionalities that could be analyzed in detail.

HYPOTHESIS

Four Lean and BIM tools (set based design, value stream mapping, a 3D model, and integrated concurrent sessions) were implemented with the hypothesis that these tools would provide a positive interaction since they would address problems earlier and facilitate the reduction of restrictions (i.e. less requests for information and fewer claims) in the construction phase.

METHODOLOGY

The approach of this research is divided in two stages: design and construction. **Figure 1** shows the steps and components in each stage. In the design process it is planned to implement four tools: value stream mapping, set based design, 3D model and ICE sessions. Then, training is necessary for those stakeholders who are unfamiliar with these tools.

At the end of the design process a qualitative analysis is done through surveys to the stakeholders involved. Also, a quantitative analysis about the results reached with the four tools at the design stage is made, each interaction is analyzed. There were two interactions analyzed: a) value stream mapping and ICE sessions and b) set based design and 3D model.

In the construction stage, two types of information are collected: requests of information and claims. That information is categorized and the ones which are linked to design is described in detail and a quantitative analysis is made using two metrics: a) number of RFI (related to design and b) claims (related to design).

The research period took from the design phase until the handover of the infrastructure to the final client. Then, the exact time frame for the design phase was 6 months and 12 months for the construction phase, so we data collection took 18 months.

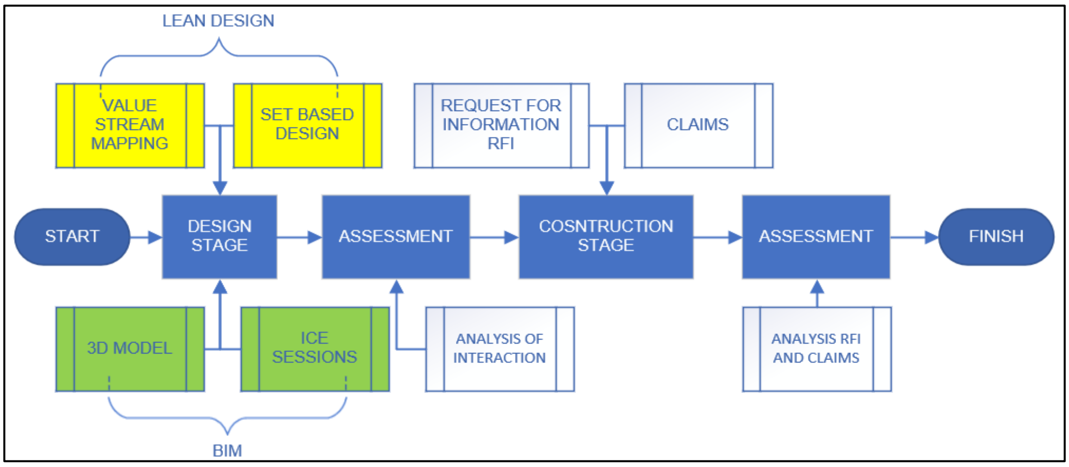

Figure 1: methodology implemented

RESULTS

1. VSM and ICE Sessions

The involvement of each of the participants (architect, structural engineer, electrical engineer and plumbing engineer) were relevant for the construction of the entire value stream mapping.. It is important to highlight that as part of the flow process it was incorporated ICE sessions as part of the mapping.

The VSM permits to analyze each step in the flow. One result was that stakeholders paid close attention to one section of the entire VSM. This section is the one that shows more interaction between architects and structural engineers at the beginning of the design process. **Figure 2** shows this interaction. In this first section, it is important to get the preliminary design in accordance with the pre dimensioning of different structural elements. It must be highlighted how the work of each other interacts and how they are involved in an ICE session. Different aspects are addressed in this ICE session such as:

height of the beams, thickness of the slabs as well as lengths and thickness of shear walls and columns. This stage finalizes with the approval of the preliminary design (predimenionsing) and an architecture update.

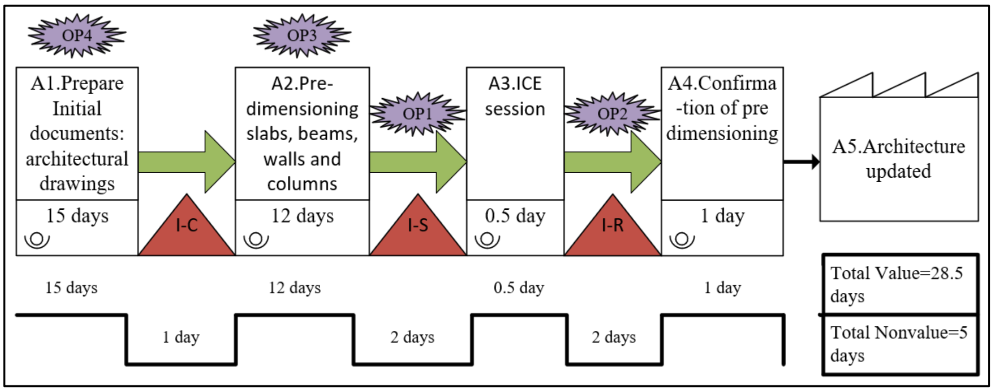

Figure 2: Actual VSM-section 1.

In this first section, the total time of value activities is 28.5 days and the total time of non value activities is 5 days. Four opportunities for improvement were detected. OP1: 2 business days takes to arrange an ICE session. OP2: the proposal from the structural engineer about pre-dimensioning is assessed by the architect in 2 business days. OP3: pre dimensioning takes 12 business days by structural engineer. OP4: architect takes 15 business days in preparing preliminary architectural designs and to have ready the geotechnical study.

Once the actual state is graphed in **Figure 2** and stakeholders understand the value chains. A realistic and future scenario is discussed and **Figure 3** shows the corresponding value stream mapping of the analyzed section.

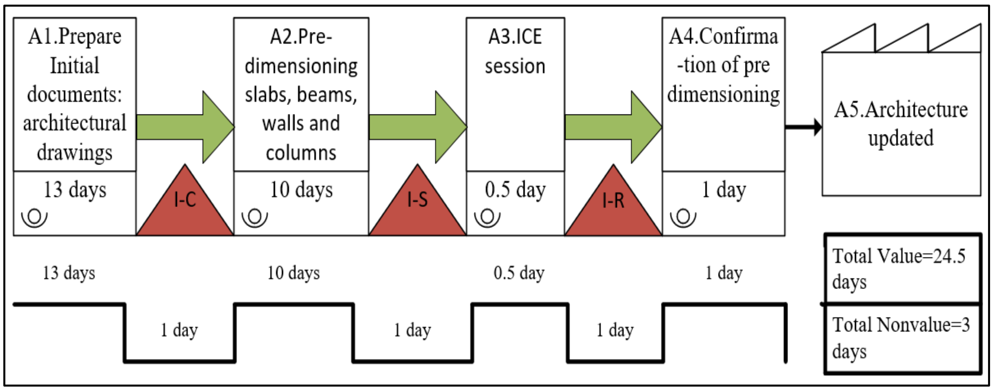

Figure 3: New and committed VSM-Section 1.

The design team was committed to this new value stream mapping (**Figure 3**) and they finally met the times. In this VSM, the total value time of the value activities is 24.5 days, which means a 14% reduction compared to the former VSM (**Figure 2**). The reduction in duration of activity 1 (A1) and activity 2 (A2) was the cause of that time saving. Moreover, the total time of non value activities is 3 days, which means a reduction of 40% compared to the former VSM.

There was a second section of the VSM that was analyzed in an ICE session. This second section starts with the updated architecture (the output in section 1) which triggers the following structural design processes: slab design, seismic analysis, beams design, shear wall design, columns design and foundation design. In this flow process an ICE session is scheduled. This section deals with issues such as: clash detection and value engineering.

At the end of the design process a survey was done to those stakeholders involved in the implementation of these two tools (VSM and ICE), 70% of participants mentioned that those tools were useful for their work and they are keen on applying them in future projects. Also, 90% of people pointed out that training was the most critical factor for success.

2.SET BASED DESIGN AND 3D MODEL

As part of the implementation of lean design tools, set based design was used. There were three different alternatives for the foundation of the building. This happened because adequate bearing capacity of the soil is reached at a great depth. The alternatives were:

Option 1: It is to use a mixture of simple spread footing with strap footing with the disadvantage that the length of the vertical elements (columns and shear walls) have to increase in order to make it possible for footings to reach the ground with enough bearing capacity.

Option 2: It is to implement micro piles as foundation in order to reach the appropriate soil with enough bearing capacity.

Option 3: it is to include a semi-basement floor. By adding a floor the level of the last basement is lowered. This inclusion decreases the length of columns and shear walls. Then, the foundation is located in a soil with appropriate bearing capacity.

A 3D model (**Figure 4**) helps stakeholders to deeply understand the implications of each alternative.

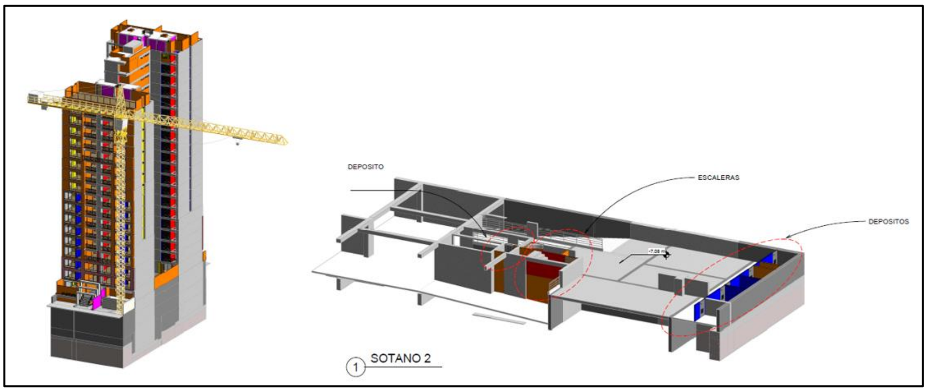

Figure 4: 3d model (left) and lower basement (right)

Those three alternatives were analyzed in terms of costs, benefits and duration (time of execution). **Table 1** shows the different options and the criteria taken into account for the selection one.

Table 1: Comparison between different options

Category	Option 1	Option 2	Option 3
Cost $	53,731	41,791	150,775
Benefits $	0	0	104,000
Net Cost	-53,731	-41,791	-46,775
Duration (days)	14	21	21

Finally, the stakeholders involved found that the third alternative could give an advantage over the others. This is because, in this option, there is the opportunity to generate two new apartments for selling (the row of benefits in the table 1). Then, the third option was selected because it gives a net cost better than option 1, which means a 12.9% reduction in cost. Even though option 3 costs 10.7% more than option 2, this opportunity to have more area to sell (two new apartments) outweigh option 2 from the business point of view of the decision makers.

At the end of the design process a survey was done to those stakeholders involved in the implementation of these two tools (SBD and 3D model BIM), 50% of participants mentioned that those tools were useful for their work and they are keen on applying them in future projects. Also, 100% of people pointed out that training and technology were the most critical factor for success.

3. Request for Information at Construction Phase

Once the design had finished, the construction phase started and during this period some requests for information (RFI) were generated by the contractor for different circumstances and moments. Then, those RFI were collected and analyzed. Four types of categories were considered: scope change, queries, design issues, and clashes.The description of each one is:

Scope changes: An instruction from the owner about changes in the scope generates doubts in the contractor. Then, an RFI was issued for details.

Queries: The contractor issued an RFI because it needed clarification or it was difficult to understand the specification by any member of the contractor´s team.

Design issues: An error in the design and/or specifications was found by the contractor and a RFI was issued in order to solve the problem.

Clashes: The designs of different specialities showed inconsistencies and incompatibilities. Then, an RFI was issued.

The following **Table 2** shows the quantity and percentage for each category of RFI for the case presented in this paper (project 1) and historical data from a previous project (project 2).

Table 2: RFI by category for project 1 and project 2

	Project 1 (Lean and BIM interaction)		**Project 2 (withouth Lean and BIM implementation)**	
Category	**Quantity**	**Percentage**	**Quantity**	**Percentage**
Scope change	47	27%	52	23%
Queries	56	32%	62	27%
Design issues	17	10%	32	14%
Clashes	54	31%	81	36%
Total	**174**	**100%**	**227**	**100%**

As it is shown in table 2, there are 174 RFI in total in project 1 which means 23.3% of reduction from project 2 . The ones that are design related are the categories: design issues and clashes that represent 10% and 31% respectively in project 1. Those two categories sum up 71 RFI in total which represents 37.1% of reduction from project 2.

An analysis of the claims presented by the contractor in this case study (project 1) was made. **Table 3** shows quantities and costs of those claims.

Table 3: Claims by category for project 1.

Category	Claims Quantity	Claims Percentage	Claims Cost $	Claims Cost Percentage
Scope change	20	22%	26.124	295
Queries	22	50%	15.386	17%
Design issues	45	24%	47.982	53%
Clashes	3	3%	1.186	1%
TOTAL	**90**	**100%**	**90.679**	**100%**

As it is shown in table 3, there are 90 claims in total in the case study (project 1). The ones that are design related are the categories: design issues and clashes that represent 24% and 3% respectively. Those two categories sum up 48 claims. Nevertheless, in terms of cost those two categories represent 54% of the total claims cost.

DISCUSSION

The results show a positive interaction between those four tools implemented in the design stage. Participants found useful tools such as VSM and Ice sessions because they had the opportunity to see the changes that occurred in the design process by reducing the total time of value and non value activities.

In the case of SBD and a 3D model there are less people interested in replicating the experience. A plausible explanation is related to the demand for knowledge in technology that is necessary in this interaction and the resistance to change by senior engineers with more than 20 years of experience in the industry. The design teams had 60% of participants with a seniority level.

A critical factor pointed by participants in the survey at the end of the design stage was training and technology. Workshops were done not only for staff personnel, but also for engineers of other companies (structural, electrical and plumbing engineer) that integrated the design team.

About the results at the end of the construction stage, they show a reduction in the number of RFI in the case study compared to project 2, which follows a traditional approach (without lean and bim). Even though this reduction is 37.1%, it is still not significant. On top of that, the total cost of claims associated with design represents 54% of the total cost. An explanation of those results at the end of the construction stage could be the fact that the company is starting with the implementation of lean and bim tools in their projects and it is expected to gain more experience applying the tools in next projects.

CONCLUSIONS

The Lean and BIM tools used in the design stage support the interaction found by Sacks et al. (2010). In particular all four tools (VSM, SBD, 3D model and ICE session) demonstrate the existence of the positive interaction between the lean principle: "decide by consensus, consider all options" and the BIM functionality "visualization of form". Nevertheless, the findings in this case study suggest another new interaction between the lean principle "focus on concept selection" with the BIM functionality "visualization of form". This interaction is not registered in the matrix shown by Sacks et al. (2010). In this new positive interaction, set based design and a 3D model plays a pivotal role because a better understanding of different design alternatives early in the design phase can be reached if a model is shown to the decision makers.

Also, a change management strategy is necessary for getting better results. This strategy must include training sessions for the design team. This is because training is a critical factor for design improvement and for maintaining changes in the organization.

As a limitation of the paper, it will be necessary to collect more data from case studies in order to enrich the knowledge in this area.

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REFERENCES

Eastman, C., Teicholz, P., Sack, R. and Liston, K.(2008). "BIM Handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors". John Wiley & Sons, Inc. New Jersey.

Ghio, V.(2000). "Productividad en obras de construcción: Diagnóstico, crítica y propuesta". Fondo Editorial de la Pontificia Universidad Católica del Perú. Lima, Perú.

Hill, K., Copeland, K., Pikel, C. (2016). "Target Value Delivering: Practitioner guidebook to implementation", Lean Construction Institute, Virginia, USA.

Koskela, L. (2000). "An exploration towards a production theory and its application to construction". D. Tech. Helsinki University of Technology. Espoo.

Morales, N. and Galeas J.(2006). "Diagnóstico y evaluación de la relación entre el grado de industrialización y los sistemas de gestión con el nivel de productividad en obras de construcción". Pontificia Universidad Católica del Perú, Lima, Perú.

Murguía, D. (2017). "Estudio de adopción BIM en Lima-Perú". Pontificia Universidad Católica del Perú, Lima. Perú.

Herrera, R., Mourgues, C., Alarcon L. and Pellicer, E. (2021) "Analyzing the Association between Lean Design Management Practices and BIM Uses in the Design of Construction Projects", Journal of Construction engineering and Management. ASCE

Sacks, R., Koskela, L., Dave, B. and Owen, R.(2010). "Interaction of Lean and Building Information Modeling in Construction", Journal of Construction Engineering and Management. Vol. 136, No 9, September 1, 2010.

Seed, W. et al. (2018). "Transforming Design and Construction: A Framework for Change", Lean Construction Institute, Virginia, USA.

Zhang X., Azhar S., Nadeem A. & Khalfan M. (2017). "Using Building Information Modelling to achieve Lean principles by improving efficiency of work teams", International Journal of Construction Management. Vol. 33, No 6, 740-752.

LEAN THEORY

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Fang, Y. and Daniel, E.I. (2021). "Defining Lean Construction Capability from an Ambidextrous Perspective." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 147–156, doi.org/10.24928/2021/0105, online at iglc.net.

DEFINING LEAN CONSTRUCTION CAPABILITY FROM AN AMBIDEXTROUS PERSPECTIVE

Yanqing Fang[1] and Emmanuel Itodo Daniel[2]

ABSTRACT

Lean construction (LC) is widely used to eliminate waste in the construction industry. However, research on LC capability is lagging relative to other works in the LC field. By exploring relevant literature on the rigid and flexible characteristics of LC, this study proposes for the first time that LC capability is an ambidextrous capability from a paradoxical lens. The investigation reveals that the concept of LC capability has no clear definition and puts forward the view that LC capability is an ambidextrous capability. The study established that LC ambidextrous capability is a paradox which consist of two dimensions—namely LC exploitative capability and LC exploratory capability. LC ambidextrous capability emphasizes striving for a balance between the two capabilities. This study contributes to current knowledge and future application of organizational ambidexterity theory to LC capability development. Regarding contribution to practice, this research would enable LC project practitioners to understand the paradoxical tensions in LC projects, and to how to deal with them. Additionally, this study brings new insight and opens a new debate on how LC ambidextrous capability could develop in the construction field.

KEYWORDS

Lean construction, ambidextrous capability, paradox, exploitation, exploration.

INTRODUCTION

The construction industry is thought to be riddled with waste and loss of value (Formoso et al., 2015). The concept of lean construction (LC), which was proposed on the basis of lean production theory, is widely used to reduce construction waste (Koskela, 1992). The lean approach is implemented to achieve the rigid targets of projects, such as schedule, quality and cost (Ballard, 1999). In this study, the rigid features of LC refer to the strict requirements for cost reduction, inventory reduction and on-time product delivery that stem from project constraints. Subsequently, several methods and tools have been used to support LC. Just in time (JIT) is a representative tool of lean management, and it reflects the rigidity of the lean approach's requirements on time points and strict requirements on inventory (Liker, 2004). However, the flexibility of LC, which is defined

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in this study as the characteristics to adjust and adapt to the changing environment, has not received equal attention. With construction projects becoming larger and more complex and the construction environment becoming more dynamic and uncertain, increasing attention has been paid to the adaptive capability or positive response of a project to uncertainty (Ballard & Tommelein, 2012). From the perspective of complex systems, some variability may be beneficial to the survival of a system (Saurin & Rooke, 2020), which also reflects LC's adaptation or response to the complex environment. For instance, buffers are designed in a project to prevent the impact of variability and resource starvation (Hopp & Spearman, 1996). Flexible capability strategies can sometimes be the most valid means to cope with construction variability and contribute to project performance by providing sufficient capability to protect resources from excessive consumption (Horman, 2001). However, the impact of LC capability on project performance is also worthy of further study.

Some studies have shown the rigid and flexible features in LC (Owen et al., 2006). However, these achievements cannot fully explain the whole nature of LC capability. Rigidity and flexibility—a pair of contradictory and symbiotic characteristics of LC—are termed 'LC ambidexterity' in this study. For a better appreciation and understanding of the application of lean in project organisation, lean capability should be viewed as ambidexterity from a paradoxical lens. This view brings in new insight on how to holistically view the impact of LC methodologies in project organisation.

Thus, this research aims to explore the ambidextrous characteristics of LC capability. The following questions are addressed: What is the current understanding of the two characteristics of LC? Are there underlying theories that could explain the relationship between these two characteristics? Can a better understanding of LC ambidextrous capability benefit their application in construction?

The method used in this investigation is a critical literature review. The structure of this paper is as follows. Firstly, a description of the rigidity and flexibility of LC and the understanding of the relationship between the two characteristics in the existing literature is provided, and the standpoint of the LC characteristics in this study is clarified. Secondly, an explanation is given for the theoretical foundation of the viewpoints put forward in this study, and the concept of LC ambidextrous capability is defined. Next, the different applications of LC ambidextrous capability in construction are discussed, and factors that promote the balanced development of LC ambidextrous capability are explained. The paper ends with conclusions and contribution.

CURRENT UNDERSTANDING OF THE RIGIDITY AND FLEXIBILITY OF LEAN CONSTRUCTION

In the field of manufacturing, discussions have emerged about some ambidextrous elements in lean and its antecedents. For example, Toyota's lean manufacturing system is an example of a 'coordination capability' to achieve a high level of alignment between its production resources or design elements (Fujimoto, 2014). The tension between rational planning and evolutionary adaptation were also emphasised by Fujimoto (2007). The famous Deming Circle contains two attitudes towards variability. Reduce variability through continuous improvement, and cope with variability through continuously improving technology. According to Deming, it is not enough to aim at customer satisfaction on the production line. Rather, it is necessary to go beyond short-term goals, keep learning and take service improvement as the permanent goal (Deming, 1982).

In the LC field, these two characteristics of LC stem from the main understandings regarding variability in current literature. Variability is very common in construction projects and should be managed effectively (Thomas et al., 2002). It is defined as 'the fact or quality of being variable in some respect; tendency towards, capacity for, variation or change' (Oxford English Dictionary, 2020).

One mainstream view is that all variability should be reduced or eliminated. Based on statistical quality theory and queuing theory, efforts should be made to reduce the variability in significant product characteristics and the temporary variability of production flow (Sacks et al., 2009). There are many discussions on reducing variability. Koskela (2000) proposed that reducing variability within flow processes should be an intrinsic goal. The LPS™ and the location-based management system are designed to decrease waste, increase productivity and shield construction activities from variability (Seppänen et al., 2010).

Another mainstream view is that not all variabilities should be eliminated. For example, people want buildings to look different (Tommelein, 2015), which requires the system to have the flexibility to adapt to different needs. For another example, the mismatches between supply and demand leads to variability, which is sometimes offset by a combination of buffers (Hamzeh, 2007). Proper buffering can make the project more JIT (Tommelein & Weissenberger, 1999). In this case, variability leads to more flexible solutions to changing circumstances, which is more conducive to the survival and development of the system.

The two different understandings of variability lead to the rigid and flexible treatment of variability presented in this study. The implication of this treatment is that the concept of LC capability should not only focus on achieving the rigid target alone but should also factor in the flexible characteristics equally because both contribute to the successful delivery of the project. Although the views of Fujimoto and Deming included the elements of the two characteristics of LC, the weakness of their theoretical foundation has led to a lack of attention to the equal treatment of the two characteristics. This research aims to introduce ambidexterity theory into the LC field and provide a theoretical explanation for the two characteristics of LC.

THEORETICAL EXPLANATION

PARADOXICAL THINKING

According to Smith and Lewis (2011, p. 86), a paradox is defined as a series of 'contradictory yet interrelated elements that exist simultaneously and persist over time'. These elements contain potential tensions and react to embrace these tensions simultaneously (Smith & Lewis, 2011). Dilemma and paradox are sometimes interchanged in conventional use, but there is an important difference between the two concepts. In a dilemma, choices are made after weighing the pros and cons, while the significance of paradox is that such a choice should not be made. The value obtained from paradoxical thinking comes from this duality (Storey & Salaman, 2009). Paradoxical tensions may exist in various forms at different levels; they may be unique at each level, or a paradox exists simultaneously at all levels, or the tension of paradoxes nested and concatenated at one level gives rise to new tensions at another (Smith & Lewis, 2011).

Lean projects are temporary production systems designed to maximise value and minimise waste while delivering products (Ballard & Howell, 2003). Still, some paradoxes remain in LC projects and might be reinforced by lean. For example, one paradox is JIT and buffers. Zero inventory is an ideal state. From the raw material to the delivery of the final product to the customer, interruptions will inevitably occur. Therefore, there must be some necessary inventory or buffer (Liker, 2004). A small inventory buffer may be suitable for construction to keep up with installation, but preparing a large buffer comes at a cost. Proper buffering can make the project more JIT (Tommelein & Weissenberger, 1999). Should we eliminate all buffers? JIT seems to reinforce paradoxical tensions. Another paradox that may be stressed by the lean approach is the paradoxical tension of standard operating procedures versus customised crafted solutions (Eaton et al., 2015). Lean thinking emphasises standardised work. Projects require rigorous standardised procedures to provide repeatable solutions, but when innovative or unexpected project tasks arise, customised crafted solutions are urgently needed, which may result in the dysfunction of standardisation policies (Eaton et al., 2015).

As a paradox is an intrinsic characteristic and dynamic factor of organisations, we need paradoxical thinking to manage paradoxical tensions. Managing paradox does not mean eliminating the paradox but rather tapping its incentive potential. Creatively capturing the two extremes, such as innovation and efficiency, is considered an effective means to manage paradox (Eisenhardt, 2000).

ORGANISATIONAL AMBIDEXTERITY THEORY

The concept of ambidexterity was first proposed by Duncan in 1976. It was argued that the management of the 'dual structure' is the core of the ambidexterity concept (Birkinshaw & Gibson, 2004). Although no unified definition of ambidextrous capability exists, at the organisational level, ambidexterity is generally considered to be a pair of contradictory and symbiotic paradoxical capabilities for organisations to perform different and often competing strategic actions at the same time (Simsek et al., 2009). The most widely used definition is the interpretation of ambidexterity by March (1991), namely exploration and exploitation.

Early research often claimed that ambidexterity is a competitive relationship (Simsek et al., 2009), and the discussion mostly centred on the opposition and conflict between exploratory and exploitative activities. However, the co-existence of exploration and exploitation in the same organisation is achieved by establishing mechanisms for the separation of time and space (Eriksson, 2013). Sequential ambidexterity refers to the temporal separation of exploration and exploitation activities in different sequences while structural ambidexterity emphasises the separation of business units for exploration and exploitation activities (Simsek et al., 2009). In the perspectives of opposition and conflict, the interdependent relationship between exploration and exploitation is ignored. In the context of a highly dynamic environment, sequential and structural ambidexterity has become more and more cumbersome and incapable of responding flexibly to the impact of external environment changes. Birkinshaw and Gibson (2004) put forward the concept of contextual ambidexterity, which is considered to represent a complementary process. Structural ambidexterity is achieved through activities that focus on alignment and adaptability when completed in separate teams or units while contextual ambidexterity is achieved when individuals allocate their time between adaptability-focused and alignment-focused behaviours (Birkinshaw & Gibson, 2004). Contextual ambidexterity requires the organisation to realise both exploitation and exploration internally and simultaneously and that exploitation and exploration are inseparable, interdependent, mutually integrated and embedded to generate synergy, not just a simple presentation in the organisation (Raisch, 2008). The emergence of contextual ambidexterity takes the paradoxical lens, emphasising that the success of the overall organisation depends on simultaneous exploration and exploitation (Smith & Lewis, 2011). Smith and Tushman (2005) called for the realisation of ambidexterity through, paradoxical thinking. Andriopoulos and Lewis (2009) analysed how paradoxical thinking can promote a virtuous circle of ambidexterity. A paradoxical solution is to seek ambidexterity or ambidextrous organisation form that simultaneously creates tight and loosely coupled organisational structures (Storey & Salaman, 2009).

DEFINITIONAL ISSUES OF LC CAPABILITY

DEFINITION OF LC AMBIDEXTROUS CAPABILITY

As revealed by the paradoxical tensions faced by LC project organisations, contextual ambidexterity is required for project organisations to have a better paradoxical solution. Contextual ambidexterity does not mean the separation of structures or sequence; instead, it emphasises striving for a balance between the two capabilities by attempting to allocate time between the activities of the two complementary capabilities (Birkinshaw & Gibson, 2004). LC capability includes both the ability to achieve the rigid goals of the project and the ability to respond flexibly to the uncertainty of the project, instead of discarding one of the two. It has the characteristics of contextual ambidextrous capability. In this study, LC ambidextrous capability is defined as follows:

> *LC capability is the capability that an organisation or individual has to achieve LC goals and an ambidextrous capability to solve both conflicting and interdependent problems. It embodies the philosophy, principles and methods of LC and is dedicated to solving the paradoxical tensions in an LC project.*

LC ambidextrous capability represents two capabilities that deal with opposing characteristics. Based on this duality, LC ambidextrous capability should be a two-dimensional construct.

LEAN CONSTRUCTION CAPABILITY DIMENSIONS

Just as Fujimoto put forward the perspective of rational planning and evolutionary adaptation, rational planning focuses on efficiency and cost, which are a reflection of rigid capability, while evolutionary adaptation is a process of gradually building capability through experiment and trial and error learning, which is a reflection of flexible characteristics. As the ability to ensure the production schedule is not enough, the ability to produce quickly to order is equally important. It is not enough to achieve short-term benefits because only continuous learning and improvement can ensure the high performance of the production system and achieve the long-term goals (Fujimoto, 2007; Deming, 1982). The views of Fujimoto and Deming have the same underlying structure as what March said concerning ambidextrous dimensions.

According to March (1991), exploitative activities are always connected with the elements of refinement, implementation, selection and efficiency, whereas exploratory activities are always associated with the elements of search, variability, discovery and experimentation. The activities of organisational ambidextrous learning, innovation and adaptability refer to the same underlying constructs of exploration and exploitation but with different labels in different contexts (Raisch & Birkinshaw, 2008). Referring to March's (1991) ambidextrous dimensions, we divide LC capability into two dimensions: LC exploitative capability and LC exploratory capability.

The LC exploitative capability dimension

LC exploitative capability is a rigid capability that tends to eliminate all variabilities to achieve continuous flow, standardisation, modularisation and the ideal state of pursuing zero inventory. Unlike tolerance for variation, it refers to maintaining the consistency and efficiency of results. This capability pays more attention to the use of existing technology and knowledge in the organisation to obtain current benefits.

The LC exploratory capability dimension

LC exploratory capability is a flexible capability that tends to eliminate the waste caused by the inability to cope with variability. This kind of capability is derived from possessing multi-skilled resources and supplying them in plenty to be capable of moving between functions, absorbing fluctuations of demand while promising the sustainability of the system operation (Horman, 2001). LC exploratory capability also focuses on employee participation, tolerates variation, encourages employee trial and error and focuses on a culture of continuous improvement.

THE DYNAMIC BALANCE OF THE TWO DIMENSIONS

In a project life cycle, LC exploitative capability and LC exploratory capability are not permanent, and the two dimensions have dynamic capability characteristics. LC ambidextrous capability is presented as contextual ambidexterity. Requirements for project consistency, short-term efficiency and benefits and project constraints are the driving factors for LC exploitative capability while personalised needs, long-term benefits and continuous improvement are the driving factors for LC exploratory capability.

Under the driving force, the growth of LC exploratory capability can promote a culture of continuous improvement, promote long-term cooperation between suppliers and promote the accumulation of social capital, which is conducive to obtaining long-term benefits to achieve the continuous growth of LC exploitative capability (Eriksson, 2013). The growth of LC exploitative capability can enable short-term goals to be achieved continuously and obtain considerable benefits. It is the necessary economic guarantee for the development of LC exploratory capability, and it is the foundation for the better development of new technologies and products that meet the personalised needs of customers (Eriksson, 2013; March, 1991). The two capabilities exist at the same time and complement each other, thereby forming a virtuous circle, which promotes the LC ambidextrous capability to reach a dynamic balance.

DISCUSSION

This section further discusses how the application of LC ambidextrous capabilities would benefit construction projects and which elements promote the balanced development of LC ambidextrous capability.

APPLICATION OF LC AMBIDEXTROUS CAPABILITY

The application of LC ambidextrous capabilities to resolve paradoxical situations has been demonstrated in the use of some lean tools. For example, the JIT method of lean, addresses the paradox of quality and efficiency (Storey & Salaman, 2009). Total quality management realises both customer-oriented and process-oriented requirements, thereby shortening cycle time and saving cost while improving customer satisfaction (Koskela et al., 2019). Deming Circle focuses on quality and efficiency through continuous improvement. A mass customisation strategy is designed to provide a variety of products for capturing customer needs while meeting the cost and lead time of mass production (Tillmann & Formoso, 2008). Other than focusing on the application of a certain tool to solve certain local problems in production management, LC ambidextrous capability can gradually be developed to more rich fields, such as the project organisational area. For example, LC ambidextrous capability can be used to resolve problems caused by the separation of the design and construction phases of a project and balance the contradiction between the interests of the individual and of all parties. Eriksson (2013) discussed the performance of structural ambidexterity, sequential ambidexterity and contextual ambidexterity in solving problems existing in the construction project organisation. Sequential or structural separation, such as focusing more on exploration in the early stages of a project and on exploitation at the end of a project during implementation, is more suitable for stable environments. The structural solutions to the problems caused by the separation of design and construction are insufficient, but contextual ambidexterity provides viable solutions to better balance those problems (Eriksson 2013).

LC AMBIDEXTERITY PROMOTION FACTORS

Gibson and Birkinshaw (2004) stated that a successful organisation should balance hard elements, such as disciplines, and stretch with soft elements, such as trust and support, in the organisational context. This section exemplifies and discusses below three factors that promote LC ambidextrous capability, because these factors can promote the dynamic balance of rigidity (exploitative) and flexibility (exploratory) of LC capability.

Commitment and cooperation: A better commitment network promotes mutual trust, information transparency and knowledge sharing among members as well as creates a better atmosphere of innovation to better promote the improvement of LC exploratory capability. The trust relationship continues to accumulate with the commitment network and close cooperation (Viana et al., 2011), and LC exploitative capability and LC exploratory capability promote and improve each other to achieve a dynamic balance. A common approach is the integrated project delivery collaboration model. Integration of lean and building information model concepts can also promote communication and collaboration (Sacks et al., 2009). LPS^{TM} enables a short feedback circle of planning and corresponding, requires team members to make a solid commitment and encourages the acceptance of diverse perspectives in making decisions to avoid greater losses (Saurin & Rooke, 2020).

Considering the project organisation as a production system: The system view is a more holistic and integrated view, such as the Lean Project Delivery System^{TM} (LPDS^{TM}). Ballard (2008) emphasised the interdependence between functions and the integration of information and resources. The LPS^{TM} is an important system tool that emphasises the authorisation of employees to plan and arrange specific tasks. However, planning activities also include buffering of work activities and focusing on overall efficiency rather than local efficiency. Functional resonance analysis is a method that can model variability propagation in LC (Saurin, 2016), thereby better predicting uncertainty and making up for the lack of flexibility from a systematic perspective in the plan. These system methods enable the short-term goals of a project to be effectively achieved, helping improve the LC exploitative capability. At the same time, the system view helps exploratory quality management practices focus on overall costs rather than local costs. It also focuses on learning feedback, buffer management, resilience engineering and sustainability that will help improve LC exploratory capability. LC exploitative capability and exploratory capability complement each other to achieve a dynamic balance.

A culture that values organisational learning and continuous improvement: Learning organisations can respond to new challenges more quickly and flexibly (Jiménez-Jiménez & Sanz-Valle, 2011). Disciplines and standards are used to guide the project to perform specific tasks, but standardisation is not a fixed implementation or a fixed layer. The standardisation of the LC project organisation is the basis for continuous improvement and a tool for empowering employees to achieve better innovation based on standards. The standardised process is a powerful guarantee to eliminate variability and improve product quality (Liker, 2004). It developed the LC exploitative capability. Organisational learning and continuous improvement are conducive to project members to continue exploring and innovating based on the implementation of standard operating procedures and the elimination of outdated and rigid standard processes. The two complement each other, and standardisation and continuous improvement are mutually reinforcing.

CONCLUSIONS AND FUTURE RESEARCH

This research explores the ambidextrous characteristics of LC capability by reviewing the literature in the fields of LC, organisational ambidexterity and paradox in order to identify what LC ambidextrous capability is and how it benefits LC. The research finds that the rigidity and flexibility of LC stem from the main understandings of variability in current literature. The investigation reveals that the concept of LC capability has no clear definition, and it puts forward the view that LC capability is an ambidextrous capability. The study establishes that LC ambidextrous capability is a paradox consisting of two dimensions, namely LC exploitative capability and LC exploratory capability, which breaks the traditional view that LC capability is biased toward exploitation or exploration. The study argues that the exploitative and exploratory capabilities of LC are interdependent and should be achieved in a dynamic balance.

This study contributes to the current knowledge and future application of organisational ambidexterity theory to LC capability development. Different contradictory situations arise during the execution of a project. For example, should the focus be on efficiency or innovation? Should it be on short-term performance or long-term performance? Although Fujimoto, Deming and others already have some ideas that take the rigidity and flexibility of LC into consideration, they have not given the theoretical explanation behind the specific phenomenon. Given the lack of theoretical foundations, the understanding of the two characteristics may be insufficient and the project paradoxes may not be properly handled. Through the introduction of organisational ambidextrous theory, the definition of LC capability is clarified. This study provides theoretical guidance for practitioners to understand the ambidextrous characteristics of LC capability, clarifies why it is necessary to balance the relationship between LC exploitation capability and LC exploration capability and identifies the factors that promote the balance of LC ambidextrous capability.

This study brings new insight and opens a new debate on how LC ambidextrous capability could develop in the construction field. More applications at the organisation level need to be explored in future research, and the organisational characteristics that are most conducive to the balanced development of LC ambidextrous capability require further study using live real-life case studies. This research direction would be the future focus of the authors.

REFERENCES

Andriopoulos,C.& Lewis,M. (2009).Exploitation-exploration tensions and organizational ambidexterity: Managing paradoxes of innovation. *Organ. Sci.*, 20 (4), 696–717.

Ballard, G. (2008). The lean project delivery system: An update. *Lean Cont. J.* , 1–19.

Ballard, G. (1999). Improving Work Flow Reliability. *7th IGLC Conf.* USA, 275–286.

Ballard, G.,&Howell, G. (2003). Lean project management. *Build.Res.Inf.*,*31*(2),119–133.

Ballard, G., & Tommelein, I. (2012). Lean management methods for complex projects. *Eng. Proj. Organ. J.*, *2*(1–2), 85–96.

Birkinshaw, J., & Gibson, C. (2004). Building ambidexterity into an organization. *MIT SLOAN Manag. Rev.*, *45*(4), 47.

Deming, W. E. (1982). Out of the crisis, Massachusetts Institute of Technology, Cambridge, MA.

Eaton, B., Elaluf-Calderwood, S., Sørensen, C., & Yoo, Y. (2015). Distributed tuning of boundary resources: The case of Apple's iOS service system. *MIS Q. Manag. Inf. Syst.*, *39*(1), 217–243.

Eisenhardt, K. M. (2000). Paradox, Spirals, Ambivalence: the New Language of Change and Pluralism. *Acad. Manag. Rev.*, *25*(4), 703–705.

Eriksson, P. E. (2013). Exploration and exploitation in project-based organizations: Development and diffusion of knowledge at different organizational levels in construction companies. *Int. J. Proj. Manag.*, *31*(3), 333–341.

Formoso, C., Bølviken, T., Rooke, J., & Koskela, L. (2015). A conceptual framework for the prescriptive causal analysis of construction waste. *23rd IGLC Conf. of the Int. Group for Lean Const.*, Perth, Australia, 454–461.

Fujimoto, T., Miller, B. (2007). *Competing to Be Really, Really Good: the behind-the-scenes drama of capability-building competition in the automobile industry* (Vol. 22). Tokyo: International House of Japan.

Fujimoto, T. (2014). The long tail of the auto industry life cycle. *J. Prod. Innov. Manag.*, *31*(1), 8-16.

Hamzeh, F., Tommelein, I., Ballard G, et al (2007). Logistics Centers to Support Project-Based Production in the Construction Industry. *15th IGLC Conf.* USA, 181-191.

Hopp, W. J., & Spearman, M. L. (1996). *Factory physics: foundations of manufacturing management*. Irwin/McGraw–Hill.

Horman, M. J. (2001). Modeling the Effects of Lean Capacity Strategies on Project Performance. *Proc. 9th Annual Conf. of the Int. Group for Lean Const.*, Singapore.

Jiménez-Jiménez, D., & Sanz-Valle, R. (2011). Innovation, organizational learning, and performance. *J. Bus. Res.*, *64*(4), 408–417.

Koskela, L. (1992). *Application of the New Production Philosophy to Construction*. CA. Technical Report No. 72. CIFE.

Koskela, L. (2000). An exploration towards a production theory and its application to construction. In *VTT Publications*.

Koskela, L., Tezel, A., & Patel, V. (2019). Theory of Quality Management: Its Origins and History. *27th IGLC Conference*, Dublin, Ireland, 1381–1390.

Liker, J. (2004). The Toyota Way: Fourteen Management Principles From the World's Greatest Manufacturer. In *McGraw-Hill*.

March, J. G. (1991). Exploration and Exploitation in Organizational Learning. *Organ. Sci.*, *2*(1), 71–87.

Oxford English Dictionary, 2020. Accessed March 24, 2021. https://www.oed.com/view/Entry/221513?redirectedFrom=variability#eid.

Owen, R., Koskela, L., Henrich, G., & Codinhoto, R. (2006). Is Agile Project Management Applicable to Construction? *14th IGLC Conference*, Chile, 51–66.
Raisch, S., & Birkinshaw, J. (2008). Organizational ambidexterity: Antecedents, outcomes, and moderators. *J. Manage.*, *34*(3), 375–409.
Sacks, R., Dave, B. A., Koskela, L., & Owen, R. (2009). Analysis framework for the interaction between lean construction and Building Information Modelling. *17th IGLC Conference*, Taipei, 221-234.
Saurin, T., & Rooke, J. (2020). The Last Planner® System as an approach for coping with the complexity of construction projects. In P. Tzortzopoulos, M. Kagioglou, & L. Koskela (Eds.), *Lean Construction: Core Concepts and New Frontiers* (1st ed., pp. 325–340). Routledge.
Saurin, T. (2016). The FRAM as a Tool for Modelling Variability Propagation in Lean Construction. *24th Annual Conf. of the Int. Group for Lean Const.*, USA.
Seppänen, O., Ballard, G., & Pesonen, S. (2010). The combination of last planner system and location-based management system. *Lean Const. Journal*, *2010*, 43–54.
Simsek, Z., Heavey, C., Veiga, J. F., & Souder, D. (2009). A Typology for Aligning Organizational Ambidexterity's Conceptualizations, Antecedents, and Outcomes. *J. Manag. Stud.*, *46*(5), 864–894.
Smith, W., & Lewis, M. (2011). Toward a theory of paradox: A dynamic equilibrium model of organizing. *Acad. Manag. Rev.*, *36*(2), 381–403.
Smith,W.,&Tushman,M.L.(2005). Managing strategic contradictions: A top management model for managing innovation streams. *Organ. Sci.*, 16 (5), 522–536.
Storey, J., & Salaman, G. (2009). *Managerial dilemmas. Exploiting paradox for strategic leadership* (1. Aufl.). Wiley-Blackwell.
Thomas, H. R., Horman, M. J., de Souza, U. E. L., & Zavřski, I. (2002). Reducing Variability to Improve Performance as a Lean Construction Principle. *J. Constr. Eng. Manag.*, *128*(2), 144–154.
Tillmann, P. A., & Formoso, C. T. (2008). Opportunities to adopt mass customisation - A case study in the Brazilian house building sector. *16th IGLC Conf.*, UK, 447-458.
Tommelein, I. D. (2015). Journey toward Lean Construction : Pursuing a Paradigm Shift in the AEC Industry. *J. of Const. Engr. and Management*, *141*(1970), 1–12.
Tommelein, I. D., & Weissenberger, M. (1999). More just-in-time: location of buffers in structural steel supply and construction processes. *Proc. 7th Annual Conf. of the Int. Group for Lean Const.*, Berkeley, California, USA, 109–120.
Viana, D. D., Formoso, C. T., & Isatto, E. L. (2011). Modelling the network of commitments in the last planner system. *Lean Const. Journal*, 55–67.

Wandahl, S., Neve, H. H., and Lerche, J. (2021). "What a waste of time" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 157–166, doi.org/10.24928/2021/0115, online at iglc.net.

WHAT A WASTE OF TIME

Søren Wandahl[1], Hasse H. Neve[2], and Jon Lerche[3]

ABSTRACT

The elimination of waste is a core focus of lean construction. Reducing waste will increase work efficiency. For several years it has been debated how flow and the efficiency of processes can be measured. Kalsaas, Koskela, and others conclude that in order to operationalize workflow measures, it must be disconnected from productivity and throughput measures and instead focus on work efficiency. However, an extensive and valid baseline of work time efficiency is missing in the community. The establishment of such becomes the objective of this research.

The method is an extensive litterateur review that identified 474 case studies of time waste measures from the 1970s until today. This sample is analyzed in different ways, among others showing that the average direct work time is 43.6%.

The results show that the sample contains considerable uncertainty, which is mainly due to an inconsistent understanding of direct work, indirect work, and waste work in the many different studies. Besides, the results show no statistically significant difference between the performance of varying trades or between countries.

The construction industry can use this research as a baseline for the current direct work level and apply this as a benchmark in a continuous improvement process.

KEYWORDS

Waste, time, work sampling, productivity.

INTRODUCTION

The construction industry is continuously searching for ways to improve, be more competitive, and generate a higher margin for shareholders and lower costs for customers. In a competitive construction environment, decreasing costs to increase market competitiveness and profits is a common goal among all construction companies. Of all the factors which influence project profits, on-site labor costs are among the most influential (Gouett et al. 2011; Moselhi and Khan 2012). On-site labor costs can be positively and negatively influenced by modern methods of construction, seeking designs and solutions that require fewer labor hours, or implementing production planning and control methods that improve efficiency. In lean construction, efficiency is pursued by removing waste and enhancing flow.

The elimination of waste is a core focus of lean production and construction; see, for example, Koskela (2000). There are seven types of waste in the lean literature:

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overproduction, defects, unnecessary inventory, inappropriate processing, excessive transportation, waiting, and unnecessary motion (Ohno 1988). Making-do has later been added as an eighth type of waste (Koskela 2004).

Concerning lean construction, the flow concept was first introduced in the Koskela (1992) seminal work towards a new theory of production in construction. The flow concept's consolidation was achieved with the TFV theory of production in construction (Koskela 2000). Today flow in lean construction is applied with the seven preconditions (Koskela 1999) in the making ready process of the Last Planner System.

Combing flow thinking and waste reduction will result in increased efficiency. Efficiency refers to executing a defined activity with the least possible amount of resources. Unfortunately, construction is challenged in terms of efficiency, as we have many flows and many workers from different trades working in a dynamic environment. Some even argue that construction is inherently wasteful, and as construction is labor-intensive, waste and time usage are central topics in the quest for efficient construction. Already in the first IGLC conference back in 1993, this was in focus as Alarcón, L. F. (1993) presented conceptual ideas of modeling waste and time. To measure waste and time usage has been in focus continually in IGLC.

IGLC Papers on Waste and Time

Waste and time management are two central concepts of lean, thus also popular topics at the IGLC conferences. Currently, the iglc.net conference database contains 1,781 IGLC conference papers. When searching for ‘time’ and ‘waste’ in title, keyword, and author, the result is 573 and 417, respectively. This equals that almost 1/3 of all IGLC papers have the word ‘time’ in the title and/or in the keywords. When narrowing the search down to the title only, 52 papers has the word ‘time’ and 54 papers the word ‘waste’ in the headline. A brief review of IGLC papers addressing time and waste reveals the most important topics, and most cited works seem to be takt time planning. Frandson et al. (2013) was the second earliest published IGLC paper on takt time and now the most cited takt time paper from IGLC with more than 120 citations. In the following years, takt time was in focus. It was conceptually compared and differentiated from LPS (e.g., Emdanat et al. 2016; Frandson et al. 2014) and location-based scheduling (e.g., Frandson et al. 2015; Seppanen et al. 2010). In the recent 3 IGLC conferences, 20 papers on takt time have been published. Around the millennium, Just-in-time was a focal point, where among others, two conceptual papers, each with more than 100 citations, made it clear how JIT should be seen as an integral part of lean construction (Tommelein and Li 1999; Tommelein and Weissenberger 1999).

Several papers have embossed the fundamental understanding of construction as a production system in terms of time usage and time waste. Kalsaas (2010) investigated time waste, both theoretically and empirically. He discussed the relationship of time waste towards the 8 categories of waste (Koskela 2004) and found through case studies that time waste only constitutes around 7% of work time. This was followed by a case study in 2013 calculating waste time to 35% (Kalsaas 2013). In IGLC, this work was referred to as measuring workflow and comprised several IGLC publications (Bølviken and Kalsaas 2011; Kalsaas 2012; Kalsaas and Bolviken 2010). However, an extensive and trustworthy review of wasted work time in construction is missing.

Turning the focus to waste, the three most cited IGLC papers on waste are all published around the millennium by well-established Lean Construction researchers Koskela (2004), Formoso et al. (1999), Polat and Ballard (2004). In addition to these, Kalsaas is also very active in researching waste in construction, with 8 publications (e.g., Bølviken and Kalsaas 2011; Kalsaas 2010; Kalsaas 2013). Out of the 54 papers on waste, the most common topic is waste as a concept, where authors explore Ohno's (1988) concept of waste in the construction context (Koskela et al. 2013). Among others, this resulted in Bølviken et al.'s (2014) Taxonomy of waste in construction. Over time, this exploration has resulted in Koskela (2004) identifying a 8th waste type of construction, called Making-do. Making-do as a waste refers to a situation where a task is started without all its standard inputs, or the execution of a task is continued although the availability of at least one standard input has ceased (Koskela 2004). In more recent years, several researchers have followed up and further explored making-do (Fireman and Formoso 2013; Fireman and Saurin 2020; Neve and Wandahl 2018), and making-do is now widely recognized as a lead waste type.

Other trends of waste research within IGLC are identifying the sources of waste (e.g., Polat and Ballard 2004; Viana et al. 2012) and waste in relation to design processes and social context (Koskela et al. 2013; Macomber and Howell 2004). Finally, Kalsaas has conducted seminal work on waste in relation to time, productivity, and efficiency, which will be further explored in the next chapter.

MEASURING TIME WASTE IN CONSTRUCTION

In 2010 Kalsaas and Bolviken (2010) wrote *"...the current lack of an accepted method for measuring flow in project-based production...*" which was the starting point for understanding, defining, and measuring flow or lack of it, i.e., time waste, in construction. Flow is a chain of events without interruptions and closely related to motion, not only of material, but in relation to all preconditions defined by Koskela (2000).

Kalsaas (2010) pointed out that time must be added to the understanding, as "excessive transportation, waiting and unnecessary motion all contain obvious aspects that can be measured in terms of time." Kalsaas conducted, therefore, a small literature study on waste time and collected empirical data through what he called 'the boss method' to conclude on the amount of value-adding worktime (VAW) and non-value-adding worktime (NVAW). VAW and NVAW refer back to Ohno's work (1988, page 138). The conclusion was that 49% of the time was value-adding. However, as we will later show, both the literature study and the empirical method had limited validity at that time.

Bølviken and Kalsaas (2011) recognized a year later themselves the need for a more valid method for measuring waste time. Thus, they review a number of direct and indirect measurement methods, even though they recognize *"...that not all that counts can be counted... On the other hand, we believe that in some cases, measurement can represent an important contribution towards providing a better factual foundation for our improvement work.*" We strongly agree with this epistemological view. At the same IGLC conference, Kalsaas (2011) concludes on the method selection that a suitable method for measuring workflow should mainly be based on VAW, i.e., the work sampling method.

In Kalsaas (2012), the purpose was to identify the causes for time waste in relation to Koskela's 7 flows, Koskela's 8th flow, and rework in general. The conclusion was that in order to operationalize workflow measures, it must be disconnected from productivity and throughput measures and instead focus on work intensity. In further work, Kalsaas points out that the premise is that flow cannot be understood without an understanding of waste and vice versa (Kalsaas 2013). Also, and perhaps more important, flow, and thus waste, should be measured during the entire production time from start in the morning to end in the afternoon, however excluding regulated breaks. Kalsaas (2013) divides the time into VAW and NVAW, where the NVAW has several subcategories like indirect work, planning, HSE, waiting, personal time, rework, etc. This division is very similar to Work Sampling, as presented in, e.g. (Neve and Wandahl 2018; Neve et al. 2020).

WORK SAMPLING

The work sampling (WS) method has been used since the 1970s to collect data on the amount of value-adding worktime, which is called Direct Work (DW) in the WS method (Gong et al. 2011). The WS method is quantitative and uses direct observations to obtain data on how craftsmen use their work time. The main topic of the published WS studies has throughout time been on how construction can be improved with regards to efficiency, Construction Labor Productivity (CLP), and in the end, construction cost and time. Looking at some of the early work on WS by Thomas (1981), he provides relevant insights on how a WS study can be planned and how the data can be analyzed.

The WS method quantifies how much time craftsmen use on DW and NVAW time. The method is based on direct observations quantified by categorizing them into suitable categories describing the work in focus. The time between each single observation must be randomized in order to avoid cyclic data. All WS studies apply a DW category. However, when it comes to the NVAW category, the picture is more blurred. Some studies categorize all none-DW time as NVAW, while other studies have a more detailed view of NVAW, including a number of subcategories. Generally speaking, NVAW time can in WS be divided into Indirect Work (IW) and Waste Work (WW), resulting in Work Sampling having three categories of time DW, IW, and WW. DW's relation to productivity has been debated throughout time, as DW directly influences the denominator and indirectly the numerator of the productivity equation. Recent studies do, though, concluded that DW is statistically significantly correlated to construction labor productivity on activity, project, and national level (Araujo et al. 2020; Neve et al. 2020).

RESEARCH AIM

This research aimed to conduct an extensive review to collect the largest sample of DW values in construction ever published. This sample should constitute a valid baseline of DW in construction, which could be applied for benchmark purposes, outline future direction in research, and guide industry in their quest of increasing efficiency of construction.

METHODS

The main method of this research is an extensive literature review. Several search strategies were combined. Firstly relevant search strings were developed based on pertinent search terms appropriate for the topic, i.e., Work Sampling, Activity Analysis, Waste, Productivity, Direct Work, and Efficiency. The search term was combined with domain terms like construction, building, and construction industry to focus the search on construction. The different search string combinations were applied to three different databases: Google Scholar, ASCE database, and the IGLC paper database. The IGLC paper database was chosen to include the most domain-specific papers and research discourse in the community. The ASCE database was included, as it is clear that Construction Labor Productivity has been a popular research topic for many of the journal papers. Finally, Google Scholar was applied as the largest open-access database. To sort the findings, a number of inclusion and exclusion criteria were applied. Only construction work was to be included. Only papers that clearly presented a DW value were included. Multiple publications of the same study were excluded.

This resulted in an initial pile of research papers included in the review. These papers were used to identify further papers by: 1) Examining papers that cited these papers. This was done based on Google Scholar. 2) Reviewing references of each paper to identify possible further literature. 3) Using identified authors to look for additional papers on the same topic from the same authors.

All identified papers were entered into a spreadsheet, including information about authors, year of study, country, DW value, IW and WW values if available, and information about the work observed. The sample was then crosschecked to remove doublets and reviewed to ensure that a DW value from a study was not included twice or more due to multiple publishing sources of the same study. After that, the sample was ready for analysis.

RESULTS

Previous DW findings were identified in 72 pieces of literature with a total of 474 DW values (N) from WS studies. The literature identified is distributed geographically as follows: North America n=300; Europe N=73; Asia/Australia N=48; Africa N=40; South America N=13. Due to the IGLC page limitation of 10 pages, including references for submission, all the references (72) are omitted.

The 474 entries large sample is without equal the largest ever presented in a Work Sampling literature review. Descriptive statistics are applied to examine the sample, whereafter implications for the IGLC society as well as for the industry are discussed.

A histogram is created for the sample, and this is visually compared with a normal distribution with mean (μ) and standard deviation (σ) from the sample itself, cf. figure 1.

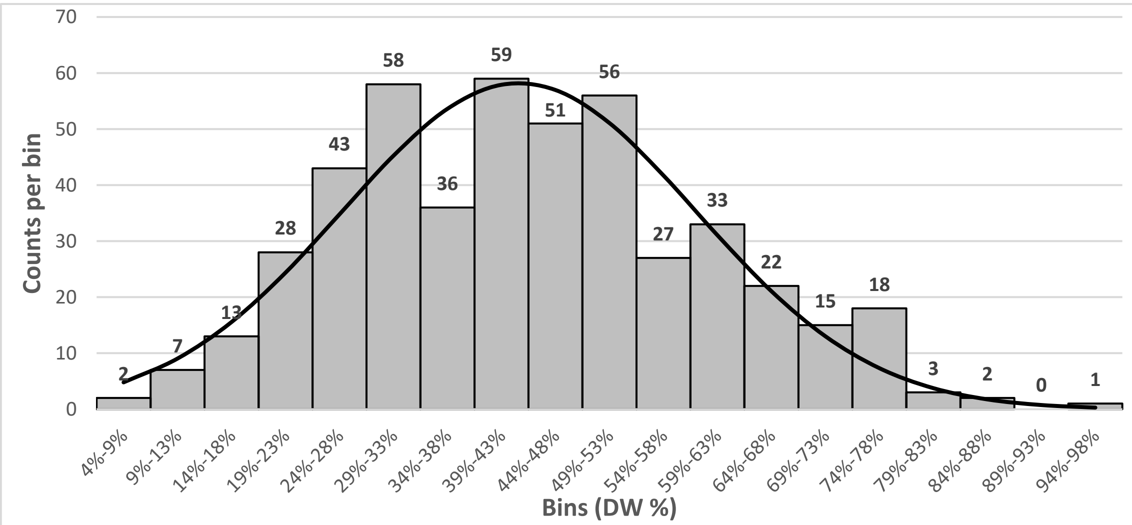

Figure 1. Histogram of n=474 DW values from previous findings, and a fitted normal distribution function with μ= 43.6% and σ=16.5%

Firstly, the sample is described by mean μ=43.6%, standard deviation σ=16.5%, and mode m=41%. The large standard deviation indicates large discrepancies in the sample, and it needs to be corrected for outliers before further statistical analysis. The problem is an inconsistent understanding of the work sampling categories, cf. the introduction chapter. Some of the studies have only measured DW (N=233), while others have measured both DW, IW, and WW (N=241). The problem is that some researchers consider IDW to be part of DW, while others consider IDW to be part of WW. That is why we in the sample can find unrealistic high DW values of, e.g., 98%. These outliers should be taken into account when analyzing and concluding on the sample.

Visually, the histogram (figure 1) fits very well with the normal distribution function, thus the sample seems to be valid and gaussian as expected. The histogram shows us that the most likely bin is bin 39%-43% representing 12% (count=59) of the sample. Bins in the interval [24% ; 58%] counts 330 data points, thus constitute 70% of the sample, which is very close to a z-score of 1. Next, the sample is described as a function of time to investigate any statistically significant developments. This is depicted in figure 2.

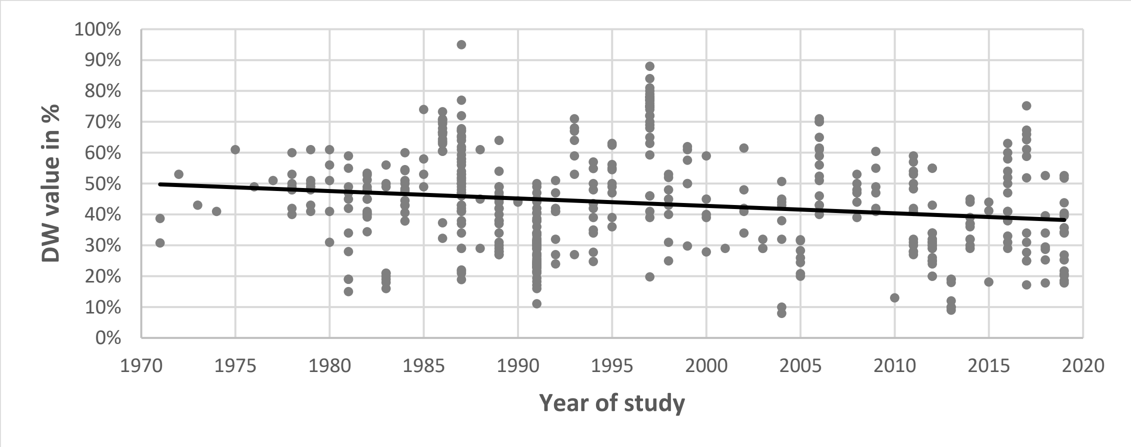

Figure 2. Development over time of n=474 DW values from previous findings. The linear trendline has R^2=0.033.

As seen on the scatter plot in figure 2, there is a weak visual indication of DW's decrease over time. However, the linear regression model has a very weak coefficient of determination R^2=0.033. Even if outliners are removed from the sample by limiting the sample to only include data points in the interval $\mu \pm \sigma$ (z-score =1), a linear regression model would still have a weak coefficient of determination R^2=0.062. Thus there is no significant development in DW over time, as time is not a predictor variable for DW.

Geographically, the samples are distributed over 23 different countries from all continents except Antarctica. Few countries have a large enough sample size to be valid. Only four countries have a sample size of +20 and are based on more than one study. USA (N=238) has a mean of μ=39.8% and σ=11.7%. Canada (N=63) has a mean of μ=47.3% and σ=16.7%. Denmark (N=25) has a mean of μ=33.1% and σ=11.0%. Norway (N=20) has a mean of μ=58.6% and σ=11.2%. Norway stands out with a larger mean than the other countries, and the Canadian samples have a larger standard deviation than the other countries. Generally speaking, the DW baseline is in the range of 30-40% ± 10%. There is no indication that the country should be a predictive variable for DW.

Many of the studies do not precisely inform what kind of work was observed in the Work Sampling study, or the study includes several trades not separated. These are from now on called unspecified. Table 1 shows DW values divided by type of trade work.

As shown in table 1, 291 out of 474 DW values have not precisely defined the observed kind of trade. The remaining 183 DW values are fairly distributed between seven generic types of trade work. The standard deviation is relatively high for all the named trades, thus one cannot conclude that the trade is correlated with the effectiveness of the work. Therefore, the type of work is not a predictor variable for DW.

Table 1: WS studies grouped by kind of trade with more than 10 samples per trade and based on more than one source of research (N=474).

Trade	Sample (N)	Mean (μ)	Std. dev. (σ)
Brick & Tiles	27	46.2%	13.2%
Carpenter	26	43.9%	15.7%
Civil	10	31.2%	9.6%
Concrete	48	38.8%	19.0%
Electrical	22	47.4%	16.5%
HVAC	25	32.0%	16.1%
Steel	25	41.3%	20.4%
Unspecified or mixed	291	45.9%	15.6%

DISCUSSION

The result showed a baseline where direct work constitutes 43.6% of the work time. The review also showed that there was some discrepancy in the categories. Several unalike categorizations have been applied in the different studies. Some studies apply only the DW category. Others use three categories, namely DW, IW, and WW. Some consider IW as a part of DW, and so continues the inconsistency. Two important learnings should be drawn from this. Firstly, the current baseline of μ= 43.6% contains a relatively considerable uncertainty, which is also reflected in σ=16.5%. Secondly, the application of work sampling and other methods of measuring wasted work time needs a more unified guideline and application. The following taxonomy is recommended Direct Work (DW) = Producing. Indirect Work (IW) = Talking, Preparing, and Transporting. Waste Work (WW) = Walking, Waiting, and Gone.

Returning to the question of whether the indirect work (talking, preparation, and transportation) should be considered waste or value-adding. Many practitioners have argued that it should be regarded as value-adding, as one cannot imaging a construction project without transportation, preparation, and talk for coordination. This is needed to complete the tasks, they argue. On the other hand, Lean theory argues that activity either adds value (transforms) or is considered waste. The distinction between DW and IW depends on the perspective that is considered. If you observe a site cleaning crew, cleaning is DW. If you observe an HVAC crew do cleaning, it is IW. Imagine two identical tasks A and B, but with a different distribution of the work time, as illustrated in figure 3.

Task A and B have the same amount of walking, waiting, and gone, but task A has more production time and less talking, preparation, and transportation than task B. Which task do you think will be completed first, task A or B? The answer can only be that task A will complete faster than task B. Thus, in order to be efficient, it is now clear that we need to minimize time spend on IW (talk, preparation, and transportation). Of course, the same count for the Waste Work, which also needs to be reduced.

The conclusion and also the recommendation of this research are therefore clear. 1) We should apply Work Sampling to get a data-driven approach and to measure our waste time. 2) Work Sgampling must include categories of DW, IW, and WW. 3) We must aim to have as much DW as possible. Moreover, WS should be used to identify waste and NVAW.

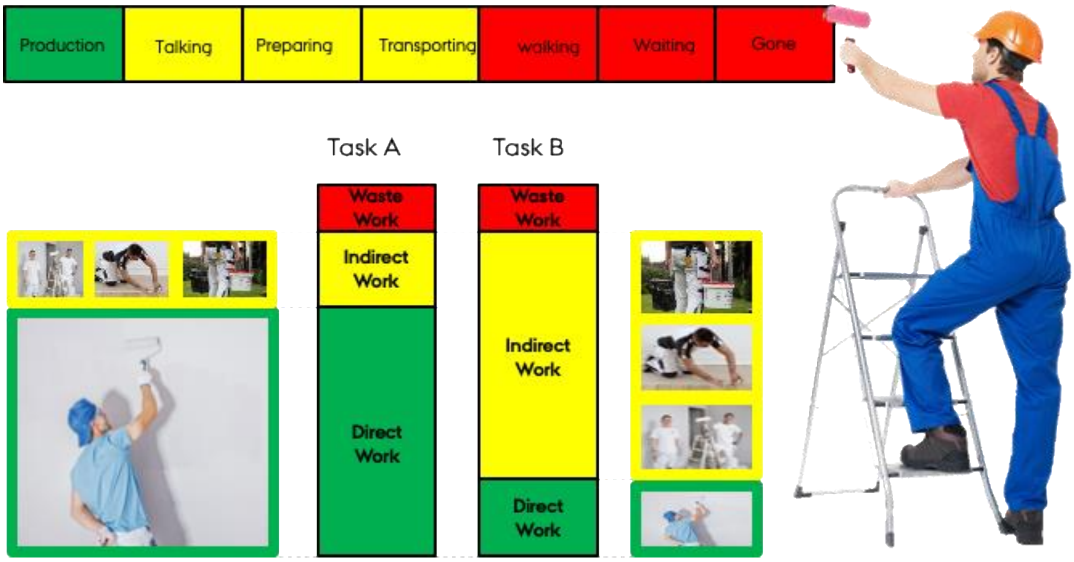

Figure 3. Two identical painting tasks, but with two different distributions of work time.

This review contributes to the Body-of-Knowledge with a large and significant baseline of DW. Practitioners can apply this baseline for benchmarking purposes by using the sample's cumulative distribution function, as illustrated in figure 4. As pointed out, the sample includes different use of Work Sampling taxonomy, which challenges the validity of this study. Adding to this is the fact that direct work can include both re-work and making-do. Very few of the studies in the sample relate critically to this. Academic and practitioner should though use this study carefully for generalizing purpose, whereas WS as method to improve a single project is with high validity.

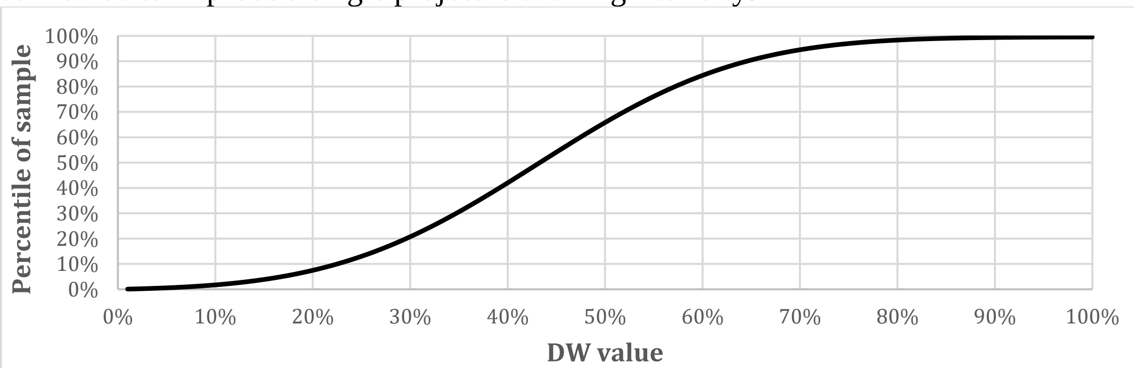

Figure 4. Cumulative Distribution Function of the DW sample (n=474).

The final part of the discussion is the connection between DW and CLP. For a starting point, one could argue that DW and CLP are not alike and not connected. CLP is an indicator of how much output is generated per resource use. DW and Work Sampling is one the contrary an indicator for efficiency and not directly linked to the output. Are there then no connections between DW and CLP? Indeed there is. The more efficient you are, i.e., the higher percentage of Direct Work, the less resource you need to produce. Resource usage is the denominator in the CLP formula; thus, the higher DW, the less resource, the higher is the productivity. This is logic!.

Nonetheless, this logic has rarely been quantified and proven in research. Recent studies do, though, concluded that DW is statistically significantly correlated to construction labor productivity on activity, project, and national level (Araujo et al. 2020; Neve et al. 2020; Siriwardana et al. 2017).

CONCLUSION

This research aimed to conduct an extensive review to collect the largest sample of DW values in construction ever published and constitute a valid baseline of DW in construction, which could be applied for benchmark purposes. The research succeeded by identifying 474 case studies of DW measures origin from 72 different publications. The sample was confirmed to be a normal distribution with a mean DW value of 43.6%, with a standard deviation of 16.5%. An effect of these results is the outline of some recommendations for the lean construction community regards waste work time and construction site efficiency. The first recommendation is to apply a more stringent taxonomy for data collection in work sampling, including three categories, Direct Work, Indirect Work, and Waste Work. The second recommendation is to apply work sampling as much as possible to enhance a data-driven approach to flow optimization. Third and final recommendation is that the optimization should focus mainly on direct work and aim to increase this as much as possible, as indirect work has to be considered waste in the purest definition of lean.

REFERENCES

Araujo, L. O. C., Neto, N. R., and Caldas, C. H. (2020). "Analyzing the Correlation between Productivity Metrics." *Construction Research Congress 2020*.

Bølviken, T., & Kalsaas, B. T. (2011). "Discussion of Strategies for Measuring Workflow in Construction." *Proc. 19th Ann. Conf. Int. Group for Lean Constr., Lima, Peru.*

Bølviken, T., Rooke, J., and Koskela, L. (2014). "The Wastes of Production in Construction – a TFV Based Taxonomy." *Proc. 22nd Ann. Conf. Int. Group for Lean Constr., Oslo, Norway.*

Emdanat, S., Linnik, M., and Christian, D. (2016). "A Framework for Integrating Takt Planning, Last Planner System and Labor Tracking." *Proc. 24th Ann. Conf. Int. Group for Lean Constr., Boston, USA.*

Fireman, M. C. T., and Formoso, C. T. (2013). "Integrating Production and Quality Control: Monitoring Making-Do and Unfinished Work." *Proc. 21st Ann. Conf. Int. Group for Lean Constr., Fortaleza, Brazil.*

Fireman, M. C. T., and Saurin, T. A. (2020). "Chain of Wastes: The Moderating Role of Making-Do." *Proc. 28th Ann. Conf. Int. Group for Lean Constr., Berkeley, USA.*

Formoso, C., Isatto, E., & Hirota, E. (1999). "Method for Waste Control in the Building Industry." *Proc. 7th Ann. Conf. Int. Group for Lean Constr., Berkeley, USA.*

Frandson, A., Berghede, K., and Tommelein, I. D. (2013). "Takt Time Planning for Construction of Exterior Cladding." *Proc. 21st Ann. Conf. Int. Group for Lean Constr., Fortaleza, Brazil.*

Frandson, A., Berghede, K., and Tommelein, I. (2014). "Takt-Time Planning and the Last Planner." *Proc. 22nd Ann. Conf. Int. Group for Lean Constr., Oslo, Norway.*

Frandson, A. G., Seppänen, O., and Tommelein, I. D. (2015). "Comparison Between Location-Based Management and Takt Time Planning." *Proc. 23rd Ann. Conf. Int. Group for Lean Constr., Perth, Australia.*

Gong, J., Borcherding, J. D., and Caldas, C. H. (2011). "Effectiveness of craft time utilization in construction projects." *Const, Mgmt. & Eco.*, 29(July), 737-751.

Gouett, M., Hass, C., Goodrum, P., & Caldas, C. (2011). "Activity Analysis for Direct-Work Rate Improvement." *Const, Mgmt. & Eco*, 137(12), 1117-1124.

Kalsaas, B. T. (2010). "Work-Time Waste in Construction." *Proc. 18th Ann. Conf. Int. Group for Lean Constr., Hafia, Israel.*

Kalsaas, B. T. (2011). "On the Discourse of Measuring Work Flow Efficiency in Construction. A Detailed Work Sampling Method." *Proc. 19th Ann. Conf. Int. Group for Lean Constr., Lima, Peru.*

Kalsaas, B. T. (2012). "Further Work on Measuring Workflow in Construction Site Production." *Proc. 20th Ann. Conf. Int. Group for Lean Constr., San Diego, USA.*

Kalsaas, B. T. (2013). "Measuring Waste and Workflow in Construction." *Proc. 21st Ann. Conf. Int. Group for Lean Constr., Fortaleza, Brazil.*

Kalsaas, B. T., & Bolviken, T. (2010). "The Flow of Work in Construction: A Conceptual Discussion." *Proc. 18th Ann. Conf. Int. Group for Lean Constr., Hafia, Israel.*

Koskela, L. (1992). "Application of the new production philosophy to construction." CIFE Technical Report 72. Stanford University.

Koskela, L. (1999). "Management of Production in Construction: A Theoretical View." *Proc. 7th Ann. Conf. Int. Group for Lean Constr., Berkeley, USA.*

Koskela, L. (2004). "Making-Do — the Eighth Category of Waste." *Proc. 12th Ann. Conf. Int. Group for Lean Constr., Helsingør, Denmark.*

Koskela, L., Bølviken, T., & Rooke, J. (2013). "Which Are the Wastes of Construction?" *Proc. 21st Ann. Conf. Int. Group for Lean Constr., Fortaleza, Brazil.*

Macomber, H., and Howell, G. (2004). "The Two Great Wastes in Organizations." *Proc., Proc. 12th Ann. Conf. Int. Group for Lean Constr., Helsingør, Denmark.*

Moselhi, O., and Khan, Z. (2012). "Significance ranking of parameters impacting construction labour productivity." *Construction Innovation*, 12(3), 272-296.

Neve, H. H., and Wandahl, S. (2018). "Towards Identifying Making-Do as Lead Waste in Refurbishment Projects." *Proc. 26th Ann. Conf. Int. Group for Lean Constr., Chennai, India.*

Neve, H. H., Wandahl, S., Lindhard, S., Teizer, J., and Lerche, J. (2020). "Determining the Relationship between Direct Work and Construction Labor Productivity in North America: Four Decades of Insights." *Journal of Construction Engineering and Management*, 146(9), 04020110.

Neve, H. H., Wandahl, S., Lindhard, S., Teizer, J., and Lerche, J. (2020). "Learning to see value-adding and non-value-adding work time in renovation production systems." *Production Planning and Control*.

Ohno, T. (1988). "Toyota Production System." *Productivity Press*, New York

Polat, G., and Ballard, G. (2004). "Waste in Turkish Construction: Need for Lean Construction Techniques." *Proc., Proc. 12th Ann. Conf. Int. Group for Lean Constr., Helsingør, Denmark.*

Seppanen, O., Ballard, G., and Pesonen, S. (2010). "The Combination of Last Planner System and Location-Based Management System." *Proc. 18th Ann. Conf. Int. Group for Lean Constr., Hafia, Israel.*

Thomas, H. R. (1981). "Can work sampling lower construction costs." *Journal of Construction Division*, 107(2), 263-278.

Tommelein, I. D., and Li, A. E. Y. (1999). "Just-in-Time Concrete Delivery: Mapping Alternatives for Vertical Supply Chain Integration." *Proc. 7th Ann. Conf. Int. Group for Lean Constr., Berkeley, USA.*

Tommelein, I. D., and Weissenberger, M. (1999). "More Just-in-Time: Location of Buffers in Structural Steel Supply and Construction Processes." *Proc. 7th Ann. Conf. Int. Group for Lean Constr., Berkeley, USA.*

Collins, D., Johansen, A., Kalsaas, B. T., Temljotov-Salaj, A., and Hamdy, M. (2021). "Brought by Degrees: A Focus on the Current Indicators of Lean 'Smartness' in Smart Cities" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 167–176, doi.org/10.24928/2021/0156, online at iglc.net.

BROUGHT BY DEGREES: A FOCUS ON THE CURRENT INDICATORS OF LEAN 'SMARTNESS' IN SMART CITIES

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ABSTRACT

The purpose of this paper is to look at the indicators to which a city can be considered to be a smart city based upon the degree it meets specific indicators within the categories of *'Social Smartness', 'Technological Smartness'* and *'Environmental Smartness'*. The data collection for this paper was conducted through desk research in academic and non-academic articles and publications that focus on smart cities and their associated indicators. This study found out common factors based upon the indicators studied. '*Social Smartness*' had a focus on the quality of life, civic engagement and wellbeing. '*Technological Smartness*' was centric on flexible technology, well utilised and defined applied technology and data. '*Environmental Smartness*' was focused on optimisation, waste management and sustainable thinking. This study offers possibilities to advance Lean thinking by looking at indicators to attribute a degree of '*Smartness*' to cities which in turn will optimise the development and operation of a Smart City and Smart Districts.

KEYWORDS

Lean thinking, smart cities, smart cities indicators, social indicators, sustainability.

SMARTNESS IN SMART CITIES

With three-quarters of the world expected to be living in denser urban areas by 2050 (Alawadhi et al., 2012, p.40), it is vital to focus studies on sustainability, welfare and resource management on the experience within the world's cities. Historically, cities were protective entities for trade and growth with their primary needs being to protect their citizens from invaders, promote trade and ensure the people had enough sources to

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survive. In many respects (except the first point), these needs remain mostly unchanged. Lean was first coined by Krafcik (1988) addressing Toyota's production system. "The machine that changed the world" by Womack et al. (1990) was significant for the development of lean practices in western countries. A central contribution was also "Lean thinking. Banish waste and create wealth in your corporation" (Womack and Jones, 1996) and the "Toyota Way" (Liker, 2003).

In the 1990s Lean was brought into construction and the built environment (Koskela, 2000; Ballard, 2000). The ideas surrounding it with regards to reducing waste, increase flow and fostering productivity have existed since the beginning of the development of cities. A city is naturally not a whole entity in itself but is a scalable one with differing needs and considerations at the urban planning level, community level, building level and citizen level. This sustainability ambition is supported by radical and challenging goals, with the European Commission setting the goal of 100 Smart Cities in Europe by 2030 (EC, 2020, p.4). A goal as ambitious as this does not just require a robust definition of what constitutes a Smart City, but also benchmarks, indicators and holistic thinking. This thinking also has to be found at the district and neighbourhood level to understand the differences and bespokeness of smart initiatives. Whilst a study focusing on the indicators of what constitutes a smart city is not new, there is a deficit in terms of how this can be applied to 'indicators of smartness' as opposed to a more binary discussion on whether simply a city is smart or not. To cite an example, Castelnovo et al. (2016) state that a city can be smart depending on the degree to which it blends ICT, and smart governance (Castelnovo et al., 2016, p.735). Whilst this can be considered to be more of a binary absolute in terms of field compatibility, others offer similar binary outcomes but at different levels of the city. The European Commission (EC) for example has developed the '*Smart Readiness Indicator*' to establish whether a building could be considered smart or not (Castevolo et al., 2016). Whilst these indicators are less binary than those mentioned by Castelovo et al. (2016) they are at the building and not the city level. An increasingly developing field and concept that attempt to tackle these issues on multiples levels are that of Smart Cities. A challenge for scholars in this aspect (as is the case for other fields at a similar level of development) is that Smart Cities encompass many fields within it (such as urban planning, architecture, social sciences and facilities management) as well as suffer from the complications associated with it lacking a universally accepted definition. An increased focus on '*Smartness*' in the context of cities is becoming of increasing importance and relevance in modern development. This in turn places stresses on existing infrastructure as we scramble to find ways to ensure the safety of citizens, as well as ensure adequate access to safe water, food and energy. With this in mind, Lean thinking may be fruitful in terms of applying this to smart cities, especially when it comes to the processes of transforming the existing built environment to smart cities in a value-creating perspective. While the mainstream Lean construction researcher for the most part address production and customer value creation (e.g. Koskela, 2000; and Ballard, 2000), Herscovici (2018) take it further to smart cities and argues that Lean thinking encourages the quest for excellence by constantly re-evaluating and improving infrastructure whilst ensuring stakeholder value maximisation and removing unevenness and waste, with will foster Smart Cities growth but ensuring that new and existing processes operate under this model (Herscovici, 2018, pp.321-322). Our stand is the values we find in the smart city concept will benefit from organising the processes of transforming and maintain existing neighbourhoods and cities to be smarter. The two concepts fit well regarding principles (Skaar et al., 2020) like respect for people (Liker 2004), involvement (Ballard, 2000), learning (Kalsaas, 2012), relational contracts and Target Value Design (Zimina et al., 2012). In this paper, we will look at existing indicators of how smart a city can be, show if aspects of a city are smart, but also the indicators of 'smartness' a city can be considered to possess.

In this study we will address the following research questions:

- **Research Question 1 -** What are current indicators exist to gauge whether a city is smart?
- **Research Question 2 -** How can these indicators be applied to demonstrate smartness within a city?

Firstly, this paper will look into the methodological approach before moving onto theory regarding defining a smart city in the context of this paper, as well as indicators. The theoretical framework for this paper also orientates itself towards the principles, before moving onto the indicator of Smart Cities. The paper is then structured by dividing the indicators between the categories of *'Social', 'Technological', 'Environmental'* smartness. These categories were chosen due to the links between the common sustainability framework of the 'triple bottom line' as well as technological aspects that are more commonly understood in existing smart cities definitions The paper will then move on to provide a conceptual framework as to how this can be applied to give smart cities indicators of 'smartness'.

METHODOLOGY AND RESEARCH DESIGN

This paper is a literature review consisting of desk research conducted on literature from academic and non-academic sources. This literature review was compiled as part of the research project Citizens a Pilots in Smart Cities (CaPs).

Data Collection and Analysis

Literature was primarily sourced through Google Scholar in the case of academic literature, and Google in the case of non-academic literature, with the disciplines of project management, smart cities, urban planning and sustainability being the primary focuses for inclusion. The specific papers chosen for inclusion here were selected due to their status in respected peer-review journals and citation level as well as their publication from worldwide respected institutions such as the United Nations. This approach was taken concerning the fact that a new definition of '*smartness in smart cities*' is not possible in a paper of this length, however, there is significant scope to offer the beginning of a framework by which one could be developed in a further publication. The indicators were then organised under the categories of '*Socially Smart', 'Technologically Smart' and 'Environmentally Smart'*. The categories were chosen as a set that was a hybrid of the triple bottom line of sustainability ('economic', 'social' and 'environmental' sustainability) combined with the Deakin and Al Waer's (2011) '*Three Factors*' of what defines a smart city, which will be outlined in the next chapter. These three categories also act as a theoretical framework for the outcomes of the literature search and were sourced from a variety of publications (Deakin et al., 2011, p.141), (Joshi et al., 2016), (UN, 2017).

HOW TO ANALYSE THE SMARTNESS OF CITIES?

In this section, we will briefly out some definitions frameworks that will relevant for a contextual understanding of the findings in this paper.

Definition of Smart Cities

Whilst the study of smart cities is becoming increasingly established a discipline, it still suffers from the challenge associated with not having a universally accepted definition. For this study, the definition by Deakin and Al Waer (2011) have been used According to the authors, a smart city can be considered smart if it contains four factors. Firstly, the implementation of an extensive range of digital and electronic technologies in cities and their communities. Secondly, the usage of information technology to change the lives and work of people living in these areas. Thirdly, implementing a wider spread of the use of these technologies and others at the government level. And finally, using technology to bring people together to innovate and enhance knowledge (Deakin et al., 2011, p.141). In terms of a definition that reflects indicators more associated with sustainability, CityKeys published a report in 2017 in cooperation with the EU Commission and Horizon 2020 outline their definition. This definition follows the triple bottom line of sustainability of social, economic and environmental sustainability. In terms of what constitutes a Smart City, they state that it must improve the quality of life for its inhabitants (including commuters, students and visitors) (social), improve resource efficiency to decrease pressure in the environment (environmental), a green economy focused on innovation (economic) and develop local democracy and governance (social) (Bosch et al., 2017, p7).

Indicators

It is also important moving to understand what constitutes an indicator in the context of this paper. According to the Collins English dictionary, an indicator can be considered to be a “*measurement or value which gives you an idea of what something is like*” (Collins, 2021). Whilst this definition does not come from a scientific publication, it is relevant to this study in the sense that the authors consider an indicator to demonstrate whether a concept (such as a smart city) is what it claims to be by evaluating it against commonly accepted factors or processes that are the link to a broad definition of it. Aside from what an indicator is in a more literal sense, there are also different kinds of indicator that are placed in different areas of a process or system. Referring once again to CityKeys, their typology consists of ‘*Input Indicators*’ that refer to the resources needed for implementation of an activity, ‘*Process Indicators*’ to indicate whether an activity took place, ‘*Output Indicators*’ that add more detail concerning the product, ‘*Outcome Indicators*’ that refer to measuring the intermediate results generated by the outcome, and ‘*Impact Indicators*’ that measure the quality and long term results of the program (Bosch et al., 2017, p. 15).

INDICATORS OF SMARTNESS – THE FINDINGS

Socially Smart

Social indicators for the Smartness of cities is prevalent in both academic and industry literature. If a Smart City can be considered to be an investment in social capital to an extent (Purnomo et al., 2016, p.161), then social indicators are entrenched in a conceptual Smart Cities framework. Many such indicators can be found in academic literature. Purnomo et al. (2016) in their systematic literature review on Smart Cities discovered several social indicators. They categorised these indicators into six main sections, with generally 3 levels of more specific sub-indicators. In terms of relevant social indicators relevant to this section, they can consider being *‘Smart Living’ and ‘Smart People’*. ‘*Smart Living*’ contains the subcategories of *‘Social security and safety, ‘Housing Quality’* and *‘Public Transport System’*. The category of ‘*Smart People*’ contains the categories of '*Education System and Facilities*' and '*Creativity*' (Purnomo et al., 2016, p. 163). An interesting observation of these indicators is that many of the aspects of '*Smart Living*' could be considered to straddle both social and structural smartness categories, which further shows the challenges associated with looking for binary indicators. Malek et al. (2021) have also looked at socially-focused indicators, however from a more formalised citizen-centric perspective. The outcomes of their review reveal indicators that are almost as much do with civic governance as they are with social smartness. Their indicators *are 'Focus on citizens' needs, not just technology', 'Decision through consensus with citizens ', 'Learn from users/citizens', 'Power needs to be delegated', 'Freedom to participate', 'Volunteers needed', 'Build good relationships'* and *'mutual trust'* (Malek et al., 2021, p.10). When comparing the different indicators of both authors, it is indicative of social smartness being not just about respecting and improving social welfare in smart cities, but also ensuring that citizens engagement in this is well defined and applied. The European Commission are an example of a non-academic actor that has considered the social aspects of smart cities and has developed indicators for them. Whilst less specific and detailed than those found in the previous citation from academia, they describe their indicators in the form of 8 criteria of smart cities preparedness levels. Amongst these 8 are two socially relevant ones consisting *of 'citizen engagement* and *'social models'*. As with academic authors previously, this focuses both on a combination of wellbeing in a city and being civically accountable through citizen participation. The European Union have also considered these aspects but from a slightly different perspective of social innovation. In a 2012 report the Urbach section of the EU stated that can be achieved by three focuses – '*Social Demand Innovations*' (responding to social demands that haven't been traditionally addressed by the market of existing institutions), '*Societal Challenge*' (innovations for a society by integrating social, environmental and environmental aspects), and '*Systemic Change*' (encompassing the other two and achieving it through organisational development and the relationship between institutions and stakeholders) ('SMART CITIES Citizen Innovation in Smart Cities, 2012. p.6). Unlike previous indicators, these social innovation categories are clearer on their links to sustainability whilst still encompassing the themes of previous indicators.

Technologically Smart

When considering what constitutes a Smart City, many a core attribute is that of technological implementation in the wider cityscape. The leap in technology in cities as well as the devices themselves have seen considerable significant advancement in recent years, with visualisation mechanism, sensors, virtual reality, augmented reality and artificial intelligence all playing a part (Jamei, 2005). With this in mind, it is crucial to understand the incorporation of technological smartness. This is recognised by Borsekova et al. (2018), who states that for a city to be '*smart*' it should utilise technological capital (as well as human and collective capital) for the enhancement and development of the urban environment (Borsekova et al., 2018, p. 18).

In terms of indicators found in academic literature, there numerous aspects that can be cited, and a small selection of which shall be discussed here. Park et al. (2018) have Smart Cities indicators that cover several topics, including those related to technological smartness. They state that a major component of a Smart City is the integration of '*Key Industry*' and '*City Infrastructure*' as a component. Within '*Key Industry*' is Smart Buildings and Smart Facilities, whilst '*City Infrastructure*' contains operation systems, sensor networks and smart devices which in turn link to control systems, data analysis, web services and telecommunications platforms (Park et al., 2018, p.2). These indicators (as superficially indicative as they are due to lack of KPI's) do not just describe specific technological services, but also a degree of how they feed into real work possibilities for citizens (e.g. interactive web services). To cite another example from academia, Joshi et al. (2016) also developed their indicators, which also encompass the technological. They propose six pillars that constitute a Smart City – *'Social', 'Management', 'Economy', 'Legal', 'Technological', and 'Sustainability'* (Joshi et al., 2016, p.903). With regards to the technological pillar, they claim that this must encompass several qualities. They cite these as *'Big Data', 'Interconnected devices', 'Information and Communication Technology'* and an '*Amalgamation of these Drivers*' (Joshi et al., 2016, p.906). Indicators of technological smartness can also be found in literature found outside of academia. CityKeys state in their report their own set of indicators. Several pages into the report they offer indicators on three categories – *'Input Indicators', 'Process Indicators'* and *'Output Indicators'*. In terms of those considered relevant for technological smartness, in '*Process Indicators*' they have diversity in ways to contact the municipality, improved digital literacy of the elderly and the standardisation of interfaces. In '*Output Indicators'* contain the openness and quality of data sets, parking guidance systems, and the likes of smart meters (Bosch et al., 2017, pp.16-27). As mentioned earlier, building-related Smart City Readiness indicators have been developed in the conjunction with the EC. As also mentioned, whilst designed to consider the building level, they could be considered applicable to the wider city level. The expression of indicators is much more focused on functionality in the context of smart city readiness, as well as flexibility. These functionality aspects are the ability to maintain energy performance and operation, adaptive buildings that are responsive to the needs of occupants as well as be flexible in terms of energy (EC, 2019, P.6). In terms of how this can be applied to technological smartness at the city level, these indicate that a technologically smart city is energy conscious, flexible and adaptive to the needs of citizens through a well-defined methodology.

Environmental Smartness in Urban Areas

In many theoretical and practical discussions on Smart Cities, it is becoming increasingly important not just to consider, but to entrench sustainability and environmental considerations. Six sustainability indicators were published by Petrova-Antonova et al. (2018) which were specifically tailored for consideration in the context of a smart city. They describe this in the context of a larger encompassing thematic area called '*Smart Nature*'. These six categories consist of *'Water', 'Pollution', 'Waste', 'Energy', 'Land'* and '*Green Environment*' (Petrova-Antonova et al., 2018, p. 488). In later more detailed descriptions of these indicators, it is clear that they intend not just to improve a Smart Cities environmental credibility, but also to improve the quality of life of citizens by reducing waste and optimising processes. Verma et al. (2018) are even more clear with regards to their indicators by stating the words 'sustainability indicators' clearly in their subject headline. In their article, they define sustainable urban development as having the qualities of '*improving quality of life through social interaction', 'easy access through a wide range of services, 'minimising energy consumption, 'sustainable transport'* and '*environmental protection and restoration*' (Verma et al., 2018, p.284). As with the previous citation, there is a clear link between sustainability being not just about environmental improvement, but also well-being and waste reduction. It is also important to consider not just smart cities on the city level, the component aspects at the building level that also combine the likes of technology. One example is Green Leasing where smart metres, technology and human behaviour come together to encourage sustainable building development in the rental market (Collins, 2018, p. 185). In Table 1 we have summarised the key principles based on the literature review, which are related to a selection of Lean principles.

Table 1 How to define a smart city

Socially smart	Technologically smart	Environmentally Smart
Citizen Participation	Feasible technological infrastructure	Initiatives to lower the carbon footprint
Educated and upskilled citizens	Well managed and utilised data	Utilise data and technology to reduce emissions on roads and in buildings
People-Centred Processes	Possibilities to learn from smart systems	A more environmentally considerate society based on improved resource management and security
High quality of life and consideration of well being	Safety and resource management a priority	Focus on quality of life in a more sustainable society
Technologically engaged citizens	Respect for data, privacy and well being	
Smart Governance		

The listed principles in Table 1 is output or outcome-based. Koskela and Kagioglou (2006) understand output as a "*thing*", e.g. a new building or a neighbourhood, while outcome includes the "processes" of usage of it and the value regarding operation and maintenance. We can also expand that outcome aspect to external impacts on the environment, city life and business. We see the Lean associated with smart cities foremost as guiding principles (Skaar et al., 2020) to encourage the output/outcome addressed in Table 1. Lean principles can guide us regarding how to organise and conduct complex creative and rather wicked design and development processes (Kalsaas, 2020) to reach the values in Smart cities. Moreover, the transformation processes should be based on the same values as the outcome we want to achieve, which is the case between Smart cities and Lean. Keywords in that context is respect for people, involvement, learning, continuous improvement and more radical innovation (Koskela, 1992), reduce waste, creating value for the participants and end-users.

CONCLUDING DISCUSSION

This paper has intended to illustrate which indicators can be used to determine the smartness of cities as well as show the commonalities between them to gauge the degree to which a city can be considered Smart based on the implementation of them.

Research Question 1 – What are the current indicators?

In terms of current indicators, however, many common factors exist between them that allows for a degree of simplification for later utility.

Table 2 – Indicator Commonalities

Smartness Categories	Thematic Area	Indicators
Socially smartness	Civic Engagement	Public participation, Citizen centred city development, Easy to use digital engagement, Smart Governance
	Quality of Life	Services access, Improvements to health, Increased mobility, Infrastructure
	Wellbeing	Happiness, connected services, change management
Technologically Smartness	Flexible Technology	Adaptive to changing needs, multi-use data, accessible technology
	Utilisation Data	Define usage, respect for privacy
	Defined Application	Stakeholder relevant, data plan, citizen access to technology and data
Environmentally smartness	Optimisation/Tradeoff	Ongoing reappraisal of infrastructure, constantly adjustment to resource use
	Waste Management	Recycling, building adaption and reuse, Citywide waste plan
	Sustainable Thinking	Reducing emissions, advanced public transport infrastructure, microgeneration, renewable energy

Table 2 represents not the indicators overall, but the commonalities that can be gauged to interpret the degree to which a city can be considered smart. By ensuring that a city has the possibility of holistically meeting some of these wider indicative categories it can turn can more holistically smart. In this table, the reader can see the indicative properties of each thematic area, which offers scope for further research the explore this ‘smartness’ with KPI’s and more advanced benchmarking. In the context of this paper, however, table 2 offers weight and validity to these thematic areas beyond the themes alone.

Research Question 2 - How can these indicators be applied to demonstrate smartness?

An attempt by a city to meet with these aspects ‘inter category’ can have the possibility to improve the indicators where a city can be considered to be smart. In the case of Socially Smart, a city with a high level of citizen engagement and participation aimed at improving the well-being quality of life of its citizens can be considered successful. If a city contains a high level of flexible technology with well utilised and applied supporting data, then it can be considered to be technologically smart. An environmentally smart city can gauge its level of smartness on the degree to which it reduced waste, optimised services and quality of life with environmental considerations at its heart. This paper has shown that not all Smart Cities are created equal and that it needs to incorporate a variety of indicators in many themes which in essence are impossible to completely cover in a paper of this length. However, what this indicative data has demonstrated is that there is a real possibility in research not just to expand the scope and definition of what a smart city is, but also to show that no definition is binary and a city can be possibly ‘*smart by degrees*’.

It would be interesting in further research to look from an increasingly micro perspective to see if city districts can have different levels of smartness and that each district or city will need a bespoke framework of its own by which to improve smartness. It is hoped that academics and non-academic researchers and visionaries can use the data in this paper not just to further entrench Lean thinking into smart cities, but possibly further incorporate other fields into the discussions and view cities not just as projects, but as canvases.

REFERENCES

Alawadhi, S., et al. (2012). *Building understanding of smart city initiatives*. International conference on electronic government, Springer.

Ballard, G. (2000). The Last Planner System of Production Control. School of Civil Engineering, The University of Birmingham, UK.

Borsekova, K., et al. (2018). "Functionality between the size and indicators of smart cities: A research challenge with policy implications." *Cities*, 78: 17-26.

Bosch. P, S. J., Vera Rovers (TNO), Hans-Martin Neumann (AIT), Miimu and A. a. A. H. (VTT). (2017). CITYkeys indicators for smart city projects and smart cities. dataplan.info, CityKeys in conjunction with the EU Commission and Horizon 2020.

Carneiro, S. B. d. M., et al. (2012). *Lean and green: a relationship matrix*, Annual Conference of the International Group for Lean Construction.

Castelnovo, W., et al. (2016). "Smart cities governance: The need for a holistic approach to assessing urban participatory policy making." *Social Science Computer Review*, 34 (6): 724-739.

Collins (2021). "Definition of 'indicator'." Retrieved 19th February, 2021, from https://www.collinsdictionary.com/dictionary/english/indicator#:~:text=An%20indicator%20is%20a%20measurement,guide%20More%20Synonyms%20of%20indicator.

Collins, D. (2018). "Green leases and green leasing in theory and in practice: a state of the art review." *Facilities*.

Deakin, M. and H. Al Waer (2011). "From intelligent to smart cities." *Intelligent Buildings International*, 3(3): 140-152.

EC (2019). Discussion document – definition and calculation methodology of the smart readiness indicator. ec.europa.eu, European Commission: 15.

Herscovici, A. (2018). "New development: Lean Thinking in smart cities." *Public Money & Management*, 38(4): 320-324.

Kalsaas, B. T. (2012). The Last Planner System Style of Planning: Its Basis in Learning Theory. Journal of Engineering, Project, and Production Management, 2(2), 88- 100. doi:10.32738/jeppm.201207.0005.

Kalsaas, B.T. (2020). Lean Construction: A management model for interdependencies in detailed design. In, *Tzortzopoulos*, P., Kagioglon, M. and Koskela, L. (Eds), Lean Construction. Core Concepts and New Frontiers, (pp. 209-229). Huddersfield: Routledge.

Koskela, L. (1992). Application of the new production philosophy to construction, CIFE Technical report #72, Stanford University.

Koskela, L. (2000). An Exploration towards a Production Theory and its Application to Construction. VTT Technical Research Centre of Finland.

Koskela, L. and M. Kagioglou (2006). On the Metaphysics of Management. 14th Annual Conference of the International Group for Lean Construction, Santiago, Chile.

Krafcik, J. F. (1988). Triumph of the Lean Production System. I Sloan Management Review, Volume 30.

Liker, J. K. (2004). The Toyota way : 14 management principles from the world's greatest manufacturer: New York : McGraw-Hill, [2004] ©2004.

IEC (2019). "Smart and Sustainable Cities." Retrieved 22 May, 2019, from https://www.iec.ch/smartcitie.

Jamei, E., et al. (2017). "Investigating the role of virtual reality in planning for sustainable smart cities." *Sustainability* 9(11): 2006.

Joshi, S., et al. (2016). "Developing smart cities: An integrated framework." Procedia *Computer Science*, 93: 902-909.

Malek, J. A., et al. (2021). "Social Inclusion Indicators for Building Citizen-Centric Smart Cities: A Systematic Literature Review." *Sustainability* 13(1): 376.

Park, E., et al. (2018). "The role of Internet of Things (IoT) in smart cities: Technology roadmap-oriented approaches." *Sustainability* 10(5): 1388.

Petrova-Antonova, D. and S. Ilieva (2018). *Smart Cities Evaluation–A Survey of Performance and Sustainability Indicators*. 2018 44th Euromicro Conference on Software Engineering and Advanced Applications (SEAA), IEEE.

Purnomo, F. and H. Prabowo (2016). "Smart city indicators: A systematic literature review." *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)* 8(3): 161-164.

Ramsden. P. (2012). *Smart cities, Citizen Innovation in Smart Cities*. Urbact.eu, European Union.

Skaar, J. , Bølviken, T. , Koskela, L. & Kalsaas, B. T. 2020, 'Principles as a Bridge Between Theory and Practice' In:, *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC).* Berkeley, California, USA, 6-10 Jul 2020. pp 1-12.

Zimina, D., Ballard, G., & Pasquire, C. (2012). Target value design: using collaboration and a lean approach to reduce construction cost. Construction Management and Economics, 30(5), 383-398.

UN (2017). Collection Methodology for Key Performance Indicators for Smart Sustainable Cities. unece.org, United 4 Smart Sustainable Cities.

Verma, P. and A. Raghubanshi (2018). "Urban sustainability indicators: Challenges and opportunities." *Ecological indicators*, 93: 282-291.

Womack, P. & Jones, D. T. (1996). Lean Thinking. Banish waste and create wealth in your corporation, London: Simon & Schuster.

Womack, J. P., Jones, D. T., & Roos, D. (1990). The Machine That Changed the World, New York: Harper Collins Publishers.

Wickramasekara, A. N., Gonzalez, V. A., O'Sullivan, M., Walker, C. G., and Abdelmegid, M. A. (2021). "Exploring Controlled Experimental Settings for Lean Construction Research." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 177–186, doi.org/10.24928/2021/0170, online at iglc.net.

EXPLORING CONTROLLED EXPERIMENTAL SETTINGS FOR LEAN CONSTRUCTION RESEARCH

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ABSTRACT

In recent years, an increasing number of research articles have been published to demonstrate the benefits of applying Lean tools using different approaches within the construction domain. However, there is a need to enhance the effectiveness of Lean Construction (LC) research by incorporating it within a controlled experimental environment. Due to the fact that many compound effects impact on the variable(s) of interest, it is challenging to develop controlled experiments in real construction projects. This controlled experimental environment can be achieved by developing a Serious Game-based Experimental Setting (SGES) for construction. For this paper, a literature review was conducted to identify synergies between the Agile Project Management (APM), Design Thinking, Lean Start-up and Design Science Research Methodology (DSRM) for establishing effective SGESs for construction management. We found that little research used Serious Games to establish controlled experiments for construction management. In conclusion, we propose 7 research questions to guide the development of SGESs for construction project management research in future.

KEYWORDS

Lean construction, design science, integration, collaboration, experiments.

INTRODUCTION

According to a review of recent Lean Construction (LC) literature in relation to the development of artifacts, such as conceptual frameworks, it is clear that researchers are using different technologies and processes, such as reliable commitment modelling (González et al. 2010), building information modelling (Sacks et al. 2013) and computer simulation (Abdelmegid et al. 2019) with Lean tools, such as the Last Planner® System.

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Also, it can be noted that effectiveness of such artifacts has not been tested in controlled experimental environments.

On the other hand, research groups who propose new artifacts in various domains, including disaster preparedness (Feng et al. 2020), IT education (Montes et al. 2021), and project management (Rumeser and Emsley 2019), have been using controlled experiments with serious games to improve the accuracy of research findings. The goal of a controlled experiment is to manipulate the variable(s) of interest while controlling all other variables that exist in the experimental environment (Pelcin 1997). However, within the LC literature, no research has been found that utilized controlled experiments with serious games. Therefore, we argue that the validity of LC research can be enhanced by introducing controlled experimental environments with serious games for LC research. Many outside factors, such as weather, work performance and supply fluctuations (AbouRizk et al. 2011), influence construction operations and impact on the variable(s) of interest, so it is challenging to develop controlled experiments in real construction projects. Therefore, we propose the use of a Serious Game-based Experimental Setting (SGES), in which features of a real construction project can be presented, controlled and replicated (to a certain extent), in order to conduct controlled experiments.

In order to utilize serious games within experimental settings for LC research, there is a need for an appropriate research methodology. Koskela (2008) argues that construction management is a form of design science because it helps to solve industry-related problems while contributing to knowledge. Also, Jarvinen (2004, as cited in Koskela, 2008) states that if a research question contains one of the terms *design*, *build*, *change*, *improve*, *develop*, *enhance*, *maintain*, *extend*, *correct*, *adjust* or *introduce*, the associated research can be considered to be design science research. Therefore, we argue that the Design Science Research Methodology (DSRM) can be an appropriate research method for LC research intending to develop artifacts. Peffers et al. (2007) presented a framework for DSRM that consists of six major phases: (1) problem identification and motivation; (2) defining the objectives for a solution; (3) design and development; (4) demonstration; (5) evaluation; and (6) communication. An artifact of the research is created during the 3rd phase, during which a serious game can be developed for better representation of the artifact (Mateevitsi et al. 2008). Serious games can be used to demonstrate the applicability of the artifact not only for the 3rd phase, but also for the 4th and 5th phases. A serious game can also be used to evaluate that artifact by using experiments and incorporating user engagement (Kato and de Klerk 2017). There are explicit synergies between serious games and DSRM towards the development of SGES.

Accordingly, the objective of this paper is to explore theoretically the development of a framework to setup SGESs, supported by the integration of Design Thinking, Lean Stat-up and Agile Project Management (APM) with Design Science Research Methodology (DSRM). To discover the existing relationships between these concepts, a literature review was carried out as the research method within the Scopus database using combinations of the following keywords: “controlled experiments,” “design thinking,” “lean start-up,” “agile,” and “design science research methodology” within the titles, abstracts, and keywords. Also, forward and backward snowballing of references were used to ensure inclusivity of the results. This is an exploratory conceptual paper, and as such, we haven’t stated a method as logic rationing has been applied to literature findings with no data analysis (i.e.,Torp et al. 2018).

LITERATURE REVIEW

In this section, we briefly introduce APM, Design Thinking, Lean Stat-up, serious games and DSRM, and report previous research on the available integrations of some of these processes. The aim is to emphasize the advantages of using those approaches in combination, which is useful for the efficient development of SGES, and facilitates conducting controlled experiments in the virtual environment with regards to LC artifacts.

AGILE PROJECT MANAGEMENT (APM)

APM is the best option in low-volume, high-variety, and highly dynamic environments (Mostafa et al. 2016). APM is based on 4 values and 12 principles (Beck et al. 2001). Agile places value on: (1) individuals and interactions over processes and tools; (2) working software over comprehensive documentation; (3) customer collaboration over contract negotiation, and (4) responding to change over following a plan. In addition, there are a number of principles that support the Agile values, including: place the highest priority on satisfying the customer through early and continuous delivery of valuable software, welcome changing requirements even late in development, deliver working software frequently from a couple of weeks to a couple of months with a preference for the shorter timescale, convey information effectively to and within a development team using face-to-face conversations, use working software as the primary measure of progress, and maintain simplicity (Beck et al. 2001).

Accordingly, since agile is a set of values and principles, it can be argued that agile provides a common foundation for making decisions effectively in software development. Abrahamsson et al. (2002) reported 8 different methods for software development based on agile values and principles. Out of those, Scrum is the most popular agile method among software developers (Rodríguez et al. 2012). Therefore, this research considers the scrum method to develop SGES. Some of the management practices and tools used in scrum are: (1) product backlog; (2) sprint; (3) sprint planning; (4) sprint review meeting; and (5) sprint retrospective meeting.

DESIGN THINKING

Design Thinking is an iterative and non-linear process for innovation which integrates human, business, and technological factors into problem forming, solving and design. Design Thinking consists of five major stages (Plattner et al. 2011). The first stage is to 'Empathize', which aims to fully understand the problem, stakeholders affected by the problem, relevant context, and its root causes as quickly as possible. To do this, the Design Thinking team can gather information in various ways, such as conducting searches, reviewing the literature, interviewing stakeholders and observing their behaviours. Based on analysis of information gathered, in the second stage ('Need-finding and benchmarking') the Design Thinking team can recognize and define the problem(s) faced by the stakeholders. 'Ideate' is the following stage, where the Design Thinking team produces different solutions that can solve any real problems identified in the previous stage. Brainstorming is a great way to generate user-centred solutions. The fourth stage is 'Prototype', which is defined by Houde and Hill (1997) as "any representation of a design idea, regardless of a medium". With the solution agreed by the team during the Ideate phase, a prototype is developed during this stage. The final stage is to 'Test', during which feedback about the prototype is collected from users.

After the Test stage, and based on feedback received from users, the Design Thinking team must go back to previous stages with the aim of upgrading the prototype to one suitable for solving the problems faced by users.

LEAN STARTUP

Lean Stat-up is a “set of practices for helping entrepreneurs increase their odds of building a successful start-up. Core components of Lean Startup are the Minimum Viable Product (MVP) and the build-measure-learn loop” (Ries 2011). According to Ries (2011) the Minimum Viable Product (MVP) is “the version of the product built in the beginning with a minimum amount of effort and the least amount of development time”. The aim of the MVP is to start the learning process, not to reach the end point of development. So, the concept of the MVP is key to the Lean Start-up approach and forces teams to focus on the most important features of a product that will bring value to the customer. Next, the Build-measure-learn loop aims to convert ideas into a product, measure responses of customers, and understand whether to pivot or proceed. Pivot is a type of change designed to assess a different fundamental hypothesis of the product.

SERIOUS GAMES

Games are purposefully designed to challenge the human imagination (Arnold et al. 2013). According to Abt (as cited in Michael and Chen 2006), in a game, players assume realistic roles, face problems, develop strategies, make decisions, and get fast feedback on the results of their actions. Michael and Chen (2006) defined serious games as “games in which education (in its various forms) is the primary goal, rather than entertainment”. Also, they stated that games provide the opportunity to learn something without the cost of real-world consequences or errors. In addition to learning, serious games are used as an assessment tool in different fields, such as education and health, with higher validity and data capturing features (Kato and de Klerk 2017).

DESIGN SCIENCE RESEARCH METHODOLOGY (DSRM)

Peffers et al. (2007) presented a methodology called DSRM, which is an iterative process for design science research. DSRM begins with four possible research entry points: (1) problem centred initiation; (2) objective centred initiation; (3) design and development centred initiation; and (4) client centred initiation. Irrespective of the point of entry, the first stage is ‘Problem Identification and Motivation’, which aims to specify the research problem; the second is to justify the significance of the solution. Based on the problem definition, objectives for a feasible solution are developed. Objectives can be quantitative or qualitative. Also, knowledge of existing solutions to the defined problem is essential for this stage, and is known as ‘Define objectives of a solution’. ‘Design and Development’ is the third stage, during which an artifact is developed as a solution idea. Models, methods, new properties of social, technical and/or informational resources are some of the examples of artifacts which can be embedded within a research contribution. The fourth stage is ‘Demonstration’, during which the applicability of the artifact is demonstrated. One or more instances of the problem must be able to be solved in this phase. This can be achieved by conducting experiments, case studies, proofs or other relevant activities. The fifth stage is ‘Evaluation’. In this stage, the performance of the artifact is measured to solve the defined problem. Objectives of the research are compared with the actual performance of the artifact generated in the demonstration phase. For evaluation of the artifact, feedback from participants and functionalities of the artifact can be used. The final stage is 'Communication', in which the solution with its utility and novelty, and its impact on the researchers and industry practitioners, are communicated.

INTEGRATION OF APM WITH DESIGN THINKING

Häger et al. (2015) presented a model (DT@Scrum) that integrates Design Thinking with Scrum, which is guided by APM. It comprises of three phases of operations. The first phase, Design thinking, focuses predominantly on Design Thinking activities; The second phase, Initial development, balances both design thinking and development activities. The third phase, Fully integrated, puts more emphasis on development. The aim of these phases was to enrich the planning of product development through innovative and user-centred ideas of Design Thinking in the beginning of the process which in turn results in a better understanding of the requirements of the software to be built.

INTEGRATION OF APM, DESIGN THINKING AND LEAN STAT-UP

Hildenbrand and Meyer (2012) linked Design Thinking and Lean Stat-up to APM in order to enhance software development for businesses. In their study, they emphasized the usefulness of Design Thinking to initiate the development process based on validated customer problems, and the importance of agile practices and lean thinking in the development of the best appropriate process. Grossman-Kahn and Rosensweig (2012) also proposed a design-led, multidisciplinary approach, the Nordstorm model, consisting of human-centred, collaborative, failure embracing, prototype-driven innovation mindsets and practices that link Design Thinking, Lean Stat-up, and APM. These authors demonstrated the scalability of that approach among cross-functional teams throughout development organisations. Paula and Araújo (2016) presented a new model by improving the Nordstorm model. According to this study, they proposed the followings: (1) User experience should be validated during the prototype phase with an interface that is closest to the final product; and (2) Design Thinking elements should be used throughout the entire development process. After performing a cross-case analysis of previous integrations between APM, Design Thinking and Lean Stat-up, Dobrigkeit and Paula (2017) presented another model called InnoDev, to improve the innovativeness in IT development. InnoDev consists of three phases: (1) Design Thinking; (2) Initial Development; and (3) Development. They argue that InnoDev is flexible enough for different business settings.

After analysing the features of the aforementioned process models, we can identify that all the Design Thinking phases, and elements of Lean Stat-up, such as MVP, build-measure-learn loop and pivot; and agile practices, such as scrum can be used to develop efficient software based on human-centred solutions. Therefore, we argue that the integration of the aforementioned management and development approaches can be used for the development of effective serious games. Also, serious games can be used as a tool for assessments incorporating user engagement without having real world consequences. Thus, serious games can be used with construction practitioners for developing CEs in a virtual environment without affecting construction operations' complex and dynamic nature. In addition, DSRM provides a methodological support to generate knowledge for LC research in relation to development of artifacts.

THEORETICAL FRAMEWORK TO SUPPORT SGES IN LC RESEARCH

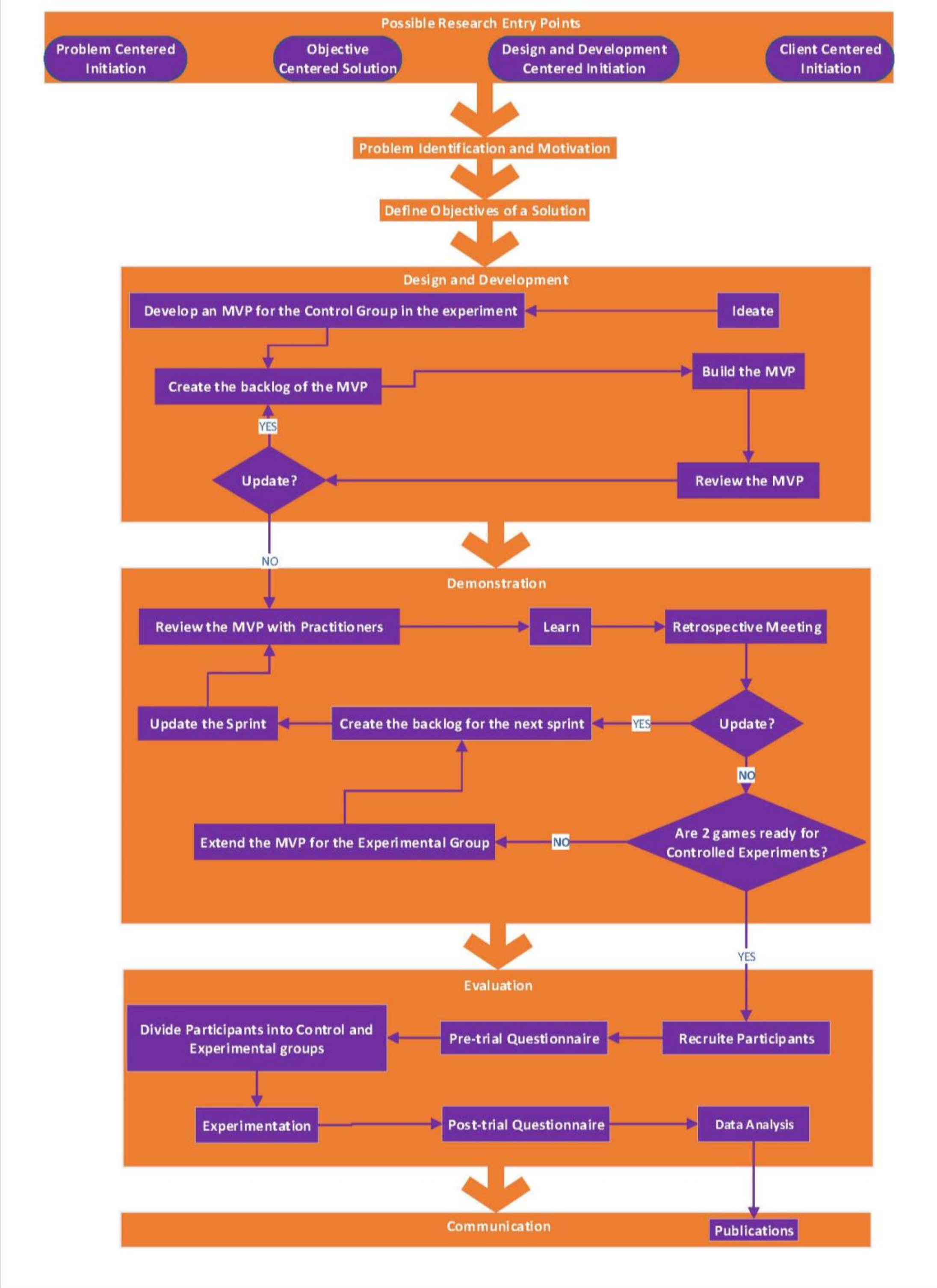

Figure 1: Conceptual integration framework for SGES

We argue that a framework that integrates DSRM, Design Thinking, Lean Stat-up and APM is useful in the development of a SGES, which is a novel methodology for experimenting artifacts, such as any designed object, including any design object, such as models, constructs, methods or new properties of technical, social or informational resources (Peffers et al. 2007), enriched with innovative solutions to real-world construction problems while also contributing to the knowledge of construction management. This approach, to a great extent, eliminates barriers to effectively testing hypotheses by providing an environment for controlled experiments in LC research.

The framework, shown in Figure 1, begins with the same four possible research entry points and the first two stages, as described in the DSRM (Peffers et al. 2007). Next, the experimental setting moves to the design and development stage. We argue that this stage should begin with the Ideate step in Design Thinking, during which a number of user-centred solutions can be generated through activities, such as brainstorming (Plattner et al. 2011). As the output of this step, we suggest the development of conceptual frameworks for two serious games that are used for CEs: (1) one game for the control group; and (2) the other game for the experimental group. We suggest demonstrating the applicability of the solution from the framework of the serious game played by the experimental group compared to the framework of the serious game played by the control group. The development of an MVP (Ries 2011) for the serious game for the players of the control group can then be initiated. As an MVP, we propose to develop the storyline, which presents the game content in a structured manner (Göbel and Mehm 2013), for that serious game. The storyline can be developed by establishing its product backlog, which is the work to be carried out to develop a product based on existing knowledge (Abrahamsson et al. 2002). After developing the storyline, it should then be reviewed by a team of domain experts in terms of usefulness, usability, credibility, desirability and value that influence the user experience. During the review, experts can propose further improvements of the MVP. Based on their suggestions, a new backlog can be created to upgrade the MVP. In this way, the initial storyline can be upgraded until the team of experts are satisfied. In order to make this process more efficient, researchers can use APM practices, i.e. scrum (Abrahamsson et al. 2002).

Subsequently, the demonstration stage is initiated, during which the interactive storyline, which was finalized by the domain experts, is further refined by exposing it to a team consisting of construction practitioners. We propose to use a tool, such as articulate storyline (Suppan et al. 2020), to perform the review process efficiently. Based on the review provided by the construction practitioners, the research team can learn how the existing storyline can be further improved iteratively, by applying the build-measure-learn loop suggested by (Ries 2011). Before starting the improvement process, the research team can organize a retrospective meeting which is a best practice of APM (Abrahamsson et al. 2002) to discuss how to improve the productivity of their serious game development process. Based on the outcome of the meeting, the research team can develop a backlog for further improvements of the interactive storyline. Accordingly, the next sprint of the storyline can be developed and demonstrated to the same team of construction practitioners. We suggest this sprint development process be repeated, build-measure-learn suggested by (Ries 2011) until the storyline is transformed into a serious game that can be used for the players of the control group of the experiment to the satisfaction of construction practitioners in terms of usefulness, usability, credibility, desirability and value that influence the user experience. After developing the serious game for the players of the control group, the same serious game can be further extended so that it is suitable for participants of the experimental group. We propose to achieve this by changing game elements relevant for the variable(s) to be tested during the CE. These elements can be extracted from the conceptual framework designed for the experimental group in the Ideate step. To make the serious game ready for the experimental group, the same development approach which combines agile practices and lean start-up elements, as was done for the controlled group, can be applied.

The fourth stage of the experimental setting is evaluation, during which the CE is conducted. This stage begins with recruiting appropriate participants to play both serious games. After recruitment, the participants should be provided with a tutorial about the gaming environment to familiarize them with the game's software and hardware. Next, a pre-trial questionnaire should gather the participants' demographics and other research-related information. The participants should then be divided into the control group and experimental group Then, the experiment can be started during which each group plays one of the two games (that were finalized in the previous stages). After the experiment, another post-trial questionnaire should be distributed to both groups to gather data regarding their user experience. Also, in-game performance of participants should be gathered by analyzing video recordings of their gameplay. Finally, responses of both groups can be assessed using appropriate analytical techniques for testing the performance of the experimental group.

The final stage is communication, which was extracted by DSRM (Peffers et al. 2007). In this stage, the solution to the real-world construction problem, with its utility, novelty, and impact on both researchers and industry practitioners via the SGES can be communicated through publications.

For example, suppose a researcher wants to assess the impact of the pull system. In that case, this methodology can be applied by developing two serious games representing a construction project: one representing the pull system and the experimental case, while the other representing the push system and the control case. During the experiment, two games generate production costs, and those can be used to test a hypothesis that the pull system reduces the production cost over the push system, while controlling other compound effects. This is impossible with traditional methods, such as case studies.

CONCLUSIONS

We propose a new methodology for conducting CEs in LC research: SGESs. We present a framework for developing a SGES that integrates Design Thinking, Lean Stat-up, APM and DSRM and that was developed using knowledge from a review of previous research integrating subsets of Design Thinking, Lean Stat-up and APM. Integrating Design Thinking, SL and APM enables efficiently developed serious games to be embedded within DSRM, providing a SGES for LC researchers. This SGES framework can be utilised to solve more industry-specific, real-world problems faced by practitioners because SGESs allow for the participation of construction practitioners. Hence, the proposed SGES framework is an innovative contribution to LC knowledge and will also streamline further contributions by enabling CEs.

In order to begin the next step in developing this SGES framework, seven research questions have been formulated to garner feedback from the IGLC community: (1) How can game design elements, game dynamics and game mechanics be determined to develop useful serious games for experiments? (2) How can participants be chosen for such experiments? (3) How can the group sizes be quantified for the control and experimental groups? (4) How can participants be allocated to control and experimental groups? (5) What types of data should be gathered during the experiment? (6) What methods can be used to collect data during the experiments? (7) What analytical techniques can be used to test research hypotheses? Based on the feedback from IGLC, the SGES framework can be finalized so that it can be used to carry out CEs related to LC research.

REFERENCES

Abdelmegid, M. A., González, V. A., O'Sullivan, M., Walker, C. G., Poshdar, M., and Alarcón, L. F. (2019). "Establishing a Link Between the Last Planner System and Simulation: A Conceptual Framework." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*, 335–246.

AbouRizk, S., Halpin, D., Mohamed, Y., and Hermann, U. (2011). "Research in Modeling and Simulation for Improving Construction Engineering Operations." *Journal of Construction Engineering and Management*, 137(10), 843–852.

Abrahamsson, P., Salo, O., Ronkainen, J., and Warsta, J. (2002). *Agile software development methods: Review and analysis*. *VTT Publications*.

Arnold, S., Fujima, J., and Jantke, K. P. (2013). "Storyboarding Serious Games for Large-scale Training Applications." *Proceedings of the 5th International Conference on Computer Supported Education*, SciTePress - Science and and Technology Publications, 651–655.

Beck, K., Beedle, M., Bennekum, A. van, Cockburn, A., Cunningham, W., Fowler, M., Grenning, J., Highsmith, J., Hunt, A., Jeffries, R., Kern, J., and Marick, B. (2001). *Manifesto for Agile Software Development*. *The Agile Alliance*.

Dobrigkeit, F., and De Paula, D. (2017). "The best of three worlds -The creation of innodev a software development approach that integrates design thinking, scrum and lean startup." *Proceedings of the International Conference on Engineering Design, ICED*, 8(DS87-8), 319–328.

Feng, Z., González, V. A., Mutch, C., Amor, R., and Cabrera-Guerrero, G. (2020). "Instructional mechanisms in immersive virtual reality serious games: Earthquake emergency training for children." *Journal of Computer Assisted Learning*, (October), 1–15.

Göbel, S., and Mehm, F. (2013). "Personalized, Adaptive Digital Educational Games using Narrative Game-Based Learning Objects." *K-12 Education*, IGI Global, 281–291.

González, V., Alarcón, L. F., Maturana, S., Mundaca, F., and Bustamante, J. (2010). "Improving Planning Reliability and Project Performance Using the Reliable Commitment Model." *Journal of Construction Engineering and Management*, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Auckland, New Zealand, 136(10), 1129–1139.

Grossman-Kahn, B. Rosensweig, R. R. (2012). "SKIP THE SILVER BULLET: DRIVING INNOVATION THROUGH SMALL BETS AND DIVERSE PRACTICES." *International Design Management Research Conference*, BOSTON, 815–829.

Häger, F., Kowark, T., Krüger, J., Vetterli, C., Übernickel, F., and Uflacker, M. (2015). "DT@Scrum: Integrating Design Thinking with Software Development Processes." 263–289.

Hildenbrand, T., and Meyer, J. (2012). "Intertwining Lean and Design Thinking: Software Product Development from Empathy to Shipment." 217–237.

HOUDE, S., and HILL, C. (1997). "What do Prototypes Prototype?" *Handbook of Human-Computer Interaction*, Elsevier, 367–381.

Kato, P., and de Klerk, S. (2017). "Serious Games for Assessment: Welcome to the Jungle." *Journal of Applied Testing Technology*, 18(December), 1–6.

Koskela, L. (2008). "Which kind of science is construction management?" *Proceedings of IGLC16: 16th Annual Conference of the International Group for Lean Construction*, 51–60.

Mateevitsi, V., Sfakianos, M., Lepouras, G., and Vassilakis, C. (2008). "A game-engine based virtual museum authoring and presentation system." *Proceedings of the 3rd international conference on Digital Interactive Media in Entertainment and Arts - DIMEA '08*, ACM Press, New York, New York, USA, 451.

Michael, D. R., and Chen, S. (2006). *Serious Games: Games that Educate, Train and Inform*. Thomson Course Technology.

Montes, H., Hijon-Neira, R., Perez-Marin, D., and Montes, S. (2021). "Using an Online Serious Game to Teach Basic Programming Concepts and Facilitate Gameful Experiences for High School Students." *IEEE Access*, 9, 12567–12578.

Mostafa, S., Chileshe, N., and Abdelhamid, T. (2016). "Lean and agile integration within offsite construction using discrete event simulation." *Construction Innovation*, 16(4), 483–525.

de Paula, D. F. O., and Araújo, C. C. (2016). "Pet Empires: Combining Design Thinking, Lean Startup and Agile to Learn from Failure and Develop a Successful Game in an Undergraduate Environment." 30–34.

Peffers, K., Tuunanen, T., Rothenberger, M. A., and Chatterjee, S. (2007). "A Design Science Research Methodology for Information Systems Research." *Journal of Management Information Systems*, 24(3), 45–77.

Pelcin, A. (1997). "The Effect of Indentor Type on Flake Attributes: Evidence from a Controlled Experiment." *Journal of Archaeological Science*, 24(7), 613–621.

Plattner, H., In Meinel, C., & In Leifer, L. (2011). *Design Thinking*. *Design Thinking*, (C. Meinel, L. Leifer, and H. Plattner, eds.), Springer Berlin Heidelberg, Berlin, Heidelberg.

Ries, E. (2011). *The lean startup: How today's entrepreneurs use continuous innovation to create radically successful businesses*. Crown Business, New York.

Rodríguez, P., Markkula, J., Oivo, M., and Turula, K. (2012). "Survey on agile and lean usage in finnish software industry." *Proceedings of the ACM-IEEE international symposium on Empirical software engineering and measurement - ESEM '12*, ACM Press, New York, New York, USA, 139.

Rumeser, D., and Emsley, M. (2019). "Can Serious Games Improve Project Management Decision Making Under Complexity?" *Project Management Journal*, 50(1), 23–39.

Sacks, R., Barak, R., Belaciano, B., Gurevich, U., and Pikas, E. (2013). "KanBIM workflow management system: Prototype implementation and field testing." *Lean Construction Journal*, 19–35.

Suppan, M., Catho, G., Robalo Nunes, T., Sauvan, V., Perez, M., Graf, C., Pittet, D., Harbarth, S., Abbas, M., and Suppan, L. (2020). "A Serious Game Designed to Promote Safe Behaviors Among Health Care Workers During the COVID-19 Pandemic: Development of 'Escape COVID-19.'" *JMIR Serious Games*, 8(4), e24986.

Torp, O., Bølviken, T., Aslesen, S., Fritzsønn, L. P., Haagensen, Å., Lombardo, S., and Saltveit, T. (2018). "Is Integration of Uncertainty Management and the Last Planner System a Good Idea?" *IGLC 2018 - Proceedings of the 26th Annual Conference of the International Group for Lean Construction: Evolving Lean Construction Towards Mature Production Management Across Cultures and Frontiers*, 658–668.

Formoso et al. (2021). "Slack in construction – Part 1: core concepts" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 187–196, doi.org/10.24928/2021/0183, online at iglc.net.

SLACK IN CONSTRUCTION - PART 1: CORE CONCEPTS

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ABSTRACT

Construction projects are known to be complex, due to being subject to uncertainty and variability. The use of buffers to protect them from the detrimental impact of variability has been well-researched. A key managerial choice is not whether or not to buffer variability, but rather how to define the necessary combination of buffers. Slack is a concept related to buffers but has been used in the literature to describe a broader range of strategies for coping with complexity. It allows an organisation to adapt to internal pressures for adjustment or to external pressures for change in policy. This paper aims to further develop the concept of slack and to unveil its relationships with other concepts and ideas that are partly overlapping such as buffers, resilience, robustness, flexibility, and redundancy. A concept map was devised in order to articulate the nature of the slack concept. This paper explores in detail this concept map and proposes a conceptual role for slack in the realm of Lean.

KEYWORDS

Slack, buffer, complexity, variability, uncertainty, concept map, waste.

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INTRODUCTION

Construction projects are known to be subject to uncertainty and variability. The use of buffers to protect them from the detrimental impact of variability has been well-researched and goes back to developments of inventory management theories (Spearman and Hopp, 2020). In past IGLC conferences several papers explored the benefits and drawbacks of buffers in construction projects (e.g., Horman et al., 2003; González et al., 2008) and were grouped under a track named Buffer Management.

Alves and Tommelein (2003) defined buffer as a cushion of resources used to protect processes against variation and delays in the delivery of resources. The suitability of certain types of buffers over others may vary according to the existing environment (Buchmann-Slorup, 2014). In construction projects, materials, time, and money are the types of buffer resources mostly accounted for, especially in production planning and control. Therefore, a key managerial choice is not whether or not to buffer variability, but rather how to define the necessary combination of buffers.

The emphasis on time and financial buffers makes sense as they are versatile resources that can address a wide range of risks. Furthermore, money can pay for capacity buffers, which is another strategy to cope with variability in construction projects (Tommelein, 2020). However, time and money can make a difference only if associated with other types of resources such as equipment, materials, labour, and space, e.g., overtime work is only useful if reliable equipment and workers are available; and money is pointless if required supplies are not available for sale.

Slack is a concept related to buffer but has been used in the literature to describe a broader range of strategies for coping with complexity. Bourgeois (1981) defines slack as a cushion of actual or potential resources that allows an organisation to adapt successfully to internal pressures for adjustment or to external pressures for change in policy. Lawson (2001) pointed out that slack plays a key role in organisational work so that people can pay attention, think, and benefit from knowledge – this is particularly important in complex projects, which require more, not less, time for monitoring and processing information. Saurin and Werle (2017) argued that slack can be created by using different strategies and a wide range of resources (e.g., time, information, material, people, money, and equipment).

The slack concept has been used in disciplines such as organisational behaviour (Lawson, 2001), innovation management (Huang and Chen, 2010), and complexity theory (Saurin and Werle, 2017). In Lean Construction, slack has also been approached by a few earlier studies. Bertelsen and Koskela (2005) defend the provision of slack for the management of complex projects. Fireman and Saurin (2020) discuss the role of slack for the reduction of waste, as it prevents failures in making-ready from immediately becoming making-do waste. Saurin (2017) argues that slack may be interpreted as a dimension of project risk management, since it involves a ubiquitous trade-off in construction projects, namely the extent to which processes should be shielded against variability without compromising efficiency.

In this research work, construction projects are regarded as complex socio-technical systems (CSSs) and must be managed as such. This implies the need for supporting resilient performance, which is the expression of how systems cope with both expected and unexpected conditions by adjusting their performance while maintaining the production of required outputs (Hollnagel, 2017). Although the use of buffers is a key strategy for creating resilience (Saurin and Werle, 2017), their use has been explored from a limited perspective. In fact, Ballard et al. (2020) argue that buffer management techniques are conceived to deal with variability that is statistically described in advance. However, when uncertainty is hard to anticipate and quantified, the narrow concept of buffer has little value (Ballard et al., 2020). Furthermore, the concept of buffer is focused on built-in and designed strategies and resources, thus neglecting resilient performance that arises from self-organisation, initiative-taking, and resourcefulness of employees. Furthermore, Iqbal et al. (2015) suggest that the focus on preventive risk management techniques does not guarantee that risks are eliminated before execution of a project and, therefore, that remedial risk management techniques, such as close coordination with subordinates and subcontractors, need to be used to reduce any risk impact.

Moreover, the need for being prepared to cope with a wide range of risks has been dramatically visible since the rise of the COVID-19 pandemic, which has affected the construction industry in many countries. Although the pandemic is a black swan (Taleb 2007) event, it stems from the same source as more mundane risks, namely the external environment that is a permanent source of uncertainty. These limitations of the buffer concept in combination with the assumption that construction projects are CSSs, demands a new terminology and theorisation capable of: (i) integrating a wide range of risk coping mechanisms that account for both formal and informal approaches, across all relevant processes at the micro, meso, and macro levels; and (ii) inspiring a revision of Lean Construction practices so as to check (and increase) the extent to which they are fit to address the growing levels of complexity and risk that characterize construction projects.

This paper aims to develop the concept of slack and to unveil its relationships with other concepts and ideas that are partly overlapping such as buffers, resilience, robustness, flexibility, and redundancy. This analysis is intended to assess the novelty and utility of the slack concept from the perspective of the Lean Construction community.

This study is not the outcome of a conventional research project, but it is the result of theoretical discussions carried out by a group of 13 academics – 5 professors and 8 graduate students - from three universities located in different countries (Brazil, UK, and USA) was formed and held 10 weekly on-line meetings during a 4-month period. The motivation for setting up this group was the perceived potential of the slack concept as an innovation in Lean Construction, based on earlier IGLC publications and research being conducted on that topic in the universities involved. The group meetings were focused on the discussion of papers on slack to establish a shared vocabulary and increase awareness of the state-of-the-art in construction and other sectors. Then, a concept map was collaboratively devised to articulate the nature of slack. This map sets a basis for a companion paper (Saurin et al., 2021) with examples and suggestions for further research.

WHAT IS SLACK?

Slack has been defined as a means to absorb uncertainty by using different types of resources (Saurin, 2017). Slack can be implemented by adopting measures that are planned in advance or that are defined in an opportunistic way. Saurin and Werle (2017) pointed out that slack does not necessarily imply extra or idle resources, as the existing resources can be adapted to a different use in order to cope with variability

Bourgeois (1981) discussed the perspective of organisational slack, suggesting three main roles for slack: (i) spare resources to prevent ruptures in the face of a surge of activity; (ii) resources that enable an organisation to adjust to shifts in external environments; and (iii) resources that allow an organisation to experiment with new products or innovations in management. Moreover, Bourgeois (1981) also identified four reasons for having slack: (i) inducement for attracting organisational participants and to maintain their membership; (ii) conflict resolution, mostly due to goal incongruence of local rationality; (iii) buffer in the workflow process (named technical buffer); and (iv) facilitator of strategic behaviour, which includes improvement and innovation initiatives. Therefore, besides coping with uncertainty or emerging events, slack can be used to fulfil demands or perform actions at a higher strategic level than is the case for buffers.

By contrast, the narrow definition of buffer as a cushion to protect processes against variability is frequently adopted in the literature. Previous studies have pointed out that the management of buffers is crucial for helping to achieve a desired level of outcome, and this is usually done by modelling the known, existing variability (Alves and Tommelein 2003; González et al. 2008). This definition of buffer is similar to the concept of technical buffer, proposed by Bourgeois (1981), which is not concerned with high-level organisational issues, such as innovation, conflicts, and strategic issues.

Another concept related to slack, used in the project management literature, is safeguard, defined by Gil (2007) as "the design and physical development work for ensuring, or enhancing, the embedment of an option in the project outcome". This definition seems to be mostly focused on work-in progress, and also on financial slack.

HOW TO IMPLEMENT SLACK?

Fireman et al. (2018) state that the implementation of slack depends on the definition of both slack resources (“what” question) and slack strategies (“know how” question). As mentioned, many different types of resources can function as slack, such as inventories, time, equipment, people, money, and information. There are different ways of categorising slack resources: (i) actual or potential: actual means that resources are somehow more than the minimum necessary to produce a given level of organisational output, while potential is related to providing people the ability to learn to be able to respond (Lawson, 2001); (ii) opportunistic or planned: planned means that the slack resources have been devised previously, considering the characteristics of the production system. By contrast, opportunistic slack exists when a resource can be used as slack despite not being its original purpose (Righi and Saurin, 2015); (iii) Time to release: some resources can be released immediately, while others may take some time to be used (Lawson, 2001); (iv) Time available: it is concerned with the time when the slack resource is available. (v) Degree of visibility: slack resources may have different degrees of visibility for the people that might demand them (Righi and Saurin, 2015).

Slack strategies can be classified in two core categories, redundancy, and flexibility. Redundancy implies excess, i.e., additional resources that are made available. Different forms of redundancy can be used, including backing up through duplication and redundant procedures (Saurin and Werle, 2017) or functions (Roberts, 1990). Hoepfer et al. (2009) suggested two categories of redundancies: (i) standby, when resources are neither loaded nor operational; and (ii) active, when the individual performing a redundant function is involved in the task at hand, and therefore is fully operational.

Flexibility is related to the fact that several resources can be used in different ways, e.g., multi-skilled workers, multi-purpose equipment. In the case of human resources, the concept of adaptability has been used to explain the capacity of human actors to change by self-organising, usually with the aim of being resilient in response to internal or external stimuli (Walker et al. 2004). Pulakos et al. (2000) stated that this is a function of the social portion of the system, being concerned with how easily workers adjust and deal with the unpredictable nature of situations, how efficiently and smoothly they can change their orientation or focus when needed, and to what extent they take reasonable actions.

Saurin and Werle (2017) proposed another category of strategy, named margin of manoeuvre, which is concerned with the degree of freedom to act, i.e., resources or people can be reordered according to the necessary conditions. Stephens et al. (2011) sub-divided margin of manoeuvre into three types: (i) maintaining local margin by restricting other units' actions or borrowing other units' margin; (ii) autonomy to create margin via local reorganisation or expand a unit's ability to regulate its margin; and (iii) coordinated, collective action of recognizing or creating a common-pool resource on which two or more units can draw. However, it seems that margin of manoeuvre represents a combination of redundancy, in some cases borrowing from other units, and flexibility, based on the autonomy of individuals or groups of people.

Saurin and Werle (2017) recognized work-in-progress as a category of slack strategy, although it can also be considered as a particular case of redundancy. It is a type of slack widely used in construction projects. From one perspective, it is regarded as an inventory of unfinished products, or alternatively as a backlog of available workplaces, which are often used as a mechanism to cope with the lack of reliability of flows (Viana, 2015).

WHY IS SLACK NEEDED?

There are two major reasons for using slack. One reason, from the organisational perspective, is to have resources for fulfilling demands or carrying out actions at a strategic level (e.g., innovation, establishing coalitions), as suggested by Bourgeois (1981). The other reason, from the production system perspective, is related to the fact that many projects must be considered as CSSs, particularly in the construction industry.

Project complexity can be described by two dimensions: structural complexity and uncertainty (Williams, 1999). Structural complexity arises in systems with many varied interrelated parts and can be interpreted in terms of differentiation and interdependency (Baccarini, 1996). Thus, the degree of complexity is associated with the number of parts as well as the extent of their interrelationships (Klir, 1985). This definition can be applied to different project characteristics, such as organisation, technology, environment, information, decision making, and systems (Baccarini, 1996).

Structural complexity is strongly related to the degree of coupling between two units, (Dubois and Gadde, 2002). Tight coupling pertains not only to the number of connections or shared variables between two units, but also to the brittleness that those connections bring to the system (Roberts, 1990). Loose coupling exists when units may be responsive to each other yet show independence in terms of effects on other units.

Uncertainty, the second dimension of project complexity, can be related to project goals (how well defined the goals are), and means (how well-defined the methods of achieving those goals are) (Williams, 1999). In either cases uncertainty might be affected by internal or external factors. In some situations, uncertainty is likened to variability, which has been defined by Hopp and Spearman (2011) as the quality of non-uniformity of a class of entities, being divided into process variability (created by things as simple as work procedure variations and by more complex effects such as setups, random outages, and quality problems) and flow variability (created by the way work is released to the system or moved between locations).

As mentioned, variability is often considered to be a predictable form of uncertainty. By contrast, uncertainty is usually defined in a broader way, as a state of unknowing where the individual lacks complete knowledge of a situation (Saunders et al. 2015). This unexplained variation can be partly caused by measurement errors, and partly by the lack of understanding about cause-and-effect relationships. In the case of CSSs, much of the uncertainty is caused by human and social influences or organisational conditions that make systems' performance difficult to predict and control (Böhle et al 2016).

In highly complex projects, due to the combination of structural complexity and uncertainty, the outcomes are said to be emergent rather than resultant (Hollnagel et al. 2015). This is the case, for instance, of making-do waste (Formoso et al., 2017). It is difficult or even impossible to explain what happens as a result of known processes or developments. Emergent outcomes are not additive, not predictable from knowledge of their components, and not decomposable into those components (Hollnagel et al. 2015).

Moreover, complexity may have an impact on the difficulty to understand and describe the system under consideration, and therefore, depends on the perception of the observer (Klir, 1985). A system is called tractable if it is possible to follow and understand how it functions. It means that the performance of that type of system is highly regular, its description is relatively simple in terms of parts and relations, with easy-to-understand details of how the system works (Hollnagel et al. 2015).

WHAT ARE THE IMPACTS OF SLACK?

There are some intended impacts of slack, i.e., expected or accounted for, while some impacts are unintended. Both can be either desirable (positive) or undesirable (negative) (Parks et al. 2017). Risk management is a discipline that considers a wide range of expected and unexpected events, to support decision-making in order to reduce the probability of adverse effects. In CSSs, predicting emerging events is a challenge, and slack can be regarded as a key risk mitigation strategy. Construction project risks may be tacitly accounted for in a fragmented manner in managerial processes such as those related to procurement, design, quality, safety, and production planning and control. Production teams also carry out risk management in everyday work when making decisions on the spot to assess trade-offs and prioritize the allocation of finite resources – e.g., when considering the risks of working overtime to complete an activity. This notwithstanding, Love and Matthews (2020) claim that systematic risk management is not widely used in construction projects

Four main categories of positive impacts of slack were identified in this investigation: (i) Resilience: is the intrinsic ability of a system to adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), so that it can sustain required operations under both expected and unexpected conditions (Hollnagel et al. 2015). (ii) Reliability: is the ability of a system and its components to perform required functions under stated conditions for a specified period of time (Rausand and Høyland, 2004). (iii) Robustness: is the preservation of particular characteristics despite uncertainty in the components or in the environment (Saurin, 2017). It reflects the ability of a system to maintain functionality when exposed to a variety of external or internal conditions and disturbances. Robustness is observed whenever there exists a sufficient repertoire of actions to counter perturbations (Whitacre and Bender, 2010). This concept is associated with the resistance and strength of a system. (iv) Flexibility of output is concerned with adapting products to fulfil specific customer requirements, without incurring high transition penalties or large changes in performance outcomes (Petroni and Bevilacqua, 2002), being strongly related to the mass customisation strategy. This capability demands several changes related to marketing, design and operations, but several types of slack may be necessary to make such changes feasible, e.g., redundant design, multi-functional teams. Those positive impacts will affect the performance of construction projects, potentially improving productivity, value generation, project duration, and image of the company for customers. From the perspective of the Lean Production philosophy, a negative impact of slack is the occurrence of waste. In this philosophy, waste is concerned with the occurrence of non-value-adding activities, i.e., activities that take time, resources, or space but do not add value from the perspective of the final customer (Ohno, 1988). Formoso et al. (2020) suggested that, instead of singular waste events, it is reasonable to expect chains of waste, i.e., chains of causes and effects in which one waste leads to another. Some types of slack can be related to waste, such as inventory of materials, work-in-progress, and unproductive time. The elimination of waste has been a driver for improvement, allowing problems that represent improvement opportunities to be identified (Ohno 1988). Therefore, slack as a potential category or source of waste should be measured and reduced, as part of continuous improvement programs.

Figure 1 presents the map that was produced based on the concepts and definitions investigated in this research work. It is divided in three zones: (i) superior (why slack is needed?); (ii) middle (what is slack?); and inferior (which are the impacts of slack?). Connections between the concepts and taxonomies are also represented in the map.

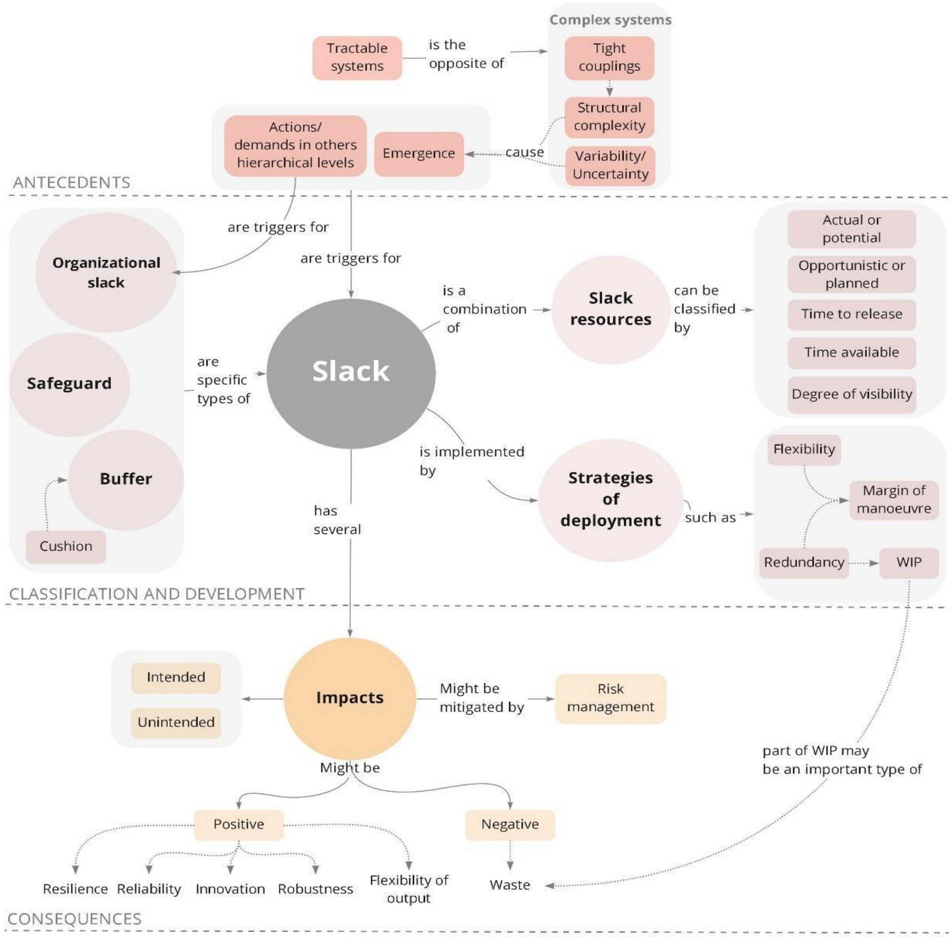

Figure 1: Concept Map

DISCUSSION AND CONCLUSIONS

Although the many notions of slack and buffer discussed seem disparate, there is a clear pattern. They can be clustered into two groups, based on the underlying conceptual framework on production. On one hand, discussions on buffers are related to a (natural) science understanding of production. On the other hand, most discussions on slack are based on seeing production as a CSS. The scientific understanding of production has been spearheaded by Spearman and Hopp (2020), which is strongly based on the queueing theory conceptualisation of production. Production is represented through flows of materials (or information). The central problem of production, as identified in Factory Physics, is uncertainty, in terms of flow and process variability. To cope with variability, there are only three countermeasures: inventories (buffers), more capacity or time (needed to produce one item). Out of these, buffers are the most important way to mitigate against variability, and mathematical models allow the optimal positioning and sizing of buffers.

Now, is this kind of (allegedly) scientific approach to production sufficient for advising on how to cope with uncertainty in production? In closer analysis, it turns out that the scientific model of production is an idealisation, where at least the following features have been abstracted away: (i) Production is modelled as a closed system, except for incoming and departing materials and information. Uncertainty is defined narrowly in terms of material and information flows. A production system is open to the world in many other ways, and vulnerable to uncertainty therein; (ii) Production is modelled as a natural science phenomenon. The usually unavoidable ingredient in production, human beings, are abstracted away, except for some buffer design methods that consider some specific types of human behaviour, such as student syndrome and Parkinson's law. In so doing, also the abilities to learn, to collaborate, and to invent new strategies for coping with uncertainties are abstracted away; (iii) The behaviours of flows and workstations are expected to be mutually independent, except in the way prescribed in the model. However, the inherent variability of a workstation may be influenced by the amount of the related buffer; (iv) The model contains a pre-determined set of behaviours and moves that a part can take. However, through human agency, new moves can be invented: the missing of one part can be encountered through making-do (Formoso et al., 2017). In turn, making-do may lead to unexpected outcomes, through emergence.

Thus, this scientific approach to production is partial. Still, it is often useful as a first analysis or baseline, and useful knowledge about the basic behaviour of production systems has been generated through it. However, for a comprehensive analysis, production needs to be conceptualized as a CSS. Then, the following features are taken into consideration: (i) Production is conceptualised as an open, evolving system, covering all uncertainties and risks from the environment of the system as well as the possibility of change, learning and creativity; (ii) Human beings, with all their capabilities, are included in the analysis; especially, uncertainty can be encountered through resourcefulness of employees or through organisational means; these forms to mitigate uncertainty are often called slack; (iii) The internal relationships between different phenomena in production are taken into account, to the extent possible; and (iv) The possibility of emergence of new outcomes is taken into account, to the extent possible.

This conceptualisation provides a different perspective for the analysis and design of production systems, in contrast to the seemingly rigorous causal theories offered by the scientific model of production. It extends the understanding of slack and related constructs, by considering the impact of different types of complexity in construction projects. These two conceptualisations should not be understood as competitors, but rather the scientific model of production should be positioned as providing one form of partial analysis when production is understood in a broader way, as a complex socio-technical system.

REFERENCES

Alves, T.C.L. and Tommelein, I.D. (2003) "Buffering and Batching Practices in the HVAC Industry." *Proc. 11th IGLC*, VA, USA.

Baccarini, D. (1996). "The Concept of Project Complexity - A Review." *Int. J. of Project Management*, Elsevier, 14(4), 201-204.

Ballard, G., Vaagen, H., Kay, W., Stevens, B., and Pereira, M. 2020. "Extending the Last Planner System to the Entire Project." *Lean Constr. Journal.*

Bertelsen, S. and Koskela, L. 2005. "Approaches to Managing Complexity in Project Production." *Proc. 13th IGLC*, Sydney, Australia.

Böhle, F., Heidling, E., and Schoper, Y. (2016). "A New Orientation to Deal with Uncertainty in Projects." *Int. J. of Proj. Mgmt, Elsevier*, 34(7), 1384-1392.

Bourgeois, J. (1981). "On the Measurement of Organizational Slack". *Acad.Mgmt Review* 6 (1): 29-39.

Büchmann-Slorup, R. (2014). "Applying Critical Chain Buffer Management Theory in Location-Based Management." *Construction Mgmt. and Economics*, 32(6), 506-519.

Dubois, A., and Gadde, E. (2002)."The Construction Industry as a Loosely Coupled System: Implications for Productivity and Innovation."*Constr. Mgmt. and Economics*, 20(7), 621-631.

Fireman, M.C.T and Saurin, T.A. 2020. "Chain of Wastes: The Moderating Role of Making-do." *Proc. 28th IGLC*, Berkeley, CA, USA.

Fireman, M.C.T, Saurin, T.A., and Formoso, C.T. (2018). "The Role of Slack in Standardized Work in Construction: An Exploratory Study" *Proc. 26th IGLC*, Chennai, India, pp. 1313–1322.

Formoso, C.T., Sommer, L., Koskela, L., and Isatto, E.L. (2017). "The identification and analysis of making-do waste: Insights from two Brazilian Construction Sites." *Ambiente Construído*, 17 (3) 183-197.

Gil, N. (2007). "On the Value of Project Safeguards: Embedding Real Options in Complex Products and Systems." *Research Policy*, Vol. 36, pp. 980-999.

González, V., Alarcón, L.F., Maturana, S., Bustamante, J.A., and Mundaca, F. (2008). "Work-in-process buffer management using the rational commitment model in repetitive projects." *Proc. 16th IGLC*, 667-678.

Hoepfer, V. M., Saleh, J. H., and Marais, K. B. (2009). "On the value of redundancy subject to common-cause failures: Toward the resolution of an on-going debate." *Reliability Engineering and System Safety, Elsevier*, 94(12), 1904-1916.

Hollnagel E., Wears, R.L., and Braithwaite, J. (2015) "*From Safety-I to Safety-II*: A White Paper". *The Resilient Health Care Net*: Published by the Univ. of Southern. Denmark, Univ. of Florida, USA, and Macquarie Univ., Australia.

Hollnagel, E. (2017). "Safety-II in Practice: Developing the Resilience Potentials". Routledge.

Hopp, W. and Spearman, M.(2011). "Factory Physics", 3 ed. Waveland Press, Illinois.

Horman, M. J., Messner, J. I., Riley, D. R., and Pulaski, M. H. (2003). "Using Buffers to Manage Production: A Case Study of the Pentagon Renovation Project." *11th IGLC.*

Huang, Y.F. and Chen, C.J. (2010). "The Impact of Technological Diversity and Organizational Slack on Innovation". *Technovation*, 30(7-8), 420-428.

Iqbal, S., Choudhry, R.M., Holschemacher, K., Ali, A., and Tamošaitienė, J. (2015). "Risk Management in Construction Projects", *Technol. Econ. Dev. Eco.*, 21(1), 65-78.

Klir, G.J. (1985) "Complexity: Some General Observations". *Systems Research*, 2(2), 131-140.

Lawson, M.B. (2001) "In Praise of Slack: Time is of the Essence". *Acad. of Mgmt.Perspectives*, 15(3), pp.125-135.

Love, P.E., and Matthews, J. (2020). "Quality, Requisite Imagination and Resilience: Managing Risk and Uncertainty in Construction." *Reliab. Engrg. & System Safety*, 204, 107172.
Ohno, T. (1988). "Toyota Production System: Beyond Large-Scale Production." *Productivity Press*, Cambridge, MA.
Parks, R., Xu, H., Chu, C.-H., and Lowry, P. B. (2017). "Examining the intended and unintended consequences of organisational privacy safeguards." *European J. of Information Systems*, 26(1), 37-65.
Petroni, A. and Bevilacqua, M. (2002). "Identifying Manufacturing Flexibility Best Practices in Small and Medium Enterprises." *Int. J. Oper. Man.*, 22 (7-8), 929-947.
Pulakos, E. D., Arad, S., Donovan, M. A., & Plamondon, K. E. (2000). Adaptability in the workplace: Development of a taxonomy of adaptive performance. Journal of Applied Psychology, 85(4), 612-624.
Rausand, M., and Hoyland, A. (2003). *System Reliability Theory: Models, Statistical Methods, and Applications*. Wiley Series in Probability and Statistics - Applied Probability and Statistics Section, Wiley.
Righi, A.W. and Saurin, T. A. (2015). "Complex Socio-Technical Systems: Characterization and Management Guidelines." *App. Ergon.*, 50, 19-30.
Roberts, K. H. and Haas. (1990). "Some Characteristics of One Type of High Reliability" *Org. Science*, 1(2), 160-176.
Saunders, F.C., Gale, A.W., and Sherry, A.H. (2015). "Conceptualising Uncertainty in Safety-Critical Projects: A Practitioner Perspective." *Int. J. of Proj. Mgmt.*, 33, 467-478.
Saurin et al., (2021). "Slack in Construction - Part 2: Practical Applications". *Proc. 29th IGLC*, Lima, Peru.
Saurin, T.A. (2017). "Removing Waste While Preserving Slack: The Lean and Complexity Perspectives". *Proc. 25th IGLC*, Heraklion, Greece (pp. 217-224).
Saurin, T.A. and Werle, N.B (2017)." A Framework for the Analysis of Slack in Socio-Technical Systems." *Reliab. Engrg.& System Safety*, 167, 439-45.
Spearman, M.L.; Hopp, W.J. (2020) "The Case for a Unified Science of Operations". *Prod. and Ops. Mgmt*. doi.org/10.1111/poms.13318.
Stephens, R. J., Woods, D. D., Branlat, M., & Wears, R. L. (2011). Colliding dilemmas: interactions of locally adaptive strategies in a hospital setting. *Proc. 4th Resilience Eng. Symp*, pp. 256-262.
Taleb, N.N. (2010). "The Black Swan: The Impact of the Highly Improbable." New York: *Random House Trade Paperbacks*, 2, 444pp.
Tommelein, I.D. (2020) "Takting the Parade of Trades: Use of Capacity Buffers to Gain Work Flow Reliability." *Proc. 28th IGLC*, Berkeley, California, USA.
Viana, D.D. (2015). "Integrated Production Planning and Control Model for Engineer-to-Order Prefabricated Building Systems." Dr. Thesis. UFRGS, Porto Alegre, Brazil.
Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. Ecology and society, 9(2).
Whitacre, J. M., and Bender, A. (2010). "Networked buffering: a basic mechanism for distributed robustness in complex adaptive systems." *Theor. Bio. Med. Model.*, 7, 20.
Williams, T.M. (1999). "The Need for New Paradigms for Complex Projects." *Int. J. of Proj. Mgmt.*, 17(5), 269-273.

Saurin et al. (2021). "Slack in construction – Part 2: practical applications." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 197–206, doi.org/10.24928/2021/0178, online at iglc.net.

SLACK IN CONSTRUCTION - PART 2: PRACTICAL APPLICATIONS

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ABSTRACT

Construction projects are exposed to a wide diversity of variabilities, which suggests the existence of a correspondent wide diversity of variability coping mechanisms, whether they are designed or not. This wide diversity is not properly accounted for by the concept of buffer, as it neglects the social and informal dimensions of coping with variability. The use of the concept of slack is proposed as an alternative. A companion IGLC 29 paper defines slack and discusses its relationships with proxy concepts such as flexibility and resilience. This paper presents nine practical examples of slack in managerial processes and topics that are of interest for the lean construction community. These examples suggest that, while slack has been concealed by the lack of theorization and consistent terminology, it is ubiquitous in lean construction. Opportunities for future studies are outlined.

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KEYWORDS

Slack, complexity, concept map.

INTRODUCTION

Construction projects are subject to a wide range of variabilities, which reflects their complex nature and interactions with the external environment. According to Koskela (2000) there are eight groups of preconditions for the start of construction tasks: design, components and materials, workers, equipment, space, connecting works, external conditions, and temporary facilities. These preconditions can vary across a number of dimensions such as time (e.g., when they are made available too late or too early) and precision (e.g., non-conformance to technical specifications) (Hollangel, 2012).

As a result, variability coping mechanisms (either designed or not) are likely to cover a wide range of possibilities. In fact, a match between variabilities and their countermeasures is necessary in complex systems as stated by the law of requisite variety (Ashby, 1991). This law states that a system can be stable only if the number of possible states of its control mechanisms is equal to or greater than the number of possible states of the system. Thus, there should be a minimum variety of (e.g., skills, materials and tools) to match the variety from the environment (e.g., demand volatility, resources availability).

However, variability coping mechanisms in construction and in other sectors are usually approached in the production management literature from a limited perspective, as formed by three types of buffers, namely capacity, inventories, and time (Spearman and Hopp, 2020). Furthermore, the literature on buffers neglects both the social and the informal dimensions of variability coping, offering an overly technical and mechanistic perspective. For these reasons, Formoso et al. (2021) (a companion publication to this paper) propose the use of a new concept and theorization capable of: *(i)* integrating a wide range of variability coping mechanisms that account for both formal and informal approaches, across all relevant processes at the micro, meso, and macro levels of project production systems; and *(ii)* inspiring a revision of lean construction practices so as to check (and increase) the extent to which they are fit to the growing levels of complexity and risk that characterize construction projects. Formoso et al. (2021) argue that the concept of slack can fulfil this knowledge gap.

Slack is defined by Bourgeois (1981) as “a cushion of actual or potential resources which allows an organization to adapt successfully to internal pressures for adjustment or to external pressures for change in policy”. Formoso et al. (2021) explored how slack is related to other proxy terms (e.g., flexibility, resilience) and presented a concept map that schematically illustrates their relationships. The present paper further illuminates the concept of slack in construction by presenting a number of practical examples derived from both the literature and the authors’ experience as lean construction scholars and practitioners. These examples encompass managerial processes and topics that are of interest to the lean construction community such as production planning and control, lean and BIM, safety management, supply chain management, and off-site construction. Based on this, we intend to reinforce the theoretical relevance and practical utility of the concept of slack to lean construction. In fact, while slack seems to be ubiquitous in lean construction, it has been concealed by the lack of theorization and consistent terminology. Opportunities for further studies are discussed.

EXAMPLES OF SLACK IN PRODUCTION MANAGEMENT

The nine examples of slack presented next stem from two sources: *(i)* research projects underway led by some of the 13 authors of this paper on the topics of lean construction, resilience engineering, and production planning and control – the authors have had access to diverse empirical settings such as large construction projects where lean construction principles have been applied (e.g., Fireman and Saurin, 2020) and the built environment of healthcare facilities (e.g., Ransolin et al., 2020); and *(ii)* reinterpretation of known management practices (e.g., BIM, escape emergency routes in buildings) from the viewpoint of slack. These examples are classified according to: *(i)* the slack strategies adopted (Table 1); *(ii)* the slack resources involved; *(iii)* the rationale for using slack (i.e., why is slack needed?); and *(iv)* the unintended consequences of using slack.

The examples are presented in Figures 1 through 9.

Table 1: Slack strategies (adapted from Formoso et al. 2021)

Slack strategies	Definition
Flexibility	The ability of an organization to deploy and redeploy its resources effectively in response to changing environmental and internal conditions (Gerwin, 1993).
Redundancy	A condition where some types of resources are provided in addition to the minimum necessary to perform a specific function (Nonaka, 1990), or when more than one resource performs a required function (Azadeh et al., 2016).
Margins of manoeuvre	It addresses the creation or maintenance of margins and additional resources that allow the system to continue to function despite unexpected demands (Saurin and Werle, 2017)

<table>
<tr><td>Strategy of deployment
Flexibility

Resources
People (amount of)
People (problem-solving perspectives)</td><td colspan="2">
</td></tr>
<tr><th>Description</th><th>Why is slack needed?</th><th>Unintended consequences</th></tr>
<tr><td>Reallocation of workers across gangs and shifts in order to meet daily production goals. This decision-making occurred in daily huddles.</td><td>In the construction of an airport terminal, the conclusion of a certain construction phase after the deadline was subject to contractual penalty. Workers were reallocated across gangs in order to compensate for delays.</td><td>The reallocation of workers implied waste from moving their equipment and tools. Also, activities from which workers were removed could be delayed.</td></tr>
</table>

Figure 1: Example 1 – slack in production planning and control (based on Fireman and Saurin, 2020)

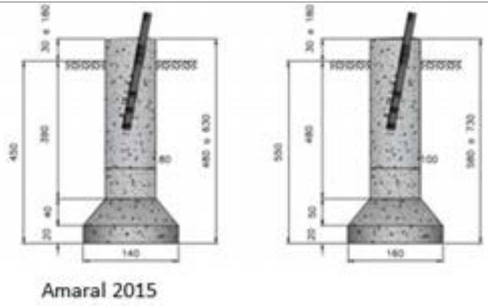
Strategy of deployment Redundancy **Resource** Design		
Description	**Why is slack needed?**	**Unintended consequences**
Alternative designs, considering different types of soil, for the foundations of electricity transmission towers.	Due to the heterogeneity of the soil and the limited soil surveys, the standard design of the foundations may not be applicable.	Extra short-term costs for producing alternative designs. These costs may pay back in the long-term as the same design is reused in other projects.

Figure 2: Example 2 – set-based product design as slack

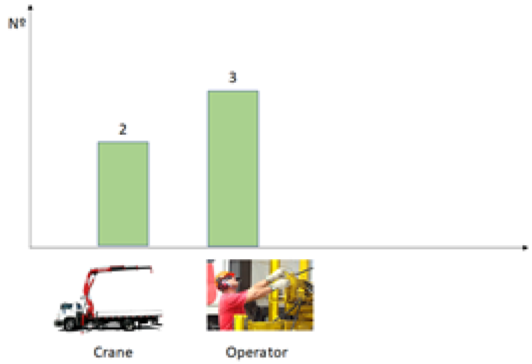
Strategy of deployment Redundancy **Resource** People		
Description	**Why is slack needed?**	**Unintended consequences**
Multi-skilled employee who can operate a crane in case the regular operator is absent for any reason	Hiring and training a new crane operator takes time.	Wages of multi-skilled employees are higher than those of regular employees. The activity from which the multi-skilled operator was removed is subject to delays.

Figure 3: Example 3 – multi-skilled workers as slack

<table>
<tr><td>Strategy of deployment
Margins of manoeuvre

Resource
Space</td><td colspan="2">
Figure source: https://participatorymedicine.org/epatients/2019/07/a-familys-guide-to-critical-care-part1.html</td></tr>
<tr><th>Description</th><th>Why is slack needed?</th><th>Unintended consequences</th></tr>
<tr><td>The layout of the patient bay in an intensive care unit can be changed to some extent in order to facilitate the provision of care (Ransolin et al., 2020).</td><td>In the standard layout, caregivers do not have 360º access around the bedside, which is necessary for some clinical procedures.</td><td>Layout changes cause discomfort to the patient and increase the risk of accidents.</td></tr>
</table>

Figure 4: Example 4 – changes in the layout of bays in hospitals as slack

<table>
<tr><td>Strategy of deployment
Margin of manoeuvre

Resources
Space
Equipment</td><td colspan="2">
Figure source:https://gleneagles.hk/facilities-services/explore-facilities-and-services/general-facilities/intensive-care-unit</td></tr>
<tr><th>Description</th><th>Why is slack needed?</th><th>Unintended consequences</th></tr>
<tr><td>Regular in-patient wards that can be adapted to intensive care.</td><td>Surges in demand, such as during the COVID-19 pandemic, imply the need for extra intensive care beds.</td><td>Some requirements of ICU clinicians may not be fully met in the adapted in-patient wards – e.g., simultaneous visibility of all beds from a central area, collaborative work.</td></tr>
</table>

Figure 5: Example 5 – In-patient wards that can be adapted to intensive care (Capolongo et al., 2020).

<table>
<tr><td>Strategy of deployment
Redundancy

Resource
Space</td><td colspan="2">
</td></tr>
<tr><th>Description</th><th>Why is slack needed?</th><th>Unintended consequences</th></tr>
<tr><td>More than one escape route or emergency exit (e.g., in case of fire)</td><td>One of the escape routes or exits may be overcrowded or temporarily unavailable</td><td>Costs with refurbishment and adaptation of facilities as to provide alternatives</td></tr>
</table>

Figure 6: Example 6 – alternative escape routes and exits as slack (Kendik, 1986).

<table>
<tr><td>Strategy of deployment
Redundancy

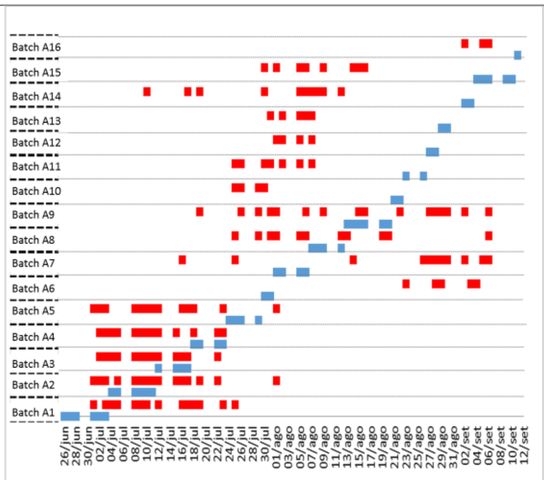
Resource
Materials</td><td colspan="2">
</td></tr>
<tr><th>Description</th><th>Why is slack needed?</th><th>Unintended consequences</th></tr>
<tr><td>Overproduction of prefabricated concrete structure in the manufacturing plant and the consequent early delivery of components to the construction site, thus increasing levels of work-in-process</td><td>Lack of synchronization between the schedules of the manufacturing plant and the construction site. Furthermore, the payment for the supplier of prefabricated components were based on the amount of materials delivered to the construction site, which encouraged overproduction.</td><td>In fact, this example of slack is closer to waste (i.e., it adds unnecessary variability) than protection against variability. High levels of work-in-process create difficulties for construction site logistics and require extra space for the storage of components.</td></tr>
</table>

Figure 7: Example 7 – work-in-progress in prefabricated building systems as slack

<table>
<tr><td>Strategy of deployment
Margin of manoeuvre

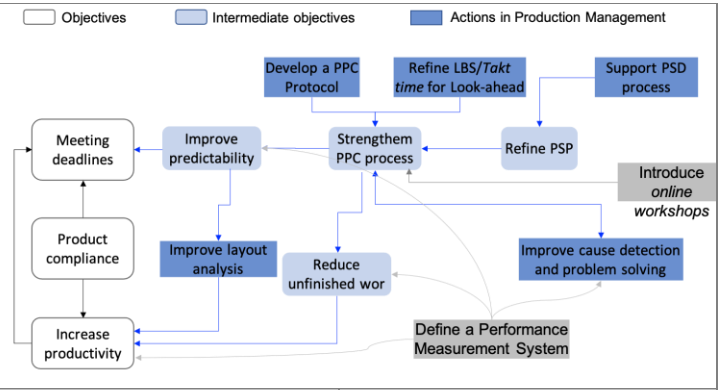
Resource
People</td><td colspan="2">
</td></tr>
<tr><th>Description</th><th>Why is slack needed?</th><th>Unintended consequences</th></tr>
<tr><td>Construction sites were closed for several weeks during the most critical phases of the COVID-19 pandemic. Technical staff changed their roles and formed a working group for reviewing and improving the company's managerial processes such as performance measurement and production planning and control</td><td>Technical staff was partly idle as a result of the closure of construction sites.</td><td>Several short and long-term benefits could arise such as the development of innovative practices, strengthening of continuous improvement as an organizational value and more reliable processes.</td></tr>
</table>

Figure 8: Example 8 – Reallocation of staff during the COVID-19 pandemic as slack

<table>
<tr><td>Strategy of deployment
Redundancy

Resource
People (problem-solving perspectives)</td><td colspan="2"></td></tr>
<tr><th>Description</th><th>Why is slack needed?</th><th>Unintended consequences</th></tr>
<tr><td>Daily huddle to discuss abnormalities and devise solutions. Workers from different hierarchical levels and specialties attend the huddles.</td><td>The nature and impacts of abnormalities are often transdisciplinary and involve several production processes. No single actor is usually capable of devising and implementing effective solutions.</td><td>Time away from core production activities during the huddles</td></tr>
</table>

Figure 9: Example 9 – daily huddle to respond to abnormalities as slack

Both examples that use daily huddles (Figures 1 and 9) emphasize the need to monitor and anticipate the system status. This is an important practice in changing environments, in which unexpected events may emerge.

Four out of the nine examples (1, 3, 8, 9) show how people can be slack resources under different circumstances. In examples 1, 3, and 8, although workers are reallocated from one task to another, there are implementation differences. In example 1, in which workers are reallocated across gangs and shifts to meet daily production goals, the identification of the need for slack occurs on the spot. Workers are shifted to a task of higher priority as a result of short-term needs. Meanwhile, in example 3, managers were well aware of the risks of having only one crane operator, and therefore they cared for the hiring of a backup crane operator who would be full-time available in the construction site.

The role of the product design process (and of the design itself) for the provision of slack was also highlighted by some examples. In example 2, a set-based design approach produced alternative designs for the foundations of electricity transmission towers – this strategy stems from the experience of the contractor and from the intrinsic uncertainty of soil surveys. In example 6, several escape routes were designed as a result of regulatory requirements. While example 2 consists of multiple redundant designs, example 6 consists of a single design that produces redundant solutions. Examples 2 and 6 also suggest that product design can be a cost-effective means of deploying slack resources – e.g., it is very likely cheaper to design alternative foundations than to make changes on the spot to adapt an inadequate design.

As for examples 4 and 5, they both refer to slack in the built environment of healthcare facilities. However, the nature of the slack strategy differs in terms of their designed or opportunistic character. In example 4 (layout of patient bays in an intensive care unit) the burden of adjusting performance lies on the shoulders of front-line caregivers. In example 5, the flexibility of in-patient wards was devised during the building design stage.

CONCLUSIONS

This paper presented nine practical examples of slack in the construction industry. The examples suggest that: *(i)* slack plays a role in a wide range of processes such as contract management, safety management, supply chain management, product design and development, and production planning and control; *(ii)* slack is deployed through a variety of strategies and resources, which are not limited to the traditional buffer resources of time, inventory, and capacity; *(iii)* slack has a social-technical nature, which means that people's behaviours and knowledge play a role as slack resources; and *(iv)* slack is often implicit in existing practices (e.g., daily huddles – example 9), which may reflect its high reliability (e.g., alternative designs for foundations – example 2) or infrequent use (e.g., alternative emergency exists – example 6) - in both cases there is a risk of taking for granted the availability of slack, which can lead to complacency. These characteristics of slack indicate that it has a broader meaning and implications than the concept of buffer. Thus, this article adds empirical evidence to the study by Formoso et al. (2021), which argues for the use of the concept of slack as an alternative to the concept of buffer in lean construction.

Furthermore, our findings suggest that the development of a descriptive and prescriptive theory of slack in construction is a goal worth pursuing as it can unify apparently disparate concepts and practices that share the same underlying fundamental properties and objectives. This theorization might be useful for making it systematic the application of slack in construction, giving visibility to its presence (or lack) and offering new tools for project managers.

As a limitation, the examples presented in this paper are short of detailed contextual information, which means that a deeper analysis of how slack interacted with other elements of the construction projects was not undertaken. For the same reason, there was no discussion of how slack evolved over time and how different slack resources could play complementary roles.

Based on the findings of this study and its companion paper, a number of opportunities for future research are proposed:

(i) The investigation of the trade-off between slack and waste, shedding light on the criteria to be accounted for when managing that trade-off;

(ii) The understanding of slack resources at different scales, encompassing the micro (e.g., construction activities), meso (e.g., project management at the site and company level), and macro levels (e.g., supply chain, regulations) of the construction industry;

(iii) The analysis of the implications of slack for innovation and resilience in construction*;*

(iv) The understanding of slack in a wide variety of management processes. Production planning and control stands out due to its central role in construction management, which makes it potentially useful for the identification of the need for slack (and deployment of slack) in other processes such as procurement, quality and safety management. In addition, the investigation of slack in product development seems to be a promising approach as it has the potential for more cost–effective solutions in comparison to those devised on the spot during the construction stage;

(v) The exploration of the interactions between slack resources and slack strategies, in order to identify synergistic relationships and possible conflicts; and

(vi) Quantitative investigations of the impact of slack on the performance of construction projects, comparing projects with different levels and types of slack.

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REFERENCES

Ashby, W.R. (1991). “Requisite variety and its implications for the control of complex systems.” In: *Facets of systems science*, pp. 405-417. Springer, Boston, MA.

Azadeh, A., Kolaee, M.H., and Salehi, V. (2016). “The impact of redundancy on resilience engineering in a petrochemical plant by data envelopment analysis.” *Proc. Inst. of Mech. Engineers, Part O: J Risk and Reliability*, 230(3): 285-296.

Bourgeois, J. (1981). “On the measurement of organizational slack.” *Academy Management Review*, 6(1): 29-39.

Capolongo, S., Gola, M., Brambilla, A., Morganti, A., Mosca, E. I., and Barach, P. (2020). “COVID-19 and Healthcare Facilities: a Decalogue of Design Strategies for Resilient Hospitals.” *Acta Biomed.*, Vol. 91, Suppl. 9:50-60. doi.org/10.23750/abm.v91i9-S.10117.

Gerwin, D. (1993). “Manufacturing flexibility: a strategic perspective.” *Management Science*, 39:395-410.

Fireman, M.C.T and Saurin, T.A. (2020). "Chain of Wastes: The Moderating Role of Making-do." In: Tommelein, I.D. and Daniel, E. (eds.). *Proc. 28th Ann. Conf. Int. Group for Lean Constr. (IGLC28*), Berkeley, CA, USA, pp. 409-420.

Formoso, C.T., Tommelein, I.D., Saurin, T.A., Koskela, L., Fireman, M.C.T, Barth, K., Bataglin, F., Viana, D.D, Coelho, R.V., Singh,V., Zani, C., Ransolin, N., and Disconzi, C. (2021). "Slack in Construction – Part 1: Core Concepts." In: Alarcon, L.F. and González, V.A. (eds.). *Proc. 29th Ann. Conf. Int. Group for Lean Constr. (IGLC29)*, Lima, Peru. In Press.

Hollnagel, E. (2012). *FRAM: The Functional Resonance Analysis Method-modeling complex socio-technical systems.* Burlington: Ashgate.

Kendik, E. (1986). "Designing escape routes in buildings." *Fire Techn.*, 22(4), 272-294.

Koskela, L. (2000). *An exploration towards a production theory and its application to construction.* Thesis (Doctor of Technology), Tech. Res. Centre of Finland (VTT), Helsinki, Finland, 296 p.

Nonaka, I. (1990). "Redundant, Overlapping Organizations: A Japanese approach to managing the innovation process." *Calif. Manage. Rev.*, 32, 3, 27-38.

Ransolin, N., Saurin, T.A., and Formoso, C.T. (2020). "Integrated modelling of built environment and functional requirements: implications for resilience." *Applied Ergonomics*, 88, 103154.

Saurin, T.A. and Werle, N.B. (2017). "A framework for the analysis of slack in socio-technical systems." *Reliability Engineering and Systems Safety*, 167, 439-451.

Spearman, M.L. and Hopp, W.J. (2020). "The case for a unified science of operations". *Prod. and Operations Manage*, In Press, doi.org/10.1111/poms.13318.

Hamzeh, F., González, V. A., Alarcon, L. F., and Khalife, S. (2021). "Lean Construction 4.0: Exploring the Challenges of Development in the AEC Industry." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 207–216, doi.org/10.24928/2021/0181, online at iglc.net.

LEAN CONSTRUCTION 4.0: EXPLORING THE CHALLENGES OF DEVELOPMENT IN THE AEC INDUSTRY

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ABSTRACT

In 1994, Lean Construction was understood as the application of Toyota Production principles to Construction. Since then, Lean Construction researchers and advocates have made two fundamental contributions: i) Lean Construction has become a production management theory in its own right; ii) Lean Construction has involved not only production management, but also people, technology, sustainability, safety, education, among others. With the arrival of the "fourth industrial revolution" or Industry 4.0, there has been seminal research attempts to acknowledge the influence of Industry 4.0 on the architecture-engineering-construction (AEC) industry (e.g. Construction 4.0), where the focus has been primarily on technology. However, for Lean Construction to keep evolving and serving the AEC industry, it must embrace the changes propelled by Industry 4.0, but maintain the people-processes-technology triad at its core. We argue that a shift towards Lean Construction 4.0 is needed, paying attention to the synergies between production management theory and digital/smart technologies. The term "Lean Construction 4.0" does represent the vision where we envision the AEC industry to be in the future, rather than its current status. The goal of this paper is not to propose an implementation plan, but to identify research needs and to motivate a discussion on the role of Lean Construction in facing the challenges of adopting Industry 4.0 in the AEC industry.

KEYWORDS

Production management theory, industry 4.0, integration, people-process-technology.

INTRODUCTION

With the rapid advancement in technology and its uses across different domains, industries are facing a new paradigm shift, where advanced digitalization, increased automation, smart future-oriented technologies, and internet of things are at the heart of this shift (Lasi et al. 2014). Industry 4.0, or the fourth industrial revolution, is the term given for this transformation, in which fundamental changes in manufacturing

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productivity, management, economics, and the workforce are expected (Rüßmann et al. 2015). The integration between Lean practices and I4.0 technologies has been already researched in manufacturing (Sanders et al. 2016;) showing the existing synergies, however, the architecture-engineering-construction (AEC) sector is yet to benefit from the existing and emerging technologies that constitute the fourth industrial revolution to deliver projects that are more effective and efficient (Sawhney et al. 2020). Although Lean Construction could be in the driver seat of this transformation, challenges and needed changes are still not clearly laid out.

The consecutive industrial revolutions are a result of leaps in technology starting with mechanization (1st industrial revolution), mass production (2nd industrial revolution), and automation (3rd industrial revolution) (Lasi et al. 2014). Industry 4.0 refers to multiple concepts including: autonomously controlled and digitalized Smart Factory, Cyber-physical Systems (CPS), decentralized self-organization, individualized product and service developments, among others (Lasi et al. 2014). With the transformation from a machine dominant manufacturing to a digital, smart and integrated manufacturing (Oztemel and Gursev 2020), Industry 4.0 is providing companies with higher levels of operational performance, agility, and profitability (Rosin et al. 2020). Rüßmann et al. (2015) indicates the nine technological concepts that represent the pillars for industry 4.0 in manufacturing industries: Big data and analytics, autonomous robots, simulation, systems integration, Internet of Things (IoT), cybersecurity, the cloud, augmented reality, and additive manufacturing.

The AEC industry started following suit by adopting some of these technologies. Research has proven the power of data analytics, such as machine learning and predictive models, in the decision-making process on AEC projects (Mansouri et al. 2020). Virtual reality, augmented reality, and robotics have also been part of the technology trends that emerged into the AEC sector (ex: Ahmed 2018). Moreover, simulation has long been utilized in the AEC industry for purposes such as risk analysis, scheduling, maintenance operations, claims, and process improvements; in fact, simulation is perceived as playing a crucial role in 'futuristic vision of automated project planning and control' (Abdelmegid et al. 2020). As for the Cyber-physical Systems (CPS), some attempts have been made to coordinate virtual models, such as Building Information Modeling (BIM), with the physical construction to improve the control over production processes. Digital twin, a pre-requisite of CPS (Lu et al. 2020), is also an emerging concept that is increasingly embraced in the AEC industry to add social, economic, environmental and business value and optimize projects; however, examples on its implementation are still limited and its broader adoption is still lacking (Building Smart International 2020). Sacks et al. (2020) proposed a digital twin construction concept to production planning and control in conjunction with lean principles, BIM, and artificial intelligence. The digital twin construction is used to proactively analyze and improve design and production through having a data-centric mode of construction management (Sacks et al. 2020). However, the researchers proposing this construct indicated some hurdles for its implementation including: technical barriers (advanced data processing software, AI tools, etc.), organizational fragmentation, and project-specific organizations that are not willing or not ready to make more fundamental changes to processes and systems in AEC projects.

With all the attempts within the AEC industry to leverage the available technologies, it is still deemed behind other sectors. The term Construction 4.0 has been proposed as part of a framework for planning, designing and delivering constructed facilities more efficiently through physical-digital transformations (Sawhney et al. 2020). Innovation is part of the cyber-physical and digital platforms needed to advance the sector on different levels. Yet, critics still consider the AEC industry is falling short in applying the core principles of Industry 4.0, as a coherent, comprehensive, autonomous, decentralized and fully coordinated system is still missing (Sacks et al. 2020).

On another note, the literature had offered material for connecting lean principles and Industry 4.0 technologies. Mayr et al. (2018) investigated how Industry 4.0 tools and lean management principles relate to each other in the existing literature; their main findings include three viewpoints: (1) lean management is an enabler for Industry 4.0; (2) Industry 4.0 advances lean management; and (3) positive correlation exists between the two. Basically, Industry 4.0 can support the execution of lean goals using for instance real-time value stream mapping (VSM), smart Jidoka system based on CPS, and 3D printing to facilitate one-piece flow and just-in-time delivery (Buer et al. 2018). On the other hand, lean manufacturing is considered a good foundation for Industry 4.0 where lean principles support identifying unnecessary activities and streamlining the process, which in return makes it easier for digitalization and automation (Buer et al. 2018). Accordingly, lean manufacturing and Industry 4.0 are said to have similar goals, complement each other, and their integration is feasible (Mayr et al. 2018). Nonetheless, very little attention has been paid to the connection of lean principles and Industry 4.0 within the AEC context.

When studying the impacts of Industry 4.0 technologies on lean principles, Rosin et al. (2020) indicated that while Industry 4.0 reinforces some lean tools, a major deficiency is the need for supporting people and the team spirit. Lean invests in people as the foundation of the company and it focuses on building teams and develop a “respect for humanity system” (Liker, 2004, chp. 16). Social transformation is foreseeable with the implementation of Industry 4.0 technologies and advancements (such as robots, self-decision-making systems, learning machines, smart cities) (Oztemel and Gursev 2020). In fact, social challenges have been discussed in the literature in connection to Industry 4.0, where risk of cyber-crime, job losses, and other related aspects can arise (Morrar et al. 2017). Therefore, more attention shall be given to the social responsibility and the focus shall go beyond the technological advancement to incorporate human-computer/human-machine interactions, social dynamics, and peoples’ needs and experiences.

In general, the AEC industry is witnessing a fundamental growth in regards to technology adoption that is perceived as relatively fast with respect to historical advancements (Mansouri et al. 2020). Accordingly, in the process of embracing Industry 4.0 developments and shifting towards Construction 4.0, a bold move is needed for the Lean Construction community to lay out this integration while discussing the challenges and the opportunities included. Scholars have discussed some of the topics for future research in relation to the synergies between Lean principles and Industry 4.0, where mainly empirical validation is needed to explore further the benefits of this integration (Pagliosa et al. 2019). Despite the benefits of Industry 4.0 technologies, several researchers have expressed their concerns corresponding ethical and moral predicaments that often come with implementing these technologies (Wang and Siau 2019).

For sustaining Lean as a leading strategy of production management in the AEC industry, this paper provides an overview on Lean Construction 4.0 and raises questions and concerns related to the adoption of Industry 4.0. The ultimate goal is to envision the upcoming changes and embrace them all while preserving the people-processes-technology triad at the core of Lean Construction 4.0. Thus, the role of Lean Construction 4.0 is to build a solid basis of responsibility and accountability to do so. The goal of this paper is to raise awareness about the need for Lean Construction 4.0, and initiate a discussion with Lean thinkers and practitioners with hopes of getting feedback on their concerns or future outlook. This paper focuses on theoretical and practical matters of Lean Construction 4.0 uptake within the AEC industry, but acknowledges that Lean Construction 4.0 is a vision for the future of the AEC industry and inspiration to reach the equivalent of "Industry 4.0" ideal rather than a description of its current status.

WHY LEAN CONSTRUCTION 4.0?

Porter and Heppelmann (2014) claim that smart and digital technologies (SDT) are evolving entire industries, changing industry structure, and altering the nature of competition; they argue that information technology (IT) has transformed twice competition and strategy during the last 50 years; and now, a third IT wave is about to fully take place. In the first IT wave (70's), automation changed how different operations, from order request and billing to CAD and manufacturing resource planning, were carried out, increasing productivity dramatically. In the second IT wave (80's), "Internet" took over which enabled integration levels never seen before across the supply chain (locally and globally). Nowadays, the third IT wave involves smart connected products, where IT is an integral ubiquitous part of this change. This is bringing a promise of unleashing even larger productivity improvements and economic growth. In fact, Porter and Heppelmann (2014)' strategic position about the impact of SDT is coincidental with the underlying benefits from Industry 4.0 in manufacturing (Xu et al. 2018), where SDT triggers more efficiencies, competition, and innovation, enabling a digital transformation of organisations. According to Porter and Heppelmann (2017), there is a gap between the physical world and the digital data generated by SDT due to the inability of current business processes and systems to convey real world information to humans (e.g. representing machinery details in 2D drawings, while in reality they are full 3D entities); thus, it is decreasing decision-making quality. In their view, the human's role is underestimated and they argue that people have unique motor and cognitive skills that technology does not have. Accordingly, powerful human interfaces are required to connect the physical, digital and human worlds effectively. In other words, they acknowledge that the people-processes-technology triad should be at the core of businesses and their strategies.

In contrast, the AEC industry's unwillingness to widely adopt SDT has pushed away the opportunity to achieve the "Industry 3.0 transformation", which is a necessary pre-condition to adopt an "Industry 4.0" state as in manufacturing (Farmer 2016). In fact, there are endemic problems in the AEC industry such as supply chain fragmentation, poor integration of information and production traceability, low levels of innovation, obsolete and myopic production management frameworks (Koskela 2000; Sawhney et al. 2020; Zhou et al. 2016), which are ultimately hindering its competitiveness, efficiency, sustainability and profitability. Even more, these problems have been arguably contributing factors delaying the transition of the AEC industry to the "Industry 3.0" state.

While the "Construction 4.0" concept has opened avenues and opportunities for the integration of STD into AEC project production and business processes (Sawhney et al. 2020), Sacks et al. (2020) stated that this concept has not yet offered a robust, coherent, and actionable framework for implementation that explicitly acknowledges systems' interrelations and autonomy to make both decentralised and fully coordinated decisions in automated supply chains and production. We also argue that Construction 4.0 lacks a deep understanding of the connections between SDT and production management theory.

In that respect, Lean Construction provides production theory principles and a methodological framework for practices to be improved and validated, respectively (Koskela 2000). In fact, Lean Construction has a three-layered framework that explicitly considers “principles and culture”, “practices", and “tools and methods” (Pekuri et al. 2012), which provides the “substratum” to deal effectively with the people-processes-technology triad that an “Industry 4.0” transformation would require in the AEC industry (or to even reach a necessary “Industry 3.0” state). In manufacturing, research revolving around the synergies between Lean Thinking and Industry 4.0 is nascent (Xu et al. 2018), with no clear answers about whether Lean enabling Industry 4.0 implementation is optimum, or the reverse is more effective (Mayr et al. 2018; Xu et al. 2018). However, there is consensus that linking Lean Thinking and Industry 4.0 is feasible and brings positive impacts to those organisations adopting this combined strategy (Mayr et al. 2018; Satoglu et al. 2018; Xu et al. 2018). In that respect, we argue that Lean Construction provides the guiding principles to optimize operations in constructions via SDT. As it turns out, we believe Lean Construction has the potential to enable Industry 4.0 in the AEC industry and maximize the intertwining synergies. In manufacturing, for instance, the term Lean Automation is a blend of Lean Production principles and Industry 4.0 technologies. But automation is not a foreign idea to Lean, as the principles of autonomation acknowledges that repeating and adding value activities are prone to automation (Satoglu et al. 2018), so there is natural extension of the Lean Production principles to Industry 4.0 as such. The point that Satoglu et al. (2018) tried to make is that Lean provides a “waste hunting” and “adding-value” environment on which a truly effective Industry 4.0 implementation can be built upon, where a sense of purpose (production theory) and problem-driven view (Lean-based methodologies) can be provided to the use of SDT. That view can be brought to the AEC industry.

In order to answer the question “Why Lean Construction 4.0?”, we argue that it is necessary to acknowledge that for Lean Construction to be evolved, it cannot ignore the clear connections and synergies with SDT and Industry 4.0 principles. We also acknowledge that over the last three decades, Lean Construction researchers have been investigating the linkages between Lean Construction principles and SDT, sometimes very timidly, unrevealing new avenues of research and development for Lean Construction. Looking at the lean literature, specifically the IGLC conference proceedings from 1996-2016, several studies (88 papers) have focused on BIM, visualization and virtual construction, and on computer application and information systems. However, discussions on advanced technologies advised by industry 4.0 within lean frameworks are still limited. Some researchers started to conceive the importance of providing frameworks and approaches that align process-culture-technology requirements in the digital transformation journey pushed by Industry 4.0 (ex: Romero et al. 2019), yet further intensive studies are still needed under the umbrella of Lean Construction 4.0.

We believe that a Lean Construction 4.0 paradigm, while still aspirational in nature, can provide the “soul” to the people-processes-technology triad when implementing Industry 4.0 in the AEC industry.

VALUE OF LEAN CONSTRUCTION 4.0 FOR BOTH ACADEMIA AND INDUSTRY

In the early 2000s, Peter Drucker, one of the leading voices in management, declared in an interview for "The Economist" (2001): “What has changed manufacturing, and dramatically increased productivity, are the new concepts. Information, Control, Automation and Robotics Technologies are less important than new ideas about manufacturing, which in advance are comparable to the arrival of mass production 80 years ago". These ideas are known as Lean Management. Peter Drucker also declared: "the essence of management is not techniques and procedures. The essence of management is to make knowledge productive, which is a good starting point for the definition of Lean Management". However, Lean Thinking "means a different approach to business and also implies a different approach to management by people who strive to operate in a Lean manner".

Our experience studying and supporting the implementation of Lean Project Management confirms Drucker's vision, and we believe this is also valid for Lean Construction 4.0. In order to implement Lean Management, the three elements indicated in Figure 1 need to be in a permanent balance: a Management Philosophy inspired by "Lean Thinking"; "Technology" and "Methods" to support the implementation of Lean Management, where Industry 4.0 technologies play a fundamental role; and a transformation of the "Culture" that should host people motivated by Lean transformation. Unfortunately, the need to maintain a permanent presence of these three elements in a Lean implementation is not recognized in many organizations, and this fact likely explains the mediocre or limited results of some implementations and organizational failures. In general, the tendency in organizations is to emphasize technologies, very often ignoring "Philosophy," which is what provides the ideas for "productive knowledge," and the transformation of "Culture," which is essential for people to become the engine of any transformation, is also often neglected.

Philosophy refers to management principles and the concepts of waste and value, which constitute in turn productive knowledge. Culture refers to the required characteristics of people to participate in a Lean transformation. Technology refers to the methods and technologies that support an implementation. The original technologies in the Toyota production system refer to Kanban planning systems, value stream maps, just in time systems, etc. In addition to the original technologies, in projects we currently use Virtual Models (BIM), Last Planner® System, Target Value Design, and we believe this proposed balance is also valid for this new stream of Industry 4.0 technologies.

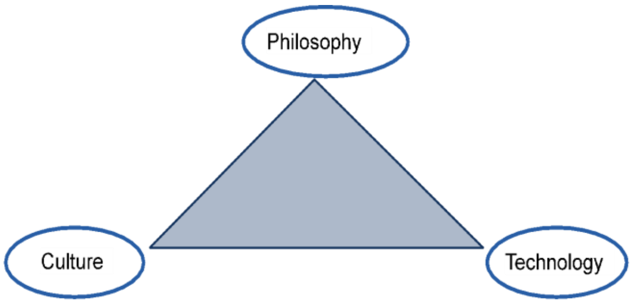

Figure 1: Three Elements of Lean Implementation

Academia can play a relevant role in supporting the AEC Industry in its effort to implement both Lean Construction and Industry 4.0, to make it an integrated effort to implement Lean Construction 4.0. This integration seems to be an appropriate subject of study for academia as shown by studies which explore the integration between Lean practices and I4.0 technologies (Sanders et al. 2016).

Due to the observed difficulties in implementing Lean Management, many studies have suggested the need for utilizing a systematic methodology to implement Lean Management in manufacturing (Mostafa et al. 2013), proposing frameworks that would avoid narrow or short-sighted approaches. Similarly, in construction, there is a need for more systematic implementation approaches where academia can contribute to provide an adequate integrated implementation framework, implementation guides, and appropriate technologies, which could lead to more successful implementation of Lean Construction and Industry 4.0.

There is a huge opportunity for research in a number of fields: obtaining empirical evidence, analyzing synergies, developing conceptual models, frameworks for integrated implementation, etc. These research efforts could probably support government efforts to provide roadmaps for implementation of I4.0 in many countries (Tortorella and Fettermann 2018) and could also benefit from funding coming from these governmental sources. The industry will benefit directly from this stream of research, which has the potential to fully use the existing synergies between Lean Construction and Industry 4.0 including: road maps for digitalization, frameworks for implementation, guidelines for lean construction 4.0 culture, process change, value streams, etc. Researchers will benefit from a better understanding of how Lean Construction and Industry 4.0 can support our effort to create a Lean and Digital construction environment to improve performance in our industry.

A VISION FOR DEVELOPMENT AND IMPLEMENTATION

Over the next 20 years, construction is expected to adopt several Industry 4.0 technologies and incorporate them into the normal way of doing business. One can currently notice several traces of broad attempts to lay down the foundation for future implementations of these technologies. This section envisions such future implementations and highlights the need for Lean Construction 4.0 principles and methods in supporting these implementations.

Starting with *Internet of things (IoT), the Cloud,* and *Big Data & Analytics*, construction projects will include a variety of sensors connected to equipment, tools, material, subassemblies, and even workers. These connected sensors will not only talk to each other but also generate loads of data that will require advanced methods of Big Data management to prepare them to be useful for analysis and for guiding process improvements. Applying the principle of autonomation as part of Lean Construction 4.0 would mean the involvement of white- and blue-collar construction professionals in designing and implementing these technologies to support workers and create a better work environment without confusion or invading workers' privacy and human rights.

Moreover, the use of *Autonomous Robots* and *Additive Manufacturing* such as 3D concrete printing is changing the whole nature of production systems in construction. Advanced robots will feature as future members of construction teams where the dynamics within this new type of team is a paradigm shift in terms of labour resource management and productivity. Lean Construction 4.0 will ensure that work environments are safe, truly collaborative (i.e. human-human, human-machine), inclusive, and transparent.

The construction industry will continue to rely on the use of *Simulation/Digital Twins* (Sacks et al. 2020) to test new changes or develop new improvements on a surrogate system to achieve a greater understanding of the real system. *Artificial Intelligence* and *Machine Learning* will continue to supply construction operations with advanced algorithms to optimize productivity while reducing cost and time. *Augmented Reality, Virtual Reality* and *Holographic Displays* (Hamzeh et al. 2019) will provide system designers, practitioners, and users with a new environment of sensory experiences that will take human-to-system interactions into unprecedented levels of data integration and people's usability. Lean Construction 4.0 will have to ensure that humans remain at the center of these implementations, paying special attention to the users' experience dimension and conditions of satisfaction in the new digitally-driven work environments, without risking any degeneration of work conditions or human relations.

Despite the benefits of Industry 4.0 technologies, several researchers have sounded the alarm on the corresponding ethical and moral predicaments that often come with implementing these technologies. The biggest concerns are centered around the privacy and ownership of data, accessibility, and cybersecurity (Wang and Siau 2019). The future of humanity is also at stake, especially that future technologies might include body and brain implants that will create controversy and several human-right issues. The role of Lean Construction 4.0 is to build a solid basis of responsibility and accountability to preserve and protect the people-processes-technology triad without endangering the human spirit, human life, planet earth, and the ecosystem.

While efficiency is a concern for the construction industry, Lean Construction 4.0 should look behind the direct efficiency of operations and aspire towards systems efficiency. This entails a harmony between 1) human needs, 2) technology, 3) construction processes, and human values of free will, peace, and sustainability. 1) Human needs: are met through engagement and inclusion, team building, training and growth, and understanding that the whole is more than the sum of the parts. The more advanced a system is at reaching a state of harmony, flow, and love between its constituents, the closer it is to achieving the goals of Lean and Systems efficiency. 2) Technology: is put into the context of how it can serve the system, how it can improve work, how it can be used in humane fashion, and how it is connected to the system. Any attempts to jump to system efficiency through a cold control of free will and forceful enforcement through technology will actually lead to degenerating value within the system and aggravating human players including: designers, producers, and users. 3) Construction processes: can be improved by increasing: transparency, value delivered to the customer, and proactive input in a continuously improving lean culture.

DISCUSSION

The goal of this paper is to engage the Lean Construction community in recognizing the need for developing Lean Construction 4.0 to address the challenges of industry 4.0. Accordingly, we present here a list of thought-provoking questions that we ask the readers to ponder upon while also inviting them to engage in the discussion and provide their valuable feedback.

1- Is there a need for Lean Construction 4.0 thinking to provide a production theoretical "substratum" and enable an effective implementation of Industry 4.0 technologies in the AEC industry?

2- What are the necessary adjustments that the Lean Construction community would introduce to Lean Construction 4.0 to cater to future challenges? What is the role of the people-process-technology triad to revamp the Lean Construction research towards a Lean Construction 4.0 ideal?

3- What type of issues would Lean practitioners face when implementing Industry 4.0 technologies? How can Lean Construction 4.0 assist in the digital transformation of firms and business in the AEC industry?

4- What changes will Industry 4.0 bring into the work of professionals in the AEC industry? What is the role of Lean Construction 4.0 in this?

5- What type of training will be required from the future workforce to be "up to date" with Lean Construction 4.0 in terms of processes and technologies?

CONCLUSIONS

This paper has laid out the future needs of the AEC industry for Lean Construction 4.0 principles and established the foundations for development of these principles to match the advancing technologies of Industry 4.0. We have highlighted our concerns and voiced several suggestions of how the future might unfold. We have also posed several questions for discussion and feedback. Answering these questions is an important step towards understanding the need of Lean Construction 4.0 to address the fourth industrial revolution without undermining the triad of people, technology, and processes.

REFERENCES

Abdelmegid, M. A., González, V. A., Poshdar, M., O'Sullivan, M., Walker, C. G., and Ying, F. 2020. "Barriers to adopting simulation modelling in construction industry." *Autom. Constr.*, Elsevier, 111, 103046.

Ahmed, S. 2018. "A review on using opportunities of augmented reality and virtual reality in construction project management." *Organization, Technology & Management in Construction: Int. J.*, 10(1), 1839–1852.

Buer, S.-V., Strandhagen, J. O., and Chan, F. T. S. 2018. "The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda." *Int. J. of Production Research*, Taylor & Francis, 56(8), 2924–2940.

Building Smart International. 2020. *Enabling an Ecosystem of Digital Twins*.

Drucker, P. 2001. "The Economist." *The Economist*, November 3, pg. 12.

Farmer, M. 2016. "The farmer review of the UK construction labour model." *Construction Leadership Council.* United Kingdom.

Hamzeh, F., Abou-Ibrahim, H., Daou, A., Faloughi, M., and Kawwa, N. 2019. "3D visualization techniques in the AEC industry: the possible uses of holography." *ITcon*, 24, 239–255.

Koskela, L. 2000. *An exploration towards a production theory and its application to construction*. VTT Technical Research Centre of Finland.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., and Hoffmann, M. 2014. "Industry 4.0." *Business & information systems engineering*, Springer, 6(4), 239–242.

Liker, J. K. 2004. *Toyota way: 14 management principles from the world's greatest manufacturer*. McGraw-Hill Education.

Lu, Y., Liu, C., Kevin, I., Wang, K., Huang, H., and Xu, X. 2020. "Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues." *Robotics and Computer-Integrated Manufacturing*, Elsevier, 61, 101837.

Mansouri, S., Castronovo, F., and Akhavian, R. 2020. "Analysis of the synergistic effect of data analytics and technology trends in the AEC/FM industry." *J. Constr. Eng. Manage.*, American Society of Civil Engineers, 146(3), 4019113.

Mayr, A., Weigelt, M., Kühl, A., Grimm, S., Erll, A., Potzel, M., and Franke, J. 2018. "Lean 4.0-A conceptual conjunction of lean management and Industry 4.0." *Procedia Cirp*, Elsevier, 72, 622–628.

Morrar, R., Arman, H., and Mousa, S. 2017. "The fourth industrial revolution (Industry 4.0): A social innovation perspective." *Technology Innovation Management Review*, Talent First Network, 7(11), 12–20.

Mostafa, S., Dumrak, J., and Soltan, H. 2013. "A framework for lean manufacturing implementation." *Production & Manufacturing Research*, Taylor & Francis, 1(1), 44–64.

Oztemel, E., and Gursev, S. 2020. "Literature review of Industry 4.0 and related technologies." *Journal of Intelligent Manufacturing*, 31(1), 127–182.

Pagliosa, M., Tortorella, G., and Ferreira, J. C. E. (2019). "Industry 4.0 and lean manufacturing." *Int. J. Manuf. Technol. Manage.*, Emerald Publishing Limited.

Pekuri, A., Herrala, M., Aapaoja, A., and Haapasalo, H. 2012. "Applying Lean in construction–cornerstones for implementation." *Proc. 20th Ann. Conf. Int. Group for Lean Construction*, San Diego, USA, 18–20.

Porter, M. E., and Heppelmann, J. E. 2014. "How smart, connected products are transforming competition." *Harvard business review*, 92(11), 64–88.

Porter, M. E., and Heppelmann, J. E. 2017. "Why every organization needs an augmented reality strategy." *HBR'S 10 MUST*, 85.

Romero, D., Flores, M., Herrera, M., and Resendez, H. 2019. "Five Management Pillars for Digital Transformation Integrating the Lean Thinking Philosophy." *Proc. 2019 IEEE Int. Conf. on Eng., Techol., and Innovation*, ICE/ITMC 2019, 1-8.

Rosin, F., Forget, P., Lamouri, S., and Pellerin, R. 2020. "Impacts of Industry 4.0 technologies on Lean principles." *Int. J. Prod. Res.*, Taylor & Francis, 58(6), 1644–1661.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., and Harnisch, M. 2015. "Industry 4.0: The future of productivity and growth in manufacturing industries." *Boston Consulting Group*, Boston, MA, USA:, 9(1), 54–89.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., and Girolami, M. 2020 "Construction with digital twin information systems." *Data-Centric Engineering*, Cambridge University Press, 1.

Sanders, A.,Elangeswaran,C., and Wulfsberg, J.P. 2016. "Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing." *J. Ind. Eng. Manage. (JIEM)*, Barcelona: Omnia Science, 9(3), 811–833.

Satoglu, S., Ustundag, A., Cevikcan, E., and Durmusoglu, M. B. 2018. "Lean production systems for Industry 4.0." *Industry 4.0: Managing the digital transformation*, Springer, 43–59.

Sawhney, A., Riley, M., and Irizarry, J. 2020. *Construction 4.0: An innovation platform for the built environment*. Routledge, Taylor & Francis Group.

Tortorella, G. L., and Fettermann, D. 2018. "Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies." *Int. J. Prod. Res.*, Taylor & Francis, 56(8), 2975–2987.

Wang, W., and Siau, K. 2019. "Industry 4.0: Ethical and Moral Predicaments." *Cutter Business Technology Journal*, 32(6).

Xu, L. Da, Xu, E. L., and Li, L. 2018. "Industry 4.0: state of the art and future trends." *Int. J. Prod. Res.*, Taylor & Francis, 56(8), 2941–2962.

Zhou, Z., Goh, Y. M., and Shen, L. (2016). "Overview and analysis of ontology studies supporting development of the construction industry." *J. Comput. Civ. Eng.*, American Society of Civil Engineers, 30(6), 4016026.

Thompson, B. R. and Nassereddine, H. (2021). "The Lifecycle Value of Facility Management Professionals" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 217–226, doi.org/10.24928/2021/0182, online at iglc.net.

THE LIFECYCLE VALUE OF FACILITY MANAGEMENT PROFESSIONALS

Benjamin R. Thompson[1] and Hala Nassereddine[2]

ABSTRACT

As the construction industry focuses its effort on adopting lean principles to eliminate waste during project execution, an argument exists to reorient the industry's lean journey to start with the operations phase. The continued absence of Facility Managers in the design process will prolong the inefficiencies of current project delivery methods. The failure to adapt planning processes to include Facility Management (FM) professionals prevent a total lean transformation of the construction industry. A question then arises about what value-adding activities exist in the operations phase to impact lifecycle costs of future projects. Using insights gained from existing literature, this paper assesses the lifecycle value of the FM industry and applies it to the Architecture, Engineering, and Construction industry to maximize the delivered value. This paper identifies five interactions between FM and Lean Principles that justify the integration of FM professionals into the development phase of a facility's lifecycle. This paper is limited to the scope of FM and design and does not account for external pressures and requirements caused by contractual agreements, fiscal requirements, or regulatory guidance.

KEYWORDS

Facility management, lean, stakeholder integration.

INTRODUCTION

As the construction industry focuses its effort on adopting lean principles to eliminate waste through the construction phase, there is an argument to reorient the industry's lean journey to start with the operations phase (Pilanawithana and Sandanayake 2017). Approximately 80% of any given project's life cycle costs occur during the operations phase (Wang et al. 2013). Facility management (FM) professionals through developed understanding of the relationships that exist between buildings, owners, businesses, and occupants can identify value-adding activities to benefit future projects. As a project progresses from conception through construction, the ability for the project team to affect change decreases whereas the cost for rework and design changes increases (Bascoul 2017). Integrating FM professionals early on during the project's lifecycle enables the project team to make informed design decisions to deliver value to both the owner and end-users and increase the long-term value of the project.

This paper's purpose is to demonstrate the added value that FM professionals can provide during the early development phases of a project's lifecycle. Furthermore, using lean philosophies and principles this paper will present a theoretical framework for

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integrating FM into the design phases to increase value for the customer and end-users. The paper is organized into three sections: (1) background (history and definitions of FM, and proposed application to some of Toyotas 14 Management Principles), (2) the literary review with discussion points, and (3) conclusion.

BACKGROUND

A BRIEF HISTORY OF FACILITY MANAGEMENT

To understand the importance of integrating FM professionals into the design process, it is necessary to understand the history and definitions surrounding the profession. Previous studies have defined FM and Bascoul (2017) compiled a detailed history, definitions repository, and list of critical areas of responsibility. A summary of Bascoul's findings is outlined below.

The birth of FM is attributed to Florence Nightingale, who made recommendations for the built environment and linked it towards patient recovery (Finch 2010). This led to the development of "evidence-based design," which can be described as the interpretation of evidence to make design decisions. The term FM was coined in the 1960s (Finch 2010) or 1970s (Haynes and Price 2002). Researchers began to study how workers interact with their workspace and noticed that offices of the time were too rigid and did not support changes in the organizations they supported (Bascoul 2017). The introduction of information technologies then enabled employers, workers, and workspaces to have fluidity, requiring FM to transform into a dynamic management process (Bascoul 2017).

DEFINITIONS

The literature review showed that there is no single definition for FM. Becker and Steele (1990) defined FM as "… [the discipline] responsible for coordinating all efforts related to planning, designing, and managing buildings and their systems...to enhance the organization's ability to compete successfully in a rapidly changing world." Barrett and Baldry (2003) stated that FM is "an integrated approach to operating, maintaining, improving, and adapting the buildings and infrastructure of an organization in order to create an environment that strongly supports the primary objectives of that organization" (Bascoul 2017). Wiggins (2014) noted that "FM is about taking control, adding value, supporting the business, ensuring that space and working environments enhance not impeded the productivity of the core activity and the staff." With regards to areas of responsibility, this research assumed three articles to provide the most encompassing definitions. Becker and Steel (1990) wrote "buildings, systems, equipment, furniture," compared to Atkin and Brooks (2015) highlighted "services and support infrastructure" (Bascoul 2017). Whereas Wiggins (2014) stated that FM professionals "[maintained] a supporting role…control of non-core activities…and [enabled businesses]." With this baseline understanding of FM history, how it has been defined, and the areas of responsibility FMs have been assigned the following conclusion can be drawn: FM professionals are facility users, business partners, and building caretakers. The experience gained from sustained operations across a wide definition of tasks provides invaluable insight that can better define the voice of the customer for design teams, constructors, and owners.

THE TOYOTA WAY

Liker (2004) compiled the lessons learned and observations from studying Toyota manufacturing plants, their workers, and leaders. The foundation of "The Toyota Way" is the detailed definition and real-world examples of the Toyota Automobile Corporations 14 Management Principles. Though, all 14 principles support a comprehensive lean transformation, the FM industry primarily interacts with five. First, the inclusion of FM professionals in the early stages of a project's lifecycle mirrors the call to "base your management decisions on a long-term philosophy, even at the expense of short-term financial goals (Liker 2004)." From the previous section, a reliable FM professional should understand the interactions between structures and building systems, therefore; they can help the project team to "only use reliable, thoroughly tested technology that serves your people and processes (Liker 2004)." Thirdly and fourthly, a total lifecycle approach to the project team "[demonstrates] respect [to] your extended network of partners and suppliers by challenging them and helping them improve," and enables teams to "make decisions slowly by consensus, thoroughly considering all options… (Liker 2004)." Finally, tracing the lessons learned through the construction hand off and operation of like facilities pushes the industry to "become a learning organization through relentless reflection and continuous improvement (Liker 2004)."

LITERATURE REVIEW AND DISCUSSION

This research started with a review of relevant literature, focusing on: FM, lean practices, and project lifecycle. The literature review was followed by a comparison of industry and lean values, and derivation of an FM metric that theoretically measures the effectiveness of FM integration and estimates the operations and maintenance costs.

FM IN PROGRAMMING AND DESIGN (PD)

FM professionals build expertise through repetition and daily interactions with businesses, employees, and building systems. The talent and knowledge of FM professionals is often overlooked during the programing and design phases of project development. Table 1 is a compilation of findings from various authors concerning the role of FM professionals in programing and design, respectively.

Table 1: The role of the FM during Programing and Design.

Phase	Sources	Key Take Away
Programing/ Consulting	Bascoul (2018) and Pilanawithana and Sandanayake (2017)	FM professionals know the behaviors, preferences, and activities of building users. They know what designs and infrastructure does and does not meet the building user's needs. Furthermore, FM professionals know the costs associated with utilities and other supporting infrastructure. They can anticipate spatial requirements based on occupant routines. The FM professional's experience is a potential value source during concept development.
Design	Fatayer et al. (2019), Islam et al. (2017), Meng (2013), Pilanawithana and Sandanayake (2017), and Tucker and Masuri (2016).	FM professionals perform an evidence based advisory role during design through personal experience and interactions with building users. Their tactic knowledge on the operation of maintainability of buildings enables them to understand the balance between the occupant, the built environment, and the natural environment. The combination of experiences alludes to a responsibility to advise building owners and the design team on future implications of energy, maintenance, and operational costs. During the design phase, they can perform performance evaluations and identify performance indicators that shape the FM strategy. FM professionals "should be able to make the client aware that proper physical design of facilities has direct consequences for the operation…" By identifying and addressing problems early in the project's lifecycle, the FM professional pulls value using the voice of future customers; the facilities end-users. Again, the FM professionals experience-based advice could enable designers to provide safer, healthier, more aesthetically pleasing, and flexible workspaces, all the while avoiding unnecessary decisions.

The purpose of early FM integration is to reduce waste during the design, construction, and operating phase by reducing over-processing (over designing of spaces, excessively complex utility, or information technology systems) and defects. FM professionals can provide cost effective recommendations when selecting supporting infrastructure. The recommendations may include methods in which the architects and engineers can integrate sustainable designs and systems to decrease costs over the project life cycle (Bascoul 2018; Pilanawithana and Sandanayake 2017). Integrating the FM professional provides the added long-term benefit of building in maintainability and sustainability (building in quality) – with respects to customer needs – must be considered from concept through design. “This will lead to the enhancement of the building’s occupant comfort level, a drop in maintenance expenditure, and in turn drop the life cycle cost of the facility.” (Fatayer et al. 2019). Meng (2013) explained that the primary concern of building owners is the value of money, more importantly the value of money over time. By integrating the FM professional early in the design process, it is possible for the owner to reduce operating and maintenance costs. In their study, Fatayer et al. (2019) showed that early integration of FM professional has a high probability of decreasing 60-90% of HVAC and plumbing defects, and up to 30% of architectural and structural defects. There is also a mild probability that electrical defects could be reduced by 30-90%

The study conducted by Islam et al (2017) originally intended to explore the impact FM professional has on sustainability. The results of the Islam et al (2017) survey suggest that there are cost benefits when including FM professional experience to determine the maintainability, constructability, and occupant satisfaction (comfort) during the design phase. Additionally, the integration of FM into the construction industry can “lead humanity’s quest for sustainability,” (Islam et al 2017) which is as an altruistic goal for modern businesses. To put some numbers on the survey results, over 75% of respondents estimated a savings of 20% of the project costs can be realized if FM professionals are included in the design process. Almost 100% of respondents agree that maintainability is a critical factor to consider during programing and design. Authors stated that the metrics and expertise for the “quest for sustainability” lie with FM professionals, and their integration into programing and design is how value is added.

A proposed method for theoretically measuring FM integration as a function of sustainability is through comparing energy requirements to the average source energy use intensity (EUI) of comparable facilities. The US Department of Energy (DOE) defines source EUI as the amount of energy required to operate a building as a function of its size (EnergyStar 2020). For the following example, statistics regarding energy requirements published by Australian DOE in 2012 is used as the numerator (*Guide* 2012).

Fraction of Performance Efficiency in Design = ∑ Estimated Annual Energy Requirements by System Type (kBtu/Sq. Ft) / Building type source EUI (kBtu/Sq. Ft)

Fraction of Performance Efficiency in Design for an Office Building: (45.396 kBtu (HVAC) + 29.1 kBtu (Lights) + 25.608 kBtu (Equipment) + 4.656 kBtu (Elevators) + 1.164 kBtu (Water) + 10.476 kBtu (Other)) / 116.4 kBtu = 1

Design teams using this measurement should consult FM professionals when planning materials, spatial requirements, and Mechanical, Electrical, Plumbing, and Fire Protection (MEP-F) systems to adopt solutions that provide a fractional value below 1. Theoretically, this would mean that the facility is designed to out-perform comparable facilities, therefore reducing the long-term costs associated with energy use.

Few literatures highlight the barriers to FM integration during the programing and design phases of the project lifecycle. Jensen (2008) offered a simple conclusion; design teams perceive FM professionals to lack qualified experiences to enhance the design process. Jensen (2008) concluded that the lack of competencies, whether through education or certifications, and the lackluster of the FM profession drives the poor perception. Bu Jawdeh (2013) added budget restrictions and the designer or owners lack of interest in and understanding of the FM professional's experience-based advice. The lack of standardization across the FM profession, regarding systems of record or within certification, could be to blame. However, this literature review did not seek out the performance gaps between owners, occupants, and end-users, and FM professionals. The performance gap's existence warrants a holistic study to define value added activities and professional expectations to help align the professions of management, ownership, and design.

Lean construction aims to increase collaboration through Integrated Project Delivery (IPD), the Lean Project Delivery System, or introduction of technologies such as Building Information Modeling (BIM). "Without FM-DP integration, the [FM professionals] and other stakeholders work separately due to the fragmentation of the [development process]." Collaboration of trades and stakeholders must include FM professionals. This integration is a value adding activity resulting in improved facility lifespan and increasing the cost benefit of early coordination activities (Tucker and Masuri 2016). FM integration should result in buildings that best fit the user's needs; that are more attractive to clients; easier to commission, control, manage, and maintain; are more cost effective; and are adaptable to changes in customer needs (Meng 2013).

FM IN CONSTRUCTION AND CLOSE-OUT (CCO)

Pilanawithana and Sandanayake (2017) conducted a literary survey and interviews of 10 FM professionals to investigate the role FM plays during a building's life cycle. The primary benefit of involving the FM professional during the construction and close-out phase is to provide continuity from what was planned to what was executed. This includes as built drawings, and changes made to supporting infrastructure: information technology and MEP-F systems. This information provides the first input for the FM to begin developing a preventative maintenance schedule. Furthermore, involving the FM professional during construction provides structural and infrastructure familiarity, and enables the FM professional to conduct quality assurance with respects to specifications of utility supply and installation (Pilanawithana and Sandanayake 2017). In addition to the collection of as-built drawings, the FM professional must collect warranties for infrastructure equipment installed to understand the warranty and liability periods, and the operations and maintenance manuals for that equipment. These documents enhance the FM professional's ability to forecast maintenance schedules and create flexibility for adaptation once building users are identified.

Considering and involving the FM professional during construction and close-out is not a non-value-added activity. Integration into the construction process provides project familiarity, accurate drawings and schematics, and documentation all enable the FM professional to increase the value of services provided. Additionally, the FM professional's understanding of occupant behaviours and maintenance procedures allows the possibility for FM professionals to perform a unique version of quality assurance and control through the lens of a customer and as an individual user.

FM IN BUILDING OPERATION (BO)

FM, in the roughest definition, has existed since people have occupied structures. It is in our nature to care for the items and property entrusted to us; and human ingenuity drives us to continually improve our environment. As businesses and structures evolved the FM profession struggled to maintain pace (Tay and Ooi 2001). This section is aimed at identifying areas of improvement within the FM industry, with the goal of linking challenges with integration opportunities.

Jylhä and Junnila (2013) presented four points explaining how the FM industry has failed to deliver value to occupants and owners. First, the FM professional receives the work but does not execute it, this results in a chain of information passing where facts are lost or diluted over time. Secondly, FM professionals have the responsibility but not the power to deliver and meet customer satisfaction. Jylhä and Junnila (2013) stated that FM professionals do not have a mechanism to process, track, and perform quality assurance on given tasks. Thirdly, end-users – businesses – have different needs and are treated differently. The business may pass responsibility for FM work to the employee, introducing stress, and increasing the risk for dissatisfaction. Lastly, the FM discipline strives to achieve a lean transformation, but the profession focused on optimizing sub-processes instead of the entire delivery process (Jylhä and Junnila 2013). Liker (2004) wrote about the Canada Post Corporation's lean transformation and summarized that their success was predicated on an environment of continuous improvement, focused leadership, and the adoption of lean philosophies. In that respect, FM will arguably continue failing to deliver value until its professional culture is changed.

The study executed by Jylhä and Junnila (2013) highlighted violations of lean principles and processes. First, they show that FM, as it is executed now, fails to define value, develop a value stream, and make it flow from the customer. Secondly, the failure to follow the steps towards lean thinking, results in the inability to create continuous flow, surface problems, use pull systems, use visual controls, and use standardized processes. The root cause of these problems is the lack of FM integration into the programming and design phases of the project lifecycle. As previously stated, if FM professionals are integrated during the programming, design, and construction phases they are able provide valuable input into the customers real needs in comparison to their perceived needs. Additionally, FM professionals can steer decisions with respects to integrating sustainable features and systems to prolong the lifecycle. Lastly, early integration builds project familiarity and enables FM professionals to develop management strategies before the facility is commissioned.

THE LEAN MANAGEMENT APPLICATIONS

This section of the paper will relate the responsibilities, goals, and benefits of early FM integration to five of the Toyota Management Principles outlined by (Liker 2004).

Principle 1. *Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals.* Alexander (1994) described the evolution of the FM discipline as the belief in inspire people to do their best by improving the processes that manage workplaces to support the businesses effectiveness and long-term goals. In comparison, Liker (2004) condensed Toyota's first principle to base decisions on long-term philosophy to Edward Deming's "constancy of purpose." Liker (2004) states that Toyota's adaptation of a "constancy of purpose" allows the automobile corporation to make short- and long-term decisions, while anchoring their workers around a shared purpose. In this regard, the construction industry's lean journey must adopt a "constancy of purpose" and consider the FM discipline to pull value from the end users.

Principle 8. *Use only reliable, thoroughly tested technology that serves your people and processes.* One of the strongest arguments for involving the FM during design is maintainability. 95% of respondents responded positively (agree or strongly agree) in the survey conducted by Islam et al (2017) that maintainability should be considered when designing structures. Bascoul (2017) noted that disregarding FM experiences with supporting infrastructure results in design inefficiencies and maintenance related problems. Liker (2004) does not conclude that using reliable technologies means to disregard new technologies. Instead, he states that Toyota only introduces new technologies once they have been thoroughly vetted by its workers. He goes on to explain that Toyota will weigh the costs and benefits of adding the new technology before fully adopting it. Similarly, architects, engineers, and contractors should incorporate experience and advice that FM professionals possess to meet the customer's needs. If a new technology is requested or considered, by the owner, a FM professional should be consulted to conduct a cost-benefit analysis, provide a list of suitable alternatives, and make long-term recommendations to the owner and design team.

Principle 11. *Respect your extended network of partners and suppliers by challenging them and helping them improve*. This principle truly applies throughout the construction project's life cycle. Toyota maintained this principle despite its growth and popularity because relationships matter, furthermore the health of the network matters. (Liker 2004). Liker (2004) developed a supply chain hierarchy of needs to demonstrate the sensitivity of business relationships between producers and suppliers. Figure 1 is an adaptation of Liker's (2004) diagram and describes the need hierarchy of FM integration. If the construction industry aims to increase long-term value for their customers through the adoption of lean philosophies, then the network of partners surrounding the industry should be considered and developed.

Principle 13. *Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly.* "Make decisions slowly by consensus" is the key phrase of principle 13. Toyota prefers a decision-making process that is characterized by group consensus and management approval. Toyota places value in the effort teams put into evaluation process during the early stages of design. Their teams analyze all possible engineering and manufacturing issues, and pass "study drawings" (books that include sketches and lists of problems and potential solutions) throughout their team to ensure all team members fully understand the scope, constraints, limitations, and risks before making or recommending a decision (Liker 2004).

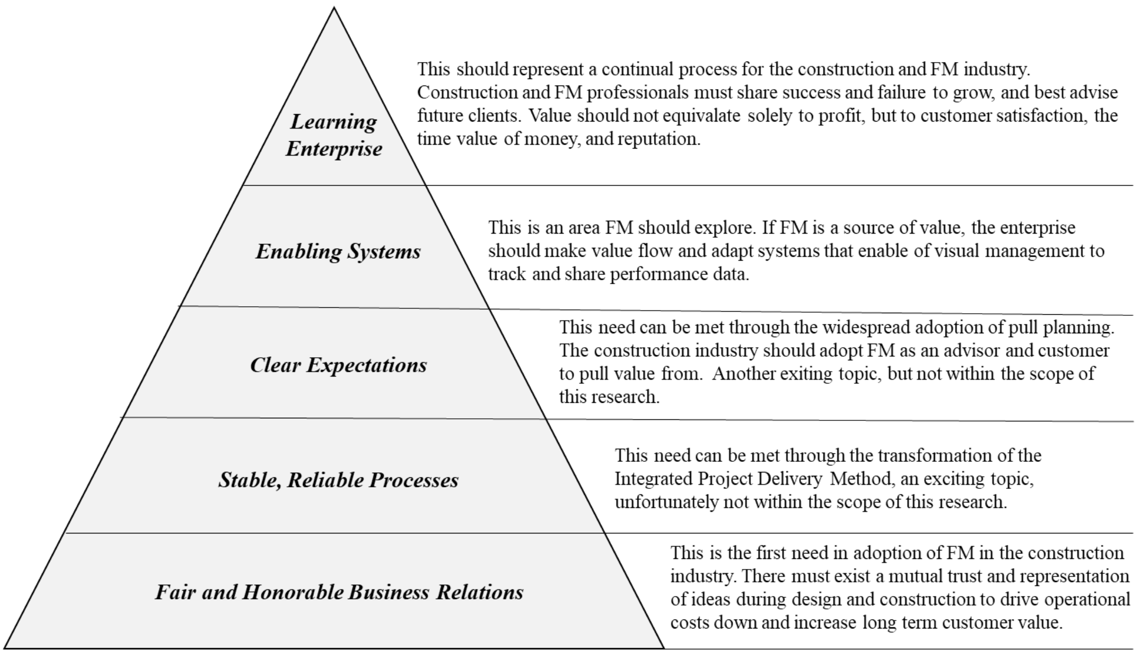

Figure 1: FM Integration Hierarchy of Needs (Adopted from Liker 2004, Figure 17-1 Supply Chain Need Hierarchy).

The construction industry is slowly adopting this principle through the development of the Last Planner® System and adoption of IPD. However, these tools should be updated to incorporate FM professionals and capture building operational experience to pull value through the design and construction phases.

Principle 14. *Become a learning organization through relentless reflection and continuous improvement.* "[The learning organization is] where people continually expand their capacity to create the results, they truly desire, where new and expansive patterns of thinking are nurtured, where collective aspiration is set free, and where people are continually learning how to learn together." (Senge 1990, cited by Liker 2004). The top of Figure 6 states that a learning enterprise should represent a continual process for the construction and FM industries. Contrary to popular thought, organizations do not only learn when they succeed; instead, failure encourages comprehensive reflection and organizational learning. Importantly, more can be said about an organization that assumes responsibility for its failures and grows from them. "…errors [are] opportunities [to learn]. …the organization takes corrective actions and distributes knowledge about each experience broadly. Learning is a continuous companywide process…." (Liker 2004). Not only is creating a learning organization a continual process and the 14th lean management principle, it can be adopted to the Deming Cycle; Plan – Do – Check – Act. (Liker 2004). Figure 2 is an adaptation of the PDCA Cycle to depict how and when the construction and FM industries can encourage continual learning.

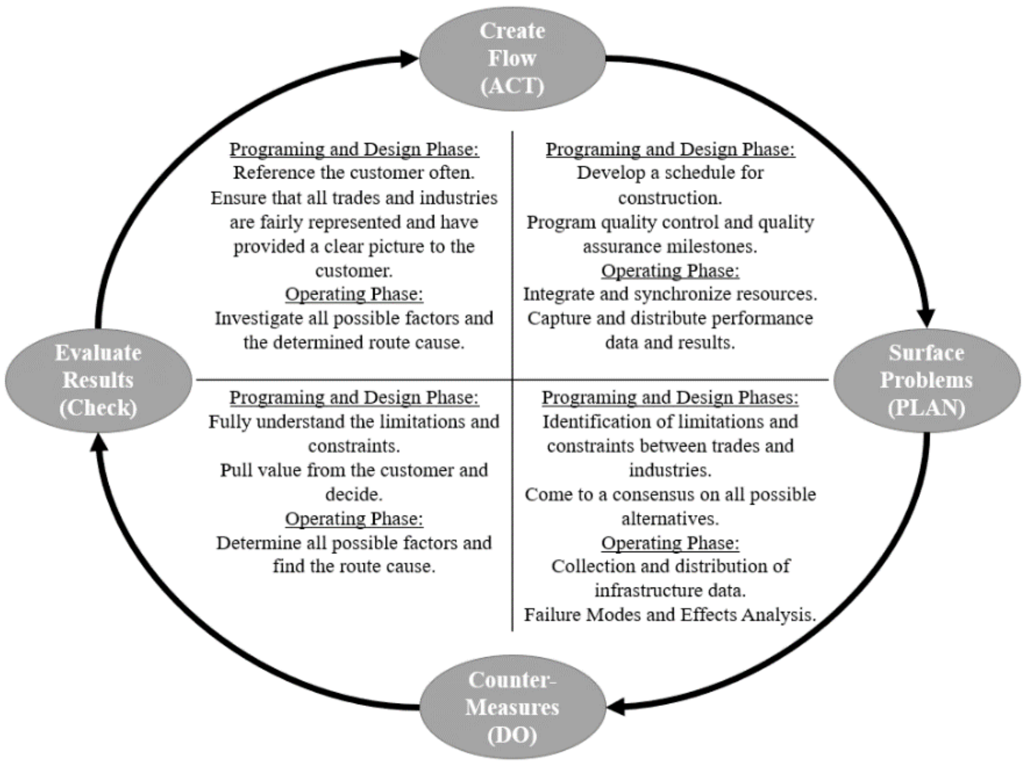

Figure 2: PDCA in Construction (Adapted from Liker 2004, Figure 20-5: Creating Flow and PDCA).

CONCLUSIONS

FM is a value adding member to the construction industries lean journey. A new definition of FM can be derived from the description of interactions and responsibilities: a long-term customer responsible for cross organizational coordination, integration, and synchronization of operational, maintenance, and improvement resources, who adds value to building users – and their businesses – by eliminating waste and providing predictability throughout the management process. Though FM professionals typically deliver value after a facility is commissioned, their understanding of how buildings and organizations interact empowers them to provide feedback during the project programing and design. Ideally, the value of FM in the development phases should be measured through observation of three like construction projects, one where the FM professional was involved during programing and planning only, one where the FM professional was involved during programing, planning, and construction (to perform FM related QA/QC), and one with no FM involvement. This study should span from programing through the first 3-5 years of operation. Researchers should collect data regarding the time and costs of rework (either in design or during construction) that relate to MEP-F systems and sustainability. Following the structures commissioning, researchers should monitor the buildings energy requirements and collect feedback from occupying businesses and personnel. These information requirements would objectively determine the cost-benefit of early FM integration.

REFERENCES

Alexander, K. (1994). "A Strategy for Facilities Management." *Facilities*, 21(11), 269-274.

Bascoul, A. M. (2017). *Managing Project Structural Complexity by Integrating Facility Management in Planning, Designing, and Execution of High-End Facility Upgrades* (Doctoral dissertation, UC Berkeley).

Bascoul, A.M., Tommelein, I.D., Tillmann, P., and Muxen, S. (2018). "Towards Facility Management Participation in Design: A UCSF Case Study." In: *Proc. 26th Annual Conference of the International. Group for Lean Construction (IGLC), González, V.A. (ed.)*, Chennai, India, pp. 505–515. doi.org/10.24928/2018/0209. Available at: www.iglc.net.

Becker, F. and Steele, F. (1990), "The total workplace", *Facilities*, 8(3), 9-14. doi-org.ezproxy.uky.edu/10.1108/EUM0000000002099.

Bu Jawdeh, H. M. (2013). Improving the integration of building design and facilities management (Doctoral dissertation, University of Salford).

Fatayer, F.A., Hassanain, M.A., Abdallah, A., Al-Hammad A.-M. (2019). "Investigation of facilities management practices for providing feedback during the design development and review stages." *International Journal of Building Pathology and Adaptation, 37(5)*, 597 – 614.

Finch, E. (2010) "Florence Nightingale: Pioneer of Facility Management." In *W070-Special Track 18th CIB World Building Congress May 2010 Salford, United Kingdom*, 132-139.

Guide to Best Practice Maintenance and Operation of HVAC Systems for Energy Efficiency (January 2012), Pages 36–37. Retrieved April 30, 2020, from https://www.environment.gov.au/system/files/energy/files/hvac-factsheet-energy-breakdown.pdf.

Haynes, B. and Price, I. (2004), "Quantifying the complex adaptive workplace", *Facilities*, 22(1/2), 8-18. doi-org.ezproxy.uky.edu/10.1108/02632770410517906.

Islam, R., Mohamed, S.F., Amin, A.B., Nazifa, T.H. (2017). "Designing of Facilities Management Sustainable Parameters for Improving Operational Efficiency." *Journal of System and Management Sciences, 7(4)*, 53-78.

Jensen, P. A. (2008). Integration of Considerations for Facilities Management in Design. In Design Management in the Architectural Engineering and Construction Sector: CIB W096 Architectural Management & TG49.

Architectural Engineering (pp. 191-199). Rotterdam: CIB. (CIB Reports; No. 319).

Jylhä, T., Junnila, S. (2013). "Learning from lean management – going beyond input-output thinking." *Facilities, 31(11/12)*, 454-467.

Liker, J. (2004). "The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer." McGraw – Hill, New York.

Meng, X. (2013). "Involvement of Facilities Management Specialists in Building Design: United Kingdom Experience." *Journal of Performance of Constructed Facilities, 27(5)*, 500 – 507.

Pilanawithana, N.M., Sandanayake, Y.G. (2017). "Positioning the facilities manager's role throughout the building lifecycle." *Journal of Facilities Management, 15(4)*, 367 – 392.

Tay, L., Ooi, J.T.L. (2001). "Facilities Management: A "Jack of All Trades?" *Facilities, 19(10)*, 357-362.

Tucker, M., Masuri, R.A. (2016). "The rational to integrate facilities management into the development process." *Property Management, 34(4)*, 332-344.

Wang, Y., Wang, X., Wang, J., Yung, P., & Jun, G. (2013). Engagement of facilities management in design stage through BIM: framework and a case study. *Advances in Civil Engineering*, 2013.

What is energy use intensity (EUI)? (n.d.). Retrieved April 30, 2020, from https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager/understand-metrics/what-energy.

Wiggins, J. M. (2014). Facilities manager's desk reference. Retrieved from http://ebookcentral.proquest.com.

Womack, J. P., Jones, D. T. (1996). *Lean thinking: banish waste and create wealth in your corporation.* New York: Simon & Schuster.

Arroyo, P., Schöttle, A., and Christensen, R. (2021). "The Ethical and Social Dilemma of AI Uses in The Construction Industry" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 227–236, doi.org/10.24928/2021/0188, online at iglc.net

THE ETHICAL AND SOCIAL DILEMMA OF AI USES IN THE CONSTRUCTION INDUSTRY

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ABSTRACT

Given the growth in data collection and application of Artificial Intelligence (AI) in the construction industry, there is a need to study the ethical and social considerations for employees in the industry and for society in general. AI could support more efficient ways of working where technology is better equipped for the tasks compared to humans. With new technologies such as AI, many decisions will be made by algorithms and not by humans. This paper explores the ethical and social dilemmas that are intrinsic in decision-making, and how they will also impact the decisions made by AI algorithms. The paper presents definitions of ethical and social dilemmas, a definition of AI, and summarizes current applications of AI in construction. It also discusses several questions associated with the current and future application of AI in the construction industry and the ethical and social dilemmas defined. This is an exploratory paper and the aim of the authors is to spark further research and discussion on the topic within the Lean Construction community, given that lean is based on respect for people and the implications of AI uses to individuals in our industry have not been understood.

KEYWORDS

Artificial intelligence, decision-making, ethical and social dilemma, biases.

INTRODUCTION

Artificial Intelligence (AI) has been on the horizon for our society since the late 1950s and recently projects and companies in the construction industry have incorporated it to support daily work routines. In the literature, we found conceptual frameworks to use AI in construction management. For example, Riad et al. (1991) present a theoretical approach for claim management in construction, where they developed algorithms for evaluating time impact analysis and to apportion damages in different delay/acceleration situations. Ko et al. (2003) developed and tested a hybrid AI model for decision-making to solve several construction management problems. In architecture and structural design, the use of AI in generative design has also been applied. For example, Oh et al. (2019) have used generative design and topology optimization to explore new design options, thus generating a large number of designs starting from limited previous design data. In

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a recent article in ENR (2021), several uses in construction are reported. For example, as applications for planning are growing quickly, companies like DPR construction are creating their own algorithms to help project teams make decisions in terms of production control or supporting owners in making facility management decisions (DPR Construction, 2019). Furthermore, commercial companies are offering algorithms to use AI for providing legal advice to small construction players to manage contractual risks.

This paper is inspired by The Social Dilemma documentary from Netflix and the book Homo Deus (Harari, 2019). These two references have sparked several philosophical discussions in all aspects of our lives, and we see the need to at least pose the questions for us, the international Lean Construction community, to discuss how ethical and social dilemmas related to the use of AI affect people in our industry. AI is used in several aspects of our daily life: automotive driving (Directions), searching for information (Google), choosing movies (Netflix), Social Platforms (FB, Instagram, LinkedIn) – all these influences what we see, which opinions we hear more, who we follow, what information is presented first, etc. AI use is already affecting not only our personal lives, but also our work lives in the construction industry. As lean practitioners, we seek to optimize processes, to work efficiently and to utilize technology where it enables us to either deliver more value or reduce waste. On the other hand, we should never forget that lean holds a common value of respect for people, and we want to make sure to preserve this in the future of the construction industry, given the probably inevitable coexistence of AI in construction (Schia et al. 2019). We think as a society all perspectives on using AI should be discussed in order to both gain the benefit and still keep asking the more fundamental and ethical questions. This should not be a discussion limited to AI developers who are trying to maximize their commercial value. Although the developers might have the best of intentions in aiming to increase the productivity of the construction industry, there might be unintended consequences of their actions.

In this paper we explore several questions associated with the current and future application of AI in the construction industry and the ethical and social dilemmas. This is an exploratory paper, and we look forward to sparking further research and discussion on the topic within our community.

METHODOLOGY

This paper uses exploratory research, which is open ended and interactive in nature; the structure is not predetermined, as opposed to confirmatory research (Stebbins, 2001). This type of research is appropriate for questions like how and why in fields where there is an absence of previous research data, as is in the case of this paper. The research question is how AI-based decisions in applications in the construction industry can present social and ethical dilemmas. Our purpose is to discuss the ethical and social dilemmas of using AI in the construction industry and the implications to preserving the respect for people working in construction. The authors have reviewed the literature 1) to first define AI as a field of study and its potentiality, and 2) to explain the ethical and social dilemmas. Then, we reviewed the literature and industry media to summarize current and potential future uses of AI in the construction industry. Finally, a discussion section is presented based on questions that emerged by associating AI applications in the construction industry with ethical and social dilemmas in decision-making.

BACKGROUND INFORMATION

Little research has been published on how AI impacts humans and human behavior. In this section, AI is defined through literature and the distinction between ethical and social dilemmas is discussed in the context of applications of AI to the construction industry.

WHAT IS AI?

Russell and Norvig (2019) studied several definitions of AI and classified them into systems (including machines) which think or act like a human, and systems which think or act rationally. These definitions create a need to study the definition of human thinking and acting, and how we define what rational acting or thinking is. Therefore, they stated that "Artificial intelligence or AI, attempts to understand intelligent entities. Thus, one reason to study it is to learn more about ourselves. But unlike philosophy and psychology, which are also concerned with intelligence, AI strives to build intelligent entities as well as understand them." To provide a satisfactory operational definition of intelligence to judge whether or not a system is acting humanly, Alan Turing (1950) designed the so-called Turing test. The test is passed if the system can demonstrate the following capabilities:

- Natural language processing to enable it to communicate successfully in English (or some other human language);
- Knowledge representation to store information provided before or during the interrogation;
- Automated reasoning to use the stored information to answer questions and to draw new conclusions;
- Machine learning to adapt to new circumstances and to detect and extrapolate patterns.

In a famous critique to AI research, Dreyfus (1972) published "What Computers Can't Do". He argued that human intelligence and expertise depend primarily on unconscious processes rather than conscious symbolic manipulation, and that these unconscious skills can never be fully captured in formal rules. Dreyfus' point is still valid to date: how can we use algorithms that try to replicate human behavior if we have not yet understood it? On the other hand, some AI algorithms are so complex that we cannot even understand them fully in retrospective.

Russell and Norvig (2019) also point out that AI has produced many significant and impressive products, even at this early stage in its development. Although no one can predict the future in detail, it is clear that AI will have a huge impact on our everyday lives and on the future course of civilization. Harari (2019) raises questions about the difference between human and AI, and asks what would happen if AI achieves superhuman intelligence: would AI then be more valuable than humans?

WHAT ARE ETHICAL AND SOCIAL DILEMMAS?

An **ethical dilemma** occurs when a decision has to be made between two alternatives in which both alternatives are not fully acceptable ethically. For example, you have to choose between two road designs. One alternative is perceived as safer by the road users, whereas the other alternative is eliminating fewer protected areas. What are you going to choose, perceived safer or preserving more nature? How would an AI algorithm judge these ethical decisions? "[E]thical dilemmas will often result in unethical behavior" (Sims

1992, p. 510). **Ethical behavior** means we are following the values, norms and rules of our society. Schermerhorn (1989) introduced four perspectives on ethical behavior: (1) justice (act based on fundamental rights), (2) moral rights (fair treatment), (3) individualism (long-term self-interest), and (4) utilitarian (best for most people). Those four perspectives can create dilemmas based on long-term vs. short-term advantage and which perspective gets prioritized. Also, the American psychologist Lawrence Kohlberg defines the highest level of moral reasoning, "Postconventional moral reasoning", as the ability to question "What is ethically right?" and "What are the wider long-term consequences?" An example is the importance of applying the spirit of the law rather than the letter of the law. Thus, when we use AI in the construction industry, we need to consider how the AI is designed, operates and learns, and how the algorithm works in the context of ethical and social problems. AI has to cope with dilemmas and, in comparison with human decision-making, which we are quick to judge, are we critically assessing the information AI delivers?

A **social dilemma** occurs in a situation where there is a conflict between self and collective interest (Van Lange et al., 2013; Dawes and Messick, 2000). For example, a social dilemma exists if the architect and the MEP designer are locally optimizing based on each separate perspective. The two designs are interdependent and therefore the fragmented views may result in a suboptimal and inefficient building. If a generative design is used to optimize only one perspective, it may not be the best for the whole project.

CURRENT USES OF AI IN CONSTRUCTION

This section presents different current uses of AI in the construction industry. Uses for the construction industry include but are not limited to automatic schedule generation for planning and control, design automation techniques like generative design or parametric design, contractual document analysis, and facility management.

PLANNING AND CONTROL

There are several AI applications currently being used in construction projects, especially around project scheduling analysis performed based on machine-learning algorithms (ENR 2021). One of the software vendors to optimize schedules (ALICE) states in an ENR article published in 2021 that the aim of this technology is to help teams avoid tedious planning tasks. He points out "Why would anyone in their right mind want to spend time crunching all the constraints on a project? It's mind-numbingly boring." This technology, based on commercially available AI algorithms, extrapolates thousands of possible ways of executing a project by running simulations of a project's 4D schedule and BIM, readjusting as variable inputs are tweaked in the project "recipe". Users make adjustments to the inputs, and the AI algorithm tells them how it will affect the construction schedule. The software developer says that the idea is not to cede decision-making to the algorithm; rather, it is about automating the process of generating possible alternate schedules (ENR 2021). These algorithms can help optimize the schedule of a project based on certain parameters; for example, the algorithm can explore crane placement and task sequencing for a construction project. But, how does the algorithm work? Since these companies have commercial interest the detailed understanding of how it works is not accessible to most people.

Schia et al. (2019) present interviews and a case study of using AI for planning on a project in Norway (studying ALICE). The study concludes that, when it comes to AI, the human-AI trust will be the most decisive factor for a successful implementation. Furthermore, it will be difficult for a worker to understand how ALICE arrives at the output, and further trust the output. Currently, the algorithm depends on human data input, but in the future when the AI algorithm has enough historical data, human input will no longer be necessary (Schia et al. 2019). This sparked other questions regarding scheduling algorithms, such as, is the schedule optimization algorithm based on the critical path method? Does it use lean principles? How collaborative is it? How does the algorithm balance different interests? Can workers input their preferences for task sequencing? How does the algorithm learn? How do we know it is successful?

GENERATIVE DESIGN

Different AI algorithms have been used in construction projects, with the purpose of optimizing the design. This type of AI application looks to generate numerous design options which are not only aesthetic but also optimized for engineering performance. Oh et al. (2019) use generative models to create design alternatives and the topology optimization to help designers choose a design alternative in an iterative manner. According to Oh et al. (2019), their framework manifests better aesthetics, diversity and robustness of generated designs than previous generative design methods.

Newton (2019) argues that Generative Adversarial Networks (GANs) are an emerging research area in deep learning that have demonstrated impressive abilities to synthesize designs; however, their application in architectural design has been limited. Newton (2019) tested the creation of 2D and 3D designs from specific architectural styles and experimented on how to train the algorithms to a desired design to control the "fidelity" and "diversity" of the design. Our questions here are: how do you define a successful design? What do "fidelity" and "diversity" mean? How do you measure them? And who is the judge behind the design? Is design transferable from project to project? Again, this raises the question of how biased the algorithm is. How does the optimization algorithm make trade-offs between designs, who decides which factors are considered in the decision? Usually, optimization algorithms seek to optimize one or two parameters or have a priority system. How aware are designers of these assumptions? Are there biases included in the algorithms?

CLAIM ANALYSIS

According to Riad at al. (1991), delays are the major cause of construction disputes; mediation is usually an effective solution, but a preventive and comprehensive approach is lacking. Riad at al. (1991) developed an AI algorithm for time-based claim management, which analyzes disputes that arise due to different types of delays (excusable/compensable, excusable/noncompensable, nonexcusable; independent, concurrent, serial) and helps determine the responsibility of each party. The algorithm utilizes a procedure called 'Time Impact Analysis' and involves the use of network-based scheduling tools to identify, quantify and explain the cause of a schedule variance (Riad at al., 1991). But, who developed the AI algorithm used in case of a claim? And, is the algorithm trustworthy?

ENVIRONMENTAL PERFORMANCE

Fernandez et al. (2019) presents the development of an equation that uses Artificial Neural Networks to predict the environmental performance of buildings in Brazil, in terms of energy, water and waste generation. Fernandez et al. (2019) argue that these equations help managers obtain a benchmark based on the current building stage and they can promote improvements in its environmental performance. But, given that the algorithms are based on data from other buildings' performance, is the benchmark appropriate? Should building design aim to perform based on the goals of society?

DISCUSSION

In this section, we discuss the concerns the authors have around AI and how AI uses could lead to ethical and social dilemmas. We acknowledge the potential benefits of current and future uses of AI. However, in this discussion we are attempting to articulate our point of view, not as a definitive conclusion, but as a starting point where we need to learn more and hope to encourage others to explore the challenges of using AI in the construction industry and the people that are affected by it. Table 1 presents a relationship between the dilemmas presented in AI uses and the discussion questions. This structure was developed retrospectively as the research is exploratory and we did not define a predetermined structure in the methodology; we are presenting it first to help the reader.

Table 1: Social and Ethical Dilemmas and Discussion Questions.

Dilemma	Discussion Questions and Key Points
Ethical Dilemma (alternatives are not fully acceptable ethically)	**What is the source of data?** AI applications will make trade-offs among ethically unacceptable alternatives.
Ethical behavior (following values, norms and rules of the society)	**Can we Trust AI Decisions?** AI applications should follow society's values and norms as they evolve. There is a risk that AI cannot adjust to ethical norms.
Social dilemma (conflict between self and collective interest)	**Are AI algorithms biased?** AI applications will have conflict regarding whose interests are prioritized, and most likely will carry bias from their creators.
	Do we need to please the algorithm? AI algorithms can also reinforce their preferences.
	Does AI impact project team motivation? We may be creating a problem if AI makes more decisions for us.

WHAT IS THE SOURCE OF DATA?

AI algorithms need data to learn. As these algorithms find more uses in the construction industry, they will also need large amounts of data to be trained. Having access to data means having access to better algorithms and the more data is used the more powerful the algorithm will be. Additionally, the AI decision-making process is impacted by the political, economic, social, technological, environmental and legal dimensions as well as by ethical boundaries and the ethical code of conduct (Brendel 2021), and "[t]o make an ethical decision [the machine] must know what an ethical conflict is [a situation where ethical rules clash with an agent's own self-interest]" (McDermott 2008, p. 6). Furthermore, based on the database and different approaches, the self-learning quality of AI is different within organizations (Brendel 2021).

Construction companies will need to decide which data to collect, and for what purposes. Finally, "When we assume information is objective, we forget that information doesn't create itself" (Flores 2012, p. 43). Often it is not considered if all the data is useful and thus needed. One point can be that we do not know if we might need the data in the future. Another point is the fear of missing something by not seeing the whole picture, having information asymmetry or by being limited by our cognition. But can AI consider everything a decision requires such as different political, moral and social interests as well as biases? Who decides which algorithm will be more successful? Which algorithm has more commercial value? Which algorithms are going to be backed by venture capital? Which companies will lead the competition on AI development? In addition, if we want to keep humans engaged in processing the information, too much data can lead to analysis paralysis or just plain confusion.

CAN WE TRUST AI DECISIONS?

Science is not always right; significant discoveries have been made that change our previous understanding. For example, in the 70s we believed that our chromosomes never change in our lives. In the 80s, scientists discovered that chromosomes could grow back due to a hormone called telomerase that is increased by healthy behaviors (Jaskelioff et al. 2011). What does this have to do with AI? AI replicates patterns, because it is learning from patterns that exist. The algorithm is learning based on the status quo of knowledge, but we discover and learn new things on a daily basis. Thus, we are imperfect, and our knowledge is not all-embracing, and neither is AI. Thus, new knowledge and experiences change our values and norms and need to be considered in the algorithm. So, are we trusting AI too much? Should we be more critical? How does it impact our daily work business? Some questions to raise regarding this topic are:

- What happens if someone believes that the algorithm is incorrect? What happens if you do not follow a recommendation made by the algorithm on a task sequence or schedule? What happened to those critical people in an organization?
- Are our brains going to become lazy if we often rely on algorithms' suggestions about what to do next without questioning them? Is AI going to be the new superhuman?
- How does AI impact the design phase of projects when relying on a generative design? What is the role of designers? Will designers be ultimately responsible for the design or will they be responsible only for providing data to feed the algorithm? Does the algorithm know what is best for us?

Moreover, some people assume that AI is objective, because the algorithm itself has no feelings. We agree, AI is more reliable, has no emotions, no moods, does not get sick, it does not require time off, and always has energy as long as it gets power. However, even though machines do not feel (for now), the task they perform uses the belief system and biases of their creators. Therefore, thinking that the algorithm is objective may not be correct if the data it used to be trained perpetuates subjective behaviors based on outdated belief systems. For example, if you want to select a successful project team, you will only be able to judge project teams based on the data available regarding their past performance and interactions.

ARE AI ALGORITHMS BIASED?

Many people think that AI can prevent or avoid biases and create an objective decision, that the data is fully transparent and traceable. It is well known that humans carry biases: if you think, you have biases. For example, we tend to more easily believe the opinions of people that have similar backgrounds and life experiences to ourselves (Nickerson et al., 1998). Even when we may be aware of our biases, we still cannot get rid of them; intensive training and a diverse group is needed to counteract them. AI is created by humans and biases are applied to a greater scale when using the algorithms. One very well-known bias is groupthink. Groupthink occurs when group members avoid disagreement (Janis and Mann 1979, 1982; Johnson and Johnson, 2009) and thus results are "caused by a lack of diverse thinking" (Schöttle et al. 2019, p. 799). Is the algorithm catalyzing groupthink? Are we going to avoid difficult conversations by relying on solutions from AI? Will it lead us to overlook important ethical dilemmas, just because we do not see the conflict? Are we able to have authentic discussions and productive conflicts in the workplace if we rely on AI? McDermott (2008, p. 6) argues that "the mere facts that the program has an explicit representation of the ethical rules, and that the humans who wrote or use the program know the rules are ethical does not make an 'explicit ethical reasoner' an ethical agent at all. For that, the agent must know that the issues covered by the rules are ethical." So, is an algorithm able to make an ethical decision without free will and emotions? Is the algorithm able to make a decision in a social complex setting? Does the person programming the algorithm have a full understanding of the social complexity and are they able to program such an algorithm? As written above, decision-making often results in trade-offs. But how does the AI decide in terms of trade-offs and does an AI have decision-making autonomy?

DO WE NEED TO PLEASE THE ALGORITHM?

Humans have the power to develop algorithms, but people that work for an algorithm often do not understand the outcome. For example, Harari in his book Homo Deus (2018) describes how Google's search algorithm is so complex that we cannot predict what the search result will be, even more if someone wants to create a successful website they have to do it so it is promoted by the algorithm (so the website's client is the algorithm not humans), people then just see what the algorithm likes. Thus, our world is shaped by how we pleased the algorithm. In the construction industry, this issue can be created when a schedule is decided by an algorithm, and now the subcontractor has to please the algorithm to get a good evaluation. There may be the case that circumstances change and following the original plan may no longer be optimal. Another example that often occurs is that structural engineering software often prescribes an amount of reinforcement in the building structure, which causes the problem of using more steel than necessary and having issues concerning compressing the concrete. Although structural engineers know this, they please the algorithm and thus produce waste. This causes a dilemma regarding sustainability and costs, and sometimes limits human creativity.

DOES AI IMPACT PROJECT TEAM MOTIVATION?

Another point that needs to be considered arises in terms of motivation. As known from the self-determination theory (SDT), autonomous motivation, necessary to accomplish engagement and self-interest for creative problem solving, is based on the fulfilment of the three psychological needs: autonomy, competence and relatedness (e.g., Deci et al. 2017; Deci and Ryan 2014; Gagné and Deci 2005; Ryan and Deci 2000; Deci and Ryan 1985). All three factors will be impacted by AI. If we trust AI, are we really making decisions autonomously? If we rely on AI, are we going to have productive conflicts from which we grow and strengthen our relationships? Are we going to learn from failure or is AI hindering humans from improving? What does collaboration in a project team look like when AI takes over? If we let AI decide for us, what does this do to our motivation and the motivation and performance of a project team (see Schöttle (2020))? Is this creating a dilemma in terms of motivation and performance? Also, if the AI chooses an alternative with which you do not agree, you are in a conflict. Will AI take over all the repetitive and standard work, and free up humans to deal with creative thinking? Will AI provide the designers with alternatives that need to be assessed by competent experts?

CONCLUSION

This paper explores AI and its uses in the construction industry. There are currently some uses in planning and control, generic design and claim management. We explored how AI-based decisions in applications in the construction industry can present social and ethical dilemmas. Finally, we discussed how using AI algorithms will pose relevant questions concerning the future of the construction industry.

There are many potential benefits to the use of AI in the construction industry, from supporting better decisions, to optimizing schedules and reducing environmental impacts. As lean practitioners, we want to make the design, planning and construction process as efficient as possible, and, if AI can help do this, it should be part of our toolkit. But we should also keep being skeptical and ask questions to make sure we do not end up with an inappropriate solution just because it is complicated to understand the process behind it. When we are busy, we are more likely to overlook potential conflicts and biases. So, when using an AI tool to work more efficiently, we might fall into the trap of a social or ethical dilemma without exploring it, and risk ending up with an inappropriate solution despite our intentions.

The authors believe that the future of construction will include more and more AI algorithms as we get better at collecting data and training the algorithms. We are not specialists within AI, and some might find our use of non-scientific references such as a documentary on Netflix confusing. But, as we also know from the use of e.g. the Last Planner System, it is when we start to respectfully question other disciplines that we proactively identify waste and build on each other's ideas to drive real innovative thinking. We want to invite the industry and the lean community to engage in debating the benefits and also potential pitfalls of using AI to improve the construction industry, to ensure the optimization is balanced, and also consider benefits for the wider society. “What is ethically right? “What are the wider long-term consequences?”

REFERENCES

Dawes, R.M., and Messick, D.M. (2000). “Social Dilemmas.” *International Journal of Psychology*, 35(2) 111-116, doi.org/10.1080/002075900399402.

Deci, E. L., Olafsen, A.H., and Ryan, R.M. (2017). “Self-Determination Theory in Work Organizations: The State of a Science.” *Annual Review of Organizational Psychology and Organizational Behavior*, 4(1) 19-43.

Deci, E.L., and Ryan, R.M. (1985). *Intrinsic Motivation and Self-Determination in Human Behavior*. New York, NY: Plenum Press.

Deci, E.L., and Ryan, R.M. (2014). “The Importance of Universal Psychological Needs for Understanding Motivation in the Workplace.” *The Oxford Handbook of Work Engagement, Motivation, and Self-Determination Theory*.

DPR Construction (2019). 3 Ways to Turn Building Data into Building Intelligence. https://www.dpr.com/media/blog/three-ways-to-turn-building-data-into-building-intelligence. Accessed: 2/26/2021.

Dreyfus, H. (1972). *What computers can’t do: The limits of artificial intelligence.* HarperCollins.

ENR (2021). “How Artificial Intelligence Can Transform Construction.” https://www.enr.com/articles/51190-how-artificial-intelligence-can-transform-construction. Accessed: 2/26/2021.

Fernandes, L.L.A, Rocha, M.J, Costa, D.B. (2019). “Prediction of Environmental Performance Indicators for Construction Sites Based on Artificial Neural Networks.”

Proc. 27th Annual Conference of the Int. Group for Lean Construction (IGLC), Dublin, Ireland, 1413-1424. doi.org/10.24928/2019/0248.

Flores, F. (2012). *Conversations for action and collected essays: Instilling a culture of commitment in working relationships.* CreateSpace Independent Publishing Platform.

Gagné, M., and Deci, E.L. (2005). "Self-determination theory and work motivation." *Journal of Organizational Behavior*, 26(4) 331-362.

Gomez, S., Ballard, G., Arroyo, P., Hackler, C., Spencley, R., and Tommelein, I.D. (2020). "Lean, Psychological Safety, and Behavior-Based Quality: A Focus on People and Value Delivery." *IProc. 28th Annual Conference of the International Group for Lean Construction (IGLC)*. Berkeley, California, USA, 97-108.

Harari, Y. N. (2016). Homo Deus: A brief history of tomorrow. Random House.

Jaskelioff, M., Muller, F.L., Paik, J.H., Thomas, E., Jiang, S., Adams, A.C., Sahin, E., Kost-Alimova, M., Protopopov, A., Cadiñanos, J., Horner, J.W., Maratos-Flier, E., and Depinho, R.A. (2011). „Telomerase reactivation reverses tissue degeneration in aged telomerase-deficient mice." *Nature*. 469, 102–106. doi.org/10.1038/nature09603.

Ko, C.H., and Cheng, M.Y. (2003). Hybrid use of AI techniques in developing construction management tools. *Automation in Construction*, 12(3), 271-281.

McDermott (2008). "Why Ethics is a High Hurdle for AI." *North American Conference on Computers and Philosophy (NA-CAP) Bloomington*, Indiana.

Newton, D. (2019). "Generative deep learning in architectural design." *Technology Architecture+Design*, 3(2) 176-189.

Nickerson R.S. (1998). "Confirmation Bias: A Ubiquitous Phenomenon in Many Guises. Review of General Psychology." 2(2) 175-220. doi.org/10.1037/1089-2680.2.2.175.

Oh, S., Jung, Y., Kim, S., Lee, I., and Kang, N. (2019). Deep generative design: Integration of topology optimization and generative models. *Journal of Mechanical Design*, 141(11).

Riad, N., Arditi, D., and Mohammadi, J. (1991). "A conceptual model for claim management in construction: An AI approach." *Computers & Structures*, 40(1) 67-74.

Russell, S.J., and Norvig, P. (2009). *Artificial Intelligence: A Modern Approach (3rd ed.)*. Upper Saddle River, New Jersey: Prentice Hall.

Ryan, R. M., and Deci, E. L. (2000). "Intrinsic and Extrinsic Motivations: Classic Definitions and New Directions." *Contemporary Educat. Psychology*, 25(1), 54- 67.

Schermerhorn, J.I. (1989). *Management for Productivity*, John Wiley, New York.

Schia, M.H., Trollsås, B.C., Fyhn, H., and Lædre, O. (2019). "The Introduction of AI in the Construction Industry and Its Impact on Human Behavior." *Proc. 27th Ann. Conf. of the International Group for Lean Construction (IGLC).* Dublin, Ireland, 903-914.

Schöttle, A. (2020). "What Drives Our Project Teams?" *Proc. 28th Ann. Conf. of the Intern. Group for Lean Constr. (IGLC).* Berkeley, California, USA, pp 313-324.

Sims, R.R. (1992). "The challenge of ethical behavior in organizations." *J Bus Ethics* 11, 505–513, doi.org/10.1007/BF00881442.

Stebbins, R. A. (2001). Exploratory research in the social sciences (Vol. 48). Sage.

Turing, A. (1950). "Computing Machinery and Intelligence." *Mind*, 59(236) 433-460.

Van Lange, P.A.M., Joireman, J., Parks, C.D., and Van Dijk, E. (2013). "The psychology of social dilemmas: A review." *Organizational Behavior and Human Decision Processes*, 120(2), 125–141, doi.org/10.1016/j.obhdp.2012.11.003.

LEARNING AND TEACHING LEAN

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A REVIEW OF COMPONENTS AND CONFIGURATIONS OF SURVEY RESEARCH IN LEAN CONSTRUCTION

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ABSTRACT

The reliability of research is substantially linked with its methodology and design. The use of surveys is one of the methods that has been commonly used in research projects. Therefore, identifying the active state and classification of the mechanisms used by the survey studies can help increase the quality of future research. Accordingly, this study reviews the survey literature on Lean Construction to identify their common components along with their configurations. To achieve this goal, a total number of seventy studies were randomly sampled from the publications pool and reviewed. Afterwards, their bibliographic and content characteristics were extracted and analysed and a total of seven common components as well as three dominant configurations were found. Through a thematic analysis, twelve main themes were identified which were further sorted by their observed frequency. The result shows the relationship between the themes and the configurations applied by the studies so far. It also discloses an overall status of the survey research in Lean Construction which can be used as a valuable lead for researchers to decide for the orientation and design of their future research projects.

KEYWORDS

Lean construction, literature review, research, survey.

INTRODUCTION

Following the advent of Lean Construction, a number of calls for reform in the construction industry have attracted many researchers from all over the globe to enhance construction productivity (Aziz and Hafez 2013; Ballard 2000; Egan 1998; Koskela and Howell 2002). Consequently, an increasing amount of theories, methods and practices have been introduced and their practical implications have been widely investigated

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through numerous studies (Ghosh and Young-Corbett 2009). Thus, a diverse range of methods and techniques have been applied by researchers to advance the various aspects of this field. Currently, conducting surveys has developed into a rigorous approach to research as a systematic method (Ponto 2015). According to the recognition-by-components theory, things should be broken down into their components to be recognized and understood (Biederman 1987). However, in the case of Lean Construction survey research, the authors have found no comprehensive study which was particularly focused on the common components used by the Lean Construction research community. This study seeks to partially close this gap by identifying and characterizing the common components and various classifications of research in Lean Construction from a sample of survey research on Lean Construction.

SURVEY RESEARCH

A survey is a type of field study, which collects data from a sample of individuals by answering a predetermined set of questions (Check and Schutt 2011; Rossi et al. 2013). The major steps of survey research are highlighted as below:

- *Design and planning, which* presents one of the crucial steps to identify requirements, limitations, and methods. In this step, the target sample is defined, the data collection method is determined, and measurement instruments are developed. The method is determined based on the specific survey requirements as well as time, cost and resource constraints (Abduh and Roza 2006).
- *Data collection,* where the researcher obtains the required information. Interviews and questionnaires are the most prevalent data collection approaches performed in survey research. Interviews can be conducted in structured, semi-structured or unstructured styles, and the sessions can take place by phone, computer or in person. The collected data can be qualitative or quantitative (Abduh and Roza 2006; Sapsford and Jupp 1996). Some studies may utilize a mix of both to increase the validity and reliability of the results (Hox and Boeije 2005).
- Lastly, *analysis* of the collected data, which eventually feeds into the key findings of the research (Alreck and Settle 1985; Singleton et al. 1999).

It should be noted that each step can involve further sub-steps that deserve in-depth exploration.

RESEARCH METHOD

At first, a total of 87 studies were selected using the search term "Lean Construction AND survey" on Google Scholar. The databased was employed to form a random sample and ensure the diversity in selections from different journals and conferences. Then, a screening step was applied in which a set of inclusion and exclusion criteria were used to refine the selection. The criteria embraced the studies that:

1. were published in the form of either a journal or conference paper
2. were published in the English language
3. were directly related to Lean Construction
4. fit into the definition of survey research

Therefore, after a round of skim and scan of the abstracts, research methods and conclusions, a total of 70 articles that met the above criteria were selected to go through the rest of the process. The next step investigated various aspects of the bibliographic information, data collection, analysis and themes used by the samples. The acquired data were coded in the NVivo software package (QSR International), which enabled the researchers to track the recurrence frequency of the coded items. During the review, the common components of the sampled survey research papers were identified and coded based on their main characteristics. Concurrently, various compositions of the main identified components were observed and grouped as study configurations. The study also conducted a content analysis using word frequency on the samples and reported the relationship between the themes and the contents. Finally, the research method and findings of the study were validated and confirmed by two researchers of the field whose demographic information is indicated in table 1. In terms of reliability and validity, the paper highly complies with the strategies suggested by Noble and Smith (2015).

Table 1- Demographic information of the validators

Research Category	Years of Experience	Level of Education	Occupation	Age
Expert 1	11	PhD	Associate professor	44
Expert 2	14	PhD	Associate professor	49

SAMPLE INFORMATION

To get a demographic grasp of the sample, the publications were classified based on the country of affiliation of their first author. In addition, a classification of developed and developing countries was made according to the United Nation’s World Economic Situation and Prospects (2020).

In general, the papers were originated from 29 countries, including 19 developing and ten developed countries. Furthermore, although the figures indicate an average number of 2.4 publications per country, the distribution between developing and developed countries was not uniform. Figure 1 demonstrates the spread of the samples over time and the classification of their country of origin. It presents an increase in the frequency of the use of survey research in Lean Construction. The overall trend shows that the surge can be seen in both developing and developed countries. Furthermore, India with seven and UK with 12 publications were identified as the most prolific countries among developing and developed countries, respectively.

As for the publication medium, a statistical analysis of the published sources indicates that the sample was comprised of 39 journal and six conference titles. The Annual Conference of International Group for Lean Construction (IGLC) and Lean Construction Journal had the biggest share of the publications in the studied samples. Yet, journal papers constituted 51 studies which account for 73% of the sample.

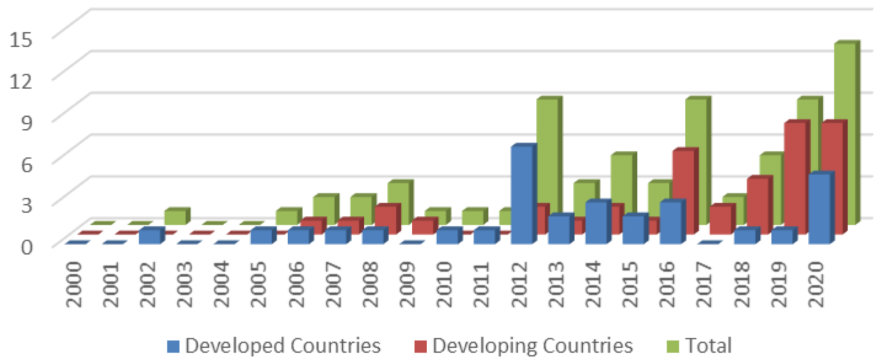

Figure 1- Distribution by year and category of their first authors' country

COMMON COMPONENTS OF THE STUDY DESIGNS

The analysis of the records indicated that an extended map of the study designs used by the survey-based research in Lean Construction is composed of the seven following components:

1. *Research concept development*: It justifies the gap, undertakes literature review to identify state of the art, provides a clear statement for the research problem(s) and research question(s). This step was present in all of the reviewed publications.
2. *Pre-design field exploration*: It is comprised of collecting the data required to formulate or complete a further step in a study. For instance, in many cases, the pre-design field exploration was used to devise questionnaires or design interviews. Almost 90% of the studies involved pre-design field exploration that was conducted based on literature reviews, interviews, observations and questionnaire surveys in the order of their frequency. The associated data was found to be of qualitative nature except in one case that quantitative data was collected using a questionnaire survey (Abduh and Roza 2006; Koohestani et al. 2020; Li et al. 2019).
3. *Study design:* this step was performed to design or formulate further steps of a study. In the majority of cases, this component involved designing a questionnaire or interview. Almost 90% of the publications included this step in their design. The majority of those that omitted this component used unstructured interviews that did not require a specific design (Abduh and Roza 2006; Bashir et al. 2013; Bygballe and Swärd 2014; Enshassi and Abu Zaiter 2014; Jasmine and Vasantha 2007).
4. *Data collection*: this was the main data collection phase upon which the findings were drawn. Therefore, it was present in all of the studies. Primary data was collected using questionnaire surveys and interviews in the majority of the cases. Other methods such as direct observations, archival review and the use of organizational databases were also utilized by this research component (Bashir et al. 2013; Enshassi and Abu Zaiter 2014; Meng 2019). The collected data were of both qualitative and quantitative nature. Nevertheless, Quantitative data was more frequent. Furthermore, in 11% of the cases, a combination of both types of data was collected (Figure 2).

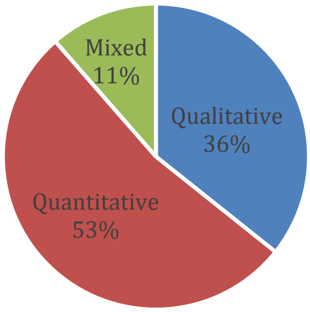

Figure 2- Types of main data in the sampled research

5. *Data analysis:* A wide range of methods were used to discover information and to make meaningful insight out of the collected data. They varied depending on the nature of the data. Yet, thematic and statistical analysis were the most prominent methods of analysing the qualitative and quantitative data, respectively. Similar to data collection, this component was also present in all of the reviewed studies (Bygballe and Swärd 2014; Enshassi and Abu Zaiter 2014; Koohestani et al. 2020).
6. *Describing the phenomenon:* This component would describe the observed patterns in the studied phenomenon. It was particularly focused on the "what" s rather than "why" s. This component was also observed in all of the sampled literature.
7. *An in-depth explanation of the phenomenon:* existed in 10% of the reviewed samples. It would develop a model, framework or approach (Li et al. 2019).

Figure 3 presents a general map of the typical arrangement of these seven components in Lean Construction survey research. The range of specific configurations used by the researchers is introduced and elaborated in the forthcoming sections.

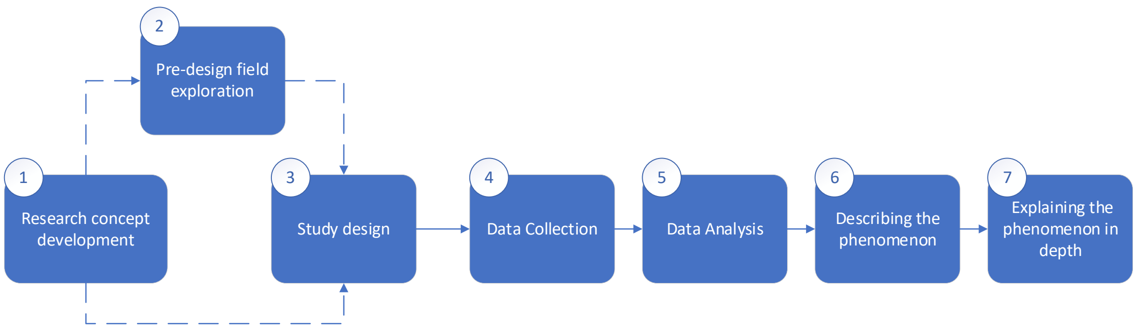

Figure 3- Identified common components of the study designs

RESEARCH CONFIGURATIONS

As explained, the use of the identified components varied by the structure and design of the reviewed studies. Accordingly, three different configurations were identified (Table 2) which include *simple*, *semi-elaborated* and *elaborated* configurations. As the table shows, five components were an integral part of all three configurations. The integral components were identified as the research concept and development (comp #1), study design (comp #3), data collection (comp #4), data analysis (comp #5), and describing the phenomenon (comp #6). However, what differentiated between the three configurations was the inclusion of the other two components. While the simple category did not involve any pre-design field exploration (comp #2) and explanation of the phenomenon (comp #7), the semi-elaborated category had component #2 added to its structure, and the elaborated category involved all the seven identified components.

Table 2- The difference between the configurations

Research Category	Comp #1	Comp #2	Comp #3	Comp #4	Comp #5	Comp #6	Comp #7
Simple	Y[1]	N[2]	Y/N[3]	Y	Y	Y	N
Semi-Elaborated	Y	Y	Y/N	Y	Y	Y	N
Elaborated	Y	Y	Y	Y	Y	Y	Y

[1] Included, [2] Not Included [3]Vary

CONTENT ANALYSIS

The findings of the publications were also thematically analysed and categorized into twelve groups. Figure 4 indicates the identified themes and their share in the studied sample. As can be seen, Lean Construction implementation barriers, benefits and success factors were the most recurring themes in the sample.

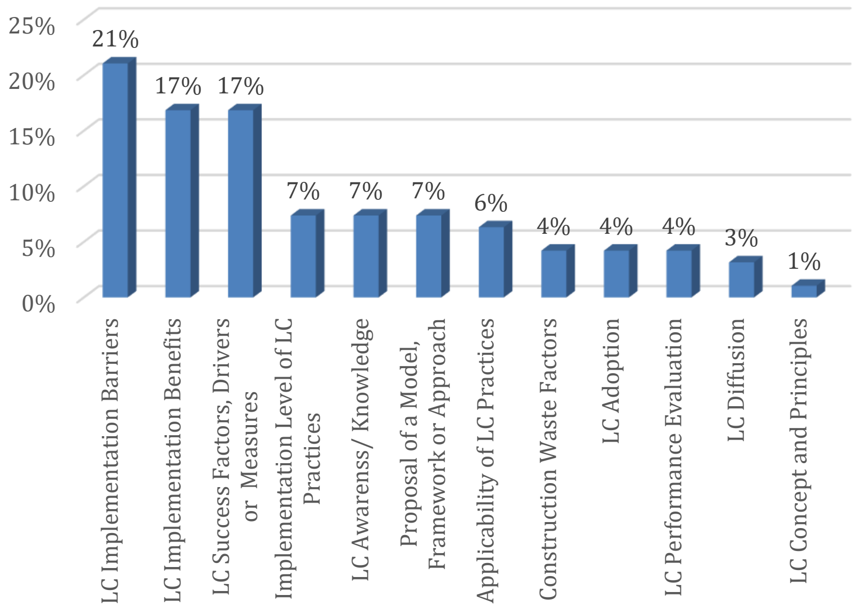

Figure 4- Themes of findings

The study also undertook a word frequency analysis which presents an effective method to obtain context and trends out of textual content (Zhong and Song 2008). Therefore, the 50 most frequent words in the sample were identified and visualized in the form of a word cloud (Heimerl et al. 2014) in figure 5. Management, implementation, safety and production were the most frequent words in declining order. Process, barriers, waste, performance, and value were the next most frequent words. These results are in harmony with the identified themes' recurrence by being closely related to the implementation phase.

Figure 5- Most frequent words in all studies

THE RELATIONSHIP BETWEEN THE CONFIGURATIONS AND THE THEMES

Figure 6 presents the frequency of the configurations in the sample along with their associated themes. As the figure shows, semi-elaborated studies were the most commonly-used configuration by comprising more than 80% of the sample. The most frequent themes in this category included implementation barriers, benefits, and success factors. Significant differences were observed between the contents of the simple configuration category and the elaborated studies. While investigating the success factors was found to be the most frequent theme in simple studies, the elaborated studies mainly involved proposing a model, framework, or approach.

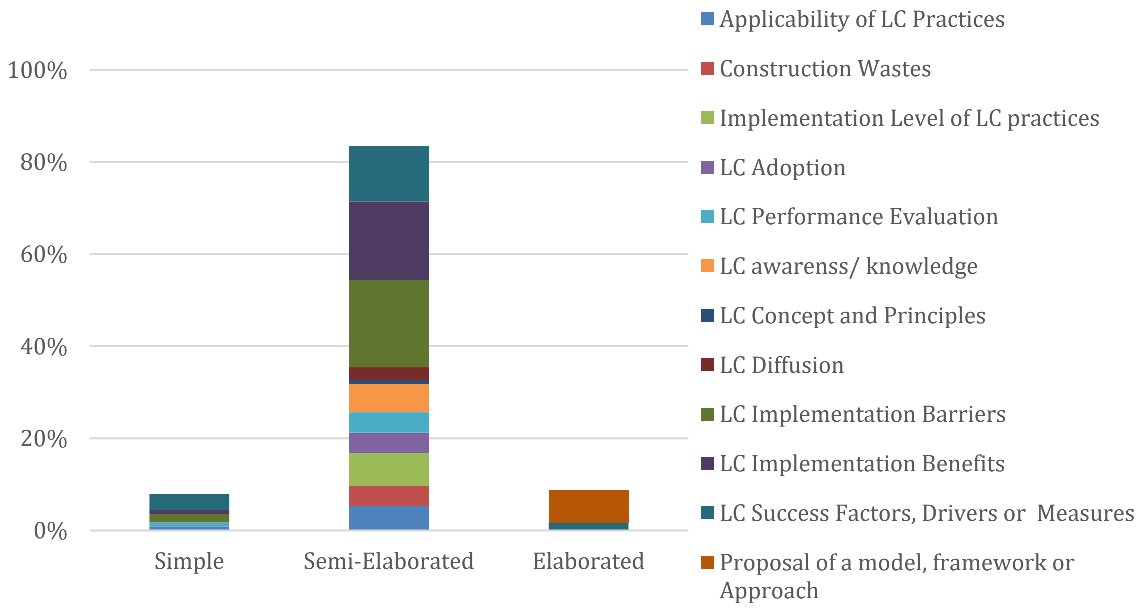

Figure 6- Themes of findings by study categories

A word frequency analysis was also conducted each for each study category. Figure 7 presents the word cloud chart generated to identify the most frequent words in each category of configuration. These charts represent both similarities and difference in the contents of the studies. These figures share the significance of the word "management" with figure 5. However, implementation was the most frequent word in studies with a simple configuration. Tools and practices were two aspects of implementation that turned to attract considerable attention in the simple configurations. Semi-elaborated studies were more concerned with managerial aspects such as process, waste, and production. The figures also show that safety and performance were two subjects that went through studies with elaborated configurations. In other words, these two subjects are ahead of the rest in being investigated extensively and in-depth.

(a) (b) (c)

Figure 7- Most frequent words in: a) simple b) semi-elaborated and c) elaborated studies

Further, the *average number of annual citations* was used as an index to indicate the level of contribution made by each study configuration. The index was calculated for each study based on the number of citations divided by the number of years that they have been available to the research community. The results were averaged and grouped by each study configuration. Figure 8 indicates the result in which a considerable difference between the contribution level of simple studies and the other two categories can be seen.

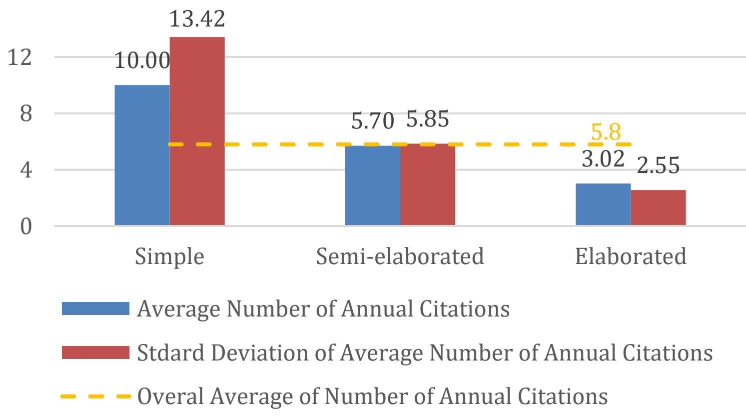

Figure 8- The average of the annual number of citations by study configuration

DISCUSSION

According to the bibliographic information of the sample, survey research in Lean Construction is observing a significant increase in recent years. It can be associated with the technological improvement that facilitates sampling, communication and ultimately data collection. Furthermore, this growing trend indicates that the value of empirical data, especially survey research, is taking a more significant part in future research outcomes. Besides, the number of countries in the sample signals that Lean Construction is still early in its global hype cycle and far from a desirable state where Lean Construction is studied and practiced in the majority of countries of the world. Thus, researchers are urged to embark on international conjoint research to promulgate Lean Construction in new countries, enhance existing practices and eventually increase Lean Construction research diffusion.

The findings and content analysis of the publications indicated that while implementation issues have been widely investigated, less attention has been paid to diffusion and adoption issues. Given the fundamental importance of the later ones, a shift is demanded in the general focus of the lean construction research community.

A relationship was observed between the content of the studies and the configurations used in the study design. The configurations were divided into three groups of simple, semi-elaborated and elaborated study. A significant difference was observed between the density of the identified configuration, which indicates a low level of diversity in methods applied to the Lean Construction survey research. So far, most of the research completed in the community falls in the semi-elaborated category. The research also described the situation (the Whats) without elaborating the reasons for the observations (the Whys). Therefore, it seems that Lean Construction research is ready to move to the next level and to start developing studies with elaborated configurations. This demand is more evident for subjects such as success factors, barriers, and benefits in particular.

Lastly, the highest contribution of simple studies and the lowest level of elaborated ones could indicate the incompleteness of the former and strength of the later. Thus, more elaborated research is encouraged as it pushes the knowledge further towards its edge.

CONCLUSION

Identifying the active state and classification of the mechanisms used by the survey studies is crucial to improve the quality of future research. To achieve this, a total of 70 survey literature on Lean Construction were reviewed to elicit their bibliographic information, common components and content characteristics. It was found that seven common components form three different configurations in Lean Construction survey research. A thematic analysis of the result revealed twelve main themes in the sampled literature which was then used together with the average number of annual citations to establish the relationships between the identified configurations. The analysis of the data also shows that interest in survey research on Lean Construction is increasing and that the empirical data will be of higher value in future research. Further, researchers are encouraged to consider more diverse methods and elaborated configurations and also to direct their studies towards more fundamental issues such as diffusion and adoption.

This study uses a random sampling method to collect data. Future research may involve a systematic literature review to ensure of the involvement of all pertinent works.

REFERENCES

Abduh, M., and Roza, H. (2006). "Indonesian Contractors' Readiness Towards Lean Construction." *14th Annual Conference of the International Group for Lean Construction (IGLC14).*Santiago, Chile, 543-549.

Alreck, P. L., and Settle, R. B. (1985). "The Survey Research Handbook. Homewood." McGraw-Hill/Irwin.

Aziz, R. F., and Hafez, S. M. J. A. E. J. (2013). "Applying Lean Thinking in Construction and Performance Improvement." *Alexandria Engineering Journal*, 52(4), 679-695.

Ballard, H. G. (2000). "The Last Planner System of Production Control." PhD Diss, University of Birmingham.

Bashir, A. M., Suresh, S., Oloke, D. A., Proverbs, D. G., and Gameson, R. (2013). "The Application of Lean Construction Tools in the United Kingdom Construction Organisations: Findings from A Qualitative Inquiry." *AEI 2013: Building Solutions for Architectural Engineering*, 64-73.

Biederman, I. (1987). "Recognition-by-components: A Theory of Human Image Understanding." *Psychological Review*, 94(2), 115.

Bygballe, L. E., and Swärd, A. (2014). "Implementing Lean Construction: A Practice Perspective." *22nd Annual Conference of the International Group for Lean Construction (IGLC22).* Oslo, Norway, 3-14.

Check, J., and Schutt, R. K. (2011). *Research Methods in Education.*, Sage Publications.

Egan, J. (1998). *Rethinking construction*, DETR.

Enshassi, A., and Abu Zaiter, M. (2014). "Implementation of Lean Tools on Safety in Construction Projects in Palestine." *22nd Annual Conference of the International Group for Lean Construction (IGLC22).*Oslo, Norway, 1205-1218.

Ghosh, S., and Young-Corbett, D. (2009). "Intersection between Lean Construction and Safety Research: a Review of the Literature." *Industrial Engineering Research Conference*.

Heimerl, F., Lohmann, S., Lange, S., and Ertl, T. (2014). "Word Cloud Explorer: Text Analytics Based on Word Clouds." *2014 47th Hawaii International Conference on System Sciences*, IEEE, 1833-1842.

Hox, J. J., and Boeije, H. R. (2005). "Data Collection, Primary Versus Secondary." *Encyclopedia of Social Management*, 1, 593-599.

Jasmine, K., and Vasantha, R. "Identification of Software Performance Bottleneck Components in Reuse Based Software Products with the Application of Acquaintanceship Graphs." *Proc., International Conference on Software Engineering Advances (ICSEA 2007)*, IEEE, 34-34.

Koohestani, K., Poshdar, M., and Gonzalez, V. (2020). "Finding the Way to Success in Implementing Lean Construction in an Unfavourable Context." *28th Annual Conference of the International. Group for Lean Construction (IGLC28),* International Group for Lean Construction (IGLC).

Koskela, L. J., and Howell, G. (2002). "The Underlying Theory of Project Management is Obsolete." *PMI research conference*, PMI, 293-302.

Li, X., Wang, X., and Lei, L. (2019). "The Application of an ANP-Fuzzy Comprehensive Evaluation Model to Assess Lean Construction Management Performance." *Engineering, Construction and Architectural Management*, 27(2).

Meng, X. (2019). "Lean Management in the Context of Construction Supply Chains." *International Journal of Production Research*, 57(11), 3784-3798.

Noble, H., and Smith, J. (2015). "Issues of Validity and Reliability in Qualitative Research." *Evidence-based nursing*, 18(2), 34-35.

Ponto, J. (2015). "Understanding and Evaluating Survey Research." *Journal of the Advanced Practitioner in Oncology*, 6(2), 168.

Rossi, P. H., Wright, J. D., and Anderson, A. B. (2013). *Handbook of survey research.*, Academic Press.

Sapsford, R., and Jupp, V. (1996). *Data Collection and Analysis.*, Sage.

Singleton, R., Straits, B., and Straits, M. (1999). "Approaches to Social Research." *Oxford University Press*, 9.

United Nations (2020). "World Economic Situation and Prospects 2020." United Nations Publications.

Zhong, Q.-Y., and Song, J. (2008). "The Developing Trend Research of Knowledge Management Overseas Based on Word Frequency Analysis." *4th International Conference on Wireless Communications, Networking and Mobile Computing*, IEEE, 1-4.

Ng, M. S. and Hall D. H. (2021). "Teaching Target Value Design for digital fabrication in an online game: overview and case study." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 249–258, doi.org/10.24928/2021/0117, online at iglc.net.

TEACHING TARGET VALUE DESIGN FOR DIGITAL FABRICATION IN AN ONLINE GAME: OVERVIEW AND CASE STUDY

Ming Shan Ng[1] and Daniel Mark Hall[2]

ABSTRACT

Digital fabrication (DFAB) for construction automation is emerging in the industry. However, DFAB requires better integration of fabrication-related information and organisation into the design process. Discrete processes in traditional delivery models such as Design-Bid-Build can hinder DFAB implementation when stakeholders find it hard to manage project costs. Target Value Design (TVD) has been proposed as possible approach to manage the DFAB design process, but management of DFAB using TVD is still new in the industry. Meanwhile, existing educational games have been successful at teaching players the basic principles of TVD principles. However, these games do not explicitly consider how players should select from advanced fabrication processes. They also have not yet been adopted for online play. This work presents an overview of an online TVD for DFAB game that can 1) help players understand basic TVD principles and 2) explicitly considers fabrication processes and resulting production times as an additional project value. The paper presents the results of a validation case played by 36 construction professionals, researchers and students in December 2020. Overall, this work contributes to the body of knowledge in learning and teaching TVD, online lean games, and technology adoption.

KEYWORDS

Target Value Design (TVD), digital fabrication, target cost, collaboration, concurrent, integrated project delivery, design management.

INTRODUCTION

Digital fabrication (DFAB) is emerging as a systemic innovation to foster automation and boost productivity in the construction industry (Agarwal et al. 2016). However, DFAB has not yet been widely adopted in projects. A key barrier that hinders DFAB adoption is the sceptical attitude from project stakeholders to manage DFAB in construction projects (Carra et al. 2018). Recent research finds that DFAB transforms design and construction processes and therefore requires better integration of fabrication-related information and organisation (Bock and Linner 2015; Hall et al. 2019; Ng et al. 2020). With traditional project delivery models such as Design-Bid-Build (DBB), information, organisation and

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process are discrete in design and construction. Stakeholders find it hard to manage project values such as costs and schedule without the knowledge of the construction process, in particular for management for novel technology implementation (Ballard 2011; Carra et al. 2018).

DFAB adoption could benefit from innovative design management approach such as the lean-based Target Value Design (TVD). TVD is lean-based approach that involves design based on detailed cost estimates (Macomber et al. 2007). TVD enables concurrent engineering, design-to-target-values and maximise values to project stakeholders (Ballard and Morris 2010; Miron et al. 2015; Tommelein and Ballard 2016; Ng and Hall 2019). However, TVD requires a radically different design management approach than found in traditional DBB projects. There is a need to educate project stakeholders about the key principles and mechanisms of TVD. To do this, the lean construction community often uses "the Marshmallow game" to teach TVD (Rybkowski et al. 2016). While the Marshmallow game has been very successful and should be considered a foundational building block for teaching TVD, two limitations relevant to this paper should be noted. First, the Marshmallow game does not translate well to an online environment, which was shown to be a need in the time of the COVID-19 pandemic. Second, the Marshmallow game does not explicitly consider the selection among advanced fabrication processes which may have a significant impact on project values such as schedule.

As an alternative, this paper presents the "Target Value Design for Digital Fabrication (TVDfDFAB) online game". This game aims to teach and leverage the use of DFAB in TVD in design. First, the paper presents an overview of the TVDfDFAB game. Next, the results of the validation in a case study undertaken in a master's degree class played by 36 industry experts, researchers and students in December 2020 at ETH Zurich in Switzerland. This is followed by the Discussion section with limitations of the game and this work, as well as the proposed future research. The work-in-progress version of the game has been published online for dissemination since November 2020 and openly accessible with the link in the footnote.[3]

POINT OF DEPARTURE

DESIGN FOR DIGITAL FABRICATION (DFAB) IN CONSTRUCTION

DFAB refers to data-driven production which aims to improve productivity and efficiency through automation in fabrication processes (Agarwal et al. 2016). It requires fabrication information to be included in early stages of the design process. However, stakeholders often find it hard to incorporate DFAB information and organisation in discrete design and construction processes in, for example, DBB projects (Ng et al. 2020). This can lead to skeptical attitudes about DFAB innovations which can hinder adoption on construction projects (Carra et al. 2018). To address this, researchers have investigated novel design approaches for DFAB such as Design for Automation (DfA) (Bridgewater 1993) and Robot-Oriented Design (Bock and Linner 2015). Ng and Hall (2019) investigate the intersection of lean management with DfMA and DFAB to identify shared practices of concurrent engineering and design-to-target-values. These two keys practices seem critical to foster organisation, information and process integration and maximise values for project stakeholders on DFAB projects (Rybkowski 2009; Ng et al. 2020).

[3] The work-in-progress (WIP) version of the game can be accessed here: https://www.research-collection.ethz.ch/handle/20.500.11850/467162

TARGET VALUE DESIGN (TVD)

TVD is an adaption of the original Toyota's target costing concept to construction industry (Zimina et al 2012). TVD was introduced to the construction industry by Macomber et al. (2007) and Ballard (2011). In many existing projects, TVD helps to maximise project values during the design process and could result in 15% to 20% below market price without compromises in quality and duration of the products and the processes (Rybkowski 2009; Zimina et al. 2012). To assist stakeholders to comprehend and adopt TVD principles in practice, the lean construction community has developed the "Marshmallow Game" presented by Rybkowski et al. (2016). In its 1-hour-20-minute version, players can experience outcome differences between a linear, silo-ed DBB design process in the first round, where no costing goals are specified, and an integrated, co-located TVD process in the second round. The materials to build the towers, time to complete the exercise, the Requests for Information (RFIs) and Change Orders during the design process are calculated. The Marshmallow game demonstrates value management in TVD in comparison with that in DBB design process (Rybkowski et al. 2016).

However, the marshmallow game simplifies the decision-making process to be exclusive of fabrication. Player are free to modify their procured materials in any way they wish with not cost implications. For example, there is no cost implication if players wish to cut up a straw into multiple smaller pieces or keep it as one single piece. While this is an intentional simplification made by the marshmallow game to avoid unneccesary complexity, it also does not reflect the reality of the considerations needed for adoption of DFAB on a construction project. Furthermore, to the authors' knowledge, no TVD games can yet be played online.

GAME DESCRIPTION

The authors of this work developed this TVDfDFAB game, which aims to assist industry practitioners and students in the construction industry to comprehend TVD principles to manage project values during the design process using DFAB technology in the fabrication. Since DFAB is still in its early stage of implementation in the industry, not many industry practitioners and students have experience in the design process for DFAB. To ensure knowledge of DFAB is not a prerequisite to play the game, the authors adopted the design process in a commercial kitchen scenario. The intended connection between the kitchen scenario and the construction industry is described later in the paper.

To cope with the remote work and online teaching, the TVDfDFAB game can be played online via video conferencing platforms (e.g., Zoom) and with open-access cloud-based documents (in this case, Google Slides and Google Sheets). The game requires a presenter or moderator to control the rundown and to present the presenter's deck throughout the game. The game is composed of two successive rounds similar to the Marshmallow game. Round 1 is intended to reflect the traditional DBB design approach; Round 2 is intended to teach the benefits of the TVD approach. In each round, the players are given a set of the player's deck on Google Slides and the player's spreadsheet on Google Sheets.

ROLES AND DELIVERABLES

The game requires players to form groups of four. Each player in the group will play the role of an Artistic Chef, a Recipe Chef, an Executive Chef or a Restaurant Owner (Figure 1) throughout the game. In both rounds, all teams have the same goal to design a plate of salad for the team's newly opened 4-star restaurant. The scope of work and deliverables of each role are the same in both rounds. The ingredients available to compose the salad are carrot, cucumber, tomato and egg. The slices have been prepared for the Artistic Chefs to select, drag and drop during the design processes. Also, the tools are available in mainly three levels of automation- manual, semi-automated and fully-automated – as listed in three columns for the Executive Chefs to select on the Google Sheet as presented in Figure 2. In both rounds, the customer requests a "best design" salad with (i) at least 500g, the heavier the better; (ii) equally balanced in weights between the given ingredients; and (iii) inspired by the Vincent van Gogh's The Starry Night painting (Figure 3). In Round 1, the customer requests for a good price, while the restaurant profit accounts for 5% of the total cost. In Round 2, the customer offers a target price, while the restaurant profit is calculated by the set target price minus the total cost. The total cost in both rounds is calculated based on the total process cost with the selected tools, the total process time, penalties for weight imbalance of the ingredients and for underweight and bonus for the extra weight above 500g.

Figure 1: The roles in a team of four in the TVDfDFAB game

Figure 2: Available ingredients and the associated tools and calculation sheet in both rounds for each team to design the salad layout and price the process

Figure 3: Design reference that mimics van Gogh's The Starry Night painting

Table 1 and Table 2 present the task details and the rundown of 15 mins duration in Round 1 and Round 2 respectively. The duration shaded in blue refers to the period when the players can actively work either on the Google Slides (as indicated with "SL") and/or on the Google Sheet (as indicated with "SH") to develop the salad design. While those shaded in green (as indicated with "View") refers to that the players can only passively observe the design processes conducted by their other teammates on both the Google Slides and the Google Sheet. The red thick vertical line indicates the design freeze cut-off time when the Artistic Chef and the Recipe Chef in each team can no longer continue their design development. In Round 1, the design process takes only 10 mins. The Executive Chef can only price the process after the design freeze; while in Round 2, the design process takes longer, with 15mins, and all players have to stop their work at the design freeze. In Round 1, the Restaurant Owner is not allowed to provide any comment throughout the design process. While in Round 2, the Restaurant Owner can provide verbal feedback during the design process. At the end of the game, the Restaurant Owner in each team has to either approve or reject the salad design based on the customer's requirements and values to the project stakeholders. The design process in Round 1 is relatively sequential while that in Round 2 adopts integrated information and organisation in the design process.

Table 1: Task details and rundown of in total 15 mins duration in Round 1

Scope of work	Deliverables	Task owner	5 min	10 min	15 min
Layout concept design	The Starry Night	Artistic Chef	SL		View
Weights optimisation	Balanced weights	Recipe Chef	View	SL+SH	View
Process pricing	Good price	Executive Chef	View		SH
Design review	Customer's values	Restaurant Owner	View		View

Table 2: Task details and rundown of in total 15 mins duration in Round 2

Scope of work	Deliverables	Task owner	5 min	10 min	15 min
Layout concept design	The Starry Night	Artistic Chef	SL		
Weights optimisation	Balanced weights	Recipe Chef	SL+SH		
Price optimisation	Good price	Executive Chef	SH		
Design advice	Customer's values	Restaurant Owner	View + Comment		

CASE STUDY RESULTS

As a preliminary validation of the effictiveness of the TVDfDFAB game, this paper reports a case study taken from one playing of the game. The game was implemented on on 7th December 2020 and played by 36 industry practitioners, researchers and master's degree students in the course "Lean, Integrated and Digital Project Delivery (LIDPD)" at ETH Zurich remotely in Switzerland. Their professional backgrounds include architecture, structural engineering and construction management. Table 3 presents the results of the case.[4]

The overall results firstly show that the mean (μ) and the standard deviation (σ) of the total time in Round 2 is shorter than in Round 1. This was because the teams were more willing to adopt DFAB to foster automation. Secondly, the mean (μ) and the standard deviation (σ) of the total cost in Round 2 is lower than that in Round 1. Thirdly, the mean (μ) profit in Round 2 is much higher than in Round 1, even though the profit in Round 1 was calculated in the way that the higher the cost, the higher the profit; while in Round 2, the profit was calculated by the set Target cost – CHF 200 – minus the total cost of the design delivered by each team. Last but not least, all design outputs in Round 2 have been approved by the Restaurant Owners base on the design performances such as the resemblance to *The Starry Night* painting. This shows that use of DFAB in TVD does not incur compromise in design of the aesthetic requirements, while achieving optimised values to stakeholders. The results of shorter time, lower cost and higher profit in Round 2 compared to Round 1 in this case results validate that this TVDfDFAB game helps to leverage the use of DFAB in TVD to maximise values in design.

Table 3: The results of ROUND 1 and ROUND 2 in the game's case study.

	ROUND 1 – DBB approach				ROUND 2 – TVD approach			
Group	Total Cost (CHF)	Profit (CHF)	Total Time (s)	Design approved?	Total Cost (CHF)	Profit (CHF)	Total Time (s)	Design approved?
1	217	11	11	×	176	24	44	√
2	321	16	37	√	185	15	36	√
3	160	8	48	√	176	24	40	√
4	327	16	78	√	192	8	26	√
5	183	9	39	√	159	41	31	√
6	167	8	29	√	160	40	33	√
7	254	13	60	×	160	40	67	√
8	194	10	61	√	152	48	28	√
9	272	14	172	√	190	10	64	√
μ	235	12	66		172	28	41	
σ	67.8	3.4	45.8		15.9	15.9	16.0	

[4] The video recording of this case study dated 7th December 2020 at ETH Zurich that demonstrates how this TVDfDFAB can be played via online platforms can be accessed here: https://www.youtube.com/watch?v=Nywx8C6QvjU

DISCUSSION

REFLECTION IN THE CONSTRUCTION INDUSTRY

Although this game adopts the commercial kitchen scenario for the DFAB processes as explained above, the roles and the design processes in both rounds mimic those in the real-world construction projects (Table 4). The project values include aesthetic and functional requirements and the process costs as the design deliverables. Within a team, there is an overall goal, which is to deliver a design to customer's target values. However, each role has their different deliverables, scopes of work and timeline to contribute to the design as shown in Tables 1 and 2 above. Therefore, the players ought to communicate with their teammates to incorporate the tradeoffs such as costs, weights and asthetic requirements with the design during the design processes. In this game, the customer does not request for fast and automated process using DFAB, but the process time accounts for one fraction of the total cost. This mimics the scenario in a typical construction project, where DFAB technology and automation might not be requested by the project owners in the project brief, but the duration of the construction process would account for a fraction of the total cost in the project.

Furthermore, different from the Marshmallow game developed by Rybkowski et al. (2016), this TVDfDFAB game demonstrates how TVD should integrate downstream fabrication process information such as tools' capability, process cost and speed information upstreams into the design development. This is made possible only by integrated organisation during the design process. This game also demonstrates the challenges in the TVD process. While the Marshmallow game does not give specific scope of work to each player, in TVDfDFAB the four roles have different deliverables and scopes of work. In the DBB design process, the Artistic Chef in a team might have more freedom of design at the beginning, where the resemblance to *The Starry Night* was the only deliverable during the first 5mins. While in the TVD process, the Artistic Chef has to coordinate with the other teammates and the deliverable of the resemblance to *The Starry Night* might not be the first priority at the beginning of the round. This game shows that the TVD approach has its challenges in design coordination, which reflects real-world TVD processes. This TVDfDFAB game allows players to experience some "pros and cons" in DBB and TVD design processes in real-world construction projects.

Table 4: How the terms in this TVDfDFAB can be reflected in the construction industry

TVDfDFAB Game	Construction	TVDfDFAB Game	Construction
Artistic Chef	Design architect	Recipe Chef	Design engineer
Executive Chef	Contractor	Restaurant Owner	Design manager
The Starry Night	Aesthetics challenge	Weight	Function/ performance
Kitchen tool	Fabrication machine	Design freeze	Tender

LIMITATIONS

This game is still in its early stage of development and requires further improvement. Amongst all, there are four key concerns, which the authors have conducted corresponding measures to address. Firstly, players with more DFAB experience in practice might perform better in the game. To address this concern, the game adopts a commercial kitchen scenario, where DFAB processes are relatively common in our daily life in many countries worldwide. Thus, DFAB practical experience is not a prerequisite;

and this would not significantly impact on the performance of the game. The validation case also shows that the results of the game were independent upon the player's experience.

Secondly, players who are more familiar with digital software might perform better in the game. To address this concern, the authors chose two common-used cloud-based platforms - Google Slides and Google Sheet, where most players are familiar with their function and ways of usage in their daily routine. For example, the ingredient pieces were all pre-created. The Artistic Chef in each team merely has to select, drag and drop, or rotate, the pieces on the Google Slides. No particular DFAB or software skills are required. Also, the weight and cost can be calculated automatically on the Google Sheet. Thus, no mathematical or engineering calculations are required during the processes.

Thirdly, this game has simplified the design process compared to that in a typical construction project. The design process in each round does not yet cover all the requirements and constraints such as material selection, regulatory compliances etc. The authors in particular explore a game which magnifies the use of DFAB in TVD in the game, which has not yet been included in state-of-the-art TVD games. A future case study can further elaborate and include more criteria of the cost elements and design requirements and explore how players can undertake a more complex design process in both the DBB and TVD processes, which take not only DFAB process but also material requirements etc. into account.

Fourthly, this game is designed in the way that the players undertaken the DBB design process first and then the TVD process. It is possible that the players got familiar with the design criteria and the the workflow in Round 1 and therefore they might have learned from experience and performed better in Round 2. To address this concern, a control group experience can be conducted where the two rounds can be played by different teams in parallel simultaneously to investigate the potential impact of this limitation. This work requires further research to explore theoretically the use of DFAB in TVD and how this helps to maximise values to stakeholders in construction projects.

Finally, it should be noted that TVDfDFAB is intented to be a complementary game to the Marshmallow game that addresses some limitations – namely as an online format in consideration of DFAB. However, this is not to suggest that TVDfDFAB should be considered a superior or replacement for the Marshmallow game which has a strong track-record of success. Instead, TVDfDFAB is proposed as an alternative and educators should consider the benefits and tradeoffs of each game.

CONCLUSION

DFAB is emerging to foster automation and boost productivity in the construction industry (Agarwal et al. 2016). However, stakeholders find it hard to manage DFAB in construction projects because DFAB transforms the design process and requires downstream fabrication-related information and organisation to move upstream for design development (Carra et al. 2018). Discrete design and construction processes in traditional delivery models such as DBB hinders DFAB implementation (Ng et al. 2020). TVD, which facilitates concurrent engineering and design-to-target-values, has been proposed as a potential design management approach to manage DFAB in the design process and maximise values to project stakeholders (Ng and Hall 2019). However, the use of DFAB in TVD in construction is still new in the industry. The authors of this work build on top of state-of-the-art TVD games such as the Marshmallow game developed by Rybkowski et al. (2016) to explore using TVD game to assist project stakeholders to comprehend TVD principles, so as to leverage the use of DFAB in TVD. This work presents a work-in-progress TVDfDFAB online game that allows players to consider DFAB processes in TVD. The game adopts a commercial kitchen scenario, where players conduct a salad design, which involves aesthetic, functional and cost challenges. Players form groups of four to conduct the design in Round 1 – DBB design process and Round 2 – TVD process successively. The roles, requirements, values and design processes mimic real-world construction projects. This work also presents a validation case played by 36 industry practitioners, researchers and students on 7th December 2020 in Switzerland. The results show that TVD helps players to implement and manage DFAB to achieve shorter time, lower cost and higher profit without compromise in design of the aesthetic requirements while achieving optimised values to stakeholders. This work further illustrates four key concerns as limitations and future research is required to explore theoretically the use of DFAB in TVD in construction projects. All in all, this work contributes to the body of knowledge in learning and teaching TVD and technology adoption.

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REFERENCES

Agarwal, R., Chandrasekaran, S., & Sridhar, M. (2016). *Imagining construction's digital future*.

Ballard, G., and Morris, P. H. (2010). "Maximizing owner value through Target Value Design." 2010 AACE International Transactions: 1-16.

Ballard, G. (2011). "Target Value Design: Current Benchmark 1.0." Lean Construction Journal, 2011, 79-84.

Bock, T., & Linner, T. (2015). *Robot-Oriented Design*. NY: Cambridge Univ. Press.

Bridgewater, C. (1993). "Principles of design for automation applied to construction tasks." *Automation in Construction*, *2*(1), 57–64.

Carra, G., Argiolas, A., Bellissima, A., Niccolini, M., & Ragaglia, M. (2018). "Robotics in the construction industry: State of the art and future opportunities." 35th *ISARC 2018 and International AEC/FM Hackathon: The Future of Building Things*.

Hall, D. M., Algiers, A., & Levitt, R. E. (2018). "Identifying the Role of Supply Chain Integration Practices in the Adoption of Systemic Innovations." *Journal of Management in Engineering*, *34*(6), 04018030.

Hall, D. M., Whyte, J. K., & Lessing, J. (2019). "Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study." Construction Management and Economics, 0(0), 1–18.

Macomber, H., Howell, G., & Barberio, J. (2007). "Target-Value Design: Nine Foundational Practices for Delivering Surprising Client Value." *AIA Practice Management Digest*, 2–4.

Miron, L. I. G., Kaushik, A., & Koskela, L. (2015). „Target value design: The challenge of value generation." *Proc. 23nd Ann. Conf. IGLC 23*, 815–825.

Ng, M. S., & Hall, D. M. (2019). "Toward Lean Management for Digital Fabrication: a Review of the Shared Practices of Lean, DfMA and DFAB." *Proc. 27th Ann. Conf. IGLC 2019*, 725–736.

Ng, M. S., Bonanomi, M. M., Hall, D. M., & Hackl, J. (2020). "Design for Digital Fabrication: an Industry needs Analysis of Collaboration Platforms and Integrated Management Processes." *Proc. of the 37th ISARC,* 318–325. Kitakyshu, Japan.

Rybkowski, Z. K. (2009). "The Application of Root Cause Analysis and Target Value Design to Evidence-Based Design in the Capital Planning of Healthcare Facilities." *PhD Diss*., Civil and Envir. Engrg, U.C. Berkeley.

Rybkowski, Z. K., Munankami, M. B., Shepley, M. M., & Fernández-Solis, J. L. (2016). "Development and testing of a lean simulation to illustrate key principles of target value design: A first run study." *24th Ann. Conf. IGLC 2016.*, 133–142.

Tommelein, I. D. and Ballard, G. (2016). "Target Value Design: Introduction, Framework & Current Benchmark." Lean Construction Institute, Arlington, VA.

World Economic Forum (2016). "Shaping the future of construction: a breakthrough in mindset and technology." World Economic Forum, Switzerland.

Zimina, D., Ballard, G., & Pasquire, C. (2012). "Target value design: using collaboration and a lean approach to reduce construction cost." *Construction Management and Economics*, *30*(5), 383–398.

Pütz, C., Lühr, G. J., Wenzel, M., and Helmus, M. (2021). "Potential of gamification for lean construction training: An exploratory study." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 259–268, doi.org/10.24928/2021/0134, online at iglc.net.

POTENTIAL OF GAMIFICATION FOR LEAN CONSTRUCTION TRAINING: AN EXPLORATORY STUDY

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ABSTRACT

For several years, Lean Construction has been an established management approach in the construction industry. Despite the high popularity of Lean Construction, the philosophy is far from being applied in all companies and projects. When changing the construction management methods, the use of Lean Construction represents a massive transformation of working methods and project culture. Studies show examples of failed implementations of Lean Construction and barriers like lacking understanding of Lean Construction methods. Thus, accompanying change by systematic change management processes is important in order to implement it successfully in the long term. Efficient and targeted training to enable the workforce to apply Lean Construction methods is one way to foster the change.

Gamification supports a motivating design of such training. The concept pursues the game-like design of non-game contexts to transfer the motivation gamers show in videogames to those non-game contexts. Despite its success in other industries, gamification has not been used frequently in the construction industry. Nevertheless, approaches of the concept are already included in Lean Construction training. In this paper we propose an exploratory study to improve the effectiveness of training on Lean Construction using Gamification. Various trainings on different Lean Construction methods like the Last Planner® System, takt planning and takt control, 5S and A3, were observed and show the potential of gamification for Lean Construction, but also room for improvements. The presented exploratory study provides guidance for the integration of gamification in Lean Construction training. Applying the concept of Gamification can improve the learning outcome of trainings and employee's motivation to use Lean Construction methods.

KEYWORDS

Lean construction, gamification, training, change management.

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INTRODUCTION

During recent years, Lean Construction has established itself as an approach to the management of construction projects. ‘Lean Construction’ is the construction industry’s attempt to implement the principles of Lean Manufacturing into the construction industry under consideration of its unique circumstances (Fiedler 2018). Lean management focusses especially on customer satisfaction by eliminating waste through continuous improvements of all processes (Liker and Morgan 2006). Different applications and principles were already in-depth presented and discussed, especially at the past 28 conferences of the ‘International Group for Lean Construction’ and the belonging proceedings.

Salem et al. (2006) summarise that especially the IGLC community is responsible for the emergence of Lean Construction techniques and approaches that changed and improved ways of planning, controlling, supply chain management and applications of visualisation techniques. Overall, those developments lead to continuous improvement. Despite these achievements, studies like Demirkesen et al.’s (2019) report barriers in introducing Lean Construction and results of poor implementation attempts. ‘Continuous improvement’ can be equated with ‘continuous change’ and implementing this continuous change of known working methods creates cultural issues such as the resistance to change (Demirkesen et al. 2019). Therefore, successful change management is required and essential for organisations to survive (Song 2009). Scholars frequently report from high failure rates of change management programs from 50 (Schaffer and Harvey 1992) to 70 % (Balogun and Hailey 2008; By 2005).

These numbers underline the importance of careful preparation and well-thought-out introduction processes for the implementation of Lean Construction. As the philosophy of Lean Construction itself states, people should be the focus of process consideration. This philosophy is shared by change management. An essential part of change management is the training of employees (Kotter 1996). For Lean Construction methods such as the Last Planner® System, studies show remaining critical socio-technical barrier in the implementation. Despite training the lack of understanding principles and methods prevails (Liu et al. 2020).

With focus on the empowerment of employees through training within the change management process, gamification is a concept that is particularly suitable to face those barriers. Gamification, derived from the word "game", is a fairly young concept that transfers the enthusiasm and engagement generated for video games, into other contexts. For this purpose, elements from games such as points, stories or levels are implemented into an everyday context like a learning environment (Deterding et al. 2011a, 2011b). Whether consciously or unconsciously, Lean Construction training already contains elements of gamification. Expanding those elements further offers great potential for improved Lean Construction implementation. Liu et al. already showed the potential of serious games for Lean Construction training in their paper on promoting the Last Planner® System through virtual reality and serious games (Liu et al. 2020). Further approaches to use serious games in the context of Lean Construction are provided by Tommelein et al. (1999) and Sacks et al. (2007). Complementary to the serious game approaches, several innovative ways of teaching lean construction have already been introduced by Tsao et al. (Tsao et al. 2013). Since the creation of serious games requires a lot of programming effort, as a further approach this paper focusses on the concept of gamification.

Based on the importance of training for successful change management processes, this paper will conceptually discuss the potential of gamification for Lean Construction training. Through literature review and observation of Lean Construction training, we analyse the gamification approaches already included in Lean Construction training. Concluding, we identify the potential for extending these approaches. We seek to advance the understanding of the potential of gamification for Lean Construction training by presenting a conceptual framework as a guide for the application of gamification in Lean Construction.

IMPLEMENTATION OF LEAN CONSTRUCTION VIA CHANGE MANAGEMENT PROCESSES

Generally applicable instructions for the implementation of innovations in companies are difficult to define, as companies differ greatly in their structure and culture. In addition, the human factor within the company is decisive for success and must be considered individually (Lauer 2010). The ideas of change management provide a basic guideline for the successful design of innovation introduction processes with a focus on the human factor (Kotter 1996). Change management is the management to fundamentally change corporate strategies and structures to new framework conditions (Schewe 2018). It describes the ideal design of the path from the starting point to the goal of change (Lauer 2010). Change management is directed inwards, i.e. towards the members of an organisation that is changing. In contrast, strategic management is directed towards the environment in order to achieve optimal adaptation. (Lauer 2010)

Phase 5 “empowering employees for board-based action” of Kotter's change management model emphasises the importance of employee training in the sense of "empowerment" as an important step in the implementation of Lean Construction. Efficient and targeted training of employees should therefore be given special attention in the implementation of change management processes around Lean Construction.

As studies show, training on Lean Construction has not always led to success so far and has left behind barriers to implementation. (Demirkesen et al. 2019; Liu et al. 2020) As an alternative approach to conventional training, we identify and discuss the potential of gamification for Lean Construction training. To this end, we introduce the concept of Gamification, which has been fairly used in the construction industry so far.

GAMIFICATION IN A TRAINING CONTEXT

Gamification is a concept that developed from the enthusiasm for games. Games convey feelings of challenge, success and engagement to a greater extent than everyday life, which leads to gamers playing games with high motivation and commitment (McGonigal 2012). People play games of their own free will, with high intrinsic motivation. Above all, the growing success of videogames means that the game industry today no longer only captivates children and young people (Rechsteiner 2020). Around 2.5 billion people worldwide regularly play computer or video games. The average age of gamers is now 37, 15% of gamers are already 60 or older (statista 2020). Transferring this enthusiasm for games to other contexts is the idea of gamification (Sailer 2016). Motivating elements of games are used in non-gaming areas, outside the usual function of games. These areas can be everyday situations like shopping, work or learning processes (Deterding et al. 2011a). Gamification is therefore not limited to training contexts. However, numerous studies show positive effects of gamification in this context (see Hamari et al. 2014; Seaborn and Fels 2015).

Concept of Gamification

The most commonly used definition of gamification is Deterding et al.'s (2011a), describing gamification as the use of game design elements in non-game contexts. In contrast to serious games, for example, gamification does not refer to fully-fledged games, but only to the use of various game design elements that are characteristic building blocks of games (Sailer 2016). Important for gamification approaches is the intentional use of game design elements to make an experience more game-like (Sailer 2016).

The following examples explain the idea of using game design elements in non-game contexts. Game elements that are particularly present in everyday life are, for example, points, rankings, a narrative or badges. In sports games like football, points often determine who wins a championship. By comparing the points of all teams, rankings are created that simultaneously visualise the value of the points. In the form of a gamification approach, points are used in frequent flyer programmes or as loyalty points. Here, the non-game context is everyday shopping. Medals in sport are badges that reflect a certain success. In a context unrelated to games, badges are used in the military to visualise ranks or special achievements (Schöpper et al. 2019). Embedding a narrative in a non-game context, is unconsciously used by parents in upbringing. Aeroplane landing at feeding time or crocodiles on the ground, making skipping from stone to stone on the way home more motivating, are examples of this.

Literature on gamification shows that it is important not to reduce gamification concepts to the application of the beforementioned common game design elements. Simply adding points, rankings and badges to an existing context does not lead to increased motivation or positive effects in the long term (Morschheuser et al. 2018). The game-like design as an intention is crucial for the success of gamification (Sailer 2016). In order to apply gamification successfully, game design elements must be used in a targeted way. The participants must be analysed, the context and the effect of the game design elements must be taken into account (Morschheuser et al. 2018).

Positive results achieved by the use of gamification in training are reported by several studies. Achieved effects are higher motivation and better performance (Sailer 2016), improved engagement, enjoyment and learning, higher participation and increased contributions (Seaborn and Fels 2015).

Approaches of Gamification in Lean Construction Trainings

As discussed above, the intention to design a game-like experience is mandatory for a gamification concept. Simply using game design elements without strategy can fail their effect. Though Lean Construction training does not implement gamification intentionally yet, approaches are already visible. Through the observation of several Lean Construction trainings, we outline those approaches, highlighting the potential for the intentional use of gamification.

In the course of the observation, we analysed eight trainings conducted both by internal and external consultants. The trainings focussed on four different Lean Construction methods: Last Planner® System (three observed trainings), takt planning and takt control (three observed trainings), 5S (one observed training) and A3 (one observed training). The trainings were carried out with different training methods to provide a reliable comparison. The variety of providers and methods trained, ensured a comprehensive picture of gamification approaches in Lean Construction trainings.

In the observed trainings, participants work in teams and have to realise projects with different levels of complexity. The main variable in all of these trainings is the degree of abstraction to which the tasks differs from actual construction processes. Examples are realistic models of houses, made out of different materials as bricks or tools, or more abstract tasks, where the teams have to assemble tools, or boxes which are not necessarily reminiscent of construction projects.

The trainings often follow the same patterns: Ahead of the first round, the participants receive information about different roles within the project teams. Information on the task and desired goals, such as a maximum assembly time, desired quality or a budget is given. The first round begins and the facilitators interact with the project teams and raise, some a little more, some a little less, the pressure on the project teams. The teams can usually not fulfil the tasks within the desired time, quality or budget. Following this first round, participants conduct a review of the processes and issues and rank their performance as well as the level of cooperation. Similarities with actual construction projects are identified and issues such as supply chain problems, the lack of enough construction time, technical issues and a high stress levels are discovered as reasons for the non-fulfilment of tasks. Afterwards, the consultants present a specific Lean Construction method. This method is applied in a second round, to fulfil a very similar or even same task as in the first round, with more or less support by the consultants. Usually, the project teams can finish the projects much better than in the first round. In a review process about this second round, the participants identify the improvements, that were made through the application of the Lean Construction method.

Some trainings carry out further rounds to practice or refine the Lean Construction methods. The apparent goal of these trainings is to impart the knowledge about Lean Construction methods, but also to motivate participants to apply them to their construction projects. This might be amplified through the experiences from the first rounds, with failed and uncomfortable processes, and the success of the rounds, where Lean Construction approaches were applied.

Observing the trainings in the role of complete observers we analysed the theoretical structure and practical implementation of the trainings in a double-blinded process. Resulting from the observation, we identified the following game design elements within Lean Construction training:

Table 1: game design elements used in Lean Construction training

Game element	Implementation in Lean Construction training
Challenge	The team has to finish a task within requested time, budget and quality
Cooperation	The work of each team member is necessary to win the challenge, without cooperation within the team it will fail
Feedback loops	After each round, participants receive feedback on their work to foster progress for the next round
Levels	Participants solve the task in two to three rounds of different complexity
Performance graphs	A matrix of teamwork and processes reflects individual progress
Points	The construction of parts per minute is measured
Roles	Each team member is assigned a different task and contributes to the goal in a different way e.g. as a main- or sub-contractor
Teams	Participants work in teams of 4-8, trying to achieve one common goal
Time pressure	Participants have a fixed amount of time to fulfil the task, the time limit is too ambitious for the first round, using additional time costs money

When using Gamification, the goal is to make an experience more game-like. With the analysed trainings, this was not the case, hence they cannot be described as gamified trainings yet. Table 1 shows nonetheless that a variety of game design elements are already implemented in such trainings. Taking these approaches further and intentionally designing Lean Construction training with game design elements to become more game-like offers the chance to achieve the positive effects of gamification described above. Those can include further engagement of employees, raising a feeling of belonging to the team and being part of the mission. Thus, proactivity and employee interaction when using Lean Construction can be strengthened (Team 2017). The following conceptual framework offers guidance how to achieve these effects.

CONCEPTUAL FRAMEWORK FOR THE APPLICATION OF GAMIFICATION IN LEAN CONSTRUCTION TRAINING

For the implementation of gamification, very complex frameworks exist (see for example Chou (2016)). None of the gamification frameworks offered in gamification literature have been generally accepted so far. Each context for the application of gamification is different and the framework used should match the circumstances of the context. As gamification has not been used frequently in the construction industry, here, the focus is on simple application. With more experience, one can prospectively consider using more complex frameworks.

A universal definition about which game design elements can be used for gamification applications does not exist and can hardly be created (Werbach and Hunter 2012). Nevertheless, there are game design elements that are used particularly frequently and have been considered for the framework presented in this paper. Lists of game design elements can be found, inter alia, in the works of Sailer (2016)[1], Werbach and Hunter (2012)[2], Marczewski (2018)[3], Wood and Reiners (2015)[4], Blohm and Leimeister (2013)[5], Zichermann and Cunningham (2011)[6] and Reeves and Read (2009)[7]. In the framework presented here, game design elements mentioned by at least two authors are considered. These provide a first overview and ideas for the use of elements. The extensibility of the list is explicitly pointed out. Table 2 lists game design elements, highlights their desired impact and offers an example how to implement them in Lean Construction trainings. The examples were derived from the observation of trainings and discussed with training providers. Definitions of game design elements are given according to Sailer (2016)[1], Werbach and Hunter (2012)[2], Marczewski (2018)[3] and Seaborn and Fels (2015)[8]. Both the listed game design elements and definitions are marked with superscript numbers indicating their source.

Table 2: game design elements used in Lean Construction training

Game design element	Observed in trainings	Definition	Recommendation of use
Avatars [1,2,5]		Visual representation of the user, identifying him*her [1]	Each team decides on a team name and develops an avatar that represents their team
Badges [1,2,3,4,5,6]		Visual icons signifying achievements [1]	Badges can visualize the success in certain areas, e.g. in time completion, in budget completion, good teamwork
Chance [2,4,6]		Elements of randomness [2]	Roles of team members can be assigned by chance, additional time or resources can be won in a lottery kind of way (e.g.

Game design element	Observed in trainings	Definition	Recommendation of use
			every five minutes each team draws an event card indicating a new incident)
Challenge [2,3,4,5,6]	✓	Element to make users feel like they earned their achievement, e.g. testing knowledge [3]	Fulfilling the task (e.g. building a house with game bricks) within the assigned time range, budget and quality
Collecting [2,3,5,6]		Items to collect, fostering relationships and feelings of purpose [3]	Building material has to be collected through a team challenge like scavenger hunt
Competition [2,3,4,5,7]		Chance for users to prove themselves against others [3]	Teams compete against each other in terms of time to complete task, number of mistakes, budget and quality
Content unlocking [2,3,6]		Kind of achievement that offers additional information/guidelines/rewards [3]	Trading resources (e.g. time, bricks, virtual currency) for additional help to fulfil the task better
Cooperation [2,4,5,6,7]	✓	Team members or individual users have to share information/help each other to be successful [2]	Each team member performs a task that is important for the overall task. Not every team member has all the information and/or authorisation to do certain tasks, so cooperation is necessary.
Feedback loops [2,3,4,6,7]	✓	Mechanic that provides users with information on their progress [3]	Breaks in between rounds to provide teams with feedback to review the process and to improve the next task
Gifting [2,3,4,6]		Allowing users to share items with other people/teams to help them achieve goals [3]	When working with limited resources (e.g. Lego bricks), teams can gift left over resources to other teams, teams can support other teams by undertaking a part of their tasks (e.g. construction site 1 has finished in time and uses their left-over time to help construction site 2)
Leader-boards [1,2,3,4,6]		Display of ranks for comparison [1]	A team leader board displays the ranking of the teams round after round showing their position in the competition
Levels [2,3,4,5,6,7]		Increasingly difficult environments, milestones indicating progress [3]	Two tasks of different difficulty, after completing the first easy task, the more difficult one can be started.
Narrative [1,2,3,4,5,7]	(✓)	Frame story, a story that is told [1]	A school building has to be finished before holidays end
Performance graph [1,2]	✓	Performance graphs graphically show the performance of users in an intra-individual comparison over a certain period of time. It is therefore a dynamic display for visualising one's own performance. [1]	A matrix of teamwork and processes reflects individual progress
Points [1,2,3,6]	✓	Numerical units indicating progress [1]	Parts per minute in construction is measured and used to compare the results of the teams
Rewards [2,3,6]		Tangible, desirable items [3]	Giving prospect of a desirable reward for well performing teams, e.g. cake, beer or other incentives

Game design element	Observed in trainings	Definition	Recommendation of use
Roles	✓	Role-playing elements of character [8]	Client, main contractor, sub-contractor, assembly line worker
Scarcity [2,6]		Making something rare to make it more desirable	Different coloured Lego bricks stand for different raw materials, not all are available in equal quantities, rare raw materials are popular
Status [3,5,7]		Textual monikers indicating progress [3]	By showing positive results in the tasks, teams can earn higher status ranking from lean construction newbie to lean construction professional
Teams [2,3,6,7]	✓	Working in groups to foster collaboration [3]	Participants work in teams of 4-8 people and try to achieve one common goal, help and advice within the team is mandatory to fulfil the task
Time pressure [3,5,7]	✓	Fixed amount of time for users to fulfil a task [3]	Fixed amount of time to fulfil task, too ambitious for first round, additional time costs virtual goods
Virtual goods [2,4,5]		Game assets with perceived or real-money value [2]	A virtual currency (e.g. poker chips) is used to trade bricks or buy additional time
Win states [2,5]		Objects that make the group winner [2]	Definition of milestones

When implementing game design elements like the examples mentioned above, a good mix of different stimuli is important. Not every user is motivated by competition. Some users will work best if they can collaborate with teammates and have a focus on relationship fostering elements. When planning a gamification application, it is important to ensure a balanced use of game design elements.

CONCLUSIONS AND RECOMMENDATIONS

The aim of this study is to improve Lean Construction implementation efforts through innovative and motivating training concepts. The study offers an overview of the need for systematic change management processes including training to ensure successful Lean Construction implementation. Observations of Lean Construction trainings were analysed and game design elements were explored. The findings indicate that Lean Construction trainings offer great potential to intentionally use gamification in their context. It is concluded that the concept of gamification is suited to tackle barriers in the implementation of Lean Construction. This is in line with publications that have already analysed the potential of serious games for Lean Construction training, but have not conducted this with a large sample size.

We present a conceptual framework as a guideline for further applications of gamification components to improve Lean Construction trainings. With this explorative approach we aim to contribute to the improvement of change management processes in lean construction. Motivating and varied training enables employees to apply Lean Construction. The empowerment of employees promotes improved results in Lean Construction projects.

Further work is required to develop and analyse a gamified Lean Construction training. The study established research questions for further research on gamification in Lean Construction. We recommend to develop and analyse case studies intentionally using gamification by using game design elements in a structured way. The analysis of their effect in trainings would offer further valuable insights for the application of gamification in Lean Construction.

REFENRENCES

Balogun, J., and V. H. Hailey. (2008). *Exploring strategic change*, Harlow: FT Prentice Hall Financial Times.

Blohm, I., and J. M. Leimeister. (2013). "Gamification: Design of IT-Based Enhancing Services for Motivational Support and Behavioral Change." *Bus Inf Syst Eng*, 5(4): 275–278. doi.org/10.1007/s12599-013-0273-5.

By, R. T. (2005). "Organisational change management: A critical review." *Journal of Change Management*, 5(4): 369–380. doi.org/10.1080/14697010500359250.

Chou, Y.-K. (2016). *Actionable gamification: Beyond points, badges, and leaderboards*, Fremont, CA: Octalysis Media.

Demirkesen, S., N. Wachter, S. Oprach, and S. Haghsheno. (2019). "Identifying Barriers in Lean Implementation in the Construction Industry." In *Proc., 27th Annual Conference of the International Group for Lean Construction (IGLC)*, Annual Conference of the International Group for Lean Construction: 157–168.

Deterding, S., D. Dixon, R. Khaled, and L. Nacke. (2011a). "From game design elements to gamefulness." In *Proc., the 15th International Academic MindTrek Conference*, edited by A. Lugmayr, H. Franssila, C. Safran, and I. Hammouda: 9, New York, New York, USA.

Deterding, S., D. Dixon, R. Khaled, and L. Nacke. (2011b). "Gamification: Toward a Definition." In *paper at the CHI 2011, Vancouver*.

Fiedler, M., ed. (2018). *Lean Construction - das Managementhandbuch: Agile Methoden und Lean Management im Bauwesen*, Berlin: Springer Gabler.

Hamari, J., J. Koivisto, and H. Sarsa. (2014). "Does Gamification Work? -- A Literature Review of Empirical Studies on Gamification." In *Proc., 2014 47th Hawaii International Conference on System Sciences (HICSS)*: 3025–3034.

Kotter, J. P. (1996). *Leading Change*, Boston: Harvard Business School Press.

Lauer, T. (2010). *Change Management: Grundlagen und Erfolgsfaktoren*, Heidelberg: Springer-Verlag GmbH.

Liker, J. K., and J. M. Morgan. (2006). "The Toyota Way in Services: The Case of Lean Product Development." *AMP*, 20(2): 5–20. doi.org/10.5465/amp.2006.20591002.

Liu, C., V. A. González, J. Liu, Z. Rybkowski, A. Schöttle, C. Mourgues Álvarez, and I. Pavez. (2020). "Accelerating the Last Planner System® (LPS) Uptake Using Virtual Reality and Serious Games: A Sociotechnical Conceptual Framework." In *Proc., 28th Annual Conference of the International Group for Lean Construction (IGLC)*, Annual Conference of the International Group for Lean Construction: 481–492.

Marczewski, A. (2018). *Even Ninja Monkeys Like to Play: Gamification, game thinking and motivational design*, [S. l.: Independently published].

McGonigal, J. (2012). *Reality is broken: Why games make us better and how they can change the world; [includes practical advice for gamers]*, London: Vintage Books.

Morschheuser, B., L. Hassan, K. Werder, and J. Hamari. (2018). "How to design gamification? A method for engineering gamified software." *Information and Software Technology*, 95: 219–237. doi.org/10.1016/j.infsof.2017.10.015.

Rechsteiner, A. (2020). "Die Geschichte der Videospiele".

Sacks, R., A. Esquenazi, and M. Goldin. (2007). "LEAPCON: Simulation of Lean Construction of High-Rise Apartment Buildings." *Journal of Construction*

Engineering and Management, 133(7): 529–539. doi.org/10.1061/(ASCE)0733-9364(2007)133:7(529).
Sailer, M. (2016). *Die Wirkung von Gamification auf Motivation und Leistung*, Wiesbaden: Springer Fachmedien Wiesbaden.
Salem, O., J. Solomon, A. Genaidy, and I. Minkarah. (2006). "Lean Construction: From Theory to Implementation." *J. Manage. Eng.*, 22(4): 168–175. doi.org/10.1061/(ASCE)0742-597X(2006)22:4(168).
Schaffer, R., and Harvey. (1992). "Successful Change Programs Begin with Results." Successful Change Programs Begin with Results (hbr.org) (Feb. 12, 2021).
Schewe, G. (2018). "Definition Change Management." Die Seite wurde nicht gefunden | Gabler Wirtschaftslexikon (Dec. 8, 2018).
Schöpper, H., F. Dörries, and S. Lodeman. (2019). "Der Gamification Effekt: Wie Sie Ihr Unternehmen mit Hilfe von motivierenden Spiel-Elementen wettbewerbsfähiger und digitaler machen." *Mittelstand 4.0-Kompetenzzentrum Hamburg*.
Seaborn, K., and D. I. Fels. (2015). "Gamification in theory and action: A survey." *International Journal of Human-Computer Studies*, 74: 14–31. doi.org/10.1016/j.ijhcs.2014.09.006.
Song, X. (2009). "Why Do Change Management Strategies Fail? - Illustrations with case studies." *Journal of Cambridge Studies 4 (1)*. statista. (2020). "Computerspieler - Anzahl in Deutschland bis 2020.".
Team, G. (2017). "Acht Vorteile der Gamifizierung Ihres Betriebs." Acht Vorteile der Gamifizierung Ihres Betriebs (game-learn.com) (Feb. 12, 2021).
Tommelein, I. D., D. R. Riley, and G. A. Howell. (1999). "Parade Game: Impact of Workflow Variability on Trade Performance". *Journal of Construction Engineering and Management*, 125(5): 304–310. doi.org/10.1061/(ASCE)0733-9364(1999)125:5(304).
Tsao, C., M. Azambuja, F. Hamzeh, C. Menches, and Z. K. Rybkowski. (2013). "Teaching lean construction: perspectives on theory and practice." *Proc. 21st Annual Conference of the International Group for Lean Construction*.
Werbach, K., and D. Hunter. (2012). *For the win: How game thinking can revolutionize your business*, Philadelphia: Wharton Digital Press.
Wood, L. C., and T. Reiners. (2015). "Gamification." In *Encyclopedia of Information Science and Technology, Third Edition*, edited by D. Khosrow-Pour: 3039–3047: IGI Global.
Zichermann, G., and C. Cunningham. (2011). *Gamification by Design: Implementing Game Mechanics in Web and Mobile Apps*, Sebastopol, CA: O'Reilly.

Rybkowski, Z. K., Alves, T. d. C. L., and Liu, M. (2021). "The emergence and growth of the on-line serious games and participatory simulation group APLSO," *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29), Alarcon, L.F. and González, V.A. (eds.)*, Lima, Peru, pp. 269–278, doi.org/10.24928/2021/0135, online at iglc.net.

THE EMERGENCE AND GROWTH OF THE ON-LINE SERIOUS GAMES AND PARTICIPATORY SIMULATION GROUP "APLSO"

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ABSTRACT

Lean simulations provide a critical "aha moment" that helps with the understanding and buy-in of key lean principles. The purpose of this article is to share the process of development and implementation of an ongoing international on-line Lean-IPD simulation experimentation community called *Administering and Playing Lean Simulations Online* (APLSO). The group emerged following the arrival of the COVID-19 pandemic to include academics from 38 universities (70%) and consultant practitioners (30%). This paper documents the inception and growth of this community so that lessons learned can be shared with the international lean construction community. Serious games and simulations were transitioned to an online format, relying heavily on commonly available software such as Zoom™ and Google Slides™. The most frequently developed simulations tended to be those most typically played by academics and consultants prior to the pandemic. The authors classified games presented, as well as identified physical simulations still needing to be converted to an online format.

KEYWORDS

Serious games, participatory simulations, on-line simulations, COVID-19, lean principles.

INTRODUCTION

The purpose of this paper is to share the process of forming and managing a global collaborative effort to transform in-person lean construction simulations to an on-line format following the emergence of the global pandemic COVID-19.

Serious games and simulations play an important role in lean construction's growing popularity and global dissemination to the construction industry. They offer the type of controlled laboratory conditions that are usually found in the physical and biological sciences where the impact of a single variable is tested and measured between rounds of

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play (Rybkowski et al. 2012; Verma 2003). Because of their abilty to test and validate process decisions at low risk, simulations impart confidence to those who teach lean.

Kristin Hill, Director of Education Programs at LCI (the US-headquartered Lean Construction Institute), estimated that approximately 100 US-based construction companies impart lean principles to their employees and trade partners through serious games and simulations (personal communication, February 5, 2021). This need to test and make explicit lean principles and tools that are sometimes difficult to grasp (Liker 2004; Tzortzopoulos et al. 2020) has generated a proliferation of activity toward the development and testing of novel lean participatory simulations both from research universities (Bhatt et al. 2016; Gonzalez et al. 2014; Howell and Liu 2012; Pollesch et al. 2017; Rybkowski et al. 2011; Rybkowski and Kahler 2014; Rybkowski et al. 2016; Sacks et al. 2007), and from industry alike (Villego 2017). Most simulations for lean construction are played in person. One of the earliest known participatory lean construction simulations played digitally was the Parade-of-Trades, developed by Choo and Tommelein (1999). Although there have been pockets of experimentation to play collaborative lean construction simulations aided by computers, these arguably did not gain much traction prior to 2020.

COVID-19 AND THE EMERGENCE OF APLSO

On March 11, 2020, the director-general of the World Health Organization declared the spread of COVID-19 to be a global pandemic. By the time of the announcement, the emerging virus had been transmitted to over 110 countries and territories. Within little more than ten days, many universities and businesses across the globe chose to transition their course work to an exclusively on-line or hybrid format, facilitated in large part by the ready availability and simplicity of the cloud-based collaborative software Zoom™. Faced with the new reality of digital or hybrid instruction, a lean consultant based in Germany e-mailed 22 internationally-based lean educators and consultants, appealing for ways to teach lean simulations on-line to help on-board new members who needed to be initiated to the Last Planner® System of Production Control (Annett Schöttle, personal communication, March 21, 2020). Finding themselves in a similarly challenging situation, the authors of this article took up the charge to organize a weekly, global, on-line lean simulation testing group which they coined as "APLSO" (Administering and Playing Lean Simulations On-Line). The original members to whom the email appeal was written were invited by the prime organizer at Texas A&M University to meet weekly on Mondays from 12:00-1:30 pm Central Time (UTC-6), with the time established according to a cloud-based scheduling poll. Hosted at Texas A&M University, the first meeting with 14 attendees was held via Zoom on March 30, 2020, and involved collaboratively playing the Maroon-White Game (Smith and Rybkowski 2013). The purpose of setting this specific time slot was to accommodate as many global time zones as possible, including those situated at completely opposite extremes, such as those from India and New Zealand.

THE GROWTH OF APLSO

Early attempts to convert in-person simulations to an online format were clunky and awkward: internet connections intermittently failed, and some participants complained of being forced to surrender their email addresses to software providers in order to participate. From the beginning the group used breakout rooms on Zoom, and shared files via Google Drive. However, by the time of the tenth week of play, the group experienced a breakthrough by transitioning to actively moving pre-defined pieces in Google Slides™ in small collaborative groups of players by using Zoom's breakout room function—sending each group a shared link set to the "editable" function. Participants were invited to facilitate their own innovative simulations with other participants in exchange for plus-delta feedback from the group during the last 15 minutes of each 90 session.

APLSO's intent was driven to fill a singular need—that is, to quickly provide a safe space dedicated to testing out newly developed interactive participatory simulations online so that lean educators could continue to offer the same caliber of instruction during social distancing that existed prior to the pandemic. A few rules were created and discussed by the group and agreed by vote, namely: (a) presentations were required to be collaboratively interactive (no straight "lectures" were permitted), (b) no recording was allowed in order to afford a sense of psychological safety to facilitators and players, and (c) simulation facilitators were asked to avoid using software that would require participants to give their email addresses to companies. Because not all players had direct access to Zoom accounts (i.e. although all could access Zoom as players, this was not always true for facilitators) the primary organizer began meeting with a presentation team the week before a new presentation, which helped facilitations run more smoothly.

OUTCOMES

The organizers were mindful and sensitive to the needs of different time zones and anticipated the possibilities for confusion when some but not all countries embraced daylight savings time. The number of registered participants grew by word-of-mouth, and when interested stakeholders sent an invitation request to the prime organizer at Texas A&M University.

Table 1: APLSO Facilitators, their Affiliations, and their Presentations listed by Date

Date	Facilitator	Affiliation	Simulation
03/30/20	Zofia Rybkowski	Texas A&M Univ., TX USA	Maroon-White Game
04/06/20	Thais Alves	San Diego State Univ., CA USA	Architectural Programming Simulation
04/13/20	Colin Milberg	ASKM Associates, MA USA	Parade of Trades (using Mural)
04/20/20	Alan Mossman	The Change Business Ltd., UK	Repair Co Exercise
04/27/20	Paul Ebbs	WSP, QATAR	Introduction to 8 flows
05/04/20	Zofia Rybkowski	Texas A&M Univ., TX USA	Choosing By Advantages
05/11/20	Paul Ebbs	WSP, QATAR	8 flows virtual simulation (cont'd)
05/18/20	Alan Mossman	The Change Business Ltd., UK	List of gaming needs
05/25/20	Colin Milberg	ASKM Associates, MA USA	Batch-Balance-Pull (using Mural Software); Sim. to Lego Airplane simulation
	Annett Schöttle	Refine, GERMANY	
06/01/20	Ehsan Asnaashari	Nottingham Trent Univ., UK	House of Cards
06/08/20	Farook Hamzeh and Salam Khalife	Univ. of Alberta, CANADA	Value capture and value management
06/15/20	Min Liu	North Carolina State Univ., NC USA	Oops Game
06/22/20	Meng Wai ("Nick") Yaw	Texas A&M Univ., TX USA	Multi-skilling game

Table 2: APLSO Facilitators, their Affiliations, and their Presentations listed by Date (cont.)

06/29/20	Hrishikesh Joshi	DCEC, Baroda, INDIA	5S Numbers Game
	Anush Neeraj	Studio Atmosis, Utter Pradesh, INDIA	
07/06/20		IGLC28 Conference: APLSO not held	
07/13/20	Alan Mossman	The Change Business Ltd., UK	Discussion about current state of gaming
07/20/20	Romano Nickerson	Boulder Associates, CO USA	DPR Block Game
07/27/20	Zofia Rybkowski and Ratnaprabha Borkar	Texas A&M Univ., TX USA	Set Based Design
08/03/20	Thais Alves	San Diego State Univ., CA USA	Silent Squares
08/10/20	Iris Tommelein, with Rafael Vigario Coelho, Vishesh Vikram Singh, Sulyn Gomez Villanueva, and Karilin Yiu	Univ. of California, Berkeley, CA USA	Mistakeproofing
08/17/20	Colin Milberg	ASKM Associates, MA USA	PDCA/ Kata game
08/24/20	Cynthia Tsao	Navilean, MA USA	Parade of Trades
	Fernanda Saidelles Bataglin, Dani Dietz, and Fabricio Vargas	Federal Univ. of Rio Grande do Sul (UFRGS), BRAZIL	
08/31/20	Ganesh Devkar with Shaurya Bhatnagar, Nimish Sharma, and Georgie Jacob	CEPT Univ., Ahmedabad, INDIA	Pass the Pennies
09/07/20	Paz Arroyo	DPR, CA USA	Choosing by Advantages
10/05/20	Cynthia Tsao	Navilean, MA USA	BBQ pull
11/02/20	Daniel Hall with Ming Shan "Charmaine" Ng	ETH Zurich, SWITZERLAND	TVD simulation
12/07/20	Ganesh Devkar, with Shaurya Bhatnagar, Georgie Jacob, and Nimish Sharma	CEPT Univ., Ahmedabad, INDIA	TVD simulation
01/04/21	Cynthia Tsao	Navilean, MA USA	Parade of Trades: Part I
02/01/21	Cynthia Tsao	Navilean, MA USA	Parade of Trades: Part II
03/01/21	Rajeswari Obulam	Texas A&M Univ., TX USA	5S Puzzle Game

*For a compilation of these simulations and related references, please refer to Rybkowski et al. (2020).

Figure 1 shows the number of participants in various countries. By March 1, 2021, the number of registered unique participants reached 115, affiliated with 17 countries (Table 2). As of that date, faculty and students affiliated with research institutions and universities comprised 70% of participants, while companies and lean consultancies comprised 30% (Table 2). Those affiliated with academia, as of this writing, have come from 38 universities as shown in Table 3. Participation of unique participants per meeting has varied from a minimum of 10 to a maximum of 38, although participation has exhibited a steady trending increase over time (Figure 2). It is important to point out that this number shows that the group had to make efforts to adapt and be flexible to play the simulations with groups of varying sizes. Also, the international character of the group requires that instructions avoid jargon that may not be common to an international community. The broad range of participants speaks to the inclusive nature of the group and simulations played, which cater to varying levels of sophistication in terms of understanding and application of lean concepts.

Figure 1: Location of Registered, Unique Participants

Table 3: Unique Registered Participants by Country and Type of Occupation

Country	R/U	C	Total	Country	R/U	C	Total
USA	43	19	62	Finland	2		2
Canada	5	4	9	Lebanon	2		2
UK	7	2	9	Switzerland	2		2
India	6	3	9	Denmark		1	1
New Zealand	3	3	6	France	1		1
Brazil	4		4	Germany		1	1
Australia	2		2	Italy	0	1	1
Chile	2		2	Norway	1		1
				Qatar		1	1
R/U:	Research Institute/ University				**80**	**35**	**115**
C:	Company/ Consultancy				70%	30%	100%

Several presentations—especially the most critical such as Parade of Trades and Batch-Balance-Pull were played multiple times over the course of the year and continuous improvement was observed. Despite some push-back from other US-participants, the US-based APLSO organizers decided not to cancel regular Monday meetings during US (or other) non-working holidays to align with the international spirit of Lean.

Out of respect for the IGLC, the group chose not to host a regular APLSO meeting that week. Instead, as lean pioneer and simulation enthusiast Greg Howell had passed away just weeks before, the IGLC organizers invited several APLSO facilitators to present their live simulations via individual Zoom links provided by the facilitators over the course of two days (Wed, July 8, and Thurs, July 9). The rooms were named in honor of the memory Greg Howell and his seminal role as an initial developer of simulations to understand and teach lean construction. Presenters and their simulations included: Colin Milberg (Batch-Balance-Pull); Meng Wai “Nick” Yaw (Card Race); Romano Nickerson (DPR Block); Iris Tommelein and Karilin Yiu (Mistakeproofing); Cynthia Tsao (Parade of Trades); Zofia Rybkowski (Repair Co); and Hrishikesh Joshi and Anush Neeraj (5S

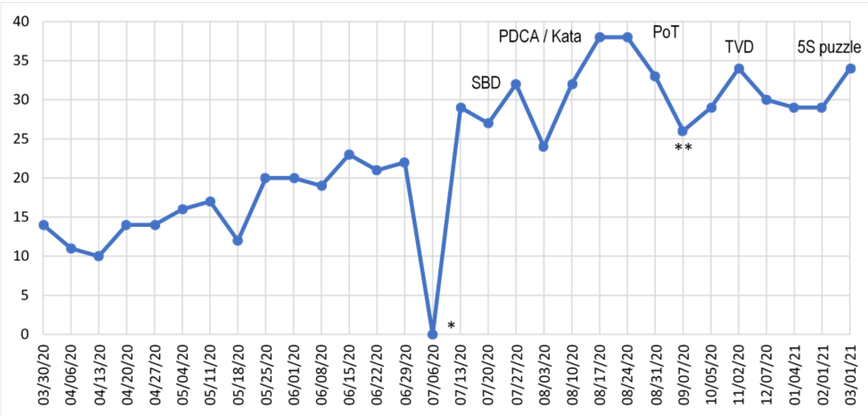
Numbers Game). The IGLC organizers collected plus-delta feedback to gauge interest in hosting simulations at future IGLC conferences. These on-line simulation sessions very likely would never have taken place at the IGLC were it not for the emergence of APLSO.

Table 4: Participation by Research Institutes and Universities

Affiliation	Country	Freq.	Affiliation	Country	Freq.
The University of Melbourne	*Australia*	1	Nottingham Trent University	*UK*	1
University of Technology, Sydney	*Australia*	1	University College London	*UK*	1
Federal University of Rio Grande do Sul (UFRGS)	*Brazil*	3	University of Huddersfield	*UK*	4
Universidade Paranaense	*Brazil*	1	Arizona State University	*USA*	1
École de Technologie Supérieure	*Canada*	1	Brigham Young University	*USA*	1
University of Alberta	*Canada*	3	Catholic University of America	*USA*	1
University of Toronto	*Canada*	1	Colorado State University	*USA*	1
FEUC - Federación de Estudiantes de la Universidad Católica	*Chile*	1	Florida International University	*USA*	1
Pontificia Universidad Católica de Chile	*Chile*	1	George Mason University	*USA*	1
Aalto University	*Finland*	2	Michigan State University	*USA*	2
Centrale Lille, a French Graduate Engineering School	*France*	1	North Carolina State University	*USA*	3
Karlsruhe Institute of Technology	*Germany*	1	Northern Arizona University	*USA*	4
CEPT University	*India*	4	San Diego State University	*USA*	1
American University of Beirut	*Lebanon*	2	Texas A&M University	*USA*	17
Auckland University of Technology	*New Zealand*	1	UC Denver	*USA*	1
University of Auckland	*New Zealand*	2	University of California, Berkeley	*USA*	6
Norwegian University of Science and Technology	*Norway*	1	University of Kentucky	*USA*	2
ETH Zurich (Swiss Federal Institute of Technology)	*Switzerland*	2	University of Oklahoma	*USA*	1
Huddersfield University / Birmingham City University	*UK*	1	Virginia Tech	*USA*	1
			Total # of Universities		**38**
			Total # of Academic		**80**

This was not the first time games were offered at IGLC. For example, Zofia Rybkowski live-facilitated the Maroon-White simulation at IGLC 21 in Fortaleza, Brazil in 2013 (Smith and Rybkowski 2013). She also facilitated the Collective Kaizen and Standardization simulation in IGLC 22 Oslo, Norway, 2014 (Rybkowski and Kahler

2014). Similarly, Alan Mossman facilitated the Magic Stick/Helium Stick simulation at the IGLC 22 as well (Discovery Village n.d.). Zofia Rybkowski and James P. Smith facilitated the Architectural Programming simulation in at IGLC 27 in Dublin, Ireland in 2019 (Solhjou Khah et al. 2019). That said, IGLC 28 was the first time lean construction simulations—and indeed the entire IGLC conference—was offered via an online format.



* APLSO meeting not held during IGLC 28; instead, on-line Greg Howell simulation sessions offered during IGLC
** APLSO transitioned from weekly to monthly meetings to accommodate academic schedules

Figure 2: Longitudinal Participation by Unique Participants

Prior to 2021 the group informally shared their simulations via email and by downloading them from the Google Drive links posted in the chat section of Zoom during the APLSO sessions. Starting in 2021, participants Colin Milberg and Cynthia Tsao moved the group consciousness to a new level by making their simulations freely available through a Creative Commons Usage Agreement in exchange for plus-delta feedback and simulation data. This enabled lean educators to more openly share their on-line simulations for use during virtual university courses across the globe—one of the original purposes for creating APLSO when the pandemic emerged. A screenshot of the Parade of Trades (PoT) simulation is shown in Figure 3. It is included here to demonstrate that although the online PoT simulation may lose some of the social benefits that often come with physical play, the developers also realized that transitioning to a digital format also enabled each trade's movement to be visually tracked as it progressed up a high-rise building—something which the physical simulation lacked.

DISCUSSION

Lean tools are being applied to construction projects around the world. However, to be truly effective and to be able to grow and improve them, the underlying lean principles that inform these tools should be deeply understood by those who implement them.

In 2000, Lauri Koskela introduced the Transformation Flow Value model of lean construction. The definition of lean published in the Lean Construction Institute's glossary is: "Culture of respect and continuous improvement aimed at creating more value for the customer while identifying and eliminating waste" (LCI 2021; Rybkowski et al. 2013). The LCI definition can help classify existing on-line lean simulations into each of the four elements stated, and identify gaps where new on-line simulations have yet to be developed. Simulations in italics (below) can currently be played on-line as an outcome of efforts by APLSO, whereas those without italics represent a sampling of physical simulations that still need to be transformed into a collaborative on-line format.

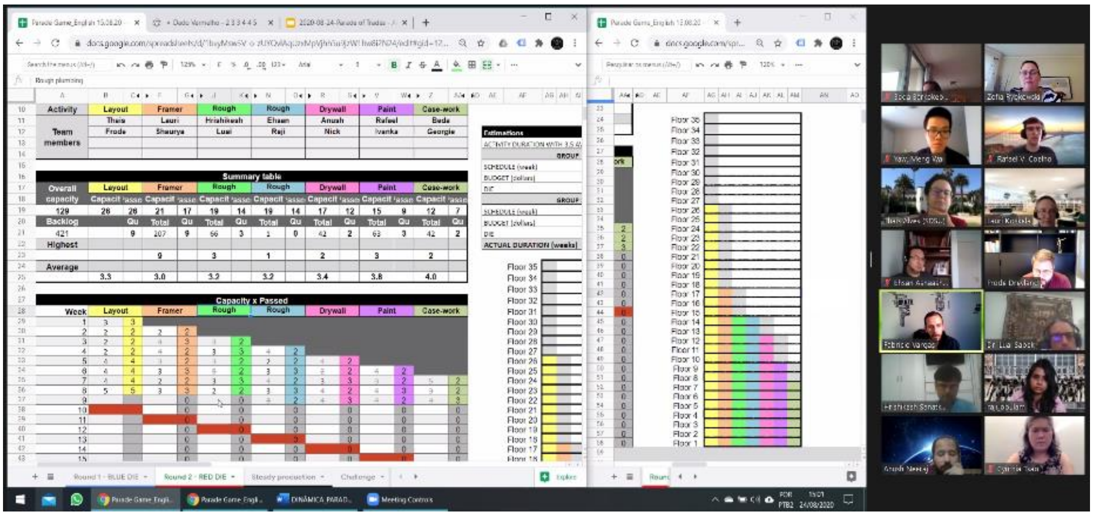


Figure 3: Example of APLSO Simulation Facilitated during APLSO (Parade of Trades, facilitated by Cynthia Tsao and Colin Milberg on August 24, 2020)

1. **Add Value:** *Choosing by Advantages Exercise; TVD Simulation*; *Oops Game; AP Simulation;* A3s;
2. **Reduce Waste:** *5S; Lego® Airplane Game (Batch-Balance-Pull, Pass the pennies); Parade of Trades; DPR Blocks; Mistakeproofing; BBQ Pull; Multiskilling game;* Value Stream Mapping*;* Villego*;*
3. **Continuous Improvement:** *Plus-Delta charts; House of Cards*; Collective Kaizen and Standardization; Ball Game; and,
4. **Culture of Respect:** *Repair Co Exercise; Red-Black Game (Variants: Maroon-White / Red-Green) game; Silent Squares*; Deming Red Bead Game; Helium Stick/ Magic Stick.

In addition to LCI's definitional categories, the need for new on-line simulations can be assessed based on classifications embedded into the Toyota Production Systems's "House of Lean" which includes concepts such as just-in-time, jidoka, heijunka, people and teamwork, continuous improvement, waste reduction, visual management, etc. (Liker 2004, Fig. 3-3). Further discussion of these principles is beyond the scope of this paper.

CONCLUSION

The purpose of this paper was to document and share the inception, growth, outcomes, and impacts of an international on-line simulation group called APLSO (Administering and Playing Lean Simulations Online) which emerged during the COVID-19 pandemic.

In total, 39 faculty members, 41 graduate students, and 35 individuals from companies/consultacies from 38 universities in 17 countries have thus far participated in the APLSO sessions. APLSO is unique in several ways including: the quick formation of the group in reaction to the pandemic challenges to effectively teach simulations online, the relatively large number of participants from both academia and industry, the variety of simulations played and concepts addressed, adaptation of technology available to fit the needs of the games and the participants, the global character of the particpants and the diversity of views considered, the cohesiveness of the community which quickly engaged on a regular basis, and the growth of participants who requested to join over time through word-of-mouth.

The organizers believe that while the group undoubtedly began because of the global pandemic, it continued to attract a steady flow of international participants perhaps because of the importace the organizers placed on a key tenet of lean—e.g. respect for people. This respect was manifest in the decision to be as welcoming and inclusive as possible of participants from multiple generations, cultures, and time zones, as well as with differing levels of prior understanding of lean—students, faculty, and practitioners alike. Embracing such a diverse range of members did lead to some cross-cultural challenges, such as confusion about the flow of ingredients for an outdoor barbeque on which one simualation was based. To ensure a sense of psychological safety for developers and participants who might be sharing and testing their new simulation for the first time, APLSO participants voted to not permit recording. Several developers made their simulations freely available through a creative commons license or via email request, which helped fill the need created by the pandemic to play simulations online. APLSO also led to some unexpected outcomes, such as an invitation from the IGLC organizers to create a number of on-line game rooms for the first time during the conference, as well as an initiative from LCI to partner with several APLSO facilitators to convert on-line simulations into dedicated educational offerings. Unlike an international conference, the agenda of APLSO was simple—to regularly make available a 90-minute interactive session where lean enthusiasts could collaboratively test simulations they had developed with participants who care about lean—and in turn receive their feedback.

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REFERENCES

Bhatt, Y., Rybkowski, Z.K., Kalantar, N. and Fernandez-Solis, J.L. (2016). "Trainathon lean simulation game: Determining perceptions of the value of training among construction stakeholders," *Proc. 24th Annual Conf. of the Int. Group for Lean Construction*, Boston, MA, USA.

Choo, H.J. and Tommelein, I.D. (1999). "Parade of Trades: A Computer Game for Understanding Variability and Dependence." *Technical Report 99-1*, Construction Eng. and Mgmt. Program, Civil and Env. Eng. Dept., University of California, Berkeley, September. https://p2sl.berkeley.edu/knowledge-center/parade-of-trades-game/ (Accessed June 10, 2021).

Gonzalez, V., Senior, B., Orozco, F., Alarcon, L. F., Ingle, J., and Best, A. (2014). "Simulating lean production principles in construction: A last planner-driven game," *Proc. 22nd Annual Conf. of the Int. Group for Lean Construction*, Oslo, Norway.

Howell, G. and Liu, M. (2012). "The Oops Game: How much planning is enough?" *Proc. 20th Annual Conf. of the International Group for Lean Construction*, San Diego, CA.

Koskela, L. (2000). An Exploration Towards a Production Theory and its Application to Construction. Ph.D. Dissertation, VTT Publications 408, Espoo, Finland, 296 pp.

Lean Construction Institute. (n.d.). "Glossary" Available at: https://tinyurl.com/2xnsswvb (Accessed February 14, 2021).

Liker, J. (2004). *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. McGraw-Hill, New York, USA.

Pollesch, P., Rovinsky, A., Alvarado III, R., and Alves, T. C. L. (2017). "House of cards—A simulation of lean construction principles," *Proc. 25th Annual Conf. of the Int. Group for Lean Construction*, Heraklion, Greece.

Rybkowski, Z. K., Abdelhamid, T., and Forbes, L. (2013). "On the back of a cocktail napkin: An exploration of graphic definitions of lean construction,"*Proceedings of the 21th Annual Conf. for the Int. Group for Lean Construction*; July 31-August 2, 2013: Fortaleza, Brazil, 83-92.

Rybkowski, Z. K., Forbes, L. H., and Tsao, C. C. Y. (2020). "The Evolution of Lean Construction education at US-based universities." In: Lean Construction: Core Concepts and New Frontiers. Tzortzopulos, P. Kaglioglou, M., and Koskela, L. Eds. Routledge, London and New York. 387-407.

Rybkowski, Z. K. and Kahler, D. (2014). "Collective kaizen and standardization: the development and testing of a new lean simulation," *Proc. 22nd Annual Conf. of the Int. Group for Lean Construction*, Oslo, Norway.

Rybkowski, Z. K., Munankami, M., Gottipati, U., Lavy, S. and Fernández-Solis, J. (2011). "Impact of cost constraints on aesthetic ranking following Target Value Design exercises," *Proc. 19th Annual Conf. of the Int. Group for Lean Construction*, Lima, Peru.

Rybkowski, Z. K., Munankami, M., Shepley, M. M. and Fernández-Solis, J. L. (2016). "Development and testing of a lean simulation to illustrate key principles of Target Value Design: A first run study," *Proc. 24th Annual Conf. of the Int. Group for Lean Construction*, Boston, MA USA.

Rybkowski, Z. K., Zhou, X., Lavy, S. and Fernández-Solís, J. (2012). "Investigation into the nature of productivity gains observed during the Airplane Game lean simulation," *Lean Construction Journal*, 78-90.

Sacks, R., Esquenazi, A. and Goldin, M. (2007). "LEAPCON: Simulation of Lean Construction of High-Rise Apartment Buildings," *Journal of Construction Engineering and Management*, ASCE, 133(7), pp. 529–539.

Smith, J. P. and Rybkowski, Z. K. (2013). "The Maroon and White Game: A simulation of trust and long-term gains and losses," *Proceedings of the 21st Ann. Conf. for the Int. Group for Lean Construction*; July 31-August 2, 2013: Fortaleza, Brazil, 987-996.

Solhjou Khah, F., Rybkowski, Z., Pentecost, A. R, Smith, J. P., and Muir, R. (2019). "Development and Testing of an Innovative Architectural Programming Simulation as a Precursor to Target Value Design," *27th Annual Conf. of the Int. Group for Lean Construction* (IGLC), González, V.A. (ed.), July 3-5, Dublin, Ireland, pp. 515-526.

Tzortzopoulos, P., Kagioglou, M and Koskela, L., eds. (2020). *Lean Construction: Core Concepts and New Frontiers.* Routledge, London and New York.

Verma, A.K. (2003). "Simulation Tools and Training Programs in Lean Manufacturing–Current Status: Final Report." National Shipbuilding Research Program, *NSRP-ASE-0301-11*, Old Dominion Univ. Norfolk, VA.

Villego® Last Planner® Simulation (2017) Available at: www.villego.com/ (Accessed: 26th Nov 2017).

Cisterna, D., Hergl, M., Oprach, S., and Haghsheno, S. (2021). "Digitalization of Lean Learning Simulations: Teaching Lean Principles and Last Planner® System." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 279–288, doi.org/10.24928/2021/0136, online at iglc.net.

DIGITALIZATION OF LEAN LEARNING SIMULATIONS: TEACHING LEAN PRINCIPLES AND LAST PLANNER® SYSTEM

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ABSTRACT

Lean simulations are an effective way to learn Lean principles and experience the impact on process optimization. However, to date, in construction these have mostly been conducted physically on site or in the office. As digital solutions for collaboration and teaching are increasingly developed in the context of the COVID-19 pandemic, Lean simulations also need to evolve by being decentralized from the project team and driven by digitalization.

This paper examines the adaptation and creation of Lean simulations that can be run on a digital platform that supports interactions between multiple participants in real time. Specifically, two simulations were created through a three-phase iterative development. The first simulation focuses on Lean principles and the second on the Last Planner® System. To evaluate the developed digital simulations, feedback was collected from the participants through questionnaires. It can be noted that all rating results were in the upper range. Research objectives were achieved: The evaluation of the technology, the fun and the design indicate that the participants can successfully interact with each other via the chosen digital platform. It also proved that digital simulations offer high flexibility, integration of technology with low costs and effort as well as a high level of sustainability.

KEYWORDS

Lean principles, Last Planner® System, digital lean simulation, collaboration, action learning.

INTRODUCTION

Since the fundamental principles of the Toyota Production System were adapted to the construction industry, the application of methods and tools within the emerging field of Lean Construction has proven to be effective in increasing customer value and decreasing waste. Nevertheless, a successful implementation of Lean depends not only on the

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understanding of the individual principles, but also on the step-by-step introduction of the whole system philosophy (Liker 2004).

In addition to understanding the technical aspects of the methods; values, behaviours, and the development of social competence – such as team cooperation and interdisciplinary understanding – should be introduced. Teaching methods of the traditional educational system are criticized for neglecting these aspects, since they focus mainly on individual competence. Experts argue that theory alone is not enough to learn Lean Principles and gain understanding for its practical application. Therefore, experiential learning is recommended. (Kriz 2003)

Combining theory with simulations (Herrera et al. 2019) or a systematic approach that both teaches and trains Lean Principles is a good way to reach this objective (Cerveró-Romero 2013; Heyl 2015). As Rybkowski et al. (2008) states: "Lean simulation games offer educational benefits that cannot be found in textbooks". To date, Lean simulations have been conducted mostly physically on site or in the office: simulations of roads construction (Heyl 2015), aircrafts production (Rybkowki et al. 2008) or the construction of buildings made with Lego® bricks are some examples of this (Dallasega et al. 2020, Gonzalez et al. 2014). As digital solutions for collaboration and teaching are increasingly developed in the context of the COVID-19 pandemic, Lean simulations also need to evolve by being decentralized from the project team and to be used as an innovative teaching tool (Gadre et al. 2011, Dallasega et al. 2020).

Digital simulations are performed on digital devices, where the environment is represented virtually, players interact with virtual elements rather than with real or tangible objects as in physical simulations (Carvalho et al. 2014). And as Abbasian-Hosseini affirms "computer simulation provides an excellent environment to implement Lean principles, study their effects, and gain a better understanding of how these principles perform." (Abbasian-Hosseini et al. 2014)

By digitalizing the simulations, two important gains are achieved compared to face-to-face simulations: (1) It eliminates the need to allocate all participants in the same place and can even allow interaction between participants from several countries around the world simultaneously and (Görke et al. 2017) (2) it is more sustainable. It reduces the number of materials needed, decreases the organizational effort in preparation and realization of the simulation, as well as the time required to carry out the event.

RESEARCH GAP AND OBJECTIVE

The digital simulations that exist today are mainly parametric models used to illustrate a real situation (Alves and Tommelein 2004; Carvalho et al. 2014; Abbasian-Hosseini et al. 2014). These models deliver the possibility to experiment with different variables of the system and to observe the effects created in function of different combinations of them (Rybkowski et al. 2008; Gadre et al. 2011).

There is a significant shortage of simulations run on a digital platform where interaction between participants is allowed in real-time. In current simulations, participants only interact with the platform or model of the system. Thus, social competencies cannot be developed. (Görke et al. 2017) Only one example of digital simulation for Lean principles with interaction between participants has been found in the literature (Kuriger et al. 2010). However, none has been found that instructs methods or tools of Lean Construction. The goal of this work is to adapt and create a Lean Construction simulation that can be run on a digital online platform, which allows real-time interactions between participants on a cloud-based game.

As a digital Lean Construction simulation has not been developed before, the first step is to develop a digital simulation for teaching general Lean principles. Best practices of user experience (UX) design were implemented (Gualtieri, M. 2009). By doing this, the objective of this first step is to test the technical, logistical, and pedagogical aspects of this new virtual approach in a controlled environment. Once these aspects are validated, the second step is to develop a Lean Construction simulation which involves more creative facets. The method chosen to for this cause is the Last Planner® System (LPS). This methodology was developed by Glenn Ballard (Ballard, 2000) and is based on Lean principles. It is mainly used for production planning and control in the construction and real estate industry.

ADVANTAGES OF DIGITAL SIMULATIONS

Physical simulations enable active and independent decision making (Gadre et al. 2011; Heyl 2015). Through visual representation of processes and metrics they allow to learn about consequences of decisions and strategies (Shannon et al. 2010). This facilitates an experiential learning of Lean principles in error-friendly, dynamic learning environments.

Digital simulations offer an added value: they are more flexible than physical simulations in terms of time, space, and number of participants (Görke et al. 2017), reducing efforts in setting up and clearing away the elements needed in the simulation (Kuriger et al. 2010) as well as reducing the costs (Abbasian-Hosseini et al. 2014).

Digital simulations are not a completely different concept compared to physical simulations, but rather an extension of them. As shown in Figure 1, the characteristics of the physical simulations will be the foundations for the development of the digital simulations. Following this premise, the simulations are designed in this work.

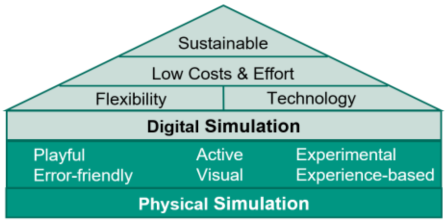

Figure 1: Advantages & enhancement through digital simulations

Concretely, the simulations are designed focusing on the following objectives: (1) to engage all participants through attracting design, providing them a social and multimedia experience (Görke et al. 2017); (2) to meet appropriate difficulty levels that range between comfort zone and the participants' willingness to compete (Vin et al. 2018) and (3) to fulfil learning goals of physical simulations such as to be instructive, fun to perform, realistic, easy to play, intuitive in applying principles and to be inspiring in terms of application in practice (Kuriger et al. 2010). The second and third objective are closely related to gamification aspects (Azmi et al. 2015): By using game mechanics such as a feedback board, virtual goods, a progress bar; game dynamics such as transparent achievements and competition; and game aesthetics such as challenges; gamification elements can be implemented.

REQUIREMENTS FOR A DIGITAL SIMULATION

In order to develop a digital learning simulation, certain requirements must be considered regarding the simulation itself, the participants as well as the moderator (Tommelein et al. 1999).

Simulation Requirements

Each simulation should be adapted to its participants (Vin et al. 2018). Regarding digital simulations, the participants' technological knowledge and their access to devices must be considered. To create an easy access to the software, even if the technological knowledge is low, a user-friendly design with clear instructions (Kuriger et al. 2010; Gadre et al. 2011) and graphics to visualize learning content (Kuriger et al. 2010) is very important. Also, the software should be compatible with the operative system of the participants. Additional devices like a mouse or a headset should be available for each participant. Duration of digital simulations is relevant since the attention span is clearly shorter and distractions by further applications on computers are possible (Kuriger et al. 2010). Lastly, according to Shannon et al. (2010), many digital simulations lack reference to reality. Therefore, a strong attention should be paid to this aspect.

Participants Requirements

Despite the emerging flexibility of a digital simulation, all participants must perform the simulation at the same time, regardless of different time zones. This time has to be blocked in all calendars of the participants (Kuriger et al. 2010).

A poor internet connection and the lack of personal contact can have a negative impact on the execution of the simulation. For this reason, participants must be encouraged to actively participate in the simulation. Their feedback should be collected and commented. A frequent shift of a practical, a feedback and a theory part has to be considered.

Moderator Requirements

Simulations should be led by a moderator in order to include all the relevant roles of a Lean Construction project. This person acts as a coach or trainer and not as a teacher (Leming-Lee et al. 2017). Besides the theoretical and practical knowledge of the simulations' objectives, the moderator should be further familiar with the software and should know how changes are made in the simulation (Shannon et al. 2010).

METHODOLOGY FOR THE DEVELOPMENT

The simulation is developed based on best practices of UX design (Gualtieri, M. 2009): Needs of the users were empathized. First, the simulation was designed, then tested internally and later with users. Finally, their feedback was implemented. This iterative procedure based on the PDCA cycle (planning, doing, control and acting) (Liker 2003) was run several times, resulting in user-oriented best practices.

In detail, as a first run, a simulation concept based on literature research was created. In the following runs, improvements were included as a basis for planning and goals were possibly adjusted. These were tested during the simulation and subsequently reviewed. In particular, a semi-standardized feedback questionnaire was distributed after two runs to its randomly assigned groups of participants. In this, they were able to evaluate the simulation on basis of individual factors such as fun and learning effect created by user interactions and game mechanics (Azmi et al. 2015). This questionnaire also allowed users to provide comments for further improvements. Using this approach, in total three runs or PDCA cycles were conducted for each of the two simulations. The first run served to check the technical requirements, the second run to test the teaching method of the didactic triangle (Tommelein et al. 1999) and the third run to check the learning success based on the objectives. The didactic triangle tests the relationship between moderator, participants, and simulation.

These runs were conducted with different groups of experts. A group of Lean experts who had already gained experience with Lean simulations participated in the first and second runs. This allowed the didactic teaching method and the underlying theory to be verified. The third run was carried out with students in the master program without a corresponding basic knowledge. This target group represents the typical group of participants in the simulation.

GUIDING A DIGITAL SIMULATION

The first technical tests resulted in the decision to use Miro as software for the execution of the simulations. Miro is an online visual collaboration platform for teamwork, which made it suitable for generating the necessary virtual collaboration environment. Through the online whiteboard the processes are visually represented and can be used by several users simultaneously. The whiteboards can be shared through links with the users.

LEAN PRINCIPLES SIMULATION

The first simulation performed was on Lean principles. This is the typical simulation flow found in the literature: perform multiple rounds of incremental implementation of the Lean Principles and record metrics to track improvements and compare between rounds. The final version of the simulation has 5 stations (see Figure 2) and a duration of one hour and thirty minutes. The objective of the simulation is to create a product through the 5 production stations.

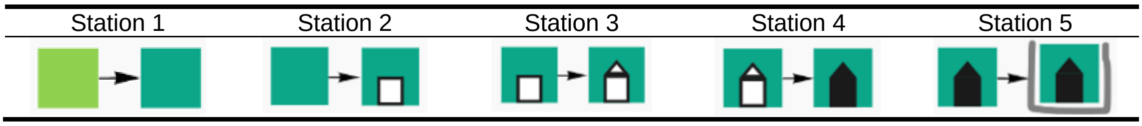

Figure 2: Lean Principles Simulation – Production flow

To achieve this, participants must play the roles of the customer, a logistician, a general manager, time managers and quality managers. Role distribution can be combined as desired. The simulation needs at least 7 participants scaling to more than 14 people. The layout of the simulation in Miro is an aerial view of a factory (see Figure 3 and scan the QR-Code to watch a short teaser). It has a production room, a warehouse, and a Big Room. It includes a visual diagram of the production flow, production performance indicators and a table to record the stress of the participants in each round. There is also an area to visualize the Lean principles applied per round. This helps to understand the impact of the application of Lean principles on the improvement of the production process.

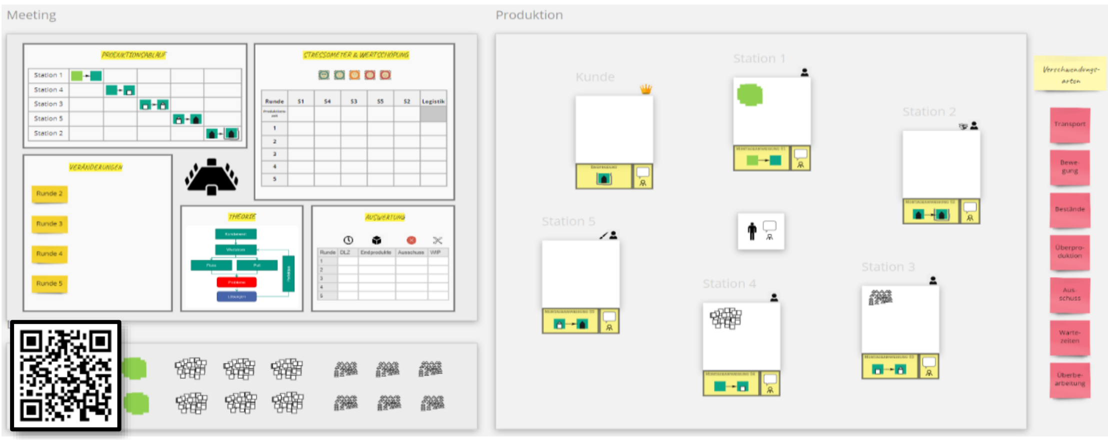

Figure 3: Lean Principles Simulation – Layout

Preparation for Playing the Simulation

The simulation starts with a short introductory presentation run by the moderator, in which the participants are taught about technical aspects, such as recommended internet browser for the simulation and the use of mouse as main interface. Basic definitions necessary for the simulation are presented. An overview of the simulation layout is shown, explaining the production flow, the roles, the general simulation rules, and the definition of waste. After that, the participants are invited to enter the virtual environment in Miro. Inside the platform a technical introduction on the Miro functionalities is given. At this point, an overview of the layout is carried out "on site", and the role distribution is made by asking the participants to place the mouse cursors to desired roles.

Test Run

Each station processes three products and the logistician transports the produced parts. Time managers measure average production time of the respective stations and document it (see Figure 3). This test run serves to get an overview of the workload of the individual stations. Later harmonization in each one of the stations is introduced as a Lean principle. This test help to check whether participants have understood their role or if they have technical problems with the tool. After finishing the test run, all materials on stations are eliminated and the moderator place new material.

Production Rounds

The simulation starts when the moderator runs the stopwatch implemented in Miro for all to see. Each of the 5 rounds lasts 3 minutes and the objective of each round is to produce as many products as possible. After each round the participants organize a continuous improvement meeting, where each station and the logistician report their stress level. The general manager records key figures such as lead time, number of manufactured products, defective parts (detected by the quality managers) or rejected products (by the costumer) and the work-in-progress parts (in stations). In the final part of the meeting, the moderator leads the discussion stimulating the identification of waste of the respective round. Then, he gives a theory input about the Lean principles which can avoid the identified waste to discuss with the participants possible process improvements to be implemented (see Table 1).

Table 1: Lean Principles Simulation – Sequence of rounds

After round...	1	2	3	4	5
Type of Waste	Transport, Movement	Inventory, overproduction	Defects, Transport	Waiting Time	Over-processing
Theory Input	Flow	Pull	One-piece-flow	Harmonization	Kaizen
Improvement applied	Production Line or U-shape	Parts collection from previous station	Batch size 1	Elimination of bottlenecks	-

Closure and findings

At the end of the event a survey was carried out to capture feedback from participants and test the knowledge acquired by them during the simulation.

The final version of the simulation was tested with 46 Lean Construction students divided into four groups. It lasted an hour and a half. All improvement suggestions were considered. Some opted for an in-line and others for a U-shaped layout of the stations; at the stations they defined separate areas for finished products and for products under construction. As a result, in the last round they applied the one-piece flow principle (reduction to lot size 1) and harmonization of the workload per station.

LAST PLANNER® SYSTEM (LPS) SIMULATION

The second simulation was designed to teach the LPS. It was based on a typical simulation process from literature research: execution of two rounds, one "conventional construction round" and a second round applying LPS. The simulation describes the construction process of the shell of a house (see Figure 4).

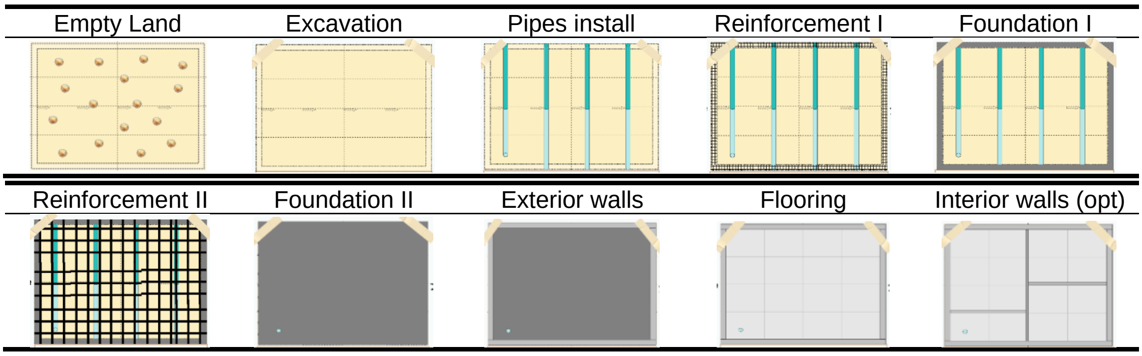

Figure 4: LPS Simulation – Construction process

Each process step (see Figure 4) is simulated by a role. The role distribution is flexible and can be combined as desired (e.g.: two roles can be played by one person). The simulation needs at least 6 participants scaling up to 15 people. Further roles not shown in Figure 4 are construction manager, quality manager and construction logistics.

The layout of the simulation is again an aerial view of a construction site (see Figure 5 and scan the QR-Code to watch a short teaser). It has a construction area, two warehouses, one set of supplier materials per round and a Big Room. In this room there is a visual diagram of the construction process, tables with LPS elements such as a collaborative planning board and performance charts with the percentage of plan completed (PPC) or the stress of the workers per round. At the bottom of the layout, there is a group of videos presenting the construction process of each trade. This emulates the insight effect of viewing a construction process in a BIM model, helping participants to get a better understanding.

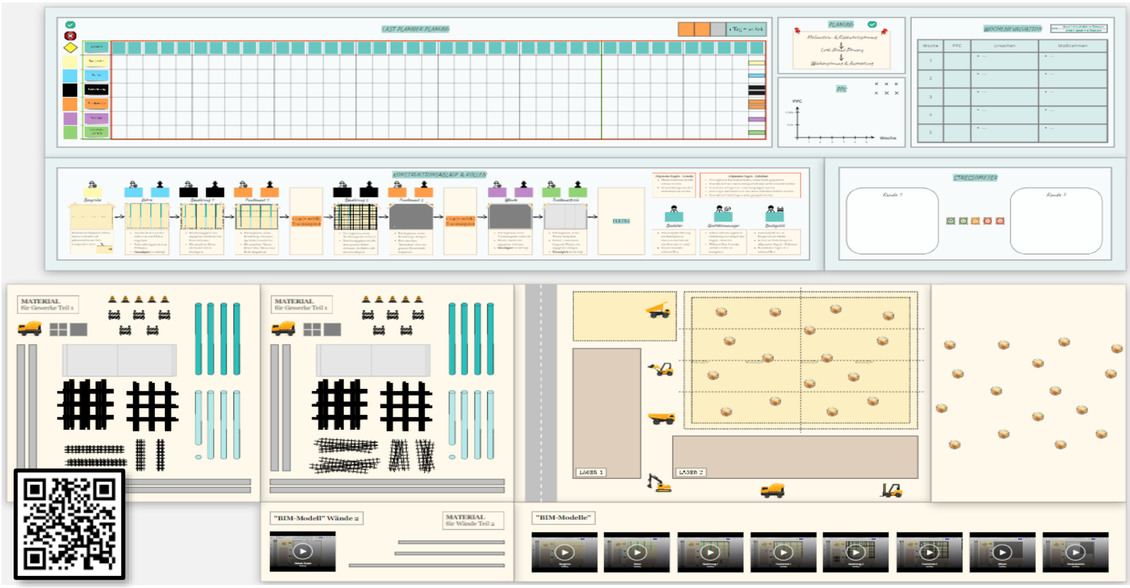

Figure 5: LPS Simulation – Layout

Preparation for Playing the Simulation

The simulation introduction and rule explanation take place directly on Miro. During this phase, all frames in Miro remain hidden. The frames are unlocked progressively according to the stage of the simulation. This avoids overloading the participants with too many elements. The construction site is shown, tasks are explained, and roles are distributed. Participants are told that the goal of the game is to complete the construction within 6 weeks (corresponding to 5 minutes).

Conventional Construction Round

The site manager is given 1 minute to organize all the trades. After this, the simulation begins when the moderator starts the stopwatch. In this first round, time is allowed to run freely until the construction is completed. When the participants finish, the moderator records the time and points out deficiencies, integrating the participants into the discussion. In addition, participants report their stress level.

Last Planner® System Rounds

Before the second round starts, the moderator gives an overview about the phases of the collaborative LPS planning. Backward planning takes place interactively with all trades, in which they define task durations (1 day = 10 seconds). When the plan is ready, the whole construction process plan is moved forward, and trades set milestones. Then, the look-ahead planning is carried out. The moderator engages the team to identify restrictions and to try solving them in advance. Each trade defines its tasks and sets commitments by pasting a digital sticky note in each committed day.

Building materials for the incoming week are provided and the second round starts with weekly interruptions (e.g., moderator says that the construction must be paused 10 seconds because of bad weather conditions): a week of 5 days is assumed, so the moderator stops the time count after 50 seconds, using a visible stopwatch.

At the end of the week the evaluation is moderated by the construction manager who fills the LPS board. Commitments and milestones are checked and depending on their completeness they are coloured red (incomplete) or green (complete) to visualize them. PPC is calculated and the causes of non-compliance are documented, as well as the measures to avoid them. The moderator supports the construction manager to involve all trades in the discussion. Special events can be introduced, these can be visualization of the construction process in a BIM model (showing a video of the process), rainy weather (stop activities for 10 seconds) and costumer request (installation of interior walls). After the last round, the moderator makes a final assessment of the project, and the stress level of the second round is filled out.

Closure and Findings

A survey was carried out at the end of the game as well. The final version of the simulation was tested with 32 Lean Construction students divided into two groups. It lasted an hour and a half. In the first conventional construction round both groups finished the construction in approximately 10 minutes and in the second round using the LPS the construction was finished in less than 5 minutes. PPC increased in the simulated weeks up to 100%. To include special events, 120 minutes should be planned.

EMPIRICAL ASSESSMENT

To evaluate the developed digital simulations, feedback was collected from the participants through questionnaires with a 1-5 Likert scale and open questions. The total number of participants for each simulation and those who took part in filling out the questionnaires can be found in Table 2. It shows the average scores obtained by both simulations in the categories of design, fun, and moderation. Design was rated higher in the LPS Simulation while fun and the moderation had a higher score in the Lean Principles Simulation.

It can be noted that all rating results are in the upper range between 4 and 5. The percentage of the technology represents the fulfilment of the technical requirements. In the LPS simulation 80% of the participants did not experience any technical problems. The fewer technical problems are reasoned since in the LPS simulation it was not necessary to mark and move multiple elements inside the Miro platform.

Table 2: Validation Digital Simulations – 1-5 Likert Scale from 1 (very low) to 5 (very high), Technology from 1% to 100% of Participants Questionnaire

	Simulation Participants	Assessment Participants	Design	Fun	Moderation	Technology
Lean Principles Simulation	57	43	4.37	4.48	4.59	70%
LPS Simulation	48	35	4.49	4.35	4.22	80%

Furthermore, the closeness to reality was measured by the participants rating the Lean Construction Simulation on a scale from 1 (hardly realistic) to 5 (very realistic). This resulted in an average value of 3.62. The freedom of decision was rated by the participants from a scale of 1 (very restricted) to 5 (very free) with an average of 3.97.

CONCLUSION AND OUTLOOK

As the results of the survey show, the research objectives defined at the beginning were achieved: The evaluation of the technology, the fun and the design indicate that the participants can successfully interact in real-time with each other via the chosen digital platform. Furthermore, the learning effect was achieved with the learning method: the participants move out of their comfort zone, are willing to get involved in the simulation and thus achieve the "aha" moment by anchoring the theory. Overall, not only were the advantages of a physical learning simulation achieved, but additional advantages of a digital simulation were included: Digital simulations offer high flexibility, integration of technology with low costs and effort as well as a high level of sustainability (see Figure 1). To support building relationships and commitment also in digital simulations, additional technologies such as Augmented Reality or Virtual Reality can be a future focus of research.

It has been shown with the implementation of the simulation that especially the freedom of decision of the participants has to be considered by the moderator. Here, especially through the digital format, the ratio between freedom (for the purpose of participants' development) and the structure given by templates and instructions must be considered. The degree of freedom can be analysed more in further runs of the simulation to find the perfect balance in between. Also, the chosen methodology and technique has proven itself, so that it can be transferred to other methods and tools. Thus, a first concept for a digital simulation for Takt planning and Takt control has already been developed.

REFERENCES

Abbasian-Hosseini, S.A., Nikakhtar, A., and Ghoddousi P. (2014). “Verification of Lean construction benefits through simulation modeling: A case study of bricklaying process.” *KSCE Journal of Civil Engineering*, 18(5) 1248-1250.

Alves, T., and Tommelein, I. D. (2004). “Simulation of Buffering and Batching Practices in the Interface Detailing-Fabrication-Installation of HVAC Ductwork.”

Azmi, S., Iahad, N. A., & Ahmad, N. (2015). "Gamification in online collaborative learning for programming courses: A literature review." *ARPN Journal of Engineering and Applied Sciences*, 10(23), 1-3.

Ballard, H. G. (2000). "The last planner system of production control." *Doctoral dissertation, University of Birmingham.*

Carvalho, C. V. de, Lopes, M. P., and Ramos, A. G. (2014). "Lean games approaches– Simulation games and digital serious games." *iJAC*, 7(1) 14.

Cerveró-Romero, F., Napolitano, P., Reyes, E., and Teran, L. (2013, July). "Last Planner System® and Lean approach process®: experiences from implementation in Mexico." *Proceeding IGLC*-21, 709–718.

Dallasega, P., Revolti, A., Sauer, P. C., Schulze, F., and Rauch, E. (2020). "BIM, Augmented and Virtual Reality empowering Lean Construction Management: a project simulation game." *Procedia Manufacturing*, 45, 50.

Gadre, A., Cudney, E., and Corns, S. (2011). "Model development of a virtual learning environment to enhance Lean education." *Procedia Computer Science*, 6, 100.

González, V. A., Senior, B., Orozco, F., Alarcón, L. F., and Ingle, J., Best, A. (2014). "Simulation Lean production principle in construction: A last planner-driven game." *Proceeding IGLC-22, Oslo, Norway*.

Görke, M., Bellmann, V., Busch, J., and Nyhuis, P. (2017). "Employee qualification by digital learning games." *Procedia Manufacturing*, 9, 231, 235.

Gualtieri, M. (2009). "Best practices in user experience (UX) design." *Design Compelling User Experiences to Wow your Customers*, 1-17.

Herrera, R. F., Sanz, M. A., Montalbán-Domingo, L., García-Segura, T., and Pellicer, E. (2019). "Impact of game-based learning on understanding Lean construction principles." *Sustainability*, 11(19) 5294.

Heyl, J. von (2015, July). "Lean simulation in road construction: teaching of basic Lean principals." *Proceedings IGLC- 23. Perth. Australia*, 406.

Kriz, W. C. (2003). "Creating effective learning environments and learning organizations through gaming simulation design." *Simulation & Gaming*, 34(4), 504.

Kuriger, G. W., Wan, H. D., Mirehei, S. M., Tamma, S., and Chen, F. F. (2010). "A web-based Lean simulation game for office operations: training the other side of a Lean enterprise." *Simulation & Gaming*, 41(4) 488-489, 500-503.

Leming-Lee, S., Crutcher, T. D., & Kennedy, B. B. (2017). "The Lean methodology course: Transformational learning." *The Journal for Nurse Prac.*, 13(9) 420.

Liker, J. (2004). "The Toyota way. 14 management principles from the world's greatest manufacturer." New York, NY: McGraw-Hill, 350 pp.

Rybkowski, Z. K., Wong, J. M., Ballard, G., and Tommelein, I. D. (2008). "Using controlled experiments to calibrate computer models: the Airplane Game as a Lean simulation exercise." *Proceedings IGLC-16*, 315.

Shannon, P. W., Krumwiede, K. R., and Street, J. N. (2010). "Using simulation to explore Lean manufacturing implementation strategies." *Journal of Management Education*, 34(2) 287, 290.

Tommelein, I.D., Riley, D., and Howell, G.A. (1999). "Parade Game: Impact of Workflow Variability on Trade Performance." *J. Constr. Eng. Manage.*, 125(5) 304-310.

Vin, L. de, Jacobsson, L., and Odhe, J. (2018). "Game-based Lean production training of university students and industrial employees." *Procedia Manufacturing*, 25, 579.

Brandalise, F. M. P., Pedo, B., Viana, D. D., and Formoso, C. T. (2021). "Exploring Visual Management Purposes in Construction Projects" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 289–298, doi.org/10.24928/2021/0146, online at iglc.net.

EXPLORING VISUAL MANAGEMENT PURPOSES IN CONSTRUCTION PROJECTS

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ABSTRACT

The application of the lean construction principle of increasing process transparency is the main purpose of Visual Management (VM), a strategy for making information clear and accessible. There are other purposes of VM, such as continuous improvement, job facilitation, and simplification. However, the connections among those purposes are not fully explored in the literature, which limits the current conceptual understanding of VM. The aim of this paper is to propose a conceptual map of the VM purposes in construction projects, based on the analysis of three VM practices. This research study is part of a broader ongoing research project which objective is learning and teaching about VM through a serious game that considers different VM aspects. Design Science Research was the methodological approach adopted in this investigation. The main findings of this study are concerned with some connections between different VM purposes. Some of these purposes are specific, while others are more generic. Moreover, a specific purpose may have a different meaning for each practice, so context analysis plays an important role. Finally, different ways of shared understanding by using VM practices have been identified, such as by adhering to standards or by encouraging collaboration.

KEYWORDS

Visual management, purpose, lean construction, learning, teaching.

INTRODUCTION

Increasing process transparency is the most cited purpose of Visual Management (VM), a strategy for making information clear and accessible (Tezel et al. 2016). In fact, visualization can contribute to information flow management, supporting communication among stakeholders, and increasing accessibility to information, which can support fast decision-making (Lindlöf 2014). Previous research has pointed out that VM purpose is not related only to the observable portion of VM practices, but especially to the "non-visual work" involved in it (Nicolini 2007).

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However, there are other purposes of VM, also named in the literature as functions or objectives, such as improving understanding of schedules (Tezel and Aziz 2017) and giving quick information feedback (Tezel et al. 2018; Valente et al. 2019). Dallasega et al. (2018) argue that VM also increases work capacity as it supports information accessibility and availability of real-time data collection and processing. Tezel et al. (2009) also provided a classification of VM purposes, such as job facilitation and simplification.

Tezel et al. (2016), in turn, suggested a systematic application of VM aiming to emphasize its benefits, but those authors pointed out that there is a mismatch between the proposed benefits of VM in the literature and those achieved in practice. That is due to the lack of conceptual clarity and the scattered literature showing an only limited understanding of VM. Besides that, research on VM is a fundamental strategy of lean production (LP) (Mejabi 2003). Tezel et al. (2016) suggest that a generic understanding of the subject is necessary, without confining it only to the production domain.

The aim of this paper is to propose a conceptual map of VM purposes, based on the analysis of three VM practices. This investigation is part of a wider research project under development which objective is learning and teaching about VM through a serious game for improving the conceptual understanding of the subject and its role as a strategy to cope with complexity in construction projects. This game allows several analyses to be carried out. Besides the discussion about purposes, other steps of the game consider different aspects of VM practices such as context understanding, requirements, the role of communication, and the role of collaboration. The artifact presented in this paper is a reflection of discussions on VM purposes that were held in the initial applications of the game. This was selected to be the first conceptual outcome of this investigation, but it is expected that other theoretical contributions might be produced as the development of the game evolves. Moreover, it is expected that future reflection on the set of concepts and practices involved in the game, based on participants' perceptions, will provide a broad understanding of the use of VM in construction projects.

PURPOSES OF VISUAL MANAGEMENT

The main purpose of VM is to increase process transparency to promote improvements in the production systems and the overall management of organizations (Tezel et al. 2016). VM is also related to the reduction variability and the elimination of non-value-adding activities (Formoso et al. 2002; Koskela et al. 2018), as well as to continuous improvement (Bernstein 2012; Brady et al. 2018; Eaidgah et al. 2016), other fundamental LP principles (Koskela 2000).

It is also noteworthy that VM enables a faster and more reliable approach of communication compared to traditional alternatives, contributing to the reduction of cycle time and to the reduction of variability, which also explains its intrinsic role in LP (Koskela et al. 2018). Tezel et al. (2009) also pointed out VM purposes of simplifying and unifying information. In fact, VM can mitigate problems related to the management of complex production systems, for example when used to support collaboration in planning and control meetings (Viana et al. 2014). Management by facts (Gunasekaran et al. 1998), discipline by following the right procedures (Hirano 1995), and direct support for other management efforts (safety management, performance measurement, and production management, etc.) can also be classified as VM purposes (Tezel 2011). VM devices can vary in form, level of standardization, and level of collaboration required by the users. On one hand, a simple visual indicator such as a board with the sentence “drink water" may not be effective in changing behavior because people are used to seeing it and no longer even think about its message. While, on the other hand, a collaborative planning board facilitates the understanding of each team about tasks to be undertaken and existing constraints, helping to organize the planning process. Therefore, some VM practices can mitigate problems related to system complexity by sharing the right information on time and removing information barriers in the work environment (Valente et al. 2019)

Another VM purpose pointed out in the literature is associated with the increase in workforce motivation (Galsworth 1997), by enabling the participation of many people in decision making (Greif 1991; Klotz et al. 2008). This helps to promote collaboration between team members (Ewenstein and Whyte 2007). Besides that, VM can facilitate work (Tezel et al. 2009), giving autonomy to the employees (Greif 1991), because it creates a sense of shared ownership, and supports on-the-job training (Tezel et al. 2009, 2016). Valente et al. (2019) described specific purposes for different VM practices that, in general, establish a common understanding and support the exchange of information, besides encouraging the joint processing of information. In fact, systematic implementation of VM establishes a visual workplace in which various purposes of VM can be observed (Tezel et al. 2016).

RESEARCH METHOD

Design Science Research (DSR) was the overall methodological approach adopted in this investigation. This approach consists of the development of artifacts for solving classes of problems (van Aken 2004; Holmström et al. 2009). DSR was adopted due to the prescriptive character of this investigation, as it comprises a dynamic process between problem understanding and solution development through incremental learning cycles (Lukka 2003). However, the research study described in this paper has a descriptive character, as its focus is on understanding the underlying ideas of VM best practices. Similarly to what is undertaken in Evaluation Research, as described by Clarke and Dawson (1999), the outcomes of such a descriptive study can be used for a prescription.

The main source of evidence used in this investigation was participant observation in the application of the VM game, as well as perceptions of students, professionals, and academics about the purpose of VM. Those perceptions were obtained through interactive online workshops among participants, using word clouds diagrams to show and discuss results.

This paper covers part of the outcomes resulting from the application of the game in three opportunities. Three VM practices were selected: “pipe template”, “exposed work execution procedure in images and video”, and “collaborative planning”. Forty-five people were involved in the workshops. All of them had a background in architecture or civil engineering: 13.3% researchers on VM, 2.2% Ph.D. students, 20% master students, 20% undergraduate students, and 44.4% practitioners.

Firstly, the research team presented an image of the practice in question explaining a situational concern and its countermeasure. Then, respondents should write their perception of the main purpose of the VM practice presented. An online and interactive presentation software was used to support respondent’s answering during the meetings, and the resulting word cloud was presented synchronously on the screen. This means that the first respondents may influence the last ones. Each respondent could write as many terms as they want until the established time limit was reached (an average of 7 minutes), and the word size in the resulting word cloud indicates the frequency that each term was mentioned: the bigger size of the word, the more often it was mentioned. Finally, the researchers and respondents discussed the diagram to refine the understanding of the purposes of that VM practice. The presentation of the results right after the voting session enabled a deeper discussion among participants.

The VM practice "pipe template" had its purposes discussed in two online meetings, "exposed work execution procedure in images and video" in three, and "collaborative planning board" in only one. The collected data were transferred to a database. Except for the first meeting to discuss "exposed work execution procedure in images and video", which was carried out in English, all other meetings were in Portuguese. Therefore, subsequently, the terms were translated into English in this database. Then researchers developed a word cloud for each VM practice discussed. All words mentioned for each practice were included in the resulting word cloud.

Finally, an analysis of words was realized: similar ones were grouped into a common term. Then, these final set of terms about the purposes of the three VM practices discussed were connected, forming a conceptual map, the main artifact of this investigation, in which the relationships between VM purposes are made explicit.

RESULTS

PIPE TEMPLATE

In construction projects, there is the need of installing hydraulic pipes in the correct location according to the design. Aiming to assure that, a possible countermeasure is to use a cut rug as a template (Figure 1 (a)). It is especially useful in projects with floor design repetition. By identifying the location where pipes should be installed, it eliminates the need to measure. The use of templates makes it easier and faster to complete the work.

As exposed in that VM practice description, the main purpose pointed out by participants was "standardization" or making a "standard" (36.4%, 8 out of 22), i.e., the cut rug is a template to be followed as a pattern for pipe installation. The consequence of using it is to reduce the probability of errors by installing pipes in the wrong places. In fact, objectives related to "mistake avoidance", such as "avoid mistakes", "mistake proofing", and "*poka-yoke*" were the second more remembered by 31.8% (7 out of 22) of respondents. Other purposes had less mention but were equally related to each other: the lean construction principle of "reduce cycle time" (4.5%, 1 out of 22) through by "eliminate set-up" (4.5%, 1 out of 22) would "increase productivity" (4.5%) as also result in more "excellence" (4.5%, 1 out of 22) of the final product. An answering frequency of 22 times resulted in the 11 purposes mentioned in the word cloud of Figure 1 (b).

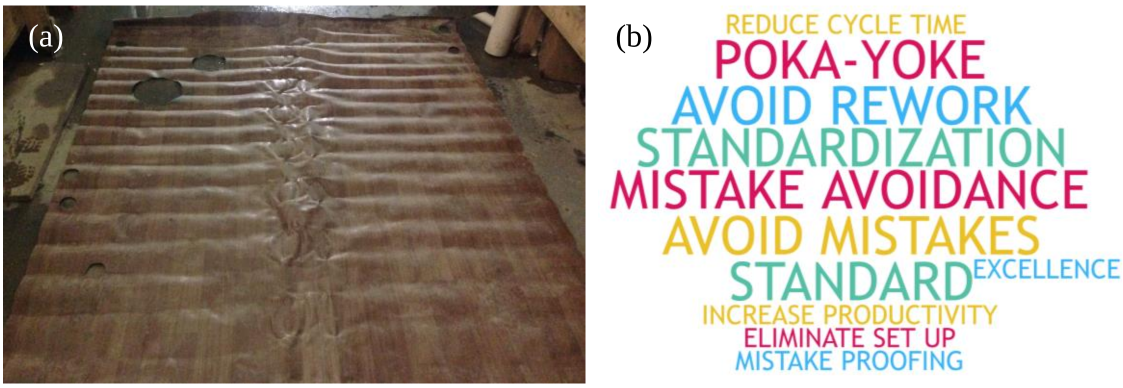

Figure 1: VM practice "pipe template" (a), and its purposes (b)

Exposed Work Execution Procedure in Images and Video

It is expected that workers should learn and be reminded on how to execute some working procedures, which are explained in the training programs. To support that, a possible countermeasure is to provide a board close to the workplace where images illustrate the procedure sequence (Figure 2 (a)). If the worker wants more information, he/she can scan the image with a mobile phone (functioning as a QRcode) and a video will be open, giving him some autonomy for learning.

"Autonomy" (also understood as "self management") and "standardization" (e.g. "delivery of job standard", and "standardize") were the most mentioned purposes for 13.7% of respondents each (7 out of 51 each). It was followed by the purpose of increasing "quality" (5.9%, 3 out of 51), and giving "visibility" (3.9%, 2 out of 51), which is strongly related to the lean principle of "increase process transparency" (Koskela 1992) mentioned as "transparency" by 2% of participants (1 out of 51). This VM practice also presented a lot of other purposes, which were pointed out by 2% (1 out of 51) of respondents each one (e.g. "learning", "belonging", and "efficiency"), totaling in 51 replies distributed in the 37 terms observed in Figure 2 (b).

Figure 2: VM practice "exposed work execution procedure in images and video" (a), and its purposes (b)

Collaborative Planning Board

There is a need to create a shared understanding of scope, key milestones, major constraints, and a logical sequence of work in the design stage. In this way, analogue (Figure 3 (a)) or virtual (Figure 3 (b)) collaborative boards can be used as a countermeasure to support master and phase planning of Last Planner® System (Ballard and Howell 1998; Howell and Ballard 1999). In response to the COVID-19 situation, the digital implementation of this VM practice through virtual meetings has become essential for making design decisions.

In fact, it does not matter where it happens, collaborative planning supported by VM had as most cited purposes the terms "commitment", "engagement", and "integration", with 11.5% each one (3 out of 26 each). These result in "collaboration", as mentioned by 7.7% of respondents (2 out of 26). Besides that, though a "share knowledge" (also mentioned by 7.7%, 2 out of 26, participants), a "common understanding" can be achieved due to the "information unit" encouraged, as argued by 3.8% (1 out of 26) of people. All 18 purposes about this VM practice pointed out in a total frequency of 26 answers are summarized in a word cloud (Figure 3 (c)).

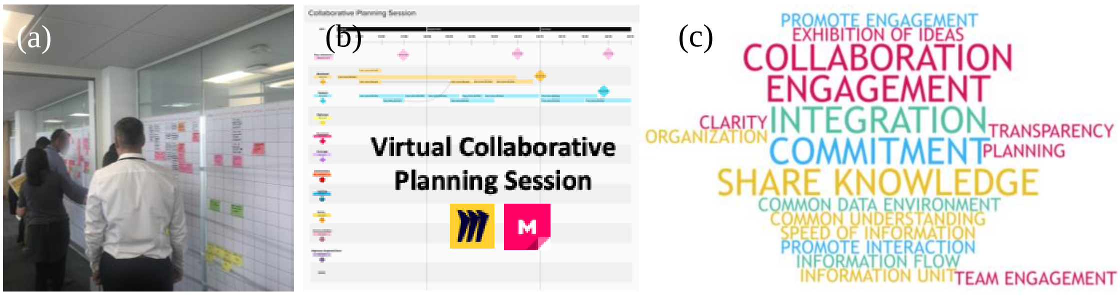

Figure 3: VM practice "collaborative planning board" analogue (a) and virtual (b), and its purposes (c).

DISCUSSION

The purposes identified by the game participants in word clouds for the three VM practices were analyzed and grouped by similarity. Twenty-four main VM purposes were found. Many of them are strongly related to each other, so the authors developed the following conceptual map (Figure 4).

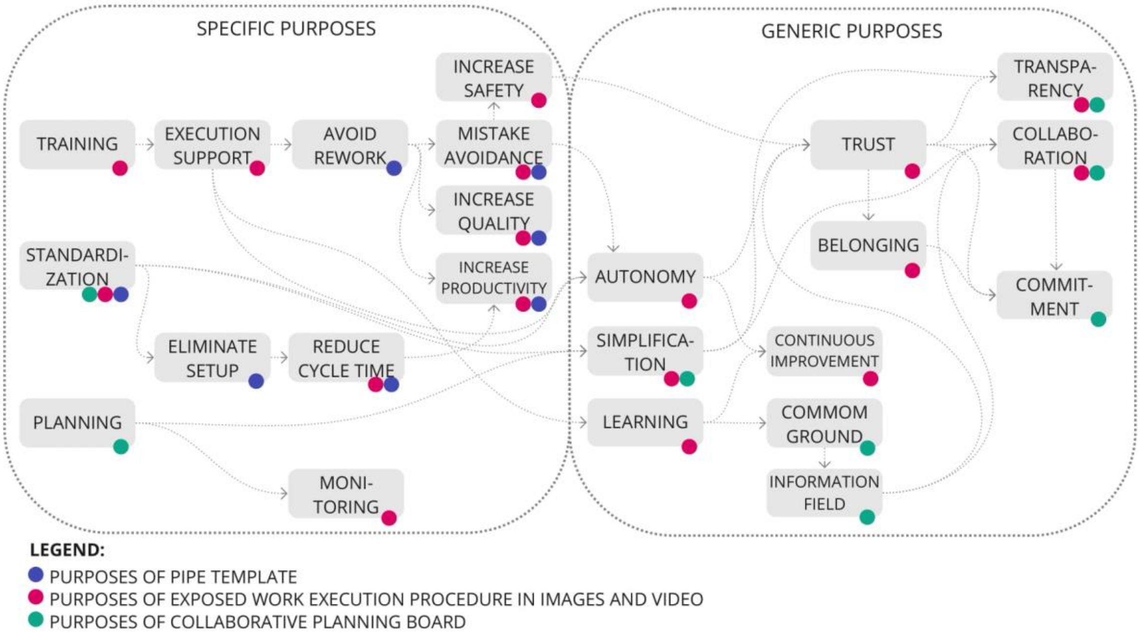

Figure 4: Conceptual map of VM purposes.

The "training" purpose, which was suggested by Tezel et al. (2016), was addressed by the VM practice of exposed work execution procedure. "Training" has a positive impact in "execution support", which can have a positive effect in "avoid rework". The purpose of 'avoiding rework' was addressed by the pipe template VM practice as workers were able to do the task correctly from the first time of execution. Thereby, an "increase of quality" and an "increase of productivity" can be observed, as well as "mistake avoidance", which can "increase safety" and also gives "autonomy" to the employee, as pointed out by Greif (1991). This "autonomy" happens especially due to the "execution support" purpose mentioned by Tezel et al. (2009), as the employee would be capable of doing the task by himself/herself, through "standard" procedures (Hirano 1995).

The "planning" purpose of the collaborative planning practice, in turn, is a way of generating "simplification" (Tezel et al. 2009) enabling people to "collaborate"

(Ewenstein and Whyte 2007) in the planning process, as it is easy to understand interdependencies between activities. Besides, facilitating "monitoring", as well as the "execution support" results in "learning". This creates a "common ground" and "continuous improvement", another objective of VM already pointed out by literature (Bernstein 2012; Brady et al. 2018; Eaidgah et al. 2016) which is also a consequence of "autonomy" (Greif 1991). If people are aware of their responsibilities, there is room for suggesting some improvements. The "common ground" is related to the unification purpose (Tezel et al. 2009), the common understanding (Valente et al. 2019), and the global management support (Tezel 2011). It allows the creation of an "information field" that together with the "increase safety" gives "trust" to the workers making decisions (Greif 1991; Klotz et al. 2008), besides supporting their "collaboration" (Ewenstein and Whyte 2007).

"Standardization" was the only purpose mentioned for the three VM practices analyzed. As mentioned by Tezel et al. (2016), it helps to simplify (“simplification”) the steps of the work and to "eliminate setup", which, in turn, "reduces cycle time" (Koskela et al. 2018), a well-known lean production principle (Koskela 1992) that "increases productivity". It also gives "autonomy" to users resulting in an environment with "transparency". In fact, VM is a strategy for increasing process transparency (Tezel et al. 2016) and it is also proportioned by "trust", strongly related to the "belonging" feeling, the shared ownership (Tezel et al. 2016) that results in the crew's "commitment". Finally, this "commitment" also is a consequence of "collaboration" caused by "trust".

As observed in Figure 4, VM practices can present a range of purposes (Tezel et al. 2016) and they can be related. Some of them are more specific, more objective, and related directly to the practice use, i.e., more related to visual work involved. These purposes are located more to the left, such as “training”, “execution support”, “planning”, and “monitoring”. In turn, others are more generic and abstracts, i.e., more related to non-visual work involved, such as “autonomy”, “transparency”, “collaboration”, and “commitment”. Those are located on the right side of Figure 4.

The three practices selected are fairly different in terms of their purposes. For example, although “standardization” was cited as a purpose of the three practices, it has a different meaning in each practice (Figure 5). The pipe template is related to the product standardization, it is focused on the result. The exposed work execution procedure is associated with the process, in which the idea is to make workers perform a task in the same way. The collaborative planning board uses the idea of process standardization differently. It standardizes the routines and the way people should interact, and also the VM interface. The interesting paradox of this practice is that standardizing the process of planning creates a means for changing the previously established plan and collaboratively affecting the final product.

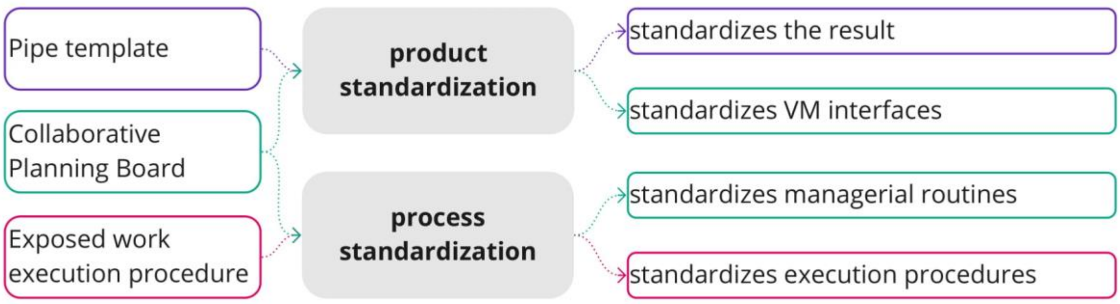

Figure 5: Different meanings of “standardization” according to the VM practice.

Comparing the main purpose of using the collaborative planning board in relation to using the pipe template, it is possible to note the latter is focused on generating adherence to the design. The activity in the field has to occur according to some established specifications. On the other hand, the former is based on the idea of changing or at least adapting, a previously established plan based on the shared understanding about the milestones among all participants.

For Koskela (2015), one of the challenges in construction management is to make people in the field adhere to the plan. That author argues that visual management could be regarded as a rhetorical strategy for making it possible, as it simplifies the information, improving shared understanding. Standards are important for making deviations clear and can be an important source for continuous improvement (Spear and Bowen 1999). Management based on the lean production philosophy means letting some room for learning, and opportunities for people to question and suggest changes. Process transparency also plays a key role in supporting learning. This study indicated that shared understanding can be obtained in different manners, such as in practices that support adherence to standards, such as in the pipe template practice, or by using collaboration to discuss and refine decisions, such as in the case of the collaborative planning board practice.

CONCLUSIONS

This investigation presents the results of an ongoing research project which aims to develop a serious game to teach VM as well as to improve the understanding of this topic. The proposed conceptual map of the relationships between VM purposes is one of the analyses that was undertaken. Perceptions of different stakeholders were used to define a set of purposes for the three practices. Then through a group discussion, the purposes were organized according to their connections, which was not explored in the existing literature.

These are the main findings so far: (i) many VM purposes are strongly related to each other, so it is useful to organize them in a conceptual map; (ii) some purposes are more specific, more objective, and related directly to the current practice, while others are more generic and abstract; (iii) one specific purpose can have different meanings in each practice, so context analysis is fundamental for purpose understanding; and (iv) shared understanding can be achieved differently, such as by adherence or by collaboration.

The analyses presented in this paper were limited to three VM practices. Future work should explore many other practices, encouraging a further reflection about the theoretical and practical understanding of VM aspects. As mentioned before, the discussion about VM purposes is only one step in the serious game, which is under development. Further studies will explore conceptual models related to other VM elements, such as context understanding, requirements, and the roles of communication and collaboration. It is expected that this body of knowledge will contribute to understanding the VM in a broader way and its use in construction projects.

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REFERENCES

Van Aken, J. E. (2004). “Management research on the basis of the design paradigm: The quest for field-tested and grounded technological rules.” *Journal of Management Studies*, 41(2), 219–246.

Ballard, G., and Howell, G. (1998). “Shielding Production: Essential Step in Production Control.” *Journal of Construction Engineering and Management*, 124, 11–17.

Bernstein, E. S. (2012). “The Transparency Paradox: A Role for Privacy in Organizational Learning and Operational Control.” *Administrative Science Quarterly*, Sage Publications, 57(2), 181–216.

Brady, D. A., Tzortzopoulos, P., Rooke, J. A., Formoso, C. T., and Tezel, A. (2018). “Improving transparency in construction management: a visual planning and control model.” *Engineering, Construction and Architectural Management*, (August), ECAM-07-2017-0122.

Clarke, A., and Dawson, R. (1999). *Evaluation Research*. *International Encyclopedia of Education*, SAGE Publications Ltd, 6 Bonhill Street, London England EC2A 4PU United Kingdom.

Dallasega, P., Rauch, E., and Linder, C. (2018). “Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review.” *Computers in Industry*, Elsevier, 99(August 2017), 205–225.

Eaidgah, Y., Maki, T. A. A., Kurczewski, K., and Abdekhodaee, A. (2016). “Visual management, performance management and continuous improvement: a lean manufacturing approach.” *International Journal of Lean Six Sigma*, 7(2).

Ewenstein, B., and Whyte, J. K. (2007). “Visual representations as ‘artefacts of knowing.’” *Building Research and Information*, 35(1), 81–89.

Formoso, C. T., dos Santos, A., and Powell, J. A. (2002). “An exploratory study on the applicability of process transparency in construction sites.” *Journal of Construction Research*, 3(1), 35–54.

Galsworth, G. (1997). *Visual systems: harnessing the power of the visual workplace*. American Management Association, New York.

Greif, M. (1991). *The visual factory: building participation through shared information*. CRC Press, Portland.

Gunasekaran, A., Goyal, S. K., and Martikainen, T. (1998). “Total Quality Management : A New Perspective for Improving Quality and Productivity.” *International Journal of Quality & Reliability Management*, 15(8), 947–968.

Hirano, H. (1995). *5 Pillars of the Visual Workplace: The Sourcebook for 5S Implementation*. Productivity Press, New York.

Holmström, J., Ketokivi, M., and Hameri, A.-P. (2009). “Bridging Practice and Theory: A Design Science Approach.” *Decision Sciences*, 40(1), 65–87.

Howell, G., and Ballard, G. (1999). “Design of Construction Operations.” 1–9.

Klotz, L., Horman, M., Bi, H. H., and Bechtel, J. (2008). “The impact of process mapping on transparency.” *International Journal of Productivity and Performance Management*, 57(8), 623–636.

Koskela, L. (1992). “Application of the New Production Philosophy to Construction.” *Center for Integrated Facility Engineering*, Stanford University, Stanford.

Koskela, L. (2000). “An exploration towards a production theory and its application to construction.” *VTT Building Technology*, (L. Ukskoski, ed.), Technical Research Centre of Finland, Espoo, Finland, Finland.

Koskela, L. (2015). "Where Rhetoric and Lean Meet." *23rd Annual Conference of the International Group for Lean Construction*, O. Seppänen, V. A. González, and P. Arroyo, eds., Perth, Australia, 527–535.

Koskela, L., Tezel, A., and Tzortzopoulos, P. (2018). "Why Visual Management?" *26th Annual Conference of the International Group for Lean Construction*, Chennai, India, 250–260.

Lindlöf, L. (2014). *Visual Management – on Communication in Product Development Organizations Department of Technology Management and Economics*. Chalmers Reproservice, Gothenburg, Sweden.

Lukka, K. (2003). "The Constructive Research Approach." *Case study research in logistics*, Series B, 83–101.

Mejabi, O. O. (2003). "Framework for a lean manufacturing planning system." *International Journal of Manufacturing Technology and Management*, 5(5–6), 563–578.

Nicolini, D. (2007). "Studying visual practices in construction." *Building Research and Information*, 35(5), 576–580.

Tezel, A. (2011). "Visual management: an exploration of the concept and its implementation in construction." University of Salford.

Tezel, A., and Aziz, Z. (2017). "From Conventional to IT Based Visual Management: A Conceptual Discussion for Lean Construction." *Journal of Information Technology in Construction*, 22, 220–246.

Tezel, A., Koskela, L., and Aziz, Z. (2018). "Lean thinking in the highways construction sector: motivation, implementation and barriers." *Production Planning and Control*, Taylor & Francis, 29(3), 247–269.

Tezel, A., Koskela, L., and Tzortzopoulos, P. (2009). "The functions of visual management." *International Research Symposium*, 201–219.

Tezel, A., Koskela, L., and Tzortzopoulos, P. (2016). "Visual management in production management: a literature synthesis." *Journal of Manufacturing Technology Management*, 27(6), 766–799.

Valente, C. P., Brandalise, F. M. P., and Formoso, C. T. (2019). "Model for Devising Visual Management Systems on Construction Sites." *Journal of Construction Engineering and Management*, 145(2), 04018138-1 04018138-17.

Viana, D. D., Formoso, C. T., Wesz, J., and Tzortzopoulos, P. (2014). "The role of visual management in collaborative integrated planning and control for engineer-to-order building systems." *22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway, 775–786.

Trentin, B. T. and Etges, B. M. B. S. (2021). "Lean Construction and Organizational Knowledge Creation." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 299–308, doi.org/10.24928/2021/0149, online at iglc.net.

LEAN CONSTRUCTION AND ORGANIZATIONAL KNOWLEDGE CREATION

Bianca T. Trentin[1] and Bernardo M. B. S. Etges[2]

ABSTRACT

It is essential for the construction industry to continuously create new knowledge, aiming at innovation and maintaining competitiveness. As for Lean Construction in addition to improving construction processes, the characteristic inherent in its implementation is that of creating collaborative, interdisciplinary moments with a high level of information sharing, which shows the great potential of the methodology for the creation of knowledge. This article sets out to analyze how people participating in Lean Construction implementation projects see the potential of Lean Construction for creating knowledge. To do so, in addition to a thorough review of the literature on the subject, the results of a form-based survey conducted with six Brazilian construction companies, partners of a consultancy company, are presented. The results show that everyone surveyed agrees that Lean Construction increases the sharing of information between people, the creation of improvement actions for projects, and finally, knowledge creation for the company. This perception is sharper in people who occupy management positions than in those in operational positions. Also, the present study concludes that the most effective way to generate organizational knowledge in Lean Construction implementation projects is to combine tools, methods and training that make use of both tacit and explicit knowledge.

KEYWORDS

Lean construction, tacit knowledge, explicit knowledge, learning, knowledge creation.

INTRODUCTION

It is widely recognized that in order to remain competitive in the market and grow sustainably, companies need to constantly create new knowledge, and thus to accompany the rapid changes in technology, markets and society today. However, there is still little understanding of how organizations create, maintain and exploit knowledge dynamically (Nonaka, Toyama and Konno 2000).

The construction industry is positioned as one of the branches of industry which has least advanced in technology and productivity gains, and knowledge is one of the essential assets for companies that strive to position themselves competitively with regard to innovation and value creation (Nonaka et al. 2014; Zhang and Chen 2016). One of the factors that contribute to this advance in promoting knowledge is the procedural view of

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production activities. Thus, implementing lean construction depends largely on organizational learning and knowledge creation. According to Zhang and Chen (2016), applying Lean can even improve the factors related to this organizational learning.

What this means is that Lean Construction is not just about learning to use tools and applying them. In reality, its essence is to create a collaborative environment between those involved in the enterprise, thereby creating moments of discussion and interaction, generating solutions, learning and creating opportunities for innovation. And what would all that be about, if not a way to create, maintain and explore knowledge dynamically? (Christensen and Christensen 2010; Skinnarland and Yndesdal 2012)

This article sets out to analyze the understanding of knowledge creation during the implementation phases of Lean Construction. Such analysis is performed based on the understanding of team members who were members of teams that implemented the methodology and tools of Lean Construction.

There is already a rich bibliography for this field of study which has been developed by academics and researchers with extensive experience in the subject and is presented in the review of the literature. However, the theme of Lean Construction is still incipient in Brazil, being mainly concentrated in consultancies and large companies. The perception of construction professionals about the results of implementing Lean Construction in Brazilian projects has hitherto been little explored in Brazil. Seeking to fill this gap, the authors conducted a survey of 6 Brazilian companies, which were undergoing stages of implementing Lean Construction and Operational Excellence in partnership with a Consulting company. The aim of the research with these six cases was to identify the participants' perception of the knowledge generated in the projects, by exploring in-depth the distinction between explicit and tacit knowledge during the implementation of Lean Construction. Moreover, these perceptions were discretized by the function and hierarchical level occupied by the respondents of the survey (operational and leadership level). From this, the main findings, the limitations of the study and issues for future research are presented.

REVIEW OF THE LITERATURE

LEARNING AND KNOWLEDGE

An organization that learns is like a process that evolves over time. In other words, it is an organization with the skills to create, acquire and transfer knowledge (Garvin 2000). Organizational learning requires individual and collective learning (Moland 2007), and it is only when people learn together effectively that organizations can change (Senge and Scharmer 2006).

The knowledge existing within an organization can be exploited when dealing with problems, thus deepening, defining and developing its own solutions (Tyagi et al. 2014). During this problem-solving exercise, teams not only take actions to find solutions, but also acquire dynamic knowledge on an ongoing basis. Organizations cannot be treated as machines that process information, but as entities that create knowledge through action and people interaction (Nonaka, Toyama and Konno 2000).

Nonaka (1994) offers a dynamic learning theory that shows a connection between the concepts of teamwork, creativity and innovation. He explains how knowledge can become available to other people by means of collaborative activities. In addition, he explains how teamwork and creativity help to test and develop knowledge (Nonaka 1994).

His theory shows how learning occurs in collaboration with other people, especially when the knowledge and experience that they have are different.

TACIT KNOWLEDGE AND EXPLICIT KNOWLEDGE

Knowledge is divided into two categories: explicit knowledge and tacit knowledge (Nonaka et al. 2014). Explicit knowledge is encoded and stored in formal language and shared in the form of data, figures, specifications, manuals, etc. so that it can be easily transferred between individuals in the organization. On the other hand, tacit knowledge is difficult to transmit and encode. It is subjective and deeply rooted in an individual's actions, attitudes, commitments, ideals, values and emotions (Zhang and Chen 2016)

The effective transfer of tacit knowledge requires personal contact, regular interaction and trust by means of sharing experiences and imitation. Many researchers consider tacit knowledge to be a source of competitive advantage and consider it more conducive to organizational innovation. This is mainly because tacit knowledge is developed based on a company's human resources in relation to the intellect, skills and experience of its employees, which are difficult to imitate, difficult to replace and can create value. However, tacit knowledge will quickly lose its meaning without the basis and support of explicit knowledge (Nonaka, Toyama and Konno 2015; Tyagi et al. 2015; Zhang and Chen, 2016).

An organization creates knowledge by exploiting the interactions between explicit knowledge and tacit knowledge. Their interaction is called 'knowledge conversion' (Nonaka et al. 2014). By using the conversion process, tacit and explicit knowledge expands in quality and quantity. This is a dynamic, continuous and self-transcending process (Nonaka, Toyama and Konno 2015; Zhang and Chen 2016). A four-stage spiral model abbreviated as SECI (Socialization, Externalization, Combination and Internalization) modes was built to represent this conversion process (Nonaka 1994; Nonaka and Takeuchi 1995).

LEAN CONSTRUCTION AND THE CREATION OF KNOWLEDGE

Lean construction aims to manage and improve construction processes at minimum cost and maximum value while considering the needs of the customer (Zhang and Chen 2016). To make the link between the knowledge creation process and Lean Construction, we draw attention to results from important and relevant studies on the topic.

The study by Zhang and Chen (2016) analyzes the tools and techniques of lean construction individually, in a quantitative way, thereby creating relationships with their effectiveness at creating knowledge. This helps to understand why tools have an important role in the construction industry. Their study finds a consequence relationship between (a) applying tools; (b) creating efficient knowledge; (c) increasing innovation in construction companies; (d) eliminating waste; and (e) maintaining competitiveness. (Zhang and Chen 2016)

The paper by Tyagi et al. (2015) also incorporates an analysis of the context of knowledge creation. Their work presents a set of ten lean construction tools and methods that have been proven to assist in the process of knowledge creation, generating context so that dynamic knowledge and innovation may take place in companies. The authors evaluate the set of lean constructions tools by using a model that involves the interplay between tacit and explicit knowledge in a "ba" context to generate knowledge during the four SECI modes and to update the knowledge assets. According to the authors, a great gain from implementing methods and tools is that expensive rework is reduced at sites because since knowledge has been created at the right time and in the right place, future projects start from a higher level of excellence, in which the culture developed sees to it that the right decisions are taken faster and the quality of the products and processes is improved (Tyagi et al. 2015).

Christensen and Christensen (2010) examine the hypothesis that Lean Construction is a tool for interdisciplinary learning and can be used to benefit organizations, not just projects. By interpreting a theoretical framework and carrying out a case study, they validate the hypothesis and conclude that cooperation between different professions and the sharing of plans lead to the sharing of learning and understanding of the construction processes of the project as a whole (Christensen and Christensen 2010).

Pasquire and Court (2013) present a model in which they propose that the formation of knowledge is a productive process within construction projects. The generation of common sense about knowledge represents a significant step towards eliminating waste in the design and delivery of construction projects (Pasquire and Court 2013).

Nevertheless, Skinnarland and Yndesdal (2012) validated the hypothesis that the Last Planner® System[3] can contribute to the process of creating knowledge in construction projects. However, they emphasize that there are premises for the success of the process, such as leadership skills and management of the leaders involved. It is imperative to establish an atmosphere within the project that builds trust, collaboration and a safe environment in terms of reporting errors and delays to people in the group. The Last Planner® System fulfills this integrating function and requires the team involved to be willing to change, based on joint reflection, by communicating and sharing new knowledge, in addition to the team's acting on explicit knowledge obtained (Skinnarland and Yndesdal 2012).

METHODOLOGY

This article was built from a qualitative survey by applying a questionnaire designed to understand the perception of the sample of participants in Lean implementation projects in Brazil about how Lean Construction contributes to creating knowledge.

The survey was applied to clients of a Brazilian Consulting Company, in which the authors of the article are members. The survey was applied to a sample of 29 respondents, from 6 different companies (2 developers and construction companies of residential buildings, 2 construction companies in the renewable energy sector, 1 construction company for industrial and commercial works and 1 energy generation and transmission company) who were actively participating in Lean Construction implementation projects that were being undertaken in partnership with the Consultancy Company. The six projects went through stages of implementing the Last Planner® System cycle, approaches to improving operations by using Kaizen and formal training. The 29 respondents were selected based on their involvement in the projects and on the positions they occupied in the companies. The research sought to have a complete and heterogeneous sample within each project.

The limited number of projects and respondents in the sample analyzed may be regarded as a limitation of the study. However, the aim of the sample is to guide understanding about knowledge creation as a result of implementing Lean Construction in the process of generating value for organizations. Moreover, from the answers obtained,

[3] "Planning methodology broadcast when implementing Lean Construction" (Ballard and Howell 1997)

graphic analyses and cross-analyses of the perceptions versus profile of the respondents could be generated, which underpinned the discussion on the topic.

The 8 questions of the survey were aimed at creating an understanding of the respondents' perception of collaboration issues, problem solving and knowledge creation in the Lean Construction projects in which they have participated. The survey can be accessed through the link: https://forms.gle/Ka4rTUbiAnvUPxVG66.

From the literature review and because of the collaborative approach promoted by the Consultancy Company in the Projects under analysis, the authors assumed that the application of Lean Construction Tools would generate an environment for sharing tacit knowledge, due to its moments of collaboration and practice, and due to the moments of acquiring skills and training and, above all, they would share explicit knowledge, for making use of data, methods and formal language. Thus, the survey sought to identify in the end what the respondents perceived as to what added the greatest value for creating knowledge for people, the project and the organization: explicit knowledge, tacit knowledge, or a combination of the two.

RESULTS

In all six companies that participated in the survey, both the practical application of Lean Construction tools, as well as formal skills training and general training on Lean Construction and Operational Excellence had taken place. In addition, in all six companies, these moments involved the participation and collaboration of people at the operational and management levels. Table 1 shows the Implementation phases included in each of the companies and the length of the time of involvement and knowledge transfer between the Consultants and the Team from the companies.

Table 1: LC tools implemented in the companies analyzed

	LC Implementation time	Application of Lean Construction Tools					Formal Skills Training	
		Line Of Balance (LOB)	Kaizen	MFV	Look Ahead	Check-in/Check-out	Training Operational Excellence	Training in LC concepts
Company 1	8 months	x	x	x	x	x	x	x
Company 2	7 months	x	x	x	x	x	x	x
Company 3	3 months		x	x	x	x	x	x
Company 4	2 months	x			x	x		x
Company 5	20 months				x	x	x	x
Company 6	5 months	x		x	x	x	x	x

It is pointed out that of the respondents, 25% hold management positions (Coordinator, Manager and Director) and 75% hold operational positions (Engineer, Analyst, Technician, Intern, Architect, Supervisor / Master of Works, Supervisor).

All 26 respondents of the survey showed that they believe that, at least at some point during the course of the projects in their companies, implementing Lean Construction tools led naturally to (1) sharing information, (2) improvement actions for projects being created, and finally, (3) to creating knowledge for the company. According to Nonaka (1994), in order for knowledge to be developed, creative chaos is necessary. This means an abundance of information, the variation of specific pieces of knowledge and collaboration. The results indicate that implementing Lean Construction tools serves as support for the creation of this abundance of information and for creativity.

More specifically, looking only at question (1) information sharing was accentuated positively due to implementing Lean Construction tools, and we can see that there is a greater degree of sharing at the project management level than at the operational level. The results for this question are positive and are shown in Figure 1. At the project management level, 86% of respondents believe that implementing Lean Construction tools always favors the greatest and best information sharing.

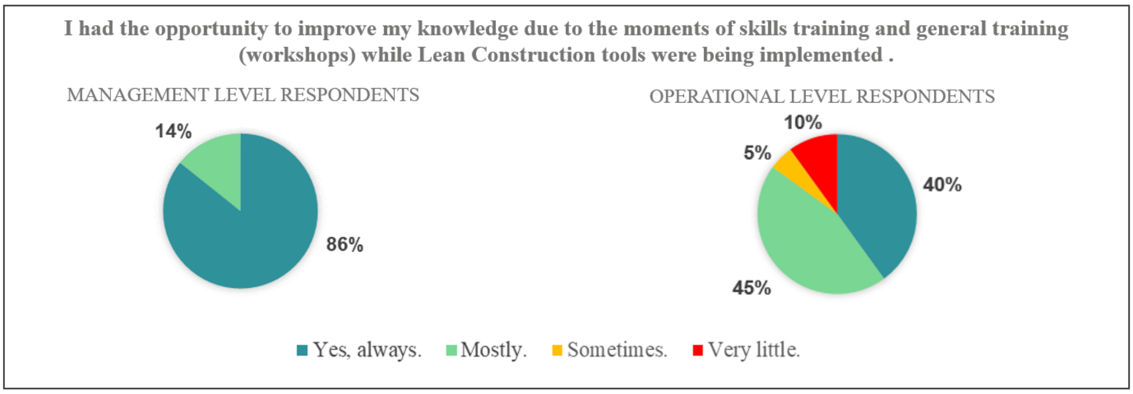

Figure 1: Answers to Question 1 of the survey

Regarding the contribution to (2) creating improvement and problem-solving actions for the project, 84.9% of the respondents identified that, in most cases of implementing Lean Construction tools, this aspect is favored. Once again, the results at the management level are more favorable than at the operational level, where 86% of respondents at the management level believe that, whenever the implementation of Lean tools occurred, improvement actions were generated, as opposed to 15% of respondents at the operational level who gave the same answer. Figure 2 illustrates the distribution with regard to generating improvement and problem-solving actions.

Figure 2: Answers to Question 2 of the survey

After having analyzed the results from (3) creating knowledge for the company, due to the collaboration and proximity created between people when implementing Lean Construction tools, the results found are equally positive, with the constant of being even more positive in the management positions of the project than at the operational level. It is highlighted in Figure 3, that, in this regard, even at the operational level, 90% of respondents believe that, in most implementations, knowledge was generated for the company.

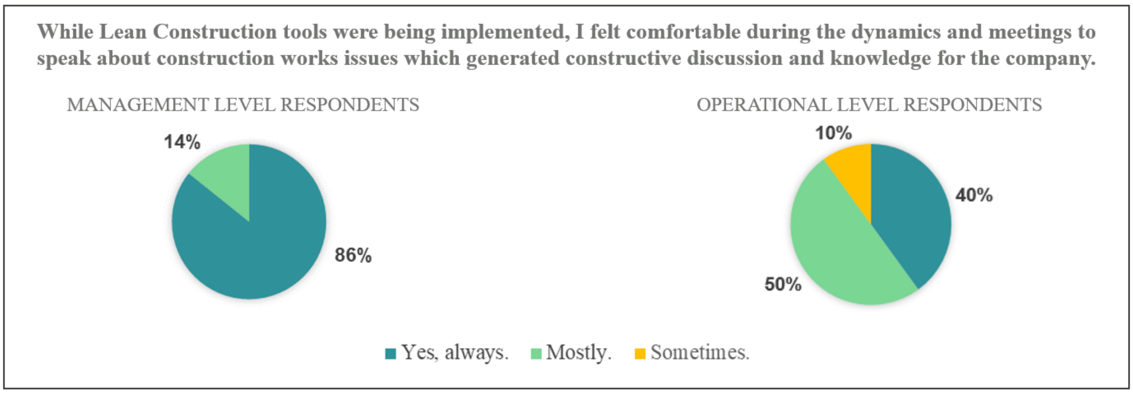

Figure 3: Answers to Question 3 of the survey

Analyzing the results of questions 1, 2 and 3, specifically the constant fact that the results are more positive at the management level than at the operational level, raises the question of how secure people at the lowest levels of the organizational hierarchy feel about speaking up at daily meetings, when Lean Construction tools are being applied and in training moments. Even though the results show that Lean allows an environment of dialogue and collaboration, it is still necessary to achieve a greater degree of maturity, with a view to taking action to reduce the defense mechanisms of employees and creating an atmosphere of learning and trust, so that no one is afraid they will be attacked or criticized (Skinnarland and Yndesdal 2014).

Nevertheless, the research sought to understand the respondents' point of view in relation to tacit and explicit knowledge. Although explicit knowledge, generated through formal training, has extremely expressive returns, tacit knowledge emerges as a great aggregator of results in the work environment: 85.2% of respondents identified that in most cases of formal skills training and general training on Lean Construction, their knowledge was improved, which allows us to infer that in these cases there was transfer and generation of explicit knowledge; and 92.6% of the respondents identified that in most cases of the practical application of the Lean Construction tools their knowledge was improved, which enables it to be inferred that in these cases there was a transfer and generation of tacit knowledge.

For Nonaka (1994) and Polanyi (1966), organizational learning occurs in the interaction between tacit and explicit knowledge, when the individual's tacit knowledge is made available, tested and transformed into practical use. On the other hand, explicit knowledge is codified and articulated, during which it can be captured, communicated, stored and promptly transmitted to other people. The results of the research in this article support what the aforementioned authors argued. When asked, 81.5% of respondents considered that the best way to generate knowledge is to combine explicit knowledge (workshops, training) with tacit knowledge (practical application of the tools), and not to use only one of them in isolation.

The fact that the study is based on a qualitative approach that was applied to 6 companies and 29 respondents is emphasized. This is a limitation with regard to validating the theories presented. Moreover, the authors' inferences that the moments of formal training/ workshops generate explicit knowledge and that the application of the tools generates tacit knowledge were carried out based on the literature review and on the collaborative character of the ongoing projects, which opens space for new validation studies.

CONCLUSIONS

This article has met its main objective by providing a broad and thorough discussion about the creation of knowledge in Lean Construction projects. The literature review together with the data collected by applying the questionnaire to the 6 companies that were focused on in this paper underpinned the basis for stating that tacit knowledge and explicit knowledge, on acting together, enable those involved in the Lean Construction Implementation process to perceive more clearly the value of knowledge development.

Christensen and Christensen (2010) Zhang and Chen (2016), Tyagi et al. (2015) and Skinnarland and Yndesdal (2012) have already attested in a similar way that Lean Construction implementation projects have great potential for generating knowledge due to their characteristic of creating interdisciplinary and collaborative learning, as their tools require the cooperation of different professionals, the sharing of plans between sectors and an understanding of construction processes as a whole.

In a complementary way, the present study concludes that the most effective way to generate organizational knowledge in Lean Construction implementation projects is to combine tools, methods and training that involve both tacit knowledge and explicit knowledge since 81.5% of the answers favor the use of the two methodologies combined. During the implementation of Lean Construction tools, the tools and methodologies provide support for the transformation of tacit knowledge into explicit knowledge in an infinite spiral (Tyagi et al. 2015), and this is perceived by the respondents. 85.2% of respondents identified that in most cases of skills training and general training on Lean Construction, their knowledge was improved, which enables it to be inferred that, in these cases, explicit knowledge was transferred and generated; and 92.6% of the respondents identified that in most cases, when Lean Construction tools were applied in practice, their knowledge was improved, which enables it to be inferred that, in these cases, tacit knowledge was transferred as was the generation of tacit knowledge. As mentioned before, although explicit knowledge, generated through formal training, has extremely expressive returns, tacit knowledge emerges as a great aggregator of results in the work environment. This research conclusion is important when analyzed in conjunction with the theory that tacit knowledge will quickly lose its meaning without the basis and support of explicit knowledge (Nonaka, Toyama and Konno 2015; Tyagi et al. 2015; Zhang and Chen, 2016).

One point observed was the variation between people in management and operational functions in the perception of knowledge generation and the formation of a collaborative environment. Therefore, it is suggested that future studies specifically verify if there are knowledge generation biases in each audience.

Although the study presents the limitation of having only 29 respondents for qualitative research, this point raised from the survey has great potential. Efforts should be made to deepen the practical use and understanding of models in order to foster operational teams to have greater confidence and involvement in the knowledge building routines by means of Lean Construction.

Still on future studies, two more points are suggested. The first is based on the fact that the sample analyzed consists entirely of Brazilian companies and participants, so future studies could replicate this research in other countries with different contexts and levels of Lean Construction maturity. The second suggestion concerns the individual analysis of each Lean Construction tool applied to the projects, regarding their characteristics of knowledge generation due to the interaction between tacit and explicit knowledge in SECI process, as presented by Tyagi et al. (2015), which analyzes different LC tools with a similar approach.

Finally, it is emphasized that it cannot be concluded from the research that creating efficient knowledge can increase innovation in construction companies, thereby solving issues, eliminating waste and maintaining competitiveness, as mentioned by Zhang and Chen (2016). Thus, it is also suggested that future studies should analyze the question: how does the knowledge generated by implementing Lean Construction promote innovation, competitiveness and the elimination of waste?

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REFERENCES

Ballard, G., and Howell, G. 1997. "Implementing lean construction: stabilizing work flow." *IGLC*, 101-110.

Christensen, R. M.; Christensen, T. N. 2010. "Lean construction facilitates learning on all organisational levels? Challenging Lean Construction Thinking: What Do We Think and What Do We Know?" - *18th Annual Conference of the International Group for Lean Construction, IGLC* 18, n. July, p. 406–414.

Garvin, D.A. 2000. "Learning in action: A guide to putting the learning organization to work". *Harvard Business Press*.

Moland, L. (2007). "Flink med folk i norske kommuner." *Fafo*, Oslo, Norway

Nonaka, I. (1994). "A dynamic theory of organizational knowledge creation." *O Organization Science*, 14-37

Nonaka, I. et al. 2014. "Dynamic fractal organizations for promoting knowledge-based transformation - A new paradigm for organizational theory". *European Management Journal*, v. 32, n. 1, p. 137–146.

Nonaka, I., and Takeuchi, H. 1995. "The knowledge-creating company: How Japanese companies create the dynamics of innovation". *Oxford Univ. Press*, USA.

Nonaka, I.; Toyama, R.; Konno, N. 2000. "SECI, Ba and Leadership: A Unified Model of Dynamic Knowledge Creation". *Long Range Planning*, v. 33, n. 1, p. 5–34.

Pasquire, C.; Court, P. 2013. "An exploration of knowledge and understanding - The eighth flow". *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*, p. 944–953, 2013.

Polanyi, M. 1966. *The Tacit Dimension*. UK: Routledge and Kegan.

Koskela, L. 2000. "An exploration towards a production theory and its application to construction". PhD Thesis, University of Technology, Espoo, Finland.

Senge, P.M., and Scharmer, C.O. 2006. "Community action research: Learning as a community of practitioners, consultants and researchers." Handbook of Action Research: Concise Paperback Edition, 195-206.

Skinnarland, S.; Yndesdal, S. 2014. "Barriers to a Continuous Learning". *Proc. 22th Ann. Conf. of the Int'l. Group for Lean Construction*. Group for Lean Construction, p. 1191–1201.

Skinnarland, S.; Yndesdal, S. 2012. "The last planner system as a driver for knowledge creation". *IGLC 2012 - 20th Conference of the International Group for Lean Construction*.

Tyagi, S. et al. 2015. "Lean tools and methods to support efficient knowledge creation". *International Journal of Information Management*, v. 35, n. 2, p. 204–214.

Zhang, L.; Chen, X. 2016. "Role of Lean Tools in Supporting Knowledge Creation and Performance in Lean Construction". *Procedia Engineering*, v. 145, p. 1267–1274.

Obulam, R. and Rybkowski, Z. K. (2021). "Development and testing of the 5S puzzle game" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 309–319, doi.org/10.24928/2021/0152, online at iglc.net.

DEVELOPMENT AND TESTING OF THE 5S PUZZLE GAME

Rajeswari Obulam[1] and Zofia K. Rybkowski[2]

ABSTRACT

Lean methods were originally developed in the manufacturing industry in the early 20th century to reduce the use of resources that did not contribute to added value. In the 1990's, there was steady growth in a movement to replicate the successes of manufacturing in the construction industry. By effectively deploying lean methods on the construction site, material and human labor that was expended with no increase in the value of the constructed work can either be reduced or reapplied to increase value.

The 5S methodology was originally developed in Japan and implemented by Toyota. The 5S system is a type of visual management tool used to handle and maintain workplace organization and efficiency. The 5S method has been adopted by lean thought leaders to improve productivity by more rigorously organizing the workplace via five sequential steps: sort, set in order, shine, standardize, and sustain.

Inspired by a popular participatory simulation to introduce players to 5S, this "5S Puzzle game" simulation was created to present the topic in a way that is more aligned with the way construction companies practice. This simulation was developed to be administered on-line in either of two ways: (1) with a single individual, or (2) with up to 4 players. The puzzle session consists of five rounds, each representing one of the S's that help a player progress from low levels of efficiency to maximally efficient processes. The stated goal of the simulation is to complete the puzzle. The actual goal is to help players experience an "aha" moment by quantifying the impact of each successive step as the player(s) progress through each round.

KEYWORDS

Construction sector, serious game, simulation, 5S, continuous improvement.

INTRODUCTION

Lean principles have been practiced in manufacturing in Japan because of observed results in enhanced performance; time to completion, cost, quality, safety, and employee morale have been shown to improve.

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According to Womack and Jones (2003), the principles of Lean production can be summarized in the following manner:

- Specify the product's value;
- Identify the value stream;
- Create uninterrupted flow in the value stream;
- Pull to consumer demand; and
- Target perfection.

Lean thought has seeded the development of successful tools for organizations to overcome unpredictability which is present in various stages of projects in the industrial sector, especially when resources are restricted (Shah and Ward 2007). This has motivated other sectors to implement lean practices (Ohno, 1988).

Lean philosophy embraces continuous improvement. 5S methods are considered to be one of the essential pre-requisites for implementing lean and can act as an important tool to improve an organization by reducing waste and optimizing costs (Lake 2008). Rich et al. (2006) describe 5S as a visual management tool of lean implementation.

5S represents five main principles which phonetically begin with "S." The first "S" stands for *Seiri,* which means to *sort* by removing unnecessary elements; the second represents *Seito*, or to *set in order* by organizing all the elements based on their function; the third represents *Seiso*, shine or clean by removing sources of dirt; the fourth represents *Seiketsu*, or *standardize* by "freezing" a system; and finally the fifth "S" *Shitsuke*, refers to *sustain* to ensure the system is maintained (Osada 1991; Table 1).

Table 1: Explanation of 5S

Japanese words	English translation	Meaning
Seiri	Sort	Sort through all items and remove unnecessary items.
Seiton	Set in order	Place all items in an optimal position.
Seisō	Shine	Clean the workplace and all relevant materials on a regular basis.
Seiketsu	Standardize	Standardize the processes used to sort, order and shine.
Shitsuke	Sustain	Ensure that the progress is maintained.

It has been observed that number of companies prefer to start with 5S as an entry point to lean to offer an "easy win" (Anderson and Mitchell, 2005). A case study where the 5S method was implemented led to impressive improvements in a pharmaceutical plant. For example, mistakes made when picking up items for reuse were significantly reduced when dedicated transport carts were used. A template was created to indicate where specific parts should be stored (Bevilacqua et al. 2015).

Other case studies concluded that 5S, when applied to healthcare services and small-scale industries resulted in cleaner, more organized workplaces with increased safety and productivity, decreased inventory, supply costs and overhead costs (Young 2014; Khedkar et al. 2012).

This paper documents the development and testing of a new simulation to familiarize employees with the 5S method. The objective behind developing this simulation was to build up a simple yet scalable game that would empower a facilitator to lead a group of participants to instinctively understand the advantages of lean because of the progress achieved during the simulation. In this simulation, principles of 5S are used to achieve the target condition by slowly reducing waste and creating an sample template that helps maximize efficiency and productivity.

Although simulations have existed for some time, their application as a mode for training has not been fully explored. Simulations act as a visual tool to assist in decision-making and to help participants understand learning outcomes. In a typical lean simulation, participants are introduced to a challenge and invited to tackle it given a set of specified constraints (Rybkowski et al. 2020). Multi-player simulations also allow teammates to collaborate and communicate with other players.

The development of interactive, visual, computerized technology has contributed to the popularity of simulations by rendering them more realistic, relatable and interactive (Gouveia 2011). Arguably, the most effective teaching methods are those that encourage learners to objectively practice and to reflect (Bransford et al. 2003). Outcomes from some research suggest that using computer simulations may be a more effective way to teach than traditional forms (Cassidy 2003, Sacks et el 2007, Tommelein et el 1999 and Visionary Products Inc. 2008).

A 5S instructional simulation already exists and is widely played by lean educators (Figure 1) sequentially demonstrating the principles of continuous improvement through 5S (Super teams n.d.). It has since been adopted by those who teach lean construction as well. Despite the game's increasing popularity, a few gaps were found in the simulation and its design if transitioned to an on-line format—e.g. inability of players to visualize progress if played online/virtually, frustration in locating numbers of smaller font, and perhaps most importantly, difficulty in relating 5S to applications for those working in the construction sector. The purpose of developing and testing a new "puzzle" format of this simulation was to fill these gaps.

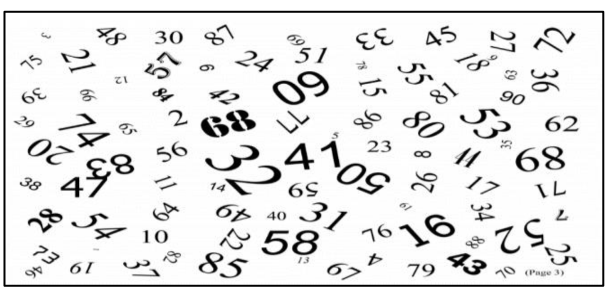

Figure 1. Reprinted from Super Teams 5S Game Handout.

METHODOLOGY

The 5S puzzle simulation presents five sequential steps of continuous improvement from a current state (worst-case scenario) to a target (ideal) state. The puzzle pieces were created using the website (TheJigsawPuzzles.com n.d.) where the depicted scene on the puzzle was purposely selected, under a creative commons license, to represent a scene from the built environment (Ratcliff). Reported results are from a first-run study with graduate students from an introductory on-line lean construction course in the Spring of 2021 of 40 students where 3 individuals volunteered to play and 37 to observe and complete feedback forms. The semester-long course was administered on-line via Zoom™ due to COVID-19 and the simulation was facilitated using editable Google Slides™, while observers gave feedback via a link to a Google Form™ provided in the Zoom chat. Observers watched player performance using the "share screen" function of Zoom. Participants were informed at the start of play that the objective was to complete the puzzle as quickly as possible. The facilitation process is described in the following sections.

DESCRIPTION OF THE SIMULATION

A brief slideshow was presented comprising the rules before the simulation begins and questions from participants were clarified. Guidelines for the game were as follows:

- Each team has four players: three will assemble the puzzle and one will keep time;
- During a single round, each player is given 30 seconds to complete the puzzle as much as s/he can before passing on to the next player to take over, for a total of 1 minute 30 seconds;
- Players are instructed to not resize, rotate, or delete the pieces;
- There is to be no verbal communication between team members;
- There will be a brief discussion after each round.

FLOW OF THE SIMULATION

The simulation was facilitated using the following schedule and the sequence is as mentioned in Table 2:

Table 2: Flow of simulation and time taken.

Interval	Time (Minutes)	Description
1	10	Briefing
2	3	Game demonstration
3	1.5	*Round 1:* Simulation about the current condition.
4	1	Evaluation form for round 1
5	1.5	*Round 2:* Simulation with waste/unwanted materials removed from site.
6	1	Evaluation form for round 2
7	1.5	*Round 3:* Simulation with a template.
8	1	Evaluation form for round 3
9	1.5	*Round 4:* Simulation with a template containing the image and the materials arranged.
10	1	Evaluation form for round 4
11	1.5	*Round 5:* Simulation at target condition.
12	1	Final Evaluation form
13	10	Final explanation and Q&A
	35.5	Total time required (minimum)

SIMULATION SEQUENCE

Round 1 exemplified a worst-case scenario with the presence of unwanted materials on a construction site, as well as a complete lack of organization. It was observed that players tended to try to complete the puzzle by searching for relevant puzzle pieces scattered among unwanted pieces; they typically separated them, and then placed them in what they perceived to be their correct positions within their given 30 seconds. The game was completed when each of the three players sequentially had a chance to play and a total time of one minute thirty seconds was reached. A screenshot of the 5S Puzzle simulation during Round 1 is shown in Figure 2. The number of correctly joined puzzle pieces was recorded at the end of each round after time is up.

The players were not permitted to verbally communicate or help one other in any way. This round has typically been shown to be the least efficient in terms of performance and was purposely designed to frustrate players by the inclusion of unwanted pieces in disarray. These conditions resulted in players considering ways to improve efficiency and productivity in the limited time. In this trial first-run-study, players were on average able to fit 7 pieces out of 20 correctly.

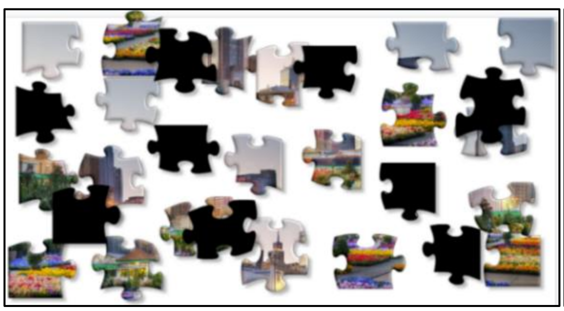

Figure 2: Round 1 of the 5S puzzle game.

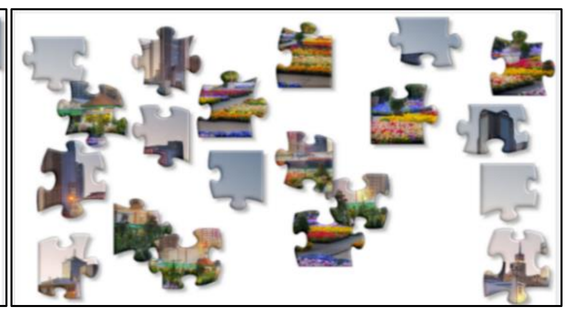

Figure 3: Round 2 of the 5S puzzle game.

During round 2 (Figure 3), players proceeded to a modified slide where *sorting* had already been completed, and waste/unwanted (black pieces) materials had been removed (improved site conditions). This revised gameboard represented a more orderly workspace where only relevant materials were included. In the experimental trial, players improved their performance by fitting on average 12 pieces out of 20 correctly. This is 5 more correct placements than during Round 1.

Round 3 (Figure 4) built upon improvements previously made; however, a template was also introduced. The template gave players an idea of the size of the puzzle and acted as a guide for the precise positioning of each piece. During Round 3 of the experimental trial, players were able to improve upon their performance of previous rounds, fitting 16 pieces out of 20 correctly—4 more than during Round 2. This round represents the second "S"—*set in order*.

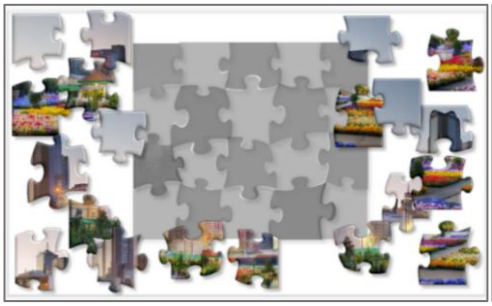

Figure 4: Round 3 of the 5S puzzle game.

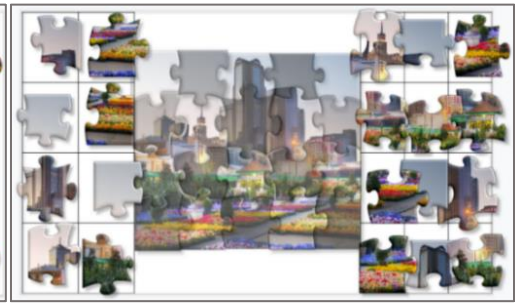

Figure 5: Round 4 of the 5S puzzle game.

During Round 4, to improve upon the immediately previous performance, the same template now included a superimposed watermark of the puzzle image (Figure 5). A table was created on either side of the template and all the pieces were displayed in the table—although out of order. In this round the players were able to fit 17 pieces out of 20 correctly. The intent of this round was to help quantify impacts of the third “S”— *shine*.

In the final round, the side tables had been additionally numbered, as was the template, and all the pieces were arranged and placed methodologically and in order within the side tables (Figure 6). This appeared to significantly increase the players’ ease in finding pieces and completing the puzzle. This was the most efficient round, as the players were able to fit all the pieces of the puzzle correctly within the first 30-seconds of the game.

Figure 6: Round 5 of the 5S puzzle game.

EVALUATION AND RESULTS

Participants of this primary first run study included a group of 40 graduate students taking an on-line Lean Construction course using Zoom. The simulation was played using editable Google Slides. Before the simulation began the students were shown a brief presentation explaining the rules of the game. The facilitator enlisted the help of three volunteers who moved the puzzle pieces during each timed round, while the rest of the class observed using the “screen share” function of Zoom. Observers were sent a link in the Zoom chat box to an on-line random number generator so researchers could link participant comments between rounds while maintaining participant anonymity. At the end of each round observers were sent links to an evaluation form using Google Forms and asked to complete the forms anonymously by consistently inputting the same random number that was personally generated by them at the start of the game.

The full set of questions asked in the evaluation form at end of each round were:

- Please enter the three-digit number you got at the random number generator.
- What appeared to get in the way of achieving a higher score?
- How do you feel about the score?

Participants were asked to input the same random number in each successive evaluation form and the number was only known to the participant. All responses were collected and tabulated in a spreadsheet. The questions in the evaluation form were chosen to assess whether the game was intuitive and helped participants understand the 5S method. At the end of play, observers were then introduced to the 5S numbers game by Superteams (n.d.). Since the 5S Numbers game already existed and was being widely played by educators and consultants in the lean construction community, the purpose of facilitating the 5S Numbers Games as well with the same participants was to determine whether or not it made sense to continue developing and improving the new “puzzle” version of the simulation.

Therefore, in the final evaluation form, participants were asked two additional questions:

- In what ways was the PUZZLE GAME especially helpful in illustrating 5S?
- In what ways was the NUMBERS GAME especially helpful in illustrating 5S?
- If you could recommend only one game for further development, which one would it be? (choose one):→5S Puzzle Game →5S Number Game

All the evaluation forms were collected anonymously, and the data tabulated in a spreadsheet for later analysis (Appendix).

The number of puzzle pieces that were correctly placed at end of each round was recorded to determine the efficiency and productivity rate in each round. The percentage of the puzzle completed was calculated by dividing the number of puzzle pieces placed correctly by the total number of puzzle pieces. This helped quantify the impact of each intervention as the game progressed. The data collected during the trial with the graduate students is shown in Table 2.

Eighty five percent (85%) of observer respondents agreed that the game demonstrated positive learning outcomes (Table 3). This suggests that the simulation creates an environment corresponding to its intended goal. They also agreed that the game allowed them to better understand the 5S method as applied to construction. This may be in part, because the *5S Numbers Game* requires participants to cross out numbers, while the 5S puzzle game more accurately replicates the process of active movement of objects required on an actual construction job site.

After completing the questionnaires, participants also gave verbal feedback. During a debrief, the facilitator engaged players in discussion about the logic of the ordering of the 5S’s to minimize wasted labor; for example, the facilitator explained why *sort* should come before *set-in-order*; and *set-in-order* before *shine, etc.* Participants were also shown before and after photographs of 5S as applied to actual construction processes.

At a minimum, the simulation may take between 20 to 35 minutes to play with an additional 10 minutes at the beginning of the game for explanation of rules. Realistically, however, facilitators should allocate at least 90 minutes to include feedback and discussion.

Table 3: Percentage completion/ efficiency as the rounds progress

Round #	Total number of puzzle pieces placed correctly (out of 20)	Percentage completion/ efficiency of the round
1	7	35%
2	12	60%
3	16	80%
4	17	85%
5	20	100%

Table 4: Evaluation of the 5S puzzle game versus the 5S number game

Name of simulation	Total number of volunteers selecting the simulation	Percentage of volunteers selecting the simulation
5S puzzle game	34/40	85%
5S number game	6/40	15%

LIMITATIONS

One limitation of this simulation as played was that the sequential process meant participants also learned the intended location of various puzzle pieces, meaning a learning curve was likely also responsible for the improved performance. It is recommended that future experiments be conducted where different teams play only one step and results are aggregated. Also, this was a first run-study; more definitive tests need to be conducted on a statistically significant sample size.

CONCLUSION

This paper reports on the development and testing of a new on-line simulation with the primary goal of developing an understanding by participants of the principles of 5S. It represents a perceived improvement, based on preliminary data, on the 5S Numbers game, which is becoming increasingly popular with lean construction educators.

According to our first-run study, this simulation (the 5S Puzzle game) appears to overcome the limitations sometimes observed in the 5S Numbers game by providing a board on which pieces are actively moved. The original contribution of this research is that it demonstrates that creating pieces that move make it easier for those learning 5S to make the mental link between 5S principles and their manifestation on an actual job site. Additional experimentation is necessary to eliminate improvements likely caused by learning curve in addition to the 5S interventions.

REFERENCES

Anderson, S. and Mitchell, P. (2005), "What is 5S really all about?", a white paper, Kaizen Solutions Inc. Accessed February 25, 2020. www.kaizenimprovement.ca.

Bevilacqua, M., Ciarapica, F. E., De Sanctis, I., Mazzuto, G., and Paciarotti, C. (2015). "A changeover time reduction through an integration of lean practices: a case study from pharmaceutical sector". Auto; 35:22-34.

Bransford, J. D. (2004). *How people learn: brain, mind, experience, and school*. National Acad. Press, Washington DC, WA.

Cassidy, O. (2003). "I try it—Utilizing multimedia simulation as a vehicle to aid experiential learning". Accessed February 25, 2021. http://www.cs.tcd.ie/Oliver.Cassidy/Meta/meta.pdf.

Gouveia, D., Lopes, D., and Vaz de Carvalho, C. (2011). "Serious gaming for experiential learning". *Frontiers in Education Conference*.

TheJigsawPuzzles.com. (n.d.). Accessed March 14, 2021. https://thejigsawpuzzles.com/&gt.

Khedkar, S. B., Thakre, R. D., Mahantare, Y. V., and Gondne, R. (2012) "Study of implementing 5S techniques in Plastic Molding" *International Journal of modern engineering research*. vol. 2, no 5, pp. 3653-3656, 2012.

Lake, H. (2008), "Analysis of human resource management practices: Indonesia's labor-intensive light manufacturing industries", *SENADA Indonesia Competitiveness Program, The United States Agency for International Development*, Patiala, pp. 1-44.

Ohno, T. (2019). *Toyota production system: beyond large-scale production*. Productivity Press, New York.

Osada, T. (1991), *The 5-S: Five Keys to a Total Quality Environment*, Asian Prod. Org., Tokyo.

Ratcliff, T. (n.d.). "Downtown Dallas from the Flower Market," Creative commons license under CC Search. Accessed February 15, 2021. https://search.creativecommons.org/photos/040afe23-4f5b-499d-a5a4-9858865c60a9&gt.

Rich, N., Bateman, N., Esain, A., Massey, L. and Samuel, D. (2006), "Lean Evolution: Lessons from the Workplace", ISBN 1139457993, 9781139457996, *Cambridge Univ. Press*, New York.

Rybkowski, Z. K., Forbes, L. H., and Tsao, C. C. Y. (2020). "The Evolution of Lean Construction education at US-based universities." In Lean Construction: Core Concepts and New Frontiers. Tzortzopulos, P. Kaglioglou, M., and Koskela, L. Eds. Routledge, London and New York. 387-407.

Sacks, R., Esquenazi, A. and Goldin, M. (2007) "LEAPCON: Simulation of Lean Construction of High-Rise Apartment Buildings", *JCEM, ASCE*, 133(7), pp. 529–539.

Visionary Products Inc. (2008). "Lean zone production methodologies: A cellular manufacturing simulation for 6 to 8 participants." Accessed February 28, 2021. www.visionaryproducts.biz/index.cfm?action=view&pdfid=232.

Shah, R. and Ward, P.T. (2007), "Defining and developing measures of lean production", *Journal of Operations Management*, Vol. 25 No. 4, pp. 785-805.

Siemer, J., & Angelides, M. C. (1995). *Evaluating intelligent tutoring with gaming simulations*. Proceedings of the 1995 Winter Simulation Conference, 1376-1382.

SuperTeams. (n.d.). "The 5S Numbers game." Accessed February 28, 2021. http://www.superteams.com/new-site/wp-content/uploads/2016/04/SuperTeams5SGameHandout.pdf&gt.

Tommelein, I.D. and Riley, D.R. (1999) "Parade Game: Impact of workflow variability on trade performance," *Journal of Construction Engineering & Management*, 125 (5), pp. 304–310.

Womack, J., Jones, D. and Roos, D. (1990), *The Machine that Changed the World*, Rawson Associates, New York, NY.

Womack, J. P., and Jones, D. T. (2003). *Lean thinking banish waste and create wealth in your corporation*. Simon & Schuster, New York.

Young, F. Y. (2014). "The Use of 5S in Healthcare Services: A Literature Review". *International Journal of Business and Social Science*, 5, 240-248.

APPENDIX: TABULATED RESULTS COLLECTED FROM OBSERVERS' GOOGLE FORMS.

Three-digit random number	In what ways was the PUZZLE GAME especially helpful in illustrating 5S?	In what ways was the NUMBERS GAME especially helpful in illustrating 5S?	If you could recommend only one game for further development, which one would it be?
155	*	*	5S Puzzle Game
158	It helped us understand the importance of organization	*	5S Puzzle Game
167	To understand and practically explain how 5S can be implemented	To understand how sorting and ordering can help you at its best.	5S Puzzle Game
219	gradual application was good	easier than the puzzle game	5S Puzzle Game
250	It shows that order helps a lot in efficiency	It shows that organization helps seed up the process with organization	5S Puzzle Game
253	It showed us the various steps of the 5S we needed to learn	how a random and reversed and different numbers can be confusing	5S Puzzle Game
263	Team work, improving productivity, follow the basic system	To standardize the process	5S Puzzle Game, 5S Numbers Game
295	Recognition.	organization	5S Puzzle Game
328	organized	it actually was not helpful.	5S Puzzle Game
397	Very helpful	Ok	5S Puzzle Game
453	shine	order	5S Numbers Game
519	The S's were followed by the distinction of colors	The players had to focus on the size and rotation to be able to get them in order.	5S Puzzle Game
534	Yes	Practical Experiment	5S Puzzle Game
547	yes		5S Numbers Game
578	understanding that black pieces were causing distraction.	Knowing that order really matters	5S Puzzle Game
583	Helped by eliminating the defect in the system represented by the black pieces		5S Numbers Game
611	It helped in the way by providing with each S as the game proceeded to the next round	Similar to the Puzzle game, with the increase in the level the organization also increased.	5S Puzzle Game
624	Puzzle game showed how eliminating waste first is the best way to start	Numbers game was helpful in learning how to look ahead and plan what is coming next	5S Puzzle Game
639	Illustrating the order of the 5S does matter and gives a easy example to follow	It can illustrate sorting and setting in order is important	5S Puzzle Game
647	We learn how to put things in proper way	proper functioning	5S Puzzle Game
648	Increase in score shows how the performance was improved in the puzzle game following the 5S .	It helped in sorting and, better visualization of the numbers	5S Puzzle Game

657	after sorting the unwanted pieces, it saves it and I think 5S will help a lot if followed	after setting the numbers in order it really easy because we are more familiar with numbers than the picture we have seen for the first time	5S Puzzle Game
Three-digit random number	In what ways was the PUZZLE GAME especially helpful in illustrating 5S?	In what ways was the NUMBERS GAME especially helpful in illustrating 5S?	If you could recommend only one game for further development, which one would it be?
659	*	It showcased the order clearly	5S Puzzle Game
661	sorting, shine	set in order, sort, standardize	5S Puzzle Game
694	The time management is the key to have good productivity and we could exactly done work on this thing with the help of these 5S.	The puzzle one is better.	5S Puzzle Game
748	It showed you how the order can improve efficiency.	It promotes order	5S Puzzle Game
777	The vivid hints allow for lucidly differentiating between the all the 5s	Less helpful	5S Puzzle Game
810	walked us through the steps	*	5S Puzzle Game
837	It followed the sequence. All aspects were covered while playing the game. It was seen how each S was represented in each round.	We had the time to play R1 and R4 only. But it sort of represented the order of the 5S's. That's good.	5S Puzzle Game
840	Direct application of the concepts	Order of things	5S Numbers Game
863	Yes	Yes	5S Puzzle Game
880	sorting - it helps showing you how sorting can be really important to fit the puzzle pieces together.	again, it helps to see how sorting between the numbers can have a big impact because once you have spotted and sort out the number, you can continue to the next sequence. the only problem is that you would have to be able to identify where the numbers are first.	5S Numbers Game
880	to organize things in a quick manner	if we can follow a set of principles will arrange it would make the work easy	5S Puzzle Game
912	The puzzle game was helpful in illustrating 5S because it included the extra black pieces which helped to show that distractions and waste can exist and it is important to identify them.	It helped to keep you on your toes and really solidified the sort aspect of 5S.	5S Puzzle Game
951	Puzzle Game	Sorting and setting order	5S Puzzle Game
982	each round explained clearly the aim of the game	each round made it easier to understand 5S	5S Numbers Game
992	Sorting and standardizing were easy to observe	Was more challenging, Sorting and standardizing were easy to observe	5S Puzzle Game

*respondent left the question blank.

Jacob, G., Sharma, N., Rybkowski, Z. K., and Devkar, G. (2021). "Target Value Design: Development and Testing of a Virtual Simulation." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 320–329, doi.org/10.24928/2021/0185, online at iglc.net.

TARGET VALUE DESIGN: DEVELOPMENT AND TESTING OF A VIRTUAL SIMULATION

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ABSTRACT

Early in the development of a lean project, Target Value Design (TVD) practices define owner value, and it is toward actualization of defined owner value that all subsequent lean practices should flow. Participatory simulations have been used to help stakeholders comprehend TVD processes before they are implemented on an actual project, enhancing their effectiveness. This paper introduces results from testing of an online version of a TVD simulation that was being used to teach TVD at universities and to practioner stakeholders before embarking on a sometimes lengthy TVD journey. The online TVD simulation described in this paper arose out of the need to continue to teach TVD despite social distancing requirements that emerged during the global COVID-19 pandemic. This paper chronicles the details associated with the online simulation: the template design, choice of suitable online platform, strategy for playing the simulation, and facilitation of post-simulation discussions. The developed simulation was tested with post graduate students of Construction Engineering and Management Programme at CEPT University. The post simulation discussion and analysis of questionnaire responses received indicate that participants enjoyed this simulation and learned important principles related to TVD. This online simulation is an evolved version of the Marshmallow Tower TVD simulation. Hence, it indicates the growing trend towards evolution of lean simulations and serious game to adjust to changing conditions.

KEYWORDS

Target Value Delivery, collaboration, target cost, virtual online simulation, lean simulation.

INTRODUCTION

Experimentation with serious games and simulations to instil the concepts and principles of lean construction among students and practitioners has been explored since the early 1980s by prominent researchers such as Greg Howell and Glenn Ballard (Rybkowski et al. 2020). Rybkowski et al. (2020) compiled a list of lean simulations facilitated by twelve academicians at major universities to impart specific lean principles. Additionally, forums such as the Lean Construction Institute (LCI) and the International Group of Lean

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Construction (IGLC) have been extensively using and encouraging lean games and simulations to motivate adoption of lean practices across the construction supply chain. The Target Value Design (TVD) simulation inspired by the "marshmallow design challenge" (Skillman 2014) is one such lean construction simulation (Rybkowski et al. 2016), which imparts the principles of the Lean-Integrated Project Delivery.

The COVID-19 pandemic severely impacted the ability of educators to facilitate lean simulation and games that were previously played in-person in a physical space. Globally, the lean community adapted to this situation by transforming and transplanting these games and simulations to the virtual realm.

This paper describes the development and testing of an improvised and transformed version of the marshmallow tower TVD simulation which can be played virtually online.

TVD SIMULATION

Target Value Design (TVD) evolved from target costing or genka kikaku. TVD involves continuous, collaborative cross-disciplinary appraisal of design proposals to improve overall value through the lens of various constraints such as cost, design, risk, constructability, quality, and time (Lee et al. 2012).

Experimentation of TVD practices and their outcomes on construction projects have been documented (Ballard and Rybkowski 2009). Do et al. (2014) state that TVD practices can help stakeholders successfully achieve a target cost that is 15% to 20% below market cost while maximizing the overall value to the project and owner. Early collaboration of stakeholders, setting a target cost and rigorous estimating are key requirements of TVD, as described by Ballard (2008).

The TVD simulation or marshmallow tower TVD simulation, developed by Munankami and Rybkowski (Rybkowski et al., 2016), was based on the "marshmallow design challenge" game by Peter Skillman. It has become widely used by university educators and lean consultants to impart principles of TVD, such as market cost, target cost, allowable cost, estimated cost, collaboration, etc. among the participants. It requires the groups of participants to design and then build a freestanding 2-feet tall tower that is no more than 2 inches out-of-plumb, using materials provided by the facilitator. Participants are then asked to optimize the design of the tower to lower the total cost by 15% to 20% without losing the overall value criteria established by the building owner (Rybkowski et al. 2020). The popularity of the TVD simulation may be due, in part, to the fact that it can be played in as little as 50 minutes, with relatively inexpensive materials. In fact, the simulation continues to be transformed following analyses and "plus delta" feedback from participants. For example, Devkar et al. (2019) had developed and tested a TVD simulation which includes BIM for visualization and rapid cost feedback. The virtual TVD simulation in this paper is an improvised version of the marshmallow tower TVD simulation which can be played virtually. This virtual TVD simulation was developed and tested at CEPT University.

SIMULATION DEVELOPMENT

INSTRUCTIONS TO PLAY

The objective of this online TVD simulation was to provide to participants a first-hand experience of the fundamental goals of Target Value Design. The game is inspired from TVD marshmallow tower game developed by Munankami and Rybkowski (Munankami 2012; Rybkowski et al. 2016), which is a widely played simulation administered in person prior to the COVID-19 pandemic. As part of a studio course named "Construction Project Formulation and Appraisal" for graduate students of Construction Engineering and Management Programme at CEPT University, the TVD marshmallow tower game had been incorporated into the course curriculum. However, during the COVID-19 global pandemic, classrooms and studios were moved to an online environment. The instructor for this studio course faced the challenge of transforming the existing TVD simulation, typically played in the physical realm, into a virtual simulation. This pressing need resulted in the crafting and testing of the online TVD simulation described in this paper.

The online TVD simulation developed by this team involved the design, construction and costing of a tower having height and base width requirements of 26 cm and 12 cm respectively. Online game templates were prepared for the students to play the simulation. The task of each team was to construct a tower with the help of shapes provided in the game template. The shapes and their three size variants are shown in Figure 1. Typically, a team of 3-4 participants was required to play this simulation. Each team member was asked to select and assume either of following roles: Designer, Contractor, or Owner. Based on the number of participants playing this simulation, two participants were allowed to play the role of Owner. However, the roles of Designer and Contractor were played by a single participant only. The simulation comprised two rounds. Round 1 modelled the traditional mode of project delivery, simulating a design-bid-build model of siloed operations along the construction supply chain, while the Round 2 simulated the type of active simultaneous collaboration required during TVD. In Round 1, the Owner was asked to prepare a strategic brief and then hand it over to the Designer. While preparing the strategic brief, the Owner could select shapes and the general aesthetics of the tower, keeping in mind specifications pertaining to the height and base width of the tower. The Designer was then asked to prepare a design of tower (Design Proposal– D1) according to requirements stated in the strategic brief prepared by the Owner. The design needed to be approved by the Owner before being handed over to the Contractor. The Contractor was then expected to construct the tower in accordance with the Design Proposal - D1, using shapes provided in the game template. Verbal communication between the Owner, Designer and Contractor was restricted in the first round. Communication between each role-play was limited to Requests for Information (RFIs) and needed to be continually documented. Although, specific time limits were not enforced for Round 1, the teams were pressed to finish as soon as possible. Pressure took the form of online streaming quotes such as "Time is the Essence of the Contract" while playing the online simulation. After the completion of Round 1, the teams were asked to calculate the cost of their constructed towers (Cost – C1). Further to this, each team had to declare its target cost (Target Cost – T1). In contrast to Round 1, Round 2 was designed as a collaborative environment where team members could collaborate and openly communicate with one other without any restrictions, beginning from design. In this round, the teams were expected to design (Design – D2) and construct their towers, keeping in mind the declared target cost, while aspiring to construct them at costs even lower than their declared target costs. At the completion of Round 2, teams were asked to calculate the cost of their constructed towers (Cost – C2). The time for completion of design and construction of each round was noted. As mentioned earlier, there was no specific time limit for finishing each round. However, it was anticipated that both rounds would be finished within 75 minutes, followed by a reflection and discussion period of approximately 20 minutes.

SIMULATION TEMPLATES DEVELOPED

The authors of this paper had been participating in the online APLSO (Administering and Playing Lean Simulations Online) forum that provides an international platform for testing and development of lean simulations using the cloud-based software. Based on learnings gleaned during a 90-minute session playing with, and collecting plus-delta feedback fromparticipants during this forum, it was observed that, for enabling participants to experience the "aha moment" that makes simulations effective in illuminating lean principles, online lean simulations require convenient software platforms that participants can trust. Because of this, the team decided to use "Google Slides" for the templates when they played this simulation at the APLSO forum. Google Slides also offers the additional feature of privacy where templates can be accessed using Google Drive without players needing to volunteer their email addresses to software companies, avoiding concerns of later email spamming by software companies.

Three groups of slides were prepared for administration of this simulation.

Instruction Slides

The *Instruction Slides* provided information related to team composition, role playing, and instructions for playing Round 1 and Round 2. The general instructions given to participating teams were: (i) complete the tower without any voids between the shapes given within the space restrictions defined in the template and having 26 cm height and a base width of 12 cm, and (ii) do not resize or change the shape of any pieces, with the one exception that shrinking (but no expanding) of the last placed piece was permitted. Dimensions of the pieces were provided in the TVD Game Playing Template as computational aids for the convenience of the players, in order to determine how best to address the final height and width specification of the two-dimensional tower.

TVD Game Playing Templates

There were two separate *TVD Game Playing Templates* to be used during Round 1 and Round 2. Both Round 1 and Round 2 consisted of Google Slides, and included an empty space for typing in the Owner's brief, uploading design proposals (Design Proposal - D1 and D2), and noting the RFIs exchanged between the Owner, Designer and Contractor. It also included a resource sheet containing pieces of various shapes and sizes, as well as a space for the construction of tower.

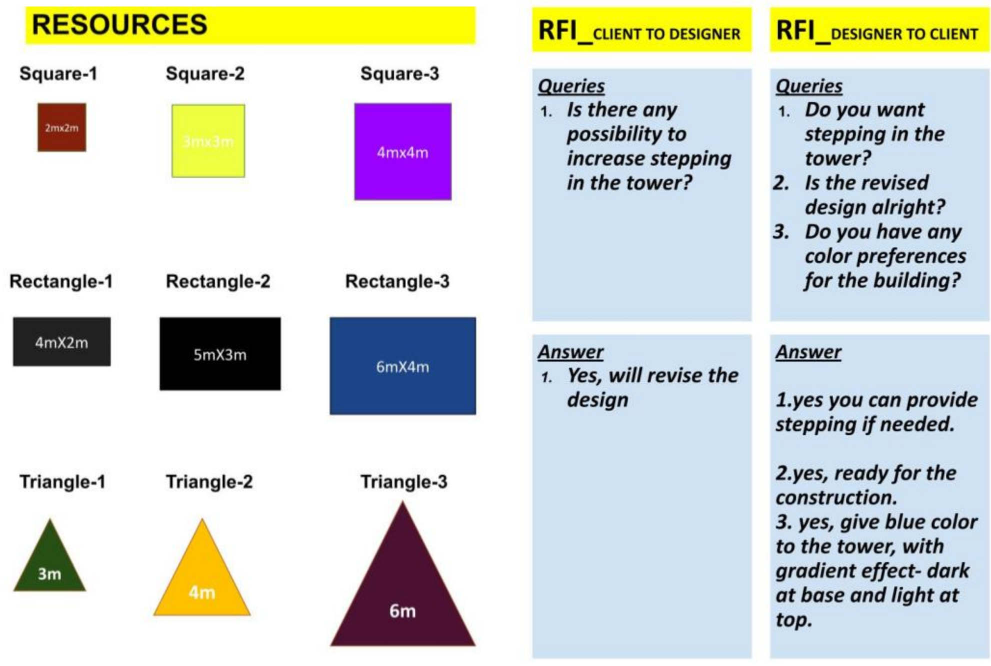
Cost Sheet Template

The Cost Sheet Template consisted of a table itemizing pre-defined cost rates of each shape, the number of shape variants used in final construction of the tower, and the total cost of tower. Both the TVD Game Playing Template and the Cost Sheet Template were made accessible by the facilitators by sending a link to Google Slides to all participants using the chat function of Google Meet. As a result of shared workspace, the hosting facilitators were able to observe the progress of each team on Google Slides as they played the simulation. This was especially helpful because the Screen Share function of Google Meet enabled facilitators to illustrate examples of team projects during the "big room" reflection and discussion stage of the exercise.

SIMULATION TESTING

The developed TVD online simulation was tested in a studio entitled "Construction Project Formulation and Appraisal." This studio was part of graduate course curriculum in Construction Engineering and Management at CEPT University. The primary objective behind this simulation was to provide an in-person experience to the students about collaborative working, early involvement of stakeholders in construction supply chain, and the process of designing to target cost. The instructor for this studio was assisted by two teaching assistants to administer this simulation.

The students involved in this studio were more familiar with the Google Meet platform for online meetings. Therefore, it was decided to use Google Meet to conduct the simulation. The students in the studio course were divided into teams of four to five. A total of 6 teams were formed and it was decided that each teaching assistant would be an observer for three teams while the instructor would oversee the overall simulation process by observing shared Google Slides templates, and addressing any specific questions raised. In total, 6 breakout rooms were created in Google Meet, one for each team. A few days before the actual playing of simulation, two power point presentations were shared with the students, including one by David Umstot and another by Prof. Lauri Koskela and Amit Kaushik. This helped the students in understanding the background of TVD. On the day of simulation, a conceptual foundation for Target Value Design was laid and the benefits delivered by TVD were highlighted with reference to the power point presentations. The discussion took approximately 20 minutes and was followed by a screen share of the "Instruction Template" in Google Slides. The students were asked if they had any questions about the simulation before they were given access to the "Game Playing Template" in Google Slides, and questions were clarified.



Resource Sheet *Filled RFI Sheet*

Figure 1 - Templates of TVD Game

The "Game Playing Template" was then shared in Google Slides with the students and they were asked to join one of the breakout rooms created in Google Meet. During Round 1, the participant playing the role of the Owner could either type the strategic brief or upload an image containing a handwritten strategic brief into the workspace provided in the "TVD Game Playing Template." The participant playing the role of Designer prepared a hand-drawn sketch of the tower on a piece of paper conforming to the strategic brief and uploaded it in the workspace named "Design Proposal" in the "TVD Game Playing

Template." During Round 1, the Designer often had to upload different interactions of the design until it was approved by the Owner. During Round 1, the teammates were not allowed to communicate verbally. A separate workspace in "TVD Game Playing Template" was included for the participants to raise their questions in the form of RFIs. The participants could type their questions in the space provided and the member of the team responsible could type back a response. Round 1 was completed in 45 minutes. At the end of Round 1, the students were asked to return to the "Main Google Meet Room." The "Cost Sheet" was then shared with students so they could benchmark the costs of the constructed tower, based on their designs from Round 1. The cost sheets had been pre-loaded with formulas to calculate the sum total costs of the constructed towers. The rationale of not sharing the "Cost Sheet" until after completion of Round 1 was to avoid any influence of cost during preparation of the "Owner Brief" and "Design Proposal – D1". As the students filled their cost sheets, the teaching assistants captured information from the cost sheets of each group and populated a shared excel sheet for the class.

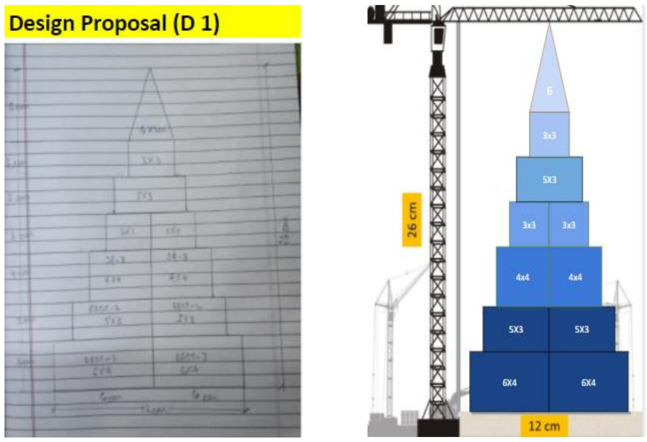
The excel sheet developed as part of TVD marshmallow tower simulation was used for the cost calculation for both the rounds (Rybkowski et al. 2016). This excel sheet consisted of three parts: 1) Establish Market Cost, 2) Establish Target Cost and 3) Design to Target Cost. A "Target Cost" was then declared by each team and noted on the spreadsheet. The instructor projected the excel sheet in the "Main Google Meet Room" and drew student attention toward the highest and lowest constructed tower costs. The instructor then calculated the market cost (average of construction cost of all towers). Allowable cost (the maximum cost to which the Owner could realistically build, determined by their financial resources and business case) was established by dropping the average cost of each tower by 20%, with the help of the cost sheet. Market cost, allowable cost, target cost, and the actual costs achieved in each round is mentioned in Table 1. The teams were then asked to return to their respective breakout rooms for five minutes and brainstorm a declared target cost. The rationale for providing a very limited time window for brainstorming was to incentivize intense collaborative discussion and to avoid a scenario wherein teams start to actually design the tower with reference to cost. After all the teams re-assembled in the "Main Google Meet Room," each team openly declared its "target cost" and the average cost of all declared target costs was calculated in the excel sheet. Then, the teams were asked to return to their respective Google Breakout Room to play Round 2.

Table 1: Comparative Cost Statement

	Team 1	Team 2	Team 3	Team 4	Team 5	Team 6
Cost (C1)	278	218	248	248	215	209
Market Cost	236					
Allowable Cost	189					
Declared Target Cost	250	190	220	200	170	190
Average Target Cost	203					
Cost (C2)	230	173	194	194	176	149

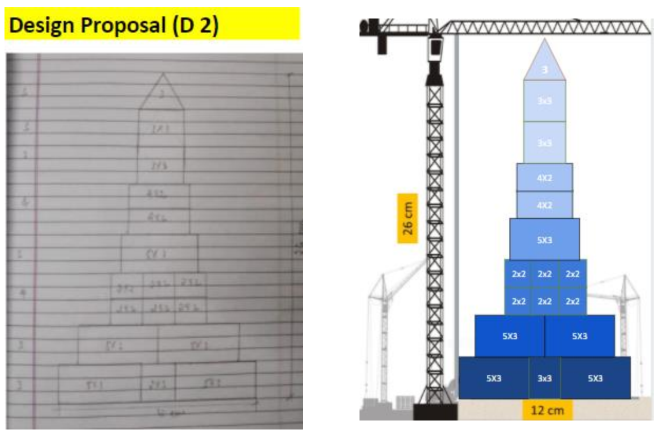
All figures are in INR. 1 USD = 72 INR.

During Round 2, the participants were instead permitted to finalize the design brief collaboratively and write or upload it on the TVD game-playing template. To foster collaboration and hasten finalization of the tower designs, the Round 2 permitted switching on of cameras and verbal communication between team members, and the Designer was permitted to show different iterations visually on camera to the Owner and the Contractor, seeking their feedback, before finalizing their team design (Design - D2)—all the while keeping in mind the declared target cost and parameters specified in the design brief. During both Round 1 and Round 2, the workspace named "Construction Site" allowed the Contractor to construct the tower according to the finalized design by copying and pasting required shapes from a laydown area named "Resources" in the "TVD Game Playing Template." Participants completed Round 2 within approximately 30 minutes, after which all teams returned to the "Main Google Meet Room." Each team filled their respective cost sheet for Round 2 and the details were captured online by the teaching assistants in the shared excel sheet. The excel sheet was shared in the "Main Google Meet Room" and teams were asked to reflect on parameters such as total cost at the end of Round 2, total cost at the end of Round 1, and declared target costs. In addition to costs from various rounds, the excel sheet captured parameters such as time of completion of design and construction in Round 1 and Round 2, and the number of RFIs incurred during Round 1. The excel sheet helped participants develop an understanding of an overview of TVD concepts and goals, including market cost, allowable cost, and target cost. Figure 2 depicts the designs prepared by the students during Round 1 and 2, the constructed tower in each round, and the populated cost sheet.



Cost Sheet (Round-1)

Item Name	Unit Cost ($)	Nos. of Units	Subtotal
Square 1	$ 3.00	0	$ 0.00
Square 2	$ 10.00	3	$ 30.00
Square 3	$ 20.00	2	$ 40.00
Rectangle 1	$ 5.00	0	$ 0.00
Rectangle 2	$ 15.00	3	$ 45.00
Rectangle 3	$ 30.00	2	$ 60.00
Triangle 1	$ 2.00	0	$ 0.00
Triangle 2	$ 5.00	0	$ 0.00
Triangle 3	$ 15.00	1	$ 15.00
Profit (10%)			$ 19.00
Total Cost			$ 209.00
Target Cost = 20% lower than Total cost			$ 167.00



Cost Sheet (Round-2)

Item Name	Unit Cost ($)	Nos. of Units	Subtotal
Square 1	$ 3.00	6	$ 18.00
Square 2	$ 10.00	3	$ 30.00
Square 3	$ 20.00	0	$ 0.00
Rectangle 1	$ 5.00	2	$ 10.00
Rectangle 2	$ 15.00	5	$ 75.00
Rectangle 3	$ 30.00	0	$ 0.00
Triangle 1	$ 2.00	1	$ 2.00
Triangle 2	$ 5.00	0	$ 0.00
Triangle 3	$ 15.00	0	$ 0.00
Profit (10%)			$ 13.50
Total Cost			$ 148.50

Figure 2- Designs prepared and actual towers constructed for Round 1 (above) and Round 2 (below)

POST SIMULATION DISCUSSION

After Round 2, during the reflection phase of this game, students were asked to consider concepts such as their understanding of collaboration, rapid cost feedback, target costing, designing to target cost, working environment, relevance of learned concepts to practice and so on. Based on this discussion, it was evident that the simulation was effective in providing a first-hand experience of TVD concepts. The instructor also used the same evaluation questionnaire developed by Munankami (2012) to evaluate the effectiveness of this online TVD simulation. Originally, the evaluation questionnaire was developed to assess the effectiveness of the marshmallow tower TVD simulation, developed, and tested by Munankami (2012). Devkar et al. (2012) used the same questionnaire for evaluating the effectiveness of a TVD simulation exercise. It was also used by Musa et al. (2019) when the TVD simulation was administered to 24 practitioners in Nigeria to test their understanding of TVD. Therefore, for consistency, the authors chose to use the same evaluative questionnaire for their online simulation. The online platform provided by Google Forms was used for administering the questionnaire and was circulated among the students at the end of the reflection/ discussion session. The students were asked to immediately provide responses to the questionnaire, since learnings and their "aha moments" were likely still fresh in their minds at the end of the simulation. In the survey form, the students were asked to rate various parameters on a 5-point Likert scale: 5 (most effective) to 1 (least effective). The questionnaire consisted of 23 questions in total, and an analysis of the most relevant responses are as follows:

A. Mutual respect and trust
B. Mutual benefit and reward
C. Collaborative innovation and decision making
D. Early involvement of key partners
E. Intensified planning
F. Open communication
G. Owner is an active member of the team
H. Understanding the value of customer

Continuous estimating and budgeting through collaboration among team membersThere were total of 22 respondents to this questionnaire. Based on the analysis of responses to the questions (Figure 3), it was observed that the students had developed an enhanced understanding of "collaborative innovation and decision making." During the post simulation discussion, the students mentioned that Round 2 helped break down typically experienced boundaries between the Owner, Designer and Contractor. Involvement of key stakeholders assisted in a team's development of innovative towers not only met Owner's needs but also lowered the cost of construction. This collaborative decision-making helped the participants understand that a win-win situation was created in Round 2, reflected in the observation that most respondents gave a higher rating (greater than or equal to 4) for the parameters of mutual trust and reward. Most notably, the analysis of questionnaire responses indicates that the concept of "target costing" was understood by the participants. Also, the efficacy of cost feedback in the design process to meet target cost and value expectations of the owner is reflected in the higher rating (equal to 5) received by the parameter "continuous estimating and budgeting through collaboration among team members." Additionally, the participants seemed aware of the efficacy of open communication, which was also rated higher (greater than or equal to 4). Given the richness of discussions between participants and the instructor during the reflection phase, as well as results from the questionnaire responses, it appears the online TVD simulation effectively served the purpose for which it was designed.

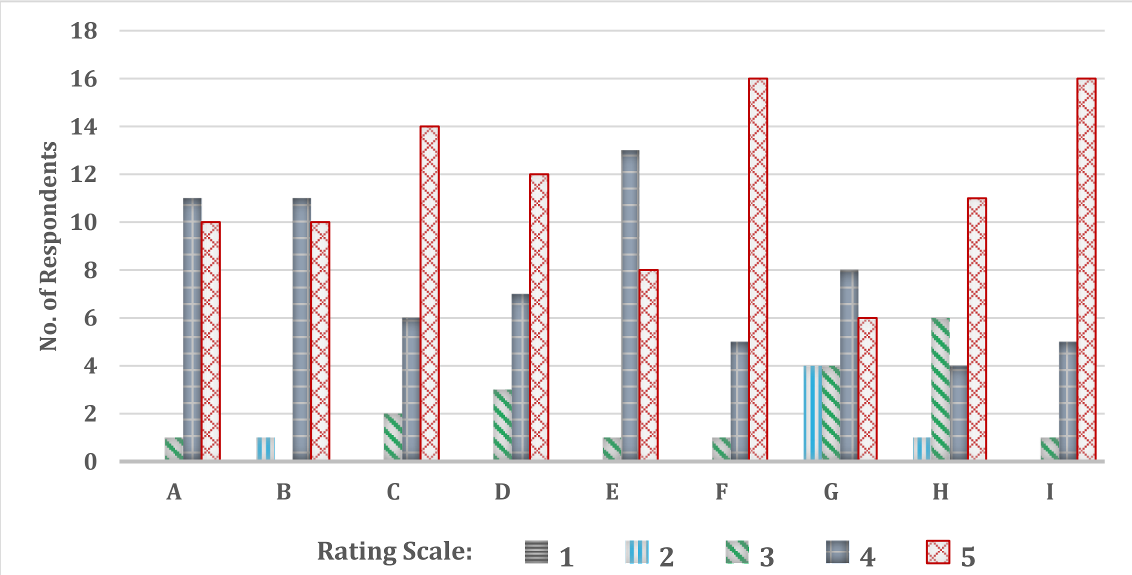


Figure 3 - Histogram showing participant's response to questions about the online TVD simulation

CONCLUSION

Target Value Design is a concept from lean construction which attempts to break boundaries created among three important construction supply chain actors, namely the Owner, Designer and Contractor. The adoption of this concept not only promises monetary gains but also cultural shifts in terms of collaboration, transparency and teamwork which is essential for efficient operations within the construction supply chain. In this context, the authors of this paper reported on the development and testing outcomes of an online TVD simulation. The development of the simulation involved creation of user-friendly instructions and templates with movable, shaped pieces to be used to build a two-dimensional tower. The simulation was administered on the Google Meet Platform and facilitated by the instructor and teaching assistants involved in development of this simulation. Responses from players were positive and appeared to indicate that key concepts critical to an understanding of TVD were being imparted. The online TVD simulation appears to have served as an effective replacement for the in-person simulation during the COVID-19 pandemic. Perhaps a more effective test of its efficacy will be whether or not this online version of the TVD simulation will continue to be played even after the pandemic has ended. The developed online TVD simulation has not explored the facet of "functionality" in terms of designs and cost effectiveness. However, it can be explored in the enhanced version of this simulation in future. Also, this simulation allows design and construction of tower in 2D, however, more advanced software platforms can be used for design and visualization of tower construction in 3D with rapid cost feedback process.

REFERENCES

Ballard, G. (2008). The lean project delivery system: An update. *Lean Construction Journal*, *2008*, 1–19.

Ballard, G., and Rybkowski, Z. K. (2009). *Overcoming the hurdle of first cost: action research in target costing*. 1038–1047.

Devkar, G., Trivedi, J., and Pandit, D. (2019). Teaching target value design: A simulation. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, 479–490. doi.org/10.24928/2019/0244.

Do, D., Chen, C., Ballard, G., and Tommelein, I. D. (2014). Target value design as a method for controlling project cost overruns. *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*, *1*(510), 171–181.

Jung, W., Ballard, G., Kim, Y.-W., and Han, S. H. (2012). Understanding of Target Value Design for Integrated Project Delivery with the Context of Game Theory. *Construction Research Congress*, 556–563.

Lee, H. W., Ballard, G., and Tommelein, I. D. (2012). Developing a Target Value Design protocol for commercial energy retrofits - Part 1. *Construction Research Congress 2012: Construction Challenges in a Flat World, Proceedings of the 2012 Construction Research Congress*, *2008*, 1710–1719. doi.org/10.1061/9780784412329.172.

Miron, L. I. G., Kaushik, A., and Koskela, L. (2015). Target value design: The challenge of value generation. *Proceedings of IGLC 23 - 23rd Annual Conference of the International Group for Lean Construction: Global Knowledge - Global Solutions*, *July*, 815–825.

Munankami, M. B. (2012). "Development and testing of a simulation (game) to illustrate basic principles of Integrated Project Delivery and Target Value Design: A First Run Study," Graduate Thesis, Texas A&M University, College Station, TX.

Musa, M., Pasquire, C., and Hurst, A. (2019). "Using TVD Simulation to Improve Collaboration." In: *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*, Pasquire C. and Hamzeh F.R. (ed.), Dublin, Ireland, pp. 503-514. doi.org/10.24928/2019/0268.

Rybkowski, Z. K., Forbes, L. H., and Tsao, C. C. Y. (2020). The evolution of Lean Construction education at US-based universities. *Lean Construction*, 387–407. doi.org/10.1201/9780429203732-19.

Rybkowski, Z. K., Munankami, M. B., Shepley, M. M., and Fernández-Solis, J. L. (2016). Development and testing of a lean simulation to illustrate key principles of target value design: A first run study. *IGLC 2016 - 24th Annual Conference of the International Group for Lean Construction*, 133–142.

Skillman, P. (2014) "Peter Skillman Marshmallow Design Challenge." https://www.youtube.com/watch?v=1p5sBzMtB3Q (March 25, 2021).

Umstot, D. (2016). *Target Value Design (Delivery) An Overview* [PowerPoint slides]. Umstot Project & Facilities Solutions LLC. https://www.lcicongress.org/pdfs/MON7_Target_Value_Design.pdf.

Bhatnagar, S. and Devkar, G. (2021). "Development and Testing of a Simulation Game on Waste Elimination using Lean Practices." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 330–339, doi.org/10.24928/2021/0190, online at iglc.net.

DEVELOPMENT AND TESTING OF A SIMULATION GAME ON WASTE ELIMINATION USING LEAN PRACTICES

Shaurya Bhatnagar[1] and Ganesh Devkar[2]

ABSTRACT

Lean concepts of waste elimination and analysis of Value-Adding (VA) and Non-Value-Adding (NVA) activities holds the potential for improved processes in a construction project and enhanced value creation for the client. Simulation games can be effectively used to impart knowledge about these concepts and tap the potential of lean philosophy in the construction industry. This paper reports the development and testing of a simulation game that focuses on waste elimination and value maximisation using lean principles. This paper chronicles the details of setting game requirements, prototype design, material selection, sequence of work, room set up, roles and scenarios and rules for different rounds. The simulation game consisted of three rounds. Round 1 involved traditional construction processes in which, lean wastes are evident, which adversely affects variables like time, cost and quality. In Rounds 2 and 3, various lean practices are introduced, with an aim to eliminate waste and to understand value-adding and non-value-adding activities. The developed simulation was tested with post graduate students at CEPT University, India. The post simulation discussion indicated that the simulation game resulted in enhanced understanding on waste, value and lean practices. This simulation game can be further enhanced by integrating aspects of value stream mapping of construction process.

KEYWORDS

Lean, simulation game, waste elimination, value maximisation, cost, lead time.

INTRODUCTION

The construction industry has been undergoing significant transformations in the areas of contracting, design management, and facility management globally to deal with challenges such as design defects, schedule delays, cost overruns, complex workflows, unreliability in output, coordination issues, inventory mismatch problems, and wastage of materials. In this context, lean philosophy has been gaining immense attention among the stakeholders of the construction industry and it is expected to play a key role in this transformation process.

Lean philosophy includes a set of tools, principles, and production techniques that identify and eliminate waste through continual improvements in processes. This lean

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philosophy focuses on four critical concepts - waste, value, continuous improvement, and respect (Rybkowski et al., 2018). Waste is the pivotal concept and has been defined by Toyota as "anything different from the absolute minimum amount of resources of materials, equipment, and manpower necessary to add value to the product" (Alarcón, 1995, p. 1). The pioneering work by Koskela (2000) on the adoption of lean philosophy in the construction sector put forth the Transformation-Flow-Value (TFV theory). The TFV theory of production emphasizes on elimination of waste and non-value adding (NVA) activities for better flow management through continuous improvement.

While lean concepts such as flow, value, waste, and value maximisation are promising and can potentially improve the construction processes, a survey of literature shows that the "lack of understanding knowledge on Lean and Complexity of Lean philosophy and terms" continues to be a potential barrier in the adoption of lean principles in the construction sector (Demirkesen et al., 2019, pp. 7-8). The gap between the concept and application of lean philosophy can be bridged by a new way of "Learning by Doing" i.e. Simulation Games. In the construction domain, lean simulation games are considered to be an effective mechanism to impart knowledge on various lean concepts in a clear, realistic, and simplified manner (Hamzeh et al., 2017; Rybkowski et al., 2018).

Bhatnagar (2020) compiled forty-seven lean simulation games from a matrix of Lean Construction Institute (2021) and papers from International Group for Lean Construction (2021) and American Society of Civil Engineers (2021). These games were analysed in terms of their learning outcomes and lean principles. The study showed that important themes such as waste elimination and value maximisation continue to be unexplored and these are not key focus areas of existing lean simulation games. The games such as LEAPCON, House of cards, Dot Simulation, Airplane Game (and its variants) deal with waste along with various other learning objectives but do not hold reduction of waste and analysis of VA/NVA as the key learning outcomes (Pollesch & Rovinsky, 2017; Rybkowski et al., 2018).

This paper analyses the development and testing of a simulation game to impart knowledge on waste elimination and value maximisation using various lean practices in the construction domain. This game is inspired from Airplane game developed by Visionary Products USA, Inc. (2021) which teaches teamwork, pull production, and the impact of supply chain logistics.

GAME DEVELOPMENT

The main intention of the proposed game is to familarise participants with waste elimination and value maximisation concepts with the help of various lean practices. Each team has to complete the target of constructing eight Lego™ houses within the stipulated time of eight minutes to get cash points for houses that are defect free. The game is played in three rounds with each round showing continuous improvement in the workflow process due to reduction in wastes by use of 5S, Supermarket, Kanban, Heijunka box, and pull planning. At the end of 8 minutes in each round, the numbers of houses constructed by each team are counted and each house is inspected. The team with highest cashpoints is declared a winner. The three keypoints – doing more with less effort, acting smarter rather than harder and reducing lean wastes are used to reach the target.

TEAM COMPOSITION

The game includes the entire cycle of a typical house construction. Each team comprises 8 players – one contractor head, one safety officer, one quality manager, and one person each for different trades such as *foundation laying, column casting, blockwork, roof work and service laying*. Additionally, 1 assistant and 2 timekeepers per team are required. The game can be played among 2 - 4 teams with one instructor. At the start of each round, the assistant conveys information about the number of targeted houses to be constructed and time limit for each round and distributes materials and templates to the Contractor Head of each team. The task of house construction is then performed by each team in accordance with the instructions. The timekeepers note the time in the format card for each team and display the results in the form of a Gantt chart on a spreadsheet on a computer. The instructor conducts debriefing sessions for players at the end of each round with the help of the assistant and timekeepers.

PROTOTYPE DESIGN

The prototype *"house"* is chosen for the game. The design is inspired from the House of Lean model and comprises *foundation, columns, block walls, roofing and services* (Liker, 2004). The design units are Lego™ blocks of required shapes, sizes, colours according to different design codes. While designing the prototype, the number of blocks used by each trade are kept different, creating an imbalance in their workload. There are four design codes – D1, D2, D3, D4. Each design code has the same constructibility of prototype but the colours of all blocks differ for each code. All the blocks are green for D1, red for D2, blue for D3 and yellow for D4. This is done to induce interest and concentration in the game. All teams are required to construct the houses with D1, D2, D3, D4 and the sequence of using design code will be based on a special symbol given to each team. Each sequence is denoted by the four special symbols – *spade, club, diamond and heart* – as shown below.

Figure 1: A - Prototype Design , B - Sequence of work, C – Sequence of design codes

MATERIALS REQUIRED

Each team is provided 1 standard 52-card deck, 5 small bowls, 200 g of shredded paper, 3 small packets of colourful small beads, 3 packs of colourful sticky notes of size 7.5 cm x 7.5 cm and 1 pack of A4 colourful sheets. Additionally, each team is provided 1 circular paper stencil of 50 mm radius, 1 cardboard stencil of A4 size with 50 mm radius circular cut-out in centre, 3-4 sketch pens/markers, 1 steel ruler, 1 adhesive tape with dispenser, 2 stopwatches, 1 compass, 1 scissors and 4 Heijunka boxes. Three copies of various templates such as specification card, format card, costing template and design sheet are provided to all teams. The design sheet has information on prototype design, design code details and sequence of design code to be followed while specification card defines important instructions such as number of targeted houses and time limit for each round to be followed while playing. Format card is a template to note the time readings for each player's entry and exit while playing. Costing template records the cashpoints paid to each trade and profit earned by the team. Pre-formulated excel template and debriefing questionnaire are also provided. Sticky notes are used as cashpoints in all rounds and as Kanban cards in Round 3. The two varieties of blocks are placed in material bowls for house construction. One is an original block from the Lego™ company while the other is sourced locally from a local brand called Peco. As per the specification sheet, blocks with Lego trademark are approved for house construction.The details of Lego and Peco blocks are mentioned in the design sheet. Few blocks for roof work are replaced intentionally for each team with duplicate Peco blocks before the start of the game. Also, some pieces are marked with a marker intentionally as shown in Figure 2, making it a defective piece and these blocks are also mixed with others by assistants. This induces defect/rework waste as the specification card gives strict instructions that the cashpoints shall only be paid for defect-free sites made up of blocks having trademark of Lego and free from any marks.

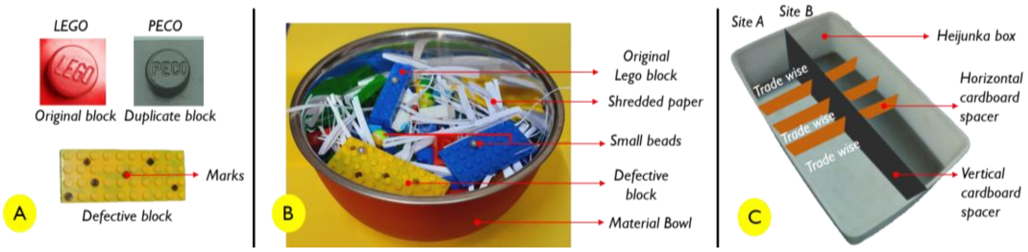

Figure 2: A -Types of blocks, B - Material bowl, C - Heijunka Box

The material bowls are not more than 150 mm in diameter and depth varies from 50-75 mm. Each bowl contains the exact number of Lego blocks required by the design sheet. Additional materials such as extra Lego blocks of different shapes, sizes, and colours, small beads and shredded paper are also added to the bowl. The bowl design and material mix are intended to introduce difficulty resulting in time and effort wastage in choosing the right Lego blocks. Heijunka boxes are used in Round 2 and 3 intead of material bowls. It is a simple rectangular box with an open top and has vertical and horizontal dividers made up of cardboard spacers. The horizontal rows define the space for each trade while the vertical columns define site-wise division. They are used for 5S and resource sharing purposes. The Heijunka box enables easy and fast check and choice of Lego blocks. The time wasted on extra, unnecessary movement can thus be considerably reduced.

SETTING UP OF ROOM

The game is required to be played in a classroom environment with accessibility to a projector screen and laptop. Each team is given two tables. The smaller table is used as a *material station* to keep Lego blocks, sheets, bowls, etc. On the right, a minimum of 4 tables (say 1200 * 600 mm each) are connected together to form a *working station*. A distance of 1800-2400 mm is kept between the two stations purposely in Round 1 and subsequently removed in later rounds. The upper half of the working station is left for material movement while the lower half is reserved for the *house* construction and is the main access to the working station for players. Eight sites (A-H) are marked on the working station with inter-site distance of 600 mm. The movement of players is required to be from left to right while playing. The waiting or queuing space is kept in front of the material station to provide hassle-free entry into working station. Some space for movement is reserved on the upper side of the working station for the quality manager. Seven sticky notes are pasted on the table as money slips to the right of each site. Each trade is given sticky notes of a specific colour. The slips are pasted at the bottom for the last trade and at the top for the first trade. The typical room layout arrangement is shown in Figure 3.

INSTRUCTIONS TO PLAY

The simulation starts with the participants dividing themselves into teams of 8 players each and the rest take up the roles of assistant and timekeepers.The tutor assumes the role of the instructor. Each team member is asked to select one of the roles mentioned in the section on team composition. Then, the facilitators give the copies of the specification card, format card, costing template and design sheet along with material to the contractor head of each team. The contractor head chooses one card from the pack of 52 cards. The chosen symbol defines the sequence of the four design codes (D1-D4) to be followed on each site while playing. Each contractor head gets 3000 cash points as advance to maximise profit and minimise expenditure. Any material, once bought, cannot be returned or refunded. The timer starts with the safety officer entering each site to paste A4 sheet and drawing a circle at the centre for the next trades to work. The respective trades join the required Lego blocks as per the design sheet and specification card. The quality manager arrives at the end for inspection, after which, cashpoints are paid to each team for defect-free houses. Timekeepers record the entry and exit of each player. After 8 minutes, the players and timers are paused for recording work-in-progress and completed sites as given in the format card. After the break, the process is continued until eight houses are built and the total time is noted. The costing template is filled by contractor head to determine the profit earned by each team at the end of the rounds. After each round, the instructor conducts debriefing sessions to summarise learnings and experiences. The durations of the three rounds (including debriefing) are approximately 50 minutes, 40 minutes and 35 minutes respectively followed by a small break after each round.

Round 1

Round 1 represents the traditional way of working depicting several lean wastes. All the material is bought at the initial stage leading to inventory and housekeeping issues. After reaching the work station, each player moves towards the material station for collecting the material and then back to the working station which is 1800-2400 mm away. Here, time is lost due to wasted movement. A batch size of 4 houses is taken for construction, which means that next trade can only start once 4 sites are completed by the previous trade. Wastage due to waiting and overproduction is experienced by the players. The safety officer pastes the A4 sheets on the table using adhesive tape. The diagonals are marked and a circle is drawn using circular stencil having a hole in the centre coinciding with the centre on paper. The non-value added time is spent in extra processing for drawing a circle. Each trade carries their material bowls from one site to another and brings it back to the material station after work, causing transportation waste. Furthermore, the bowl’s ingredients are placed in a disorganized manner, leading to extra motion of hands for searching the right block in the bowl. The use of defective blocks for roof work also leads to rework.

Round 2

Round 2 represents the use of Supermarket, 5S, Heijunka box and workplace design to improve the workflow and waste elimination. In this round, material is sorted initially by the quality manager, during when, defective pieces, small beads and shredded paper are removed. Only sorted blocks are kept on the material station in a well organised manner, which reduces excessive inventory, housekeeping, and rework issues. The batch size is reduced to 1 which means that the next trade can enter the site immediately after the previous trade finishes without much waiting. The material station adjoins the working station, which reduces unnecessary movement. Each Heijunka box is kept between two adjacent sites to fill the sorted Lego blocks as per the exact requirement only in the respective shelves for each site as well as trade. The quality manager fills the box every 50 seconds for every next two trades in 3 turns, thereby easing inventory management. The use of 5S and co-location concepts reduces the time for searching the right blocks. The safety officer follows fewer steps to draw the circle by simply placing a different cardboard stencil (A4 size with circular cut-out of 50 mm radius). The glue stick replaces the use of adhesive tape to paste the A4 sheet. The overall workflow is improved but overproduction can still be observed.

Round 3

Round 3 shows the effects of pull planning, Kanban and workload balancing on the work flow. The rules in Round 3 pertaining to batch size and material sorting are similar to Round 2. In Round 3, the column casting is combined with foundation laying and the activity of putting roof studs is combined with blockwork laying. Thus, the player for column casting is removed from the game. Now, each player has similar cycle times as shown in Figure 5. Workload balancing reduces internal waiting and manpower use. In addition, all players now depend upon the last person completing their activity on the certain site to move to next site. Each player pastes a sticky note on their right after completing their activity on one site. Every player in the flow sees to their left side to check if the note (or Kanban) has been pasted to move to the next site. This means that no player can start work on the the next site until the work of the previous player has been completed. This reduces overproduction.

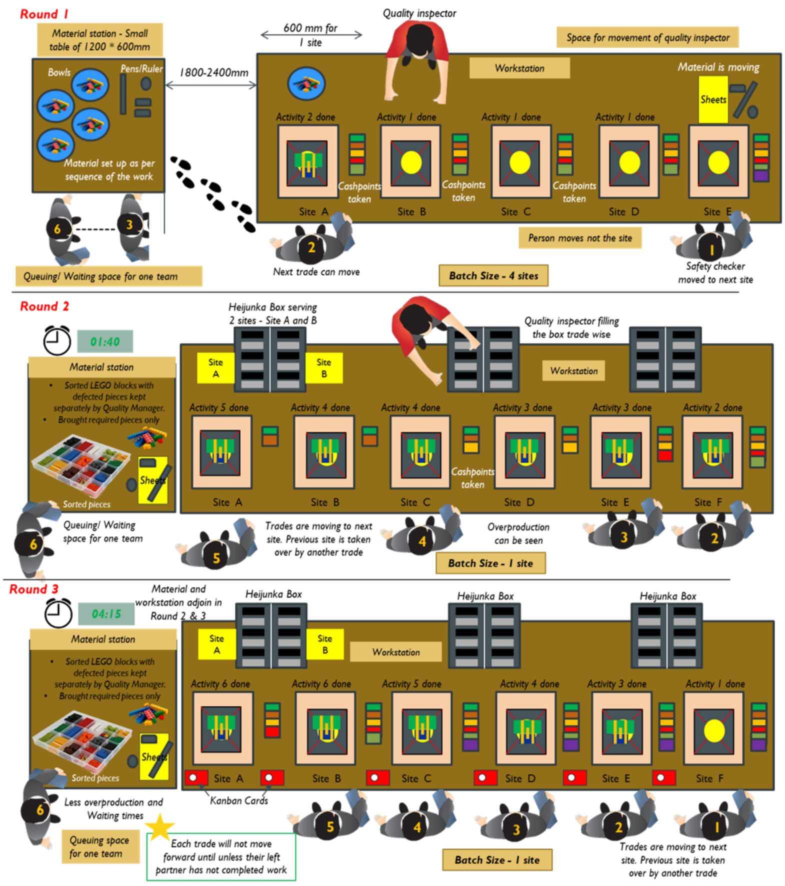

Figure 3: Sequence of work in different rounds

COSTING SYSTEM

The costing template is filled at the end of each round to calculate profit earned by each team on the basis of assumptions defined in this section. A total of 3000 cashpoints is given to each team's contactor head as advance for the construction of eight sites at the start of the game. The total cashpoints earned (profit) are calculated for the complete lead time. A positive sign (+) shows money given to or available with the contractor head while a negative sign (-) shows money given by the contractor head. The contractor head pays for the design cost, material cost, cost of each trade work/site, housekeeping, and rework. In return, he gets paid 400 cashpoints per site upon completion of each defect-free site irrespective of rework. The contractor head's profit is the difference between the expenditure and pay recieved. The team with higher profit or cashpoints wins the game.

GAME TESTING

The game was designed with the help of an internal testing group from the inception stage. The internal testing group consisted of 10-12 students of Master's program of various disciplines related to built environment. To test the *prototype design* and *game sequence*, numerous runs were played in small sections along the game development for analysing their behaviour towards the designed plot and to check their responsiveness to what is required or planned. The cycle times and scenarios were recorded with stopwatches and videography respectively to analyse how the game would proceed. At a later stage, a small part of game testing was performed with a different group due to pandemic constraints.

The testing was focussed on whether the game achieves the fulfilment of it's learning objectives namely waste elimination and analysis of Non-Value Adding (NVA) as well as Value-Adding (VA) activities. Time and cost were considered the drivers of the attention of the participants towards waste elimination and differentiation of non-value added activities, to streamline the workflow in the construction processes. The improvement in workflow by understanding of VA/NVA activities and waste reduction was expected to result in time and cost saving.

After playing Round 1, the players reported experiencing excessive waiting, unnecessary motion, extra-processing with added steps and inventory, overproduction before requirement and housekeeping issues. Round 1 had inconsistent flow due to the presence of lean wastes experienced by players. On the other hand, the use of supermarket and 5S concepts with Heijunka box and reduction of batch size in Round 2 streamlined the flow and increased workability by reducing the possible NVA activities in mainly safety checking, quality checking, roof work activities and material sorting. A few snapshots of testing are shown below in Figure 4.

Figure 4: Snapshots from internal testing

In Round 3, the introduction of pull planning and Kanban concepts balanced the overproduction and workload balancing brought further process optimisation and consistency in the workflow rather than showing huge cycle time reduction. This round showed how the similar tasks can be combined to bring cycle time for each trade close to each other to reduce waiting. The effect of improvement in workflow was analysed using the two variables – Time and Cost taken to complete the target. Round 1, 2 and 3 were played multiple times (approximately 4 - 5 runs) with the testing group and the average of the results for time and cost calculations were considered for analysis. The average cycle time of each trade to complete one site was recorded in the format card by timekeepers and is shown in the figure below.

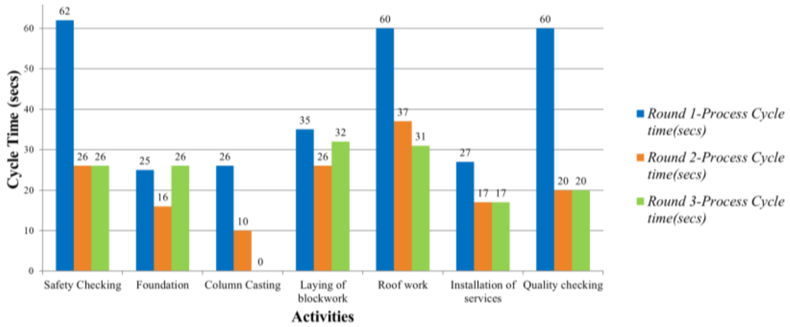

Figure 5: Cycle time comparison of each trade for each round

Considering the duration of game in mind, the game design adopted a simpler mechanism to map the process flow and lead time with the help of Gantt charts in an excel spreadsheet. After each round, the Gantt charts were prepared in the pre-formulated excel spreadsheet by timekeepers using average cycle time to determine the actual lead time taken by each team to complete the target of 8 houses. The spreadsheet had three worksheets for the three rounds. Each worksheet had the site number (A-H) in columns and the timeline (in seconds) in rows. Each cell was of square shape. Different colours were used to map the time taken by different players for each site. The Gantt chart showed the complete lead time and the process flow followed by each team during the game as shown in Figure 6. The resulting Gantt charts were projected on screen to the students and used as a point of discussion by the instructor for identifying VA/NVA activities, wastes, major bottle necks and problems, possible ways of cycle time reduction, and implementation process improvements as part of the debriefing sessions.

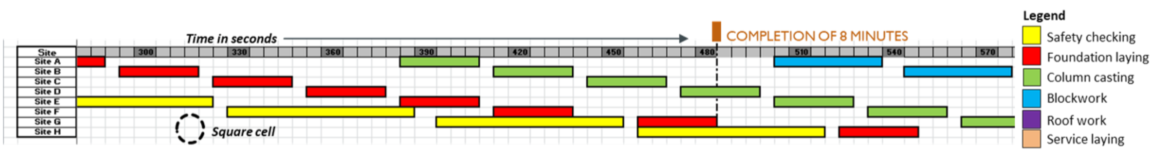

Figure 6: Part section of Gantt chart for Round 1

Cost templates were also filled by the contractor head of each team. The results of the Gantt chart and cost template in each round are summarised and analysed in the comparative statement shown in Table 1. The Round 1 lasted 25 minutes while Round 2 and 3 were completed near the target time of 8 minutes. It has been observed that there were considerable improvements in Round 2 and 3 because the cycle time reduced by 35 to 67 % for each trade. The improvements could be substantially attributed to the use of practices such as 5S, Supermarket, Heijunka box, and Kanban for waste reduction in Round 2 and Round 3. However, there is a possibility that improvement could also be, to a small extent, attributed to the increased familiarity of the participants with the game from Round 1 to Round 2 and 3. Cost is also another major driving force in construction industry and so was adopted in the game. As shown in comparative statement below, the profit increased over each round due to optimization of the quality as well as quantity of materials. This led to a manageable inventory and fewer reworks.

Table 1: Comparative statement of results of each round

Parameters	Round 1	Round 2	Round 3
Profit earned (cashpoints)	2710	3700	3940
Time taken to complete task (min.)	25	8.2	7.4
Cashpoints earned per minute	108	453	531
Cashpoints made in 8 minutes	864	3624	4248

The flow simplification impacted the time as well as the cost. The lead time over the three rounds reduced considerably from 25 minutes to 7.4 minutes and accounted to more than 300% improvement. The rate at which the profit was being earned over the rounds increased by 500% i.e. (4248/864=4.92). This means that the same amount of work can be performed in one third of the time and five times more money can be gained as compared to first round. So, the profitability was high in the later rounds. Game testing showed that maximising time spent on value-adding activities such as building the block and minimising time spent on non-value added activities like moving things around, searching for the right block, waiting and quality checking in the later rounds reduces the cycle times of each trade, thus, leads to time as well as cost saving.

POST SIMULATION DISCUSSION

At the end of each round, a 15-minute debriefing session was conducted by the instructor with help of the assistants and timekeepers. The interactions were in the form of group discussion and collecting "plus-delta" to summarise their learnings and share their experiences of the game. For consistency, the instructor used a 12 pointer debriefing questionnaire that helps in systematic perspective analysis of the participant's learning outcomes. The questionnaire focussed on highlighting VA/NVA activities and waste elimination concepts, real life applications of these concept and receiving feedback on the game design in terms of simplicity, ease, fun element, etc. The discussion on process flow with respect to waste and VA/NVA activities were assisted by the Gantt charts shown on projector screen. The impact of actions was linked to the time and cost variables. A collective feedback was collected from each team first and later shifted to the specific players regarding their opinion and experience. The plus points of the feedback were regarding the design of material bowls used in Round 1, use of house prototype and cost variable for the game. The participants reiterated the seamless and gradual infiltration of the concepts in the game; the type of wastes was understood in Round 1; the usefulness of 5S, supermarket and Heijunka box was understood in Round 2; the efficacy of Kanban and Pull planning was seen in Round 3. The deltas were regarding the space arrangement and use of different colours for different trades in a single design code. Later, a single colour was decided for all blocks for a design code to avoid complicated flow. Based on the richness of the discussion, it was evident that the simulation was effective in providing a first-hand experience of waste elimination and value maximisation by the use various lean practices.

CONCLUSION

This game was developed with the intent to impart knowledge on lean philosophy concepts such as waste elimination and value maximisation. Testing of the game showed that participants understood these concepts after playing it. The efficacy of application of these concepts on important variables such as time and cost overrun was also understood by the participants. This game could help in bringing clarity to the minds of the participants to proceed confidently in future systematic identification and elimination of waste in real life construction processes. The preparation of Gantt charts provided participants with the opportunity to learn graphical representation of process mapping and will help them switch to more advanced ways of mapping for real life scenarios. The limitation of this study is that it used a simplistic mapping mechanism of time and flow with the help of Gantt charts. The knowledge gained from this game can be enhanced further in the form of current and future state maps by integrating the aspect of value stream mapping in a simulated form.

REFERENCES

Alarcón, L. F. (1995). Training Field Personnel to Identify Waste and Improvement Opportunities in Construction. *3rd. Annual Conference International Group for Lean Construction, University of New Mexico, Albuquerque, USA, 16-19 October*.

American Society of Civil Engineers. (2021). *Research Papers*. ASCE Journals, Browse Journals by Titles and by Topics | ASCE Library.

Bhatnagar, S. (2020). *Lean Simulation Game - Exploring a perspective to study Value Stream Mapping*. Graduate Thesis, CEPT University, Ahmedabad, India.

Demirkesen, S., Wachter, N., Oprach, S., & Haghsheno, S. (2019). Identifying Barriers in Lean Implementation in the Construction Industry. *27th Ann. Conf. of the Intl. Group for Lean Construction (IGLC). Dublin, Ireland, 3-5 Jul 2019*, 157–168.

Hamzeh, F., Theokaris, C., Rouhana, C., & Abbas, Y. (2017). Application of hands-on simulation games to improve classroom experience. *European Journal of Engineering Education*, *42*(5), 471–481. doi.org/10.1080/03043797.2016.1190688.

International Group for Lean Construction. (2021). *Conference Papers*. IGLC.net - Index.

Koskela, L. (2000). An exploration towards a production theory and its application to construction. *VTT Publications*.

Lean Construction Institute. (2021). *LCI Simulation Matrix*. LCI-Simulation-Matrix.pdf (leanconstruction.org).

Liker, J. K. (2004). The Toyota Way: 14 Managment principle from the world's greatest Manufacturer. In *McGraw-Hill, New York*.

Pollesch, P., & Rovinsky, A. (2017). House of Cards – A Simulation of Lean Construction Principles. *25th Annual Conference of the International Group for Lean Construction. Heraklion, Greece, 9-12 Jul 2017*, 373–380.

Rybkowski, Z. K., Forbes, L. H., & Tsao, C. C. Y. (2018). The Evolution of Lean Construction Education (Part 1 of 2): At US-based Universities. *26th Annual Conference of the International Group for Lean Construction. Chennai, India, 18-20 Jul 2018*, 1013–1023. doi.org/10.24928/2018/0447.

Visionary Products USA, Inc. (2021). *Lean Zone® Production Methodologies*. Lean Zone® Production Methodologies (lean-zone.com).

Biotto, C., Herrera, R., Salazar, L., Pérez, C., Luna, R., Rodrigheri, P., and Serra, S. (2021). "Virtual Parade Game for Lean Teaching and Learning in Students from Brazil and Chile." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 340–349, doi.org/10.24928/2021/0203, online at iglc.net.

VIRTUAL PARADE GAME FOR LEAN TEACHING AND LEARNING IN STUDENTS FROM BRAZIL AND CHILE

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ABSTRACT

The use of games in engineering teaching is common practice in classes with lecturers all over the world. However, due to the COVID-19 pandemic, undergraduate civil engineering education became virtual and remote. In this context, many games traditionally played in person among students have undergone adaptations to the digital environment. The game "Parade of Trades" or "Parade Game" is used worldwide to teach the effects of variability in construction workflows in linear, dependent and sequential production systems. An adapted version of the game to the virtual environment was proposed by ASKM & Associates LLC and Navilean LLC. It was presented at the International Group for Lean Construction Congress (IGLC 2020). This version of the Parade Game was applied in three different high education institutions in Brazil and Chile. The game's effectiveness for teaching the variability concept was tested by administering a questionnaire before and after the game with the Production Planning and Control course's students in Civil Engineering. The main contribution of this study is the evaluation of learning brought by the game. Results show an increase of 20% in the correct answers in the post-game questionnaire, demonstrating that the students captured the game's main concepts.

KEYWORDS

Engineering education, lean games, parade game, COVID-19, virtual teaching.

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INTRODUCTION

The "Parade of Trades" or "Parade Game" consists of a game to demonstrate the impacts of variability on a construction project, in which multiple teams are working independently, and often, sequential activities (Choo and Tommelein 1999). Playing this game teaches the concept of workflow reliability, where workflow is expressed by the number of units of work that get passed from one construction trade to the next. The game is based on a simple linear sequence of sequentially dependent process steps with hand-offs from one stage to the next determined by the roll of a die, thus mimicking a process subject to variability (Tommelein et al. 1999; Tommelein et al. 1998).

Despite being initially a personal game simulation or a computer simulated-based game, the Parade Game can also be played physically in a classroom. The game lends itself to a rich discussion of strategies to cope with variability in production systems. Since the Parade of Trades was introduced as a teaching tool for Lean construction in the late 1990s, it has not only become a widely used exercise in classroom and practitioner training settings to teach Production Planning and Control concepts (Tommelein 2020), but also a reference system for further study by scholars worldwide (Deshpande and Huang 2011). At the onset of the crisis caused by COVID-19 in early 2020, the traditional educational model, based on masterclasses and linear teaching materials, required adaptation to the demands of society. As a result, it became necessary to use technology to address the challenges experienced by several universities, from traditional learning to emergency remote teaching (ERT), and the impact on apprenticeship and student satisfaction (Hodges et al. 2020).

In such circumstances, five researchers and academics from different institutions (Brazil, Chile, Ecuador, and Spain) decided to create the Research Group of Young Researchers for Architecture, Engineering, and Construction Industry (YR4 AECI – www.yr4aeci.org) on May 29th, 2020.

One of those challenges was to find ways to adapt the Parade Game back to the virtual environment without using computer simulations. There are several reasons for not using the game with computer simulation, some examples proposed by Deshpande and Huang (2011) are (1) unawareness of the capabilities of simulation tools, (2) difficulty in obtaining the necessary resources (i.e., computers and simulation software), and (3) the instructor's inability to use the latest technology.

In this way, a version created by ASKM & Associates, LLC and Navilean LLC under copyright Creative Commons license - Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) was presented at the 28th Congress of the International Group for Lean Construction (IGLC 2020) during the lean construction gaming session. Furthermore, the template developed in MS Excel was made available to the simulation participants by the game facilitator.

This work aims to measure the students' learning of the variability concept using the Parade Game version developed by ASKM & Associates. For that, the authors compared the results of the game application in three different universities of South America, those being: Universidade Federal de São Carlos (UFSCar), Universidad Nacional Andrés Bello (UNAB) and Pontificia Universidad Católica de Valparaíso (PUCV).

BACKGROUND

ORIGIN OF PARADE OF TRADES GAME

Initially, Greg Howell created the game to teach construction students at the University of New Mexico in early 1994. In 1998, the Parade Game was developed to research lean construction and new materials management technologies (Tommelein et al. 1999). In this version, the game takes place in a computing environment using the dice game strategy and the software STROBOSCOPE, an acronym for STate and ResOurce Based Simulation of COnstruction ProcEsses. Stroboscope is a simulation programming language specifically designed to model construction operations of any complexity (Martinez 1996). Alarcón and Ashley (1999) also developed a Parade Game version using the simulation program @Risk.

The Lean Construction Institute (2020) markets a game kit containing seven sets of 35 colored chips; 7 dice sets - each pack has ten dice in total: 3 reds, three blues, three blacks, one green; 49 spreadsheets; 7 scoresheets; 1 instruction manual; 1 Parade of Trades in CD-Room. The computer simulation allows students to experiment with various alternatives to sharpen their intuition regarding variability, process yield, buffers, productivity, and team sizing (Tommelein et al. 1999).

THE NEW VERSION OF PARADE OF TRADES

The game consists of the execution of seven activities, linear and sequential, that must occur on each floor of a 35-story building. The game has the following objectives: (1) to understand the effect of process variability on the workflow of dependent activities, distinguishing the production capacity of the teams; (2) to understand what buffers are and what they are for; and (3) to interpret a flowline of the game's activities. The definitions of the concepts used in the game are:

- Production capacity: the number of activities per unit of time that a crew is technically able to finalize if there are no constraints (Tommelein et al. 1999).
- Production rate: number of activities per unit of time a team can perform when considering different constraints such as lack of material, incomplete predecessor activity, or wrong place for work (Tommelein et al. 1999).
- Buffers: Strategy to protect dependent activities to ensure their execution as planned (i.e., by making the crew have service packages available to execute so that the constraints do not influence the actual production) (Koskela 2000; Tommelein et al. 1999).
- Flowline chart: graphical representations of the number of service packages performed as a function of time, making it possible to verify the location of the services performed, identify the cycle, waiting time, and variability, making the process transparent (Priven et al. 2014; Tommelein et al. 1999).

The game is played in two rounds to understand the concepts presented; each one is available in the template tabs, and the results obtained in them must be compared with the steady production tab. The game is based on dice probabilities, using cubic dice with six faces. Figure 1 illustrates the dynamics of the game.

The game requires eight people: one is the facilitator who leads the game, and the other seven are the crew' leaders of each activity. The last activity, Accessories, will only start in the seventh week, namely, in the game's seventh round. Each activity's production capacity in each round is defined by the number displayed in the dice rolled by the crew's leader of that activity. Thus, the maximum production capacity of a team is six floors per week (round), and the minimum is one floor per week; consequently, the average productivity of each crew is 3.5 floors per week. The average productivity for the seven activities on the 35 floors of the building is determined after concluded the first activity, "Layout", will be completed on all 35 floors in the 10th week, and the last activity, "Accessories", will be completed in the 16th week.

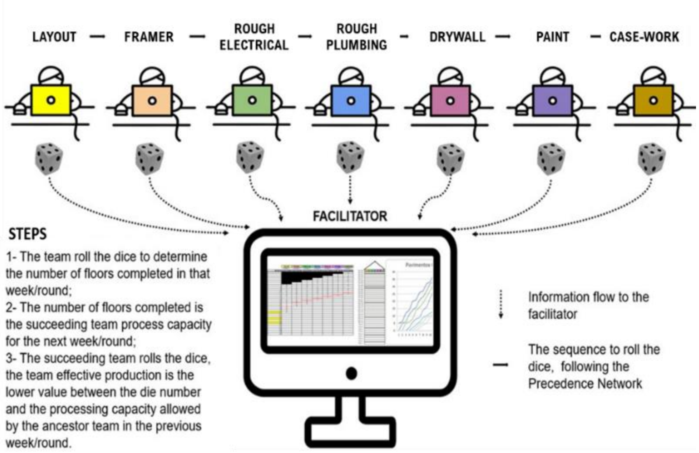


Figure 1: Parade Game version adopted in this work

Let us consider that all activities achieve the maximum production capacity (six floors per week). The first activity will be completed in the 6th week and the last activity in the 12th week. If we consider the minimum production capacity (1 floor per week), the building's deadline extends to 41 weeks. Since the proposed game is based on the chances that six-sided cubic dice can result in each roll, the building's deadline should be between 12 to 41 weeks.

For the first seven rounds, one activity is included at a time, so only the "Layout" team rolls the dice in the first round, resulting in productivity for the week. Then, in the second round, the "Framer" team starts rolling the dice to result in this team's production capacity for the week. However, at this time, the production of the predecessor team ("Layout") in the previous week should be considered to identify whether the production capacity might be reached or not.

In the first seven weeks, in each round, a new activity or team is included in the game, and its production capacity for the week is defined by the number displayed on the die. As crews execute the possible production in each round/week, the 35 floors of the building will be progressing until all the seven teams arrive at the last floor, i.e., when the game ends. At this moment, it is possible to (a) draw the flowlines chart according to the productivity executed by the crews every week; (b) interpret and analyze the impact of variability in crews' productivity in successor activities; and (c) discuss the use of buffers to protect the production against variability. The final discussion with the students is essential to achieve the learning objectives proposed by the game.

RESEARCH METHOD

The main activities conducted were: (1) population selection for applying the game; (2) questionnaire development; (3) game application; and (4) game results analysis.

Population Selection for Applying the Game

The game was played by three student groups in three universities, one from Brazil and two from Chile. The main characteristics of each course and the game participants are summarized in Table 1.

Table 1: Description of the courses and game participants

	Universidade Federal São Carlos (UFSCar)	Pontificia Universidad Católica de Valparaíso (PUCV)	Andres Bello University (UNAB)
Bachelor course	Civil Engineering	Civil Engineering	Civil Engineering
Name of the course	Planning and Control of Production	Planning and Control of Projects	Lean Construction
Application day	September 3rd 2020	October 14th 2020	October 15th 2020
Platform	Google Meet Platform	Zoom	BlackBoard
Number of students	60	23	7
Number of responses	54	22	7

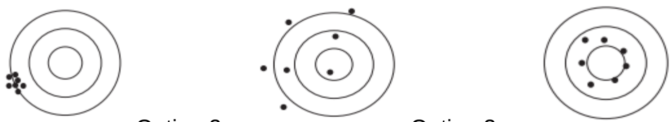
Due to the COVID-19 pandemic, classes were offered remotely on an emergency basis and not mandatory. We collected 83 responses from this questionnaire from a total of 90 participating students. Students do not know the correct answers.

Questionnaire Development

The task of creating the questionnaire involved three main steps. Firstly, two of the authors of this paper developed a pilot questionnaire. For that, they determined the questionnaire format, the questionnaire length, and the concepts to evaluate. Then, an expert committee made by the rest of the authors of this paper (5 members) reviewed the questionnaire to make sure it was accurate, free of item construction problems, and grammatically correct. In addition, during the questionnaire evaluation, the committee analyzed the validity of the constructs, those being: process variability, buffers, and flowline. The construct validity can be evaluated by estimating its association with other variables (or measures of a construct). Furthermore, in this study, for understanding the constructs, several concepts were adopted (production capacity and production rate), as previously mentioned. Finally, the final version of the questionnaire (Table 2) was developed, and the correct answers were highlighted in bold.

Table 2: Questionnaire developed for evaluating the learning of the concept of variability through the game Parade of Trades

N°	Questions and alternatives
1	What effects of high variability (in construction processes with dependency relationships) on a construction project? a: Increases productivity, decreases runtime, and improves performance. **b: Decreased productivity, increases runtime, and reduces performance.** c: None of the above. d: All previous ones. e: I don't know the answer.
2	What is the difference between processing capacity and production rate? a: There is no difference between the two concepts. **b: Processing capacity is always greater than or equal to the production rate**. c: Production rate can be greater than processing capacity. d: Production rate can never be achieved. e: I don't know the answer.

N°	Questions and alternatives
3	What is a flow line?
	a: A graphical way to represent the performance of a process.
	b: Mathematical model of representation of the relationship between activities.
	c: Model of representation of the production rhythm.
	d: A graph of the representation of the dependency relationship between activities.
	e: I don't know the answer.
4	In a flowline, what does it mean when the lines of two activities are parallel?
	a: That the activities ended within the same time frame.
	b: That both activities are the same construction process.
	c: That activities have the same productivity during the week.
	d: That the processing capacity of the two activities is the same.
	e: I don't know the answer.
5	What are buffers?
	a: They are a tool to eliminate waste from processes.
	b: They are used to reduce uncertainty in the construction.
	c: It is a kind of constructive process to improve productivity.
	d: They are a mechanism to avoid possible impacts of variability.
	e: I don't know the answer.
6	If your goal is to reach the target, which of the scenarios below do you prefer?
	a: Option 1.
	b: Option 2.
	c: Option 3.
	d: I don't know the answer.
	
	Option 1 Option 2 Option 3
7	Looking at the image below, tell us what buffers are for in production planning?
	a: Prevent the train from advancing beyond the end of the track.
	b: Prevent a production activity from advancing beyond the scheduled time.
	c: Protect the platform from possible impacts of trains that cannot break before.
	d: Protect a production activity from possible impacts of other production activities that fail to end within the established deadline.
	e: I don't know the answer.

GAME APPLICATION

The game application involved four different phases: (1) Pre-game questionnaire: Access and answer to the questionnaire; (2) Game presentation to students: play the game with volunteers; (3) Play the game with all the students (volunteers and facilitators); and (4) Post-game questionnaire: re-answer the same questions.

In the first phase, the students received the access link to a virtual questionnaire composed of seven multiple-choice questions, including "I don't know the answer" as one of the answer alternatives.

In the second phase, the game was presented to the students by sharing the teacher's screen, and its objectives and rules were described. The first game round was developed with the teacher as a facilitator and volunteer students as team leaders of the seven activities depicted in the network of Figure 1. The facilitator collected the crews' productivity information and typed in the template available in MS Excel. It was possible to follow the activities' progress on the building's different floors in each round (Figure 2). As described above, students representing each activity reported the number obtained by throwing the virtual dice (a designated website was used). The first-round results were represented in the flowline graph of Figure 3b, and the variability and buffers concepts were explored with the students.

In the third phase, the first volunteer students from the first round became facilitators of a new round with other students. They used a virtual meeting platform to create new meeting rooms and invited seven students to join them. After the completion of this new match, the graphs of the groups of students that reached the shortest and longest lead time of the building construction were compared and discussed again, observing the characteristics of the steady production flowlines (Figure 3a), and, again, reinforcing the concepts of variability and buffers.

The fourth and final phase was dedicated to re-answer the questionnaire presented in Table 2 to measure the learning brought after the game.

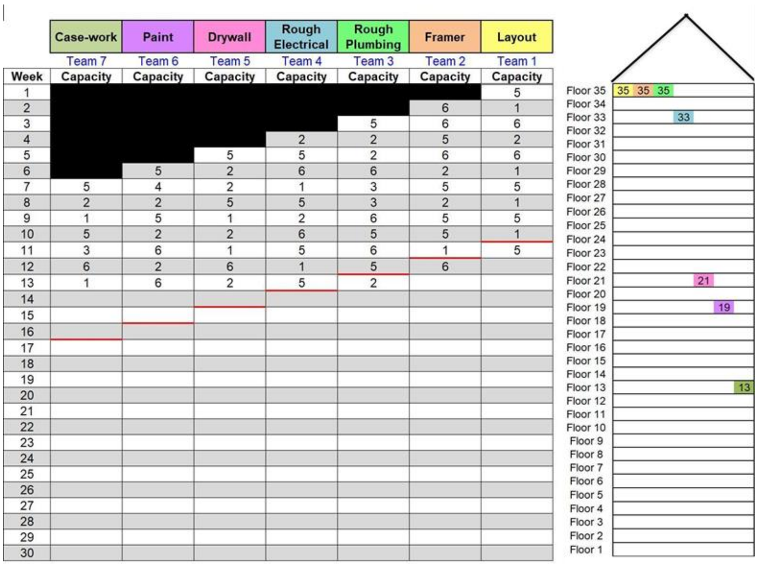


Figure 2: Game scenario (first-round): week 13 of the building process. Teams 4 to 7 have not yet finished their tasks.

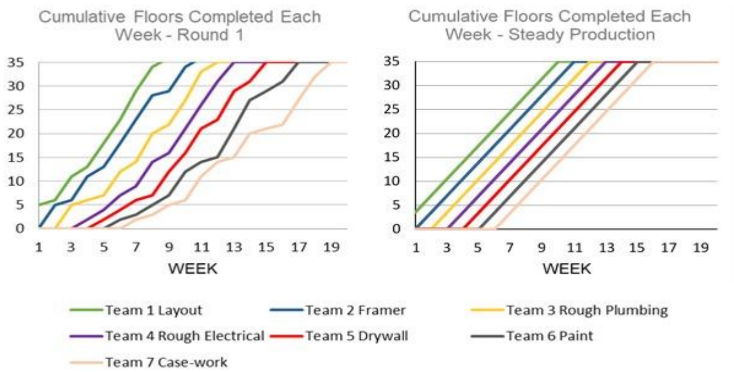


Figure 3: Graphs of flowlines of (a) performed by the teacher-facilitated, and (b) steady production

GAME RESULTS ANALYSIS

At the end of the game, the students answered two additional questions. Firstly, the students answered the following question "Do you believe that this sort of game strengthens the process of teaching-learning?" For this question, the Likert Scale of five points was adopted: (1) strongly disapprove; (2) disapprove; (3) neutral; (4) approve; and (5) strongly approve. Secondly, the students answered the closed question: "Would you like to play other games like today's game in the future?"

Finally, a reflection was made comparing the initial and final results, analyzing the correct answers and the most common errors. The analysis consisted of calculating, in each question, the percentage of students who answered correctly before and after the game. Additionally, in each question, the percentage of students who did not know the answer before and after the game was calculated.

RESULTS AND DISCUSSION

We analyzed the pre-and-post-game responses provided in the questionnaire. Figure 4 presents the percentage of correct answers per question before and after the game application. Also, Figure 5 shows the percentage of students who marked the alternative "I don't know the answer" before and after the game. In general, there was an increase of 20% in the correct answers in the post-game scenario and a decrease of 12% in the "I don't know" answer, therefore reinforcing that virtual educational games are an essential learning tool. The following is a question-by-question analysis.

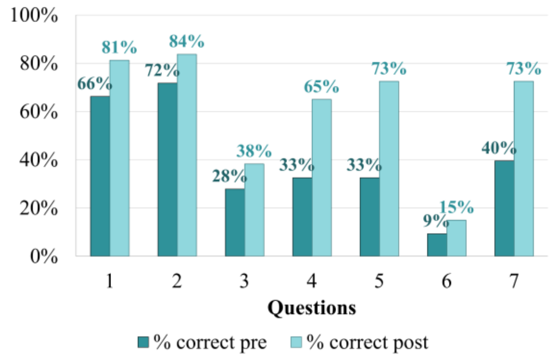


Figure 4: Percentage of students' correct answers to the pre-and-post-game questionnaire

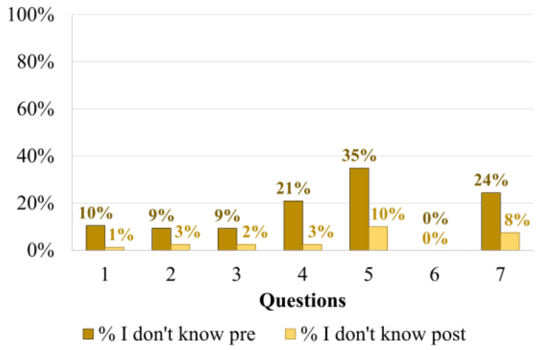


Figure 5: Percentage of students' "I don't know the answer" to the pre-and-post-game questionnaire

First, question 1, related to the impact of the variability in the construction process, has a high percentage of correct answers, even in the pre-game scenario (66% of correct answers, Figure 4, i.e., most of the civil engineering students sensed the impact of variability before playing the game). Then, post-game, this percentage rises to 81% (Figure 4) of correct answers, while the percentage of students who responded that they did not know the answer decreased by 9% (from 10% to 1%, Figure 5). Therefore, it is possible to infer that most of the increase in correct answers is associated with students who were not sure of the impact of variability before the game was played.

Second, question 2, related to the difference between the processing capacity and production rate, has a high percentage of correct answers in the pre-game scenario (72%, Figure 4). After the game, the correct answers' portion increased to 84% (difference of 12%, Figure 4), and the percentage of students who did not know the answer was only reduced by 6% (from 9% to 6%, Figure 5). In post-game, a group of students who did not know the answer succeeded in answering correctly, and a percentage of students who answered incorrectly in the pre-game succeeded in answering correctly after the activity.

Third, questions 4, 5, and 7 had the most significant correct answers from pre-game to post-game. Only about one-third of the students answered correctly in the pre-game, while two-thirds of the students got the correct answer in the post-game. Notably, in question 5, associated with buffers' concept, 35% of the students answered "I do not know the answer" in the pre-game, a percentage that was reduced to 10% in the post-game questionnaire (Figure 5).

Finally, it is observed that, for questions 3 and 6, less than half of the students selected the correct alternative even after the game (38% and 15% of correct answers, respectively, Figure 4). In this context, it is also observed that question 3 had a high frequency of "I do not know the answer" alternative, even after the game application (9%, Figure 5). These observations indicate that the knowledge necessary to answer such questions correctly was not sufficiently explored by the game for most students, despite the knowledge gained in the pre-and-post-game stages. Mainly, question 6, related to the concepts of precision and accuracy, is the one with the lowest percentage of correct answers (9% in the pre-game and 15% in the post-game, Figure 4); additionally, students did not doubt their answer, always preferring low precision (high variability) and high accuracy. These results reinforce the need for a paradigm change in production systems and variability in construction projects. Questions 3 and 6 explore, respectively, the concepts of flowline and how variability influences decision-making. These concepts were addressed after applying the game and should be put in focus in classes. Subsequently, most students can understand these concepts and apply them to production planning and control.

The results of the game evaluation to measure the level of approval from "strongly disapprove" to "strongly approve" indicate that most students consistently approve of the game. To summarize, 56% of responses strongly showed approval, 32% approve, 11.5% indecision, and 0% answers were strongly disapproving or disapproving. Regarding the students' interest in playing a similar game in the future, the yes-no question's results indicate that 87.5% of the students would like to play again, 2.5% of the students would not like to repeat, and 10% would like to play again of the students showed indecision.

CONCLUSION

This study aimed to evaluate the effectiveness of the "Parade of Trades" game for teaching the variability concept. A questionnaire was developed and tested with the Production Planning and Control course's students in Civil Engineering in three universities, one from Brazil and two from Chile. The main contribution of this study is the evaluation of learning brought by the game.

By administering the same questionnaire in two phases, before and after the game, it was possible to measure the students' learning about the concepts addressed by the game. Evaluating the pre-and-post-game responses, there was an increase of 20% of correct answers and a reduction of 9% in the alternative "I don't know the answer" in all questions. Besides, this work allows educators in engineering, architecture, and construction schools to use the game in virtual environments. The experience of applying the Parade of Trades game to the virtual environment proved successful, considering the students' engagement and the use of different tools that facilitate remote teaching.

This work's main limitations where the virtual game was applied in only two countries; therefore, it is recommended that the game and questionnaires be used in a larger sample of countries and cultures. In addition, in the three applications of the game, the educators did not explain previous concepts theoretically; therefore, it would be interesting to evaluate two scenarios (1) with previous theoretical explanation and (2) without an earlier theoretical explanation. The questionnaire's answers were anonymous, which did not allow individual traceability of the percentage of correct answers of each student before and after the game; therefore, it is recommended to conduct a personal analysis and evaluate if there are significant differences between the pre-game and post-game. The results of the application of the questionnaire showed a low percentage of achievement in the identification and comparison between the concepts "precision" and "accuracy" - question 6; therefore, it is necessary to review how to integrate these concepts in the game and check if the question related to this topic is the one allows demonstrating the understanding of these concepts.

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REFERENCES

Alarcón, L.F., and Ashley, D.B. (1999). "Playing games: Evaluating the impact of lean production strategies on project cost and schedule." *Proc. 7th Ann. Conf. Int. Group for Lean Construction*, p.263-274, Berkeley, USA.

Choo, H. J., and Tommelein, I. D. (1999). "Space scheduling using flow analysis." *Proc. 7th Ann. Conf. Int. Group for Lean Construction*, p.299-312, Berkeley, USA.

Deshpande, A.A., and Huang, S. H. (2011). "Simulation games in engineering education: A state-of-the-art review." *Computer Applications in Engineering Education*, v.19, n.3, p.399-410. doi.org/10.1002/cae.20323.

Hodges, C., Moore, S., Lockee, B., Trust, T.; Bond, A. (2020). "The difference between emergency remote teaching and online learning." *Educ. Rev.* 27, v.3, p.1–12.

Koskela, L. (2000). "An exploration towards a production theory and its application to construction." 296 f. *Doctoral thesis.* Technical Research Centre of Finland, VTT Building Technology, Finland.

Lean Construction Institute (LCI). (2020). "*Parade of trades simulation*." https://www.leanconstruction.org/learning/game-simulations/parade-of-trades-simulation/.

Martinez, J.C. (1996). "STROBOSCOPE State and Resource Based Simulation of Construction Processes." *Doctoral thesis*, University of Michigan, Ann Arbor, Michigan. Available in: http://www.ioannou.org/stroboscope/strobo-pubs.

Priven, V., Sacks, R., Seppänen, O., and Savosnick, J. (2015). "A lean workflow index for construction projects." *Proc. 22nd Ann. Conf. Int. Group for Lean Construction*, p.715-726, Oslo, Norway.

Rybkowski, K.S., Forbes, L. H., and Tsao, C. (2018). "The evolution of lean construction education (Part 1 of 2): At US-based universities. *Proc. 26th Ann. Conf. Int. Group for Lean Construction*, p.1013-1023, Chennai, India.

Tommelein, I. D., Riley, D. R. and Howell, G. A. (1998), "Parade Game: Impact of Workflow Variability on Succeeding Trade Performance" *Proc. 6th Ann. Conf. Int. Group for Lean Construction*, p.13-15, Guarujá, Brazil.

Tommelein, I. D., Riley, D. R., and Howell, G. A. (1999). "Parade game: Impact of workflow variability on trade performance." *J. Constr. Eng. Manag.*, v.125, n.5, p.304-310. doi.org/10.1061/(ASCE)0733-9364(1999)125:5(304).

Tommelein, I. D. (2020). "Takting the Parade of Trades: Use of Capacity Buffers to Gain Work Flow Reliability." *Proc. 28th Ann. Conf. Int. Group for Lean Construction*, p.421-432, Berkeley, USA.

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People, Culture, and Change

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A CASE-BASED STUDY OF LEAN CULTURE AMONG SOUTH AFRICAN CONTRACTORS

Fidelis Emuze[1] and Willem Mpembe[2]

ABSTRACT

Problems such as low productivity, poor health and safety, poor working conditions, waste and insufficient quality, and poor performance are experienced in the South African construction industry. The call for change is necessary as South African construction is constrained by a lack of required skills and under-performing employees and management, which collectively generate waste on projects. However, lean construction (LC) concepts, tools and techniques could be used to resolve such problems that exist in South African construction.

Thus, the study reported in this paper was undertaken to investigate how contractors could help to drive the implementation of lean construction in South Africa. A multi-case-study research design was used to discover how contractors could address implementation problems by adopting a lean culture. The results from the study, obtained through cross-case analysis, showed that the contractors perceived that LC cannot be implemented so there is significant scope for tackling resistance to change through engaged LC education and training.

KEYWORDS

Contractors, culture, leadership, lean construction, people.

INTRODUCTION

Lean construction (LC), which is the application of lean thinking to the design and delivery of projects (Tommelein & Ballard, 2016), has been practised in other countries in recent years but has not been adopted fully in the construction industry in South Africa. LC is understood to be a new project management philosophy which differs from traditional project management in the ways in which goals are pursued, phases are structured, and the ways in which the phases and the participants within each phase are related (Ballard & Howell 2003). LC is not only a way to reform how work on projects is performed, but also a way to design production systems to minimise waste of materials, time, and effort in order to generate the maximum possible amount of value (Forbes & Ahmed 2020).

According to Emuze and Ungerer (2014), change is necessary in South African construction that is constrained by a lack of appropriate skills, motivation and leadership, and under-performing employees, which fuel the wastes encountered in the sector. Various chronic problems, such as low productivity, poor safety, inferior working

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conditions, waste and defects are experienced in South African construction, similar to other countries around the world (van Rooyen 2010). However, other countries (especially developed countries in North America and Europe) have embraced LC to solve some of these common problems. AL-Najem et al. (2012) noted that there is growing concern in the corporate world about the implementation of lean practices in large organisations and small- and medium-sized enterprises (SMEs). One of the reasons for this is a lack of understanding of culture, and the critical issues of lean implementation are related to organisational culture (AL-Najem et al. 2012).

The need for change in South African construction is evident from the number of performance-related issues that have appeared in media headlines relating to fatalities and overruns of project time, amongst others (Emuze & Ungerer 2014). Contractors should consider the implementation of lean practices to improve project and business outcomes. However, the efforts of contractors will fail to have an effect if organisational cultural barriers, militating against successful implementation, are not identified and understood. In effect, knowing the cultural barriers of an organisation helps to achieve successful implementation of LC to obtain optimal results (Sarhan & Fox 2013).

The central research question of this study was how contractors could help to drive the implementation of lean construction in South Africa. Although management problems facing contractors, and the leadership attributes that affect how contractors think and act lean were also examined in the study, in this paper, the data on how managing organisational culture could help contractors to engender lean practices in their enterprises have been presented.

OVERVIEW OF HOW CULTURE AIDS LEAN PRACTICES

Lean principles relate mainly to reducing waste in either project or organisational processes. Thus, establishing an organisational culture with a waste elimination mind-set promotes the lean philosophy (Puvanasvaran et al. 2015). According to Scoggin (2017), it has been reported that cultures not only affect the psychological process of individuals, but also the sociological, political, and economic functioning of organisations. Culture is a key factor in successful implementation of lean principles, for it determines the acceptance or rejection of ideas or processes and, ultimately, whether an organisation can be sustained in a competitive environment (Pakdil & Leonard 2015). Contractors are involved directly in the process of implementation and, therefore, have an understanding of organisational culture, its impact on performance, and its effects on employees' behaviour. Puvanasvaran et al. (2015) mention that it is necessary also to change the organisational structure to make it more flexible, and continue by arguing that flexibility enables the redeployment of organisational resources to satisfy customers' needs. To avoid employees' resistance to change, it is critical to involve all employees in the adoption of the principles from the start.

Organisational culture has an impact on performance since it affects behaviour, and also it is a key factor in the success of lean processes because culture determines whether an idea or process is accepted or resisted (Santorella 2017). Organisational culture also provides employees with an organisational identity, which normally begins with a leader who articulates and implements particular ideas and values in the form of an organisational vision. Implementation of lean practices requires significant investments by the organisation, including time and money but, if employees return to previous behaviour, the improvement cannot be sustained over time and fails. An effective, lean manufacturing transformation requires an organisation to identify and address the culture within its working environment (Ahmad 2013; Fadnavis et al. 2020). Fadnavis et al. (2020) showed that there is a positive correlation between organisational culture and the ability of team members to engage in structured problem-solving practices for continuous improvement. Thus, leaders need to possess an understanding of the various types of organisational cultures in order to create and align the organisational structure effectively to the desired lean system.

Leadership, communication, empowerment and teamwork are elements of lean culture that are essential to improvement (Rubrich 2012). These four elements will help contractors to develop guiding principles or behavioural expectations. Sarhan and Fox (2013) show that although there seems to be positive trends in the development of a lean culture amongst UK contractors, but there is a major lack of understanding of how to successfully apply lean to specific construction processes and activities. According to Sarhan and Fox (2013 p.3), the construction industry is known to be opportunistic, prone to conflict and resistant to change. Therefore, changing traditions and behaviour is a necessary prerequisite for implementing LC in South Africa. Several authors have discovered that structural patterns in resistance to change, apathy towards, or limited, training, and lack of contractor engagement hinder the implementation of lean practices in organisations (Rooke 2020).

Having explored how LC should be implemented by contractors in South Africa, van Rooyen (2010) contended that construction companies need to learn how to manage in an environment of rapid change and uncertainty, and LC offers concepts and tools to assist them. Nine years after the study by van Rooyen (2010), it is still unclear whether such learning is taking place within construction organisations in South Africa.

RESEARCH METHOD

The scope of this study involved three building projects in Bloemfontein, South Africa. The three cases were on-going, commercial construction projects at the time of data collection in 2019. A case-study research strategy was used for the study as it promotes in-depth inquiries (Yin 2013). The data were collected by conducting semi-structured interviews, supported with a demographic questionnaire.

Creswell (2013) emphasised that, when dealing with case studies, a researcher must select a sampling strategy that represents multiple perspectives in order to build sound empirical evidence. According to Yin (2013), the sampling strategy determines the depth of the accumulated empirical detail. For this reason, the sample was selected according to the purposive convention, as explained by Yin (2013).

The three projects were selected purposively, based on the experience of the main contractors in terms of managing projects. The same criteria (experience and exposure) were followed in selecting the consulting professionals who were interviewed. The interviewees included contract managers, site agents, a site engineer, construction project managers, foremen, supervisors, quantity surveyors, artisans, and general workers and their respective assistants, as shown in Table 1. The consulting engineer's team had been appointed to advise the projects in all three cases, which was why they were considered as being part of managing the projects. The client and sub-contractors did not form part of the interviews because they did not form part of running or managing the projects.

Table 1: Demographic Data

Case	Construction Team	Consulting Team	No.
Case Project 1: (Retail Organisation)	1 Site manager 3 Foremen 1 Jnr Foreman 1 Artisan (steel)	2 Project managers	**9**
Case Project 2: (Parking Garage)	1 Project manager 1 Director 1 Contract manager 1 Jnr Site agent 1 Project administrator 2 Jnr Quantity surveyors	1 Contract manager 1 Technician	**8**
Case Project 3: (Refurbishment)	1 Contract manager 1 Jnr Contract manager 1 Quantity surveyor 2 Jnr Quantity surveyor 1 Site engineer	1 Principal technician 1 Project manager	**8**
Total Interviewees			**25**

The data analysis in case studies involves consolidating details about the case by examining, categorising, tabulating, and assembling the evidence to produce meaning. Yin (2013) mentioned that similarities across cases lead to replication of results in multiple case studies. Such replication provides the basis for compelling arguments. Also, Yin (2013) highlighted five analytical techniques for textual data analysis. These include pattern matching, explanation building, time series analysis, logic models, and cross-case synthesis. Cross-case analysis was suitable for this research since it involved data from interviews that were required to interpret the elements of each case. The textual data from the interview followed the open ended questions while the statistical data presented in the next section are descriptive to summarise the perspectives of the interviewees. Most of the interviewees agreed that LC is a process of eliminating waste, which can be implemented in South Africa (Table 2). They affirm their awareness of LC and other related concepts so there is a basis for their participation on the study. However, there level of engagement is limited as outlined in Emuze et al. (2017).

RESULTS AND INTERPRETATIONS

In Table 2, it is shown that, of the 25 interviewees, 23 (six from case project 1, nine from case project 2 and eight from case project 3) agreed that LC involves a continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream, and pursuing perfection in the execution of a construction project, while two disagreed with the statement. The responses showed that most of the interviewees were familiar with LC principles. As indicated in the table, 21 interviewees affirmed that they were aware of the possible impact that LC could have on South African construction. However, 18 of them indicated that, as contractors, they did not think LC could be implemented in South Africa.

Table 2: Interviewees' Perceptions of Lean Construction Principles

Questions	Interviewees' Responses		
	Yes	No	Unsure
Lean construction is continuous process of eliminating waste and meeting all customer requirements, and pursuing perfection on a project.	6+9+8 (23)	2	0
Awareness of the impact of lean construction in South Africa.	6+9+6 (21)	1+2 (3)	1
As a contractor, do you think lean construction can be implemented in South Africa?	4+7+7 (18)	2+2 (4)	2+1 (3)

In Table 3, it is shown that 21 interviewees perceived that there was resistance to LC in South Africa, while four of them disagreed. The lack of knowledge about LC among contractors was proposed as a major reason for the slow pace of adoption and four of the interviewees did not agree with the notion. However, most interviewees (23) agreed or strongly agree that leadership in organisations would play a major role in LC becoming mainstream in South Africa. The interviewees also concurred that adopting LC could help to reduce problems in South African construction. Thus, they believed that there should be increased awareness.

Table 3: Perceptions of Contractors' Attitude towards Lean Construction

Aspect	Strongly Disagree	Disagree	Agree	Strongly Agree
There is resistance to change to LC in South Africa	0	2+1+1 (4)	5+6+5 (16)	1+2+2 (5)
Lack of LC knowledge is the reason why South African construction is taking time to develop the system.	0+1 (1)	1+1+1 (3)	4+3+5 (12)	3+5+1 (9)
Leadership plays a significant role in organisations transforming to LC.	0	1+1 (2)	4+4+4 (16)	3+4+2 (9)
Adopting a new system such as LC can help reduce problems in South African construction.	0+1+1 (2)	0+0+0	3+3+6 (12)	5+5+1 (11)
There is a need to increase LC awareness in South African construction.	0+0+0	0+1+1 (2)	1+4+2 (7)	6+5+5 (16)

DATA RELATING TO ORGANISATIONAL CULTURE

The first question put to the participants about organisational culture was whether South African contractors are set in their ways or would they be willing to change.

In Case Project 1, most participants responded positively that contractors would be willing to change their culture. They indicated "Yes", if the benefits of lean construction were to be made clear to all contractors, they would be willing to change. In Case Project 2, the majority responded "No", the organisations just needed to be exposed to better working conditions, such as LC, and firms would see the benefits. In Case Project 3, the majority responded "Yes", more information about LC and awareness would educate them more and, even though people were resisting change, with appropriate systems in place, people would adjust. The responses, as shown in Table 4, indicated that, while change towards LC is possible, the fixation on profit, low awareness of LC benefits, and unethical practices would slow down uptake of the approach. The creation of awareness by leaders in contracting firms, who also prioritise ethical ways of profit-making, should help to dismantle resistance to change. Knowing the dimensions that influence lean effectiveness and the way in which they exercise their influence, would enable company leaders to develop an organisational culture that would support the implementation of lean practices (Pakdil & Leonard 2015).

Table 4: Responses Related to Change in Organisational Culture

Case	Interview Responses
Case Project 1	• No, they are not and the unwillingness to change will derail the success the firms envisage to achieve but they recognise change is inevitable. • Yes, they can change and some are willing because of the economy that is against their company, lack of projects, being feared of company being liquidated. • If the benefits of lean construction were to be made clear to all, I believe they or other contractors will change.
Case Project 2	• No, they are fearful to adopt new changes. • No, they just need to be exposed to better working conditions such as lean and they will see the benefits. • Yes, they are somehow set in their ways; most contractors neglect quality of work they deliver.
Case Project 3	• Yes, many are set but corruption plays a big role on projects. • Yes, more information on lean and awareness will educate them more about lean. • Yes, even though people are resisting change but, with right systems in place, people will adjust. • No, South African contractors' main focus on project is making money instead of delivering to meet customer satisfaction.

The second question put to the participants about organisational culture was whether their company could operate at more profitable levels with their current leadership culture. Across the cases, the majority indicated "Yes", their company could operate at more profitably with the current leadership, while few participants indicated "No", change was needed in management and that there was not enough synergy within management.

The purpose of this question was to check whether a different leadership approach to management could make a difference in their performance. In Table 5, it is shown that few interviewees were in favour of an alternative leadership approach to managing their projects. There were only a few dissenters among them. The comments in Table 4 and 5 showed that there was scope for engaged and informed LC training among the firms involved in the case projects.

Table 5: Responses to Organisational Culture Relating to Leadership Style

Case	Interview Responses
Case Project 1	• Yes, diversity and commitment to apply lean concept should be key. • Yes, in terms of tendering such as charging high from doing projects, but as for running the projects things are done smoothly. • No, the leadership is fine.
Case Project 2	• Yes, fresh ideas bring new thinking. • Yes, the current leadership approach has to be utilised and judging the challenges currently facing management it is quite clear that a different option or choice can be tried. • Yes, there is always better way or different leadership approach to better what is currently done. • No, we have great management team.

The third question about organisational culture asked the participants to indicate whether a different leadership approach to management could make a difference to company performance.

Relating to the practice of organisational culture, the responses in Table 6 indicated that the elements of LC were not addressed adequately. In Case Project 2, the project team admitted that the current leadership approach had to be utilised and, judging from the challenges currently facing management, it was quite clear that a different option should be tried. In Case Project 3, the team responded that the management and leadership were tools, so bringing in new ideas would lead the firm to greener pastures, as change towards improvement is always needed and LC would bring that. The responses in Case Project 1, where the majority believed that current leadership was fine, gave an opportunity to engage the team with LC philosophies, such as continuous improvement.

Table 6: Responses to Organisational Culture Relating to the Viability of LC

Case	Interview Responses
Case Project 1	• Yes, can improve productivity and also save money. • It can improve some sort of way maybe on financial side; company can get more money out of it.
Case Project 2	• Yes, we will finish project within the client budget. • Yes, provided that what lean entails, how it should be implemented and continue to use it. • Yes, it encourages sustainable construction and sustainable construction as a key dimension of sustainable development, making construction saving a lot of cost on material and procedures. • Yes, it is better for construction and the future development policies of organisations. • Yes, lean with the aim of decreasing time, waste of material and increase in production need to involve all parties in the project from design team to planning.
Case Project 3	• Yes, lean is a sustainable thing. • Yes, lean provides essential features such as clear set of objectives for delivering projects. • Yes, company can see ways to mitigate delays and cost overruns; also removal of waste. • Yes, lean will ensure better management skills which will improve overall work environment in terms of material handling, staff participation and productivity. • Yes, workers will be exposed to training and would be better at what they are doing on site. • Yes, lean thinking will minimise waste and encourage efficiency.

The fourth question about organisational culture asked the interviewees whether lean thinking was a viable option for better performance and management change in their company.

The participants had different views on LC being a viable option for better performance. In Case Project 1, the majority responded “Yes”, LC could improve productivity, it could improve the financial in side some way, and the company could gain more money out of it. In Case Project 2, the interviewees responded “Yes”, LC would be better for construction and the future development work of organisations. With the aim of decreasing time and waste of material, and increasing production, it would be necessary for LC to involve all parties in a project from design team to planning. In Case Project 3, the interviewees said “Yes”, LC would ensure better management skills, which would improve the overall work environment in terms of material handling, staff participation and productivity. Also, workers would be exposed to training and would be better at what they were doing on site.

CONCLUSIONS

The question of how contractors could help drive the implementation of lean construction in South Africa was examined in the qualitative study reported in this paper. The findings of the study revealed that, although awareness of LC existed, contractors were resisting implementation. While some contractors believed that change was necessary and that LC promised great potential, there was dissent amongst the participants in the study sample. The interviewees were yet to come to the understanding that LC is based on a culture of respect and continuous improvement, aimed at creating value for the client by removing waste from the design and construction process (Seed 2017). As an illustration, the interviewed contractors can try to learn from DPR Construction. The form is an LC leader that attributed its success to its people and culture Maestas & Parrish, 2014). In the firm, values and foundational principles are aligned to the positive change in the company.

It can be argued that the lack of projects demonstrating LC, the lack of hands-on experience of LC, and limited LC competencies among the contracting teams contributed substantially to their perspectives. The variance in views about LC might account for the inability of the project team-members interviewed to address the concepts in their organisations. Also, the interviewees had little knowledge of LC and its benefits according to the data.

Given that knowledge can be acquired through observation and study, it is essential to make LC education and training more accessible to practitioners through formal qualifications and continuous professional development (CPD) courses. Although researchers in tertiary education in South Africa are now producing treatises, dissertations and theses on LC from mainly two universities, the renewal of curriculum will add more strength to this endeavour. In a short time, availability of CPD courses could assist busy professionals such as the interviewees who indicated that their management have not tried LC in their performance improvement drive.

Thus, it was apparent that LC culture was lacking among contractors in the region. The challenge to implement LC lies in the establishment of an organisational culture that will enable the system to operate better in project-based, organisational settings. A step in the right direction to remedy the situation would be to use leadership, communication, empowerment, and teamwork (four elements) to effect change of culture in organisations. Doing so will support the use LC to create a common language and culture in contracting firms by providing an environment in which people with varying competencies and education can come together for a common good, which is about creating value for the client and society (Rubrich 2012).

Further research would examine how the cultural framework, which is inclusive of the four elements mentioned, could be deployed in construction companies in South Africa.

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REFERENCES

Ahmad, S.A.S. (2013). “Culture and lean manufacturing: Towards a holistic framework.” *Aust. J. Basic Appl. Sci.*, 7(1), 334-338.

AL-Najem, M., Dhakal, H. N. and Bennett, N. (2012).” The role of culture and leadership in lean transformation: A review and assessment model.” *International Journal of Lean Thinking*, 3(1), 120-138.

Ballard, G. and Howell, G. (2003). “Lean project management.” *Building Research & Information,* 31(2), 119-133.

Creswell, J.W. (2013). “Qualitative inquiry & research design: Choosing among five approaches (3rd ed.).” Thousand Oaks, CA: Sage.

Emuze, F., Masoga, T., and Sebetlele, C. (2017). “Lean Opportunity Assessment of Contractors’ Supply Chain in South Africa.” In: LC3 2017 Volume II – Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC), Walsh, K., Sacks, R., Brilakis, I. (eds.), Heraklion, Crete, Greece pp. 797–804. doi.org/10.24928/2017/0052.

Emuze, F. and Ungerer, H. (2014). “Change in South Africa Construction: Lessons from Lean Thinking.” *Proc., 22nd Annual Conf. of the International Group for Lean Construction,* Oslo, Norway, pp. 1121-1131.

Fadnavis, S., Najarzadeh, A. and Badurdeen, F. (2020). “An assessment of organizational culture traits impacting problem solving for lean transformation.*” Procedia Manuf*., 48, 31-42.

Forbes, L. H. and Ahmed, S. M. (2020). *Modern construction: Lean project delivery and integrated practices.* 2nd edition. Boca Raton: CRC Press.

Maestas, A. and Parrish, K. (2014). 'Exploring the Roots of Lean Culture at DPR Constuction - A Case Study in Lean culture' In:, Kalsaas, B. T., Koskela, L. & Saurin, T. A., 22nd Annual Conference of the International Group for Lean Construction. Oslo, Norway, 25-27 Jun 2014. pp 1413-1424.

Pakdil, F. and Leonard, K. M. (2015). “The effect of organizational culture on implementing and sustaining lean processes.” *Journal of Manufacturing Technology Management*, 26(5), 725-743.

Puvanasvaran, P., Tian, R. K.S. and Vasu, S.A. (2014). “Lean environmental management integration system for sustainability of ISO 14001:2004 standard implementation.” *Journal of Industrial Engineering and Management*, 7(5), 1124-1144.

Rooke, J. (2020). People and knowledge: Lean organization. In: P. Tzortzopoulos, M. Kagioglou and L. Koskela eds. *Lean construction: Core concepts and new frontiers*. London: Routledge, pp. 85-101.

Rubrich, L. (2012). *An introduction to Lean Construction: Applying lean to construction organizations and processes*. Fort Wayne, IN: WCM Associates.

Santorella, G. (2017). *Lean culture for the construction industry: Building responsible and committed project teams*. 2nd edition. Boca Raton, FL: Taylor & Francis.

Sarhan, S. and Fox, A. (2013). "Barriers to implementing lean construction in the UK construction industry." *The Built & Human Environment Review*, 6, 1-17.

Seed, R. (2017). *Transforming design and construction*. Arlington, VA: Lean Construction Institute.

Scoggin, J. C. (2017). The interdependency of lean implementation and organization development, PhD Thesis, Business Psychology, npp., nnp.

Tommelein, I.D. and Ballard, G. (2016). "*Lean construction glossary*". Berkeley: P2SL.

Van Rooyen, I. J. (2010). *Lean construction. Should lean construction be part of a construction company's objective in South Africa*. BSc (Hons) in Construction Management, University of Pretoria.

Yin, R. (2013). *Qualitative research from start to finish*. New York: The Guilford Press.

Salazar, L. A., Pardo, D., and Guzmán, S. (2021). "Results of Key Indicators from Linguistic Action Perspective in Pandemic: Case Study." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 363–372, doi.org/10.24928/2021/0114, online at iglc.net.

RESULTS OF KEY INDICATORS FROM LINGUISTIC ACTION PERSPECTIVE IN PANDEMIC: CASE STUDY

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ABSTRACT

Due to the low productivity of the construction sector and current global pandemic conditions, it is essential to analyze interpersonal relationships at work, engagement and labour productivity, through the management of commitments. Therefore, this article seeks to measure and analyze key Linguistic Action Perspective (LAP) indicators to examine commitment management in Last Planner® System (LPS) weekly work planning meetings during the pandemic (virtual and face-to-face meetings). The case of study methodology was used in 27 projects of a construction company in Colombia, in which the authors analyzed the results of LAP engagement indicators and compared them to the PPC, determining Spearman´s correlation coefficient in each indicator and finding that the projects that had strong correlations were those where: the percentage of progress was between 65% and 95%; average PPC was between 60% and 90%; a "Big Room" was used; and the meetings had between 10 and 20 attendees. For future research, we propose the use of other methods of relationship, causation and/or prediction analysis, such as Structural Equation Models or Machine Learning, a future methodology for virtual or semi-face-to-face meetings and the study of other performance indicators.

KEYWORDS

Linguistic action perspective, pandemic, case Study, Last Planner® System.

INTRODUCTION

CONTEXT

Several studies have shown that Lean practices manage to reduce construction times and cost, energy consumption and particulate matter; as well as improving conditions of safety, occupational health and interpersonal relationships (Ahuja 2013; Bajjou et al. 2017; Belayutham et al. 2017; de Carvalho et al. 2017; Ogunbiyi et al. 2014; Salgin et al. 2016; Verrier et al. 2016; Weinheimer 2016; Weinheimer et al. 2017). However, most of the research conducted has focused on reducing tangible waste, leaving in a secondary

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place the reduction of waste from intangible resources that are mainly caused by inadequate planning practices (Hamzeh et al. 2019).

Therefore, Last Planner® System (LPS) has focused its efforts on increasing planning reliability and performance levels (Ballard and Tommelein 2016). Because of this, it is essential to achieve adequate commitment management at weekly planning meetings, as coordinated action is required through a complex network of request and promises (Ballard and Tommelein 2016). For this reason, Howell et al. (2004) propose Linguistic Action Perspective (LAP) developed by Flores (2015). LAP is based on four stages, which form the network of commitments: 1) preparation of a request; 2) negotiation and agreements; 3) execution and declaration of compliance; and 4) acceptance and declaration of satisfaction (Salazar et al. 2018). To properly measure and control commitment management, Salazar et al. (2020) propose a LAP Indicator System, through the Design Science Research (DSR) methodology.

STATE OF THE ART AND PRACTICE

When reviewing the Web of Science database, the authors found four articles regarding "Linguistic Action Perspective" or "Language Action" in construction projects (Isatto et al. 2015; Salazar et al. 2020; Viana et al. 2017; Zegarra and Alarcon 2017). However, from these studies, including the countless IGLC publications (Howell et al. 2004; Long and Arroyo 2018; Viana et al. 2011; Zegarra and Alarcón 2013), there is only one proposal for LAP indicators (Salazar et al. 2018, 2019, 2020), but it does not explain the relationship between how these commitments are established and the outcome. In addition, only partial results of the relationship between some LAP indicators, Percentage Plan Completed (PPC) and Social Networks are shown in the publication of Retamal et al. (2020). Therefore, the publication of this case study in the pandemic, will show the measurement and control of commitments indicators in planning meetings focusing on team engagement for the first time.

NEED AND RELEVANCE OF RESEARCH

According to the above, we found a shortage of studies detailing how LPS directly affects constructions projects, since most authors propose indicators and they show the results, but do not explain how they achieved those results. Adding the particular situation we are currently living with the pandemic, we consider it essential to focus on interpersonal relationships at work, engagement and labour productivity, measuring and controlling the indicators proposed by Salazar et al. (2020) about LAP as a complement to LPS. This due to the fact that the greatest amount of effort has been made in reducing waste from tangible materials, neglecting waste from intangible resources and human behavior (Hamzeh et al. 2019). The latter is of vital importance because the core of Lean Construction is the people (Li et al. 2020).

For all of the above, our purpose is to measure and analyze key LAP indicators to review commitment management at weekly LPS meeting during the pandemic (virtual and face-to-face meetings), particularly the "Engagement" indicators proposed by Salazar et al. (2020). For this reason, we focus our study especially in the first two stages from the network or chain of commitments: preparation of a request, and negotiation and agreements. Both of them are carried out in the LPS weekly planning meetings in which we consider that the repetitive behaviors of the participants could affect a correct commitment management. We consider it to be a new knowledge, as these indicators are recent and have not been evaluated to date in a case study. So, we believe that measuring the engagement of last planners during weekly planning will be a contribution to the state of art and practice.

RESEARCH METHOD

The authors adopted the case study methodology because it allows in-depth and multifaceted scans of complex problems in a real environment (Yin 2003). This methodology applies when research addresses descriptive or explanatory questions: for example, what happened, how and why?, when the researcher has little control over events and when the phenomenon is contemporary (Yin 2003).

This research was developed in a construction company out of which 27 residential building projects were evaluated in different regions of Colombia, during the months of September to November 2020. Our goal was to analyze the results of LAP indicators and compare them with the PPC to determine whether there was a relationship between human behaviour in meetings (or trusted environment), reliability of commitments and labor productivity.

We selected this company because it has been using LPS for several years, outsourcing much of the construction activities (more actors are involved during the process) and because of its willingness and intention to participate in this research and adopt new tools that allow it to improve the management of commitments in its projects. By 2019, the company had an LPS implementation level of 76% and made use of tools such as: Master planning; Phase planning; Lookahead planning with Percent of Constraint Removal (PCR); Weekly work planning with Percent Plan Completed (PPC); Visual management; and Causes of non-compliance analysis.

Recently and as part of a pandemic labour reactivation strategy, the company began to make use of the "Engagement" indicators proposed by Salazar et al. (2020), in order to control and improve interpersonal relationships at work and engagement during weekly work planning meetings.

RESULTS OBTAINED

For each of the projects studied, we recollected and summarized the following information (Table 1): number of meeting attendees, percentage of non-attendees, percentage of progress of each project, duration of the meeting, number of weeks of information collection, average PPC, average scheduled activities, and meeting place. This data collection was needed in order to be able to perform the analysis of the results and to have a more in-depth understanding of the differences between projects.

Then, we perfomed a correlation analysis between the LAP indicators of "Engagement" and the PPC based on Spearman´s correlation coefficient or Spearmen´s Rho. This coefficient evaluates the monotonous relationship between two continuous or ordinal variables and determines their statistical dependence by comparing the ranges and order numbers of each variable (Moreno 2008). It is a non-parametric linear association measure that, unlike Pearson´s correlation coefficient, allows to take into account outliers that would otherwise affect its calculation in the Pearson coefficient (Moreno 2008). This coefficient is used when the data does not meet the parametric statistic assumptions required to use the Pearson coefficient (Moreno 2008).

Considering that the LAP indicators of "Engagement" measure human behaviors and attitudes, Spearmean´s chosen coefficient interpretation scale is a proposal by Dancey &

Reidy for the area of psychology (Akoglu 2018). For this specific case, a correlation value of 1 means that as there is an increase in the number of people following any of the behaviors studied, the PPC also increases. A value of -1 indicates that an inverse relationship between the behaviors and the PPC is observed.

Table 1. Summary of Project Data and Conditions

Project	Number of assistants	Percentage of absence	Percentage of advance	Time (min)	Weeks	PPC average	Scheduled activities average by week	Meeting place
P1	14	6,95%	50,00%	85	7	61,81%	36	Container
P2	14	38,01%	80,00%	75	10	54,33%	56	Workplace dining room
P3	22	17,74%	59,00%	82	10	58,45%	115	Container
P4	15	13,84%	54,00%	53	12	86,15%	60	Parking
P5	16	6,63%	48,00%	146	9	56,62%	81	Container
P6	11	29,27%	50,00%	61	11	53,22%	150	Communal living
P7	16	3,72%	52,00%	59	10	89,86%	49	Parking
P8	15	10,61%	24,00%	126	10	78,01%	51	Next to container
P9	12	19,23%	52,00%	69	11	80,72%	31	Communal living
P10	19	10,10%	69,00%	56	11	82,60%	36	Workplace dining room
P11	15	21,00%	73,00%	66	11	77,58%	29	Next to container
P12	11	9,26%	9,00%	47	9	78,09%	18	Construction camp
P13	26	9,18%	65,00%	98	12	72,46%	46	Workplace dining room
P14	13	0,61%	38,00%	99	11	76,89%	48	Container
P15	14	23,03%	68,00%	131	9	66,99%	54	Boardroom
P16	11	27,27%	77,00%	82	10	71,67%	23	Workplace dining room
P17	15	3,13%	18,00%	134	11	57,20%	44	Container
P18	16	3,06%	45,00%	74	10	75,54%	77	Workplace dining room
P19	19	17,10%	54,00%	80	12	63,40%	90	Boardroom
P20	10	10,03%	59,00%	93	9	39,26%	125	Parking/Communal living
P21	7	63,39%	96,00%	31	10	51,93%	40	(Virtual)
P22	16	8,96%	32,00%	67	10	80,60%	39	Workplace dining room
P23	8	9,72%	12,00%	48	10	76,36%	12	Container
P24	15	5,26%	70,00%	174	9	64,45%	57	Container
P25	13	34,58%	47,00%	77	11	65,83%	55	Construction camp
P26	10	16,79%	87,00%	48	11	77,60%	42	Next to container
P27	17	8,05%	40,00%	67	12	60,12%	53	Boardroom

Table 2 shows the results of this analysis, where we selected only correlations with significance level of less than 0.1. Values in green refer to strong and moderate negative correlations (which means that the lack of engagement of the participants in LPS weekly plan meetings is inversely related to the PPC) and values in red refer to strong and moderate positive correlations (meaning that the engagement of participants in LPS weekly plan meetings is directly related to the PPC).

Additionally, Table 3 displays the frequency (the number of projects where the behavior is repeated) and force summary with which correlations appear in all projects. For example, the value between the Strong-Negative line and column E2 describes the fact that we found a strong inverse correlation between the indicator E2 (Checks cell phone) and the PPC in 8 different projects.

Table 2. Correlations between Engagement and PPC

	Person is late	Checks cell phone	Cell phone rings	Talks on the cell phone	Leaves the room	Walkie-talkie sounds	Talks on walkie-talkie	Does not speak	Does not take notes	Does not look at the person who is speaking
Project	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**
P1	-0,90									
P2										
P3		-0,76			-0,74					
P4		-0,65								
P5	-0,84								0,66	
P6	0,63	0,84		0,72					-0,82	
P7		-0,66	-0,63	-0,76	-0,87					
P8			-0,79	-0,75					-0,98	
P9		-0,72			0,77					
P10			0,63	0,55						
P11	-0,65								-0,73	
P12			-0,77	-0,77						
P13		-0,79						-0,68	-0,75	
P14		-0,79								
P15		-0,79		-0,73	-0,69					
P16			-0,69	-0,77						
P17		-0,63	-0,79							
P18		-0,81		-0,54	-0,50					
P19		-0,74								
P20		0,77	0,75						-0,85	0,74
P21	-0,68									
P22										
P23										
P24	0,85	-0,92			0,85				0,95	
P25									-0,70	
P26		-0,65							-0,67	
P27			-0,69							

Table 3. Frequency and Strength of Correlations between Engagement and PPC

Correlations			Person is late	Checks cell phone	Cell phone rings	Talks on the cell phone	Leaves the room	Walkie-talkie sounds	Talks on walkie-talkie	Does not speak	Does not take notes	Does not look at the person who is speaking	SubTotal	Total
			E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**		
Negative	**Strong**	<-0,7	2	8	3	5	2	0	0	0	5	0	**25**	**39**
	Moderate	(-0,4;-0,7)	1	4	3	1	2	0	0	1	2	0	**14**	
	Weak	(-0,4;-0,1)	0	0	0	0	0	0	0	0	0	0	**0**	
	None	(0;-0,1)	0	0	0	0	0	0	0	0	0	0	**0**	
Positive	**Strong**	<0,7	1	2	1	1	2	0	0	0	1	2	**10**	**13**
	Moderate	(0,4;0,7)	1	0	1	1	0	0	0	0	0	0	**3**	
	Weak	(0,1;0,4)	0	0	0	0	0	0	0	0	0	0	**0**	
	None	(0;0,1)	0	0	0	0	0	0	0	0	0	0	**0**	

ANALYSIS AND DISCUSSION

After analyzing the results and conditions of each Project, we discovered that depending on the specific characteristics of these, we obtained different levels of correlations between LAP and PPC "Engagement" indicators. Within the characteristics that generated weak correlations, we found projects where: No attendances were high (usually greater than 20%); average project PPC of less than 50%; PPC close to or greater than 90% (specific case of P7 where in 10 of 11 weeks the PPC was between 87% and 96%, but the average was below 90% for a specific week); meetings lasting more than 2 hours; meetings with 10 or fewer attendees; and finally, the percentage of progress was lower than 15% an above 95% in some cases.

On the other hand, the projects that had strong correlations were those where: the percentage of progress was between 65% and 95%; average PPC was between 60% and 90%; a "Big Room" was used, and the meetings had between 10 and 20 attendees.

It is important to mention that in long-term meeting, maintaining the concentration of attendees becomes more difficult (Romney et al. 2019), so managing time is key. Therefore, we note that factors such as the size and progress of the project, number of commitments, number of attendees (number of subcontractors) and the discussion of technical aspects, affected the duration.

By deepening our analysis, we found that the indicators that had strong correlations most often are those that are related to cell phone use: "Checks cell phone", "Cell phone rings" and "Talks on the cell phone". This is consistent with previous claims that the cell phone can negatively affect labor productivity (Malan 2019; Thornton et al. 2014). Although within the protocols of the construction company it is forbidden to use the cell phone, it was very complex to avoid its use because the participants argued that it was their working tool. We believe that its use should be avoided, since while the cell phone may be useful in a working context, social media is a factor of distraction and deconcentration. Moreover, we observed that the "Leaves the room" indicator in almost all cases, was related to going out to answer the cell phone.

On the other hand, the "Does not take notes" indicator is the second most frequent strong correlation between indicators. Although it should not be necessary to take notes if and LPS board is used, we noted that those responsible did not always go to check the tasks fulfilled and missing during the week. However, we believe that this indicator is complementary to the board and minutes of the meeting, particularly in this case study, the result obtained may be due to the outdoor and stand-up meeting in some projects, which made it difficult for attendees to take notes.

Although some of the "Engagement" indicators had lower frequency in correlations, this does not necessarily mean that they are not related to the reliability of commitments and labour productivity. For example, in the case of the "Person is late" indicator, we noted that punctuality is an important factor in the reliability of commitments and even the same people with the Project, as there is a lack of commitment to the meeting, colleagues and the project (when someone is constantly late). In this specific case, we believe that it has no direct relationship with the PPC because in the context of the Works studied, the star of the meeting was delayed until there were an acceptable number of people to begin the meeting.

Likewise, according to the ideal operation of LPS in planning meetings, each last planner should say what they committed to do last week, what they did last week, why commitments were not met, what they should and can do this week and what they need from others to carry out their tasks. In this way, everyone must participate in the meeting and it would not be necessary to measure the indicator "Does not participate in the meeting". But in each company and even in each work LPS is adapted according to the magnitude of the work, number of contractors and time limits for meetings.

In the case of the construction company studied, in the programming phase of weekly activities, all subcontractors had to intervene by saying aloud which activities they were committing to perform by locating the post-it on the LPS board. But sometimes more people from those indicated or people without decision-making power within their company attended, so they did not intervene. Faced with this situation, we consider that the only way to know if someone "does not add value to the meeting" is with this indicator, as no last planner should be missing or left over.

We consider that the "Walkie-talkie sounds" and "Talks on Walkie-talkie" indicators are no longer relevant as they have generally been replaced by the cell phone. In addition, the "Does not look at the person who is speaking" indicator can be a Good indicator of how many people actually pay attention, although it was very complex to measure it by the facilitator (professional assigned by the builder to measure the indicators)

On the other hand, as the data were taken during the global health crisis due to the pandemic, the results could be affected by changes in projects due to bio-security protocols, including:

Open-pit meetings: here distraction is easier because of the noise itself that is generated in projects, where people take advantage to answer the phone, talk to each other, solve doubts. In addition, there are workers who pass through the meeting place or come to make some request, among others.

Stand-up meetings: it makes it uncomfortable to stand still (distractions are sought and notes are difficult to take).

Virtual or semi-face-to-face meeting: in these cases, it becomes more difficult to control the meeting and evaluate the indicators of commitments used. Indicators such as punctuality and checking the cell phone lose meaning because people can enter the meeting without even being in front of the screen. In these meetings, usually those who end up leading are the heads of work and the structure of the meetings changes: usually a single person speaks, dictating one by one the commitments and asking others whether they agree or not, LPS board is not used.

Physical distance between people: it makes it difficult to hear by distance.

Outdoor LPS board: as it is usually completed with post-it, some of them may be taken off by wind, losing the traceability of some commitments.

In short terms, we were able to see that the indicators of "Engagement", when measuring human behaviors, varied due to working conditions in pandemic and influenced compliance and correct management of commitments.

RESEARCH LIMITATIONS

In this case of study, LAP´s "Engagement" indicators were compared only to the PPC, as it is the most widely used and most representative indicator of LPS, but they could be compared to other project performance indicators such as yields and cost. Additionally, correlation analysis is a method that allows you to identify the relationships between two variables but does not necessarily represent a causality between them, which is why an in-depth analysis is required to determine causalities. So other methods of analysis should be considered, such as Structural Equation Models (SEM), which allows the study of causal relationships between directly observable data. Similarly, an analysis from

Machine Learning could be performed because it could determine behavior patterns and thus create predictive systems.

Moreover, considering the relationships identified in this study, it might be valuable to develop a methodology based on LAP for meetings and work in a virtual environment, as well as to analyze the impact of the use of social networks on construction projects.

Finally, the scope of the research only considered high-rise construction projects in Colombia in Pandemic times and with low to medium LPS implementation levels. In addition, the authors only analyzed the data, as these were collected by facilitators (professional assigned by the builder to measure the indicators) of the construction company, which can certainly affect the reliability and variability of the results.

CONCLUSIONS

This paper shows a case of study where LAP "Engagement" indicators were measured and analyzed in a real context, pandemic construction projects. The authors conducted a correlation analysis between these indicators and the PPC, finding that there is an important relationship between cell phone use and note-taking at weekly planning meetings and the PPC. In addition, we identified that relationships are stronger and appear more frequently when the project progress rate is between 65% and 95%; the average PPC is between 60% and 90% or nearby values; meetings are held in enclosed spaces and have 10 to 20 attendees. Other indicators in which we expected to have a high correlation such as "person is late", we think had little relation to the PPC due to specific factors in this study, such as difficulty in measurement, relevance in the actual context of the project (use of indicators without monitoring and expert accompaniment) and changes in working conditions due to the pandemic. Given the relationships found we can say that the use, control and traceability of LAP "Engagement" indicators in the post-pandemic context are extremely useful to improve the management of commitments and with it, the application of LPS construction projects. So, research certainly represents a new knowledge and contribution to the state of art and practice in LPS, not only in a post-pandemic context, but also because indicators measure aspects of the behavior of construction workers that have been under-studied to date. However, we also found long-term barriers to research due to data reliability and variability, number of projects, weeks studied and the use of PPC as the sole indicator of comparison. Finally, for future research we propose the use of other methods of relationship, causality and/or prediction analysis such as SEM or Machine Learning, a future methodology for virtual or semi-face-to-face meetings and the study of other performance indicators.

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REFERENCES

Ahuja, R. (2013). "Sustainable construction: Is lean green?" *ICSDEC 2012: Developing the Frontier of Sustainable Design, Engineering, and Construction - Proceedings of the 2012 International Conference on Sustainable Design and Construction*, 903–911.

Akoglu, H. (2018). "User's guide to correlation coefficients." *Turkish Journal of*

Emergency Medicine, 18(3), 91–93.
Bajjou, M. S., Chafi, A., Ennadi, A., and El Hammoumi, M. (2017). "The practical relationships between lean construction tools and sustainable development: A literature review." *Journal of Engineering Science and Technology Review*, 10(4), 170–177.
Ballard, G., and Tommelein, I. (2016). "Current Process Benchmark for the Last Planner System." *Lean Construction Journal*, 13(1), 57–89.
Belayutham, S., González, V. A., and Yiu, T. W. (2017). "Lean-based clean earthworks operation." *Journal of Cleaner Production*, 142, 2195–2208.
de Carvalho, A., Granja, A., and da Silva, V. (2017). "A Systematic Literature Review on Integrative Lean and Sustainability Synergies over a Building's Lifecycle." *Sustainability*, Multidisciplinary Digital Publishing Institute, 9(7), 1156.
Flores, F. (2015). *Conversaciones para la Acción: Inculcando una cultura de compromiso en nuestras relaciones de trabajo (Conversations For Action and Collected Essays: Instilling a Culture of Commitment in Working Relationships)*. (M. Flores, ed.), Lemoine Editores, Bogotá, Colombia.
Hamzeh, F., Al Hattab, M., Rizk, L., El Samad, G., and Emdanat, S. (2019). "Developing new metrics to evaluate the performance of capacity planning towards sustainable construction." *Journal of Cleaner Production*, Elsevier Ltd, 225, 868–882.
Howell, G. A., Macomber, H., Koskela, L., and Draper, J. (2004). "Leadership and Project Management: Time for a Shift from Fayol to Flores." *12th Annual Conference of the International Group for Lean Construction*, S. Bertelsen and C. T. Formoso, eds., Helsingør, Denmark.
Isatto, E. L., Azambuja, M., and Formoso, C. T. (2015). "The Role of Commitments in the Management of Construction Make-to-Order Supply Chains." *Journal of Management in Engineering*, ASCE, 1801 Alexander Bell Dr, Reston, VA 20191-4400 USA, 31(4), 04014053.
Li, S., Fang, Y., and Wu, X. (2020). "A systematic review of lean construction in Mainland China." *Journal of Cleaner Production*, Elsevier Ltd, 257, 120581.
Long, D., and Arroyo, P. (2018). "Language, moods, and improving project performance." *Proc. 26th Annual Conference of the International. Group for Lean Construction (IGLC)*, V. González, ed., Chennai, India, 495–504.
Malan, J. (2019). "The Influence of Digital Distraction on cognitive load, attention conflict and meeting productivity." *Thesis*, University of Cape Town.
Moreno, E. (2008). *Manual de Uso de SPSS. Universidad Nacional de Educación a Distancia*, Madrid, España.
Ogunbiyi, O., Oladapo, A., and Goulding, J. (2014). "An empirical study of the impact of lean construction techniques on sustainable construction in the UK." *Construction Innovation*, 14(1), 88–107.
Retamal, F., Salazar, L. A., Herrera, R. F., and Alarcón, L. F. (2020). "Exploring the Relationship Among Planning Reliability (PPC), Linguistic Action Indicators and Social Network Metrics." *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC)*, I. D. Tommelein and E. Daniel, eds., Berkeley, California, USA, 109–118.
Romney, A. C., Smith, I. H., and Okhuysen, G. A. (2019). "In the trenches: Making your work meetings a success." *Business Horizons*, "Kelley School of Business, Indiana University," 62(4), 459–471.
Salazar, L. A., Arroyo, P., and Alarcón, L. F. (2020). "Key Indicators for Linguistic

Action Perspective in the Last Planner® System." *Sustainability*, Multidisciplinary Digital Publishing Institute, 12(20), 8728.

Salazar, L. A., Ballard, G., Arroyo, P., and Alarcón, L. F. (2018). "Indicators for Observing Elements of Linguistic Action Perspective in Last Planner® System." *Proc. 26th Annual Conference of the International. Group for Lean Construction (IGLC),* V. A. González, ed., Chennai, India, 402–411.

Salazar, L. A., Retamal, F., Ballard, G., Arroyo, P., and Alarcón, L. F. (2019). "Results of indicators from the Linguistic Action Perspective in the Last Planner(r) System." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC),* Pasquire C. and Hamzeh F.R., ed., Dublin, Ireland, 1241–1250.

Salgin, B., Arroyo, P., and Ballard, G. (2016). "Exploring the relationship between lean design methods and C & D waste reduction: Three case studies of hospital projects in California [Explorando la relación entre los métodos de diseño lean y la reducción de residuos de construcción y demolición: tres ." *Revista Ingenieria de Construccion*, 31(3), 191–200.

Thornton, B., Faires, A., Robbins, M., and Rollins, E. (2014). "The Mere Presence of a Cell Phone May be Distracting." *Social Psychology*, 45(6), 479–488.

Verrier, B., Rose, B., and Caillaud, E. (2016). "Lean and Green strategy: the Lean and Green House and maturity deployment model." *Journal of Cleaner Production*, 116, 150–156.

Viana, D. D., Formoso, C. T., and Isatto, E. L. (2011). "Modelling the network of commitments in the last planner system." *19th Annual Conference of the International Group for Lean Construction*, Lean Construction Institute, Lima, Perú.

Viana, D. D., Formoso, C. T., and Isatto, E. L. (2017). "Understanding the theory behind the Last Planner System using the Language-Action Perspective: two case studies." *Production Planning & Control*, Taylor & Francis Ltd, 2-4 Park Square, Milton Park, Abingdon OR14 4RN, Oxon, England, 28(3), 177–189.

Weinheimer, N. (2016). "The process of green building certification: An examination regarding lean principles." *IGLC 2016 - 24th Annual Conference of the International Group for Lean Construction*, 53–62.

Weinheimer, N., Schmalz, S., and Müller, D. (2017). "Green building and lean management: Synergies and conflicts." *IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction*, 911–918.

Yin, R. K. (2003). *Case Study Research: Design and Methods*. *SAGE Publications*, Applied Social Research Methods. Volume 5, Thousand Oaks, CA.

Zegarra, O., and Alarcon, L. F. (2017). "Variability propagation in the production planning and control mechanism of construction projects." *Production Planning & Control*, Taylor & Francis Ltd, 2-4 Park Square, Milton Park, Abingdon OR14 4RN, Oxon, England, 28(9), 707–726.

Zegarra, O., and Alarcón, L. F. (2013). "Propagation and distortion of variability into the production control system: Bullwhip of conversations of the last planner." *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*, The International Group for Lean Construction, Fortaleza, Brazil, 589–598.

Seppänen, O., Lavikka, R, Lehtovaara, J., and Peltokorpi A. (2021). "Improving street reconstruction projects in city centers through collaborative practices." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 373–382, doi.org/10.24928/2021/0116, online at iglc.net.

IMPROVING STREET RECONSTRUCTION PROJECTS IN CITY CENTERS THROUGH COLLABORATIVE PRACTICES

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ABSTRACT

Renovation and relocation of underground utilities and renovating the streets are essential to maintain urban infrastructure. In cities, street reconstruction projects cause substantial harm to citizens in the form of traffic jams, noise, and poor access to businesses. Although some harm is unavoidable, the harm could be mitigated, for example, by decreasing overall construction durations. We used design science research to diagnose the current state of street reconstruction projects in the City of Helsinki and to develop a new model aimed at shortening project durations. The diagnosis was made based on interviews, workshops, observations, a survey, and an archival study. The identified key root causes of problems were lack of collaboration and inflexible contract forms in projects with high uncertainty. The new model was co-created with stakeholders participating in these projects, including a collaborative development phase, a shared situation picture among actors, and joint risk analysis of all parties. The study's key contribution was the way to use design science research to start a lean implementation in a challenging project type with multiple public stakeholders. The City of Helsinki will pilot and further develop the model in three street reconstruction projects.

KEYWORDS

Street reconstruction, contract forms, collaboration, trust, design science research.

INTRODUCTION

Renovation and relocation of underground utilities, located under the streets, are essential for cities as infrastructures get older and need to be renewed. At the same time, traffic systems and roads are also typically renovated. Citizens and businesses suffer from several side effects of these street renovation projects, such as traffic jams and noise, as these projects are frequently delayed.

Although requirements for street renovation projects are often quite exact, a lot of uncertainty exists in underground conditions due to insufficient documentation of existing conditions, such as bedrock elevation or existing utilities. The projects also typically

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involve multiple utility systems, such as streets, heating, water, electricity, and telecommunication networks, owned by different stakeholders, making the coordination and governance of such projects challenging (Vilventhan and Kalidindi 2018).

Typically, cities as public entities are bound by competition laws and tend to use traditional contract forms, such as design-bid-build (DBB) (Rizk and Fouad 2007), which have been shown to function poorly in an environment with uncertainty (e.g. Lahdenperä (2012). Early contractor involvement through partnering and competitive dialogue before the preferred bidder is chosen have been suggested as implementation strategies for large infrastructure projects (Opsahl et al. 2015; Wondimu et al. 2016). Collaborative contract forms are an attractive alternative but hard to implement in a public entity if the project is not financially big enough or if the renovated utilities are owned by multiple organisations. On the other hand, better coordination between local public authority and utility companies in the design process can prevent unexpected delays (Sturgill et al. 2014).

Because of the number of stakeholders involved, coordination of work is crucial. In lean construction, collaborative methods such as the Last Planner® System (LPS) (e.g. Ballard 2000) have been proposed to improve the coordination process and plan reliability. In addition to LPS, digital tools may be required to achieve a shared situation picture (Kärkkäinen et al. 2019). Increased transparency brought by lean and digital tools combined with more collaborative contract forms could lead to increased trust between stakeholders, contributing to innovations and reducing project buffers (Uusitalo et al. 2019), thereby decreasing project duration and the harm to citizens. Although good solutions have already been reported in other contexts, additional research based on a thorough diagnosis of the current state is required to develop a holistic solution that applies to the context of street renovation.

This paper aims to diagnose and construct a practical solution to street renovation projects to minimise delays and harm to citizens. Empirical research is conducted in the context of street renovation projects in the City of Helsinki. Helsinki's existing infrastructure requires renovation, and new streets are being built at an increasing pace due to the age of infrastructure and population growth. This infrastructure must stay functional during the renovation period and provide citizens with clean water, heating, cooling, electricity, and connectivity to the internet.

Currently, street works in Helsinki cause considerable harm to street users. The main problems of street projects are the excessively long durations of construction work and the significant direct and indirect disadvantages they cause in their area of influence. Work causes disruption while congesting key traffic routes to the detriment of street residents, businesses, and other users. The disruptions cause financial losses for various stakeholders. Construction sites and traffic arrangements pose safety risks to street users. Site areas often have inadequate service levels for road users, e.g., inadequate signage and uneven pavements. The city started a major development effort which included this research study and several other practical initiatives related to, e.g., communication with stakeholders and applications for citizens to provide real-time feedback.

One of this research's practical aims is to reduce street projects' disadvantages during construction. For this reason, the study explores the current way of conducting and managing street renovation projects and developing operations comprehensively. The design phase has been covered to the extent that the on-site turnaround times are concerned. Improvement of the design process itself is not the subject of research. The study will apply lean thinking as it has been successful in improving construction flow.

For example, a case study conducted by Kung et al. (2008) showed that water and sewer service installations' productivity was improved through lean principles. Currently, lean thinking or digital tools are not widely adopted in street renovation projects.

The study aims to answer two questions: 1) *What are the root causes of long durations of street reconstruction projects?* and 2) *How to implement lean and digital tools to develop these projects?* The paper is structured as follows. After presenting the methodology, a diagnosis of the current state of the road renovation projects is presented. Then, the proposed solution is formed. Finally, the results are discussed, conclusions are made, and suggestions for future research initiatives are provided.

METHODOLOGY

The study was executed as a design science research (DSR), a research method aiming to solve a practical problem (Baskerville et al. 2018). DSR forms an iterative process where the solution is created in tight collaboration with researchers and practitioners, suiting exceptionally well for the study's aim (Holmström et al. 2009). As a practical problem to be solved, we investigated the street reconstruction projects in the City of Helsinki centre.

In this study, DSR is formed around three steps: i) diagnosis of the problem, ii) formulation of a solution and iii) discussion of the study's contribution and further action steps. First, we diagnosed the problem with semi-structured interviews of representatives from all major stakeholders (the City of Helsinki, utility companies, contractors, designers). Then, we organised a workshop to get a common understanding of issues. After that, we conducted observations on four on-going projects and implemented a survey of existing communication practices on one construction project. Finally, we conducted an archival study of documentation related to three completed projects. Table 1 shows the data used for diagnosis.

Table 1: Data sources for diagnosis

Data type	Data collection period	Analysed materials
Interviews	2/2019-6/2019	55 interview sessions with 75 participants (15 City of Helsinki, 23 contractors, 10 designers, 20 utilities, 7 others)
Document analysis	5/2019-6/2019	Three projects – contracts, schedules and their updates, meeting minutes, site diary
Site Observations	11/2018-12/2018 and 5/2019-6/2019	Observations in four projects: situation picture, collaboration and trust, problems and their solutions
Survey	5/2019-6/2019	Survey related to communication in projects, conducted in one project, 29 respondents
Workshop	20.5.2019	33 participants (6 City of Helsinki, 6 contractors, 4 designers, 9 utilities, 7 others)

The semi-structured interviews were used to get an initial diagnosis of the current state and challenges and potential development ideas. Interviews were recorded and transcribed verbatim by using a transcription service. The interview questions for different stakeholder groups varied and focused on issues of interest to that stakeholder group. All interviewees were asked about the current process, challenges and best practices in different stages of the process. Data analysis was based on qualitative content analysis, where extracts were coded to themes first for each stakeholder type and then further by problem type. In classification, root cause analysis was used to understand what happened and why. Because different stakeholder groups had a very different understanding of root causes of problems, observation and document analysis were used to validate the found root causes in a real context. The same themes as in interviews were used to classify these observations.

Next, we organised two workshops to help define a solution. As starting information for workshops, we presented the findings from the diagnosis phase. The first workshop focused on improving collaboration and problem-solving in projects, and the second workshop on improving situational awareness in projects. Based on these workshops and our diagnosis, we developed a proposed new model in collaboration with the city. The model was validated in a final workshop with all stakeholders, and modifications were made based on stakeholder feedback.

DIAGNOSIS

An interesting result from the interview study was the wide disagreement between stakeholder groups regarding the root causes of street renovation projects' delays. This lack of common understanding was verified with the survey, site observations, and the diagnosis workshop. Due to space limitations, we present the views of each key stakeholder type separately, then briefly describe the results of observations and document analysis and finally present our synthesis of results.

Contractors tended to emphasise the imbalanced distribution of risks to project parties and the inability to participate enough in the design phase. Their challenge was the obligation to coordinate work without all parties' commitment, especially the utility companies. The designs could not be followed due to continuous surprises in subsurface conditions. The fixed-price contract forces the contractor to maximise the utilisation rate of expensive equipment, increasing the harm caused to citizens because new areas need to be excavated when work stops in another area due to an open problem. The bottleneck identified by all contractors was the speed of decision-making by the city. According to the contract, the contractor should never proceed with change order work before written confirmation. Still, they had to start several changes at their own risk to maximise resource utilisation and prevent disputes in practice.

The representatives of the city had a very different view of the root causes. Their perception was that contractors did not plan their work adequately and did not update the plans when changes occurred. The city could not accept change order requests timely because the contractors failed to provide enough detailed justification, requiring multiple iterations of each change request. Rather than being proactive and proposing solutions, contractors sent information of deviations and stood by waiting for a response.

For various **utility companies** (teleoperators, district heating, water, tram lines, etc.), the key challenge was operating in a multi-project environment. Each company's scope related to one project is quite small, so it does not make sense to sit through each 3-hour meeting. Information about projects starting comes too late and inconsistently from different people or organisations. The designs are not coordinated well enough between the various owners of infrastructure below the street. There is no transparency to project schedules. Much of the time, the work is delayed from the schedule and then urgently required, but the utility companies need to plan their resources over hundreds of projects.

The key problems from the **designers'** point of view were the last-minute change requests in design and in getting starting information for design from various project stakeholders. Especially soil information and information of the location of existing utilities is inadequate when designing the project. Latitude and longitude coordinates are known for many systems but not the elevation. The amount of money spent on investigations of current conditions was deemed inadequate.

The analysis of observations and documentary evidence confirmed that there is a lack of collaboration in the projects. The schedules and planning had shortcomings and were not updated regularly by contractors. All analysed projects started degenerating into a dispute after the first time extension request by the contractor. At this point, the documents, meeting minutes, and observed meetings started to turn increasingly hostile. Change order requests were open for months, and clarifications were asked related to most change orders. There were many change orders – during the excavation phase, the projects had unexpected problems on 19% (project 1) to 66% (project 3) of days during periods when excavation was being done. All these problems started a change order process that often took months to resolve.

However, one of the observed projects (project 4) was different even though it had a similar contract as the other analysed projects. The contractor and client had managed to achieve a good and collaborative approach. The contractor was proactive and proposed a solution for each issue. The Owner was ready to decide whether to proceed with the contractor's solution immediately. Designers were sent as-built measurement information after implementation, and they updated the designs. All paperwork was completed later and the change order hours were booked and invoiced. The contractor was operating at its own risk without following the change order process specified in the contract. Although the project had delays during construction, the project was the only investigated project that finished on time.

Based on data analysis, the root causes of delays were identified and validated in the workshop. At this point, we were able to achieve enough common understanding of root causes to start working on the solution, although the parties' opinions were still quite far from each other. Table 2 shows a summary of identified root causes.

DEVELOPING THE SOLUTION

The initial solution ideas were collected during interviews and discussed during the first diagnosis workshop. Two additional workshops were organised during the development of the solution. Workshop 2 focused on improving collaboration and changing the contracts. Workshop 3 focused on collaborative planning and situational awareness. All workshops included participants related to all main stakeholder groups. Workshops were conducted using facilitated small group discussions with researchers taking detailed notes in each small group. Table 3 summarises the main results of the workshops.

Based on these workshop findings, two meetings were organised between the researchers and the City of Helsinki. The workshop results were discussed in the meetings, and a new model was developed based on workshop results. All recommendations could not be implemented in the new model due to legal constraints on public entities or lack of willingness, but the resulting model included changes for all stages of the process. In addition to stages that were traditionally part of the process, a new development stage was added before the construction phase.

In the design phase, the key changes were in the change of city departments' role, additional soil investigations, and the definition of risks and uncertainties. The design phase requires more participation from the city organisation responsible for overseeing the construction phase to evaluate constructability. Risks and uncertainties should be defined already in the design phase and used to inform additional soil studies. The number of test excavations and soil studies will be increased substantially.

In preparation for construction, the key changes relate to the way the main contractor is selected. The call for bids will include constraints on scheduling and the risk analysis performed in the design phase. Public procurement requires a price component, but the focus will shift to evaluating the contractor's planning expertise, bringing new ideas in the development phase, plans to decrease harms on citizens, and the ability to recognise risks and opportunities. The goal is to find a collaborative partner for the development phase.

Table 2: Root causes of delays as proposed and validated in the workshop

Root causes of long durations	Description
Contract form	In most projects, Design-Bid-Build is used as the contract form. The contract form does not create prerequisites for flexible implementation of projects without considerable risk to the contractor
Continuous deviations	Deviations from design impact duration because work cannot proceed before the deviation has been resolved. Most common deviation categories: 1) surprising soil conditions 2) missing information about utilities and 3) surprising underground structures
Reacting to deviations and change management	Change orders require written approval from the city before implementation, including work method and possible cost and schedule impacts. In practice, the written approval is not received timely but requires a lengthy process. Work often proceeds at the risk of the contractor. Time and attention of management are used on paperwork.
Collaboration and trust	The collaborative and trustful atmosphere is possible to achieve and has led to good outcomes (e.g. project 4). However, in general current contract form does not create good preconditions for trust. Instead of collaborative problem solving, the current model leads to documenting problems and communicating with the other party through claims and formal letters.
Challenges related to schedules and logistics	Good planning of work is important for avoiding delays. The current process does not allow enough time for planning and rather emphasises quick start of work. Most contractors do not have adequate planning skills or resources. Schedules should be updated flexibly during the project to give each party an up-to-date view of what is expected
Situational awareness	There is a lack of situational awareness for all stakeholders who are not full time on site. Real-time situational awareness is important for all parties to ensure schedule updates when deviations happen.

In the new model, which is illustrated in Figure 1, the development phase has a critical role. In the development phase, the project's rules are defined, and answers to open questions are collaboratively developed. Collaborative planning using the Last Planner® System is performed. The end result of the development phase includes a common risk analysis and risk management plan. Each identified risk includes an allowance in money and time. Risks can be controlled by additional investigations in uncertain areas to confirm design assumptions. Additionally, the systems for real-time situation picture are defined.

In the construction phase, decision-making is made considerably faster by predefined risks and decision paths. Decision-making is moved closer to the site enabling the Owner’s supervisor to make immediate decisions. Changes related to recognised risks can be immediately resolved without requiring a change order process. In addition, schedules are continuously updated based on the process agreed in the development phase. The head contractor procures required IT systems to allow transparency. Transparency to construction operations allows much quicker handling of change requests from the site. Any schedule changes and costs can be validated based on the situation picture. Technologies include, for example, web-based scheduling systems, machine control systems, drones, and fixed cameras.

The model was validated in a workshop (13.11.2019) with 44 participants. Collaboration and trust were emphasised, and the need for an external lean consultant to facilitate the development phase's first implementations. Utility companies emphasised the need for effective, facilitated meetings. The participants emphasised that although the design phase already develops quite detailed designs (based on available information). Getting a shared understanding of constructability and mitigating risk with further studies should decrease the cycle times of projects significantly. Harm can also be decreased in other ways, such as innovations related to temporary traffic control measures. Based on the positive feedback from the workshop, the City of Helsinki decided to start pilot implementations in three projects.

DISCUSSION

Developing an improved process for street reconstruction projects proved to be extremely challenging due to a high number of stakeholders involved in relatively small projects. All stakeholders had different views of root causes of long durations of street projects, typically focusing on issues with other stakeholders. Achieving a common understanding of root causes was a lengthy process and required extensive evidence from various sources such as interviews, observations, a survey, and an archival study and debate in co-creative workshops. As the result of the diagnosis, a common understanding of key issues was achieved.

Design-Bid-Build contract type is not suitable for a project type with continuous needs for changes due to uncertain starting data. Flexibility, collaboration, and trust are required to cope with uncertainty and Design-Bid-Build tends to lead to opportunistic behaviour, lack of trust and can even prevent collaboration (Kortenko et al. 2020). Indeed, the only observed project that achieved collaboration and on-time delivery did so at an increased contractual risk to the contractor. While these findings are quite expected for any researcher in the lean domain, they need to be shown to apply in each separate context if a real impact is sought. Convincing a public entity to change their procurement practices that have been used for decades is not an easy task (e.g. Love et al. 2008) and may require this kind of extensive evidence collection.

Table 3: Participants and key results of workshops

Workshop	Partici-pants	Main results
Workshop 1 (20.5.2019) Common under-standing of challenges	Contractors: 6 Designers: 4 Utilities: 9 City: 6 Others: 7	**1. Developing collaboration between stakeholders:** Implementing a development phase before construction: collaborative scheduling, identifying of decision paths, change management rules. Common risk analysis and predefined ways to handle risks. Common incentives for commitment to project objectives. **2. Surprises and reacting to them:** More soil investigations needed during preparation. Decision making closer to site. More use of BIM models in the process. Time and money contingencies to allow flexible change process. **3. Real-time situation picture:** All parties agreed that transparency and development of situation picture is beneficial but requires trust.
Workshop 2 (24.9.2019) Contract forms and improving collabora-tion	Contractors: 5 Designers: 6 Utilities: 10 City: 7 Others: 10	**1. Changes related to designers:** Life cycle thinking to projects. Change of approach to emphasise constructability rather than just end product. Increasing prefabrication of elements. Detailed reviews of designs in collaboration with contractors in development phase. **2. Changes related to contractors:** Alliance / IPD is too heavy contract form for most street projects. Potentially use Design-Build with collaborative development phase as a template. **3. Changes related to utilities' owners:** Better real-time communication of schedule changes. Design coordination requires more time and active collaboration **4. Measurement and evaluation of harm:** Citizen body for the continuous evaluation of harms caused by contractors and which harm is acceptable. Continuous measurement of harm and solutions.
Workshop 3 (21.10. 2019) Real-time situation picture, production planning and control	Contractors: 7 Designers. 4 Utilities: 9 City: 8 Others: 10	**1. Improved starting data.** Classification of uncertainty related to design. Checklists for design to control uncertainty. Documenting assumptions and uncertain areas and reviewing them with the contractor and using methods which do not require excavation to evaluate current conditions. Use of drone measurements to get measurements of actual data after excavation. **2. Real-time situation picture and BIM models:** All stakeholders should be trained in using BIM models and providing information for situation picture during the development phase. Incentives for transparency and collaboration. No punishments for sharing data. 3. **Collaborative production planning and control:** Collaborative production planning using the Last Planner® System, continuously rolling look-ahead schedule for the next six weeks. All stakeholders should participate, and all should have tasks in the schedule. 4. **Internal communication:** Development required on communication methods used: emphasise user interface and speed. Clear duration targets for decisions and RFIs. Continuous measurement of the decision process.

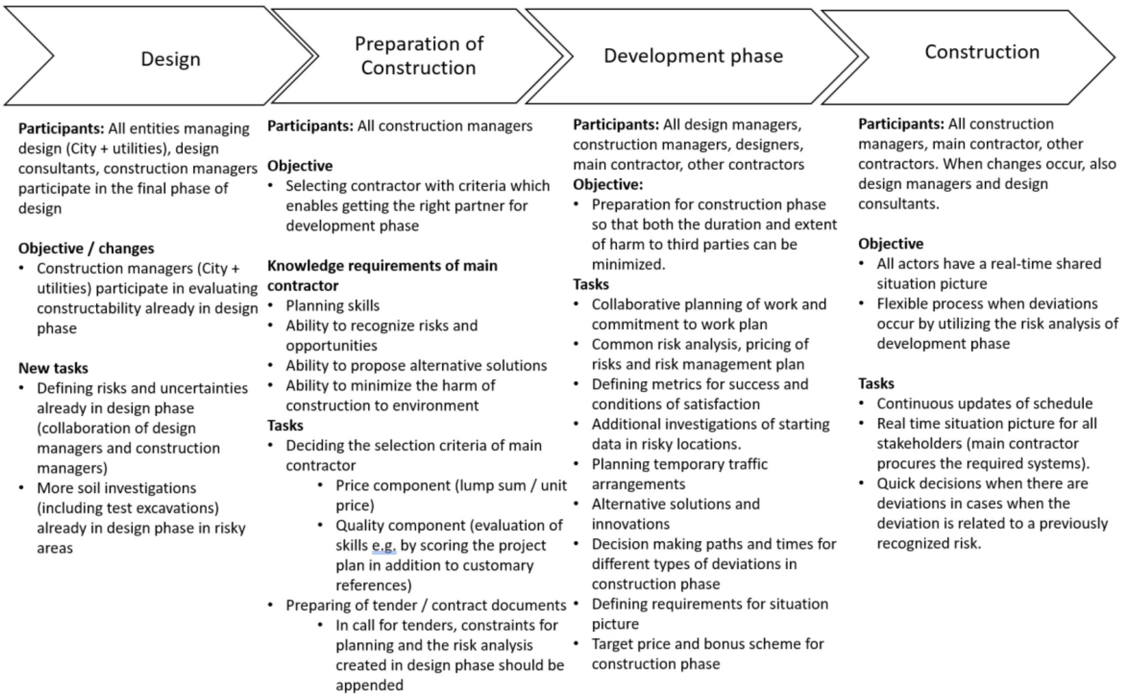

Figure 1: The new model based on the workshops

The proposed process itself also has limited novelty for a lean researcher or practitioner. The solution includes familiar pieces such as a development phase, use of the Last Planner® System for collaborative planning, increased prefabrication, and developing a shared understanding of risks. The key learnings of interest to lean practitioners are more related to the journey than the destination. Research-driven process change should generalise to other contexts where the Owners are reluctant to change their ways.

The research achieved its objective. Stakeholders were able to agree on root causes and a new way to procure and implement street reconstruction projects. The city has started using the new model in three new street reconstruction projects. The procurement in these projects has been based on a target price, including a development phase. The projects are currently on the way. Two of the three projects have reported good results from the development phase, but one has reported major challenges in collaboration. These differences will be investigated in future research.

CONCLUSIONS

The root causes of long durations of street reconstruction projects (RQ1) are linked to high uncertainty related to soil conditions, existing structures, and locations of utilities. The Design-Bid-Build contract form is too inflexible to deal with continuous changes caused by inadequate starting data for design. The work of various contractors needs to be better coordinated. A common understanding of the decision-making process and key risks is required in order to react faster when risks occur.

The stakeholders were able to agree on a new model for street reconstruction. The developed model is the answer to the second research question (RQ2). The model includes several lean elements, such as a collaborative development phase with joint risk analysis, movement away from Design-Bid-Build to target price with a bonus pool associated with project objectives, collaborative planning using Last Planner® System, and digital situational awareness for all parties. The study's key contribution is not the model itself but the way of using Design Science Research to achieve a common understanding of root causes and kick off a lean implementation in a challenging environment.

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REFERENCES

Ballard, H.G., 2000. The last planner system of production control. Thesis (PhD). The University of Birmingham.

Kortenko, S. , Koskela, L. , Tzortzopoulos, P. and Haghsheno, S. (2020) Negative Effects of Design-Bid-Build Procurement on Construction Projects. In: *Proc. 28th Annual Conference of the International Group for Lean Construction*. Berkeley, California, USA, 6-10 Jul 2020. pp 733-744.

Kärkkäinen, R., Lavikka, R., Seppänen, O. and Peltokorpi, A. (2019). Situation Picture Through Construction Information Management, in: *10th Nord. Conf. Constr. Econ. Organ.*, pp. 155–161.

Lahdenperä, P. (2012) Making sense of the multi-party contractual arrangements of project partnering, project alliancing and integrated project delivery. *Construction Management and Economics*, vol. 30, no 1, pp. 57–79.

Love, P.E.D., Davis, P.R., Edwards, D.J. and Baccarini, D. (2008) Uncertainty avoidance: public sector clients and procurement selection. *International Journal of Public Sector Management, Vol. 21 No. 7*, pp. 753–776. doi.org/10.1108/09513550810904550.

Opsahl, H., Torp, O., Lædre, O., Andersend, B. and Olsson, N. (2015) Implementation Strategies in Large Infrastructure Projects. In: *Proc. 23rd Ann. Conf. of the Int'l. Group for Lean Construction*. Perth, Western Australia, July 29-31, pp. 319-328.

Rizk, T. and Fouad, N. (2007) Alternative Project Delivery Systems for Public Transportation Projects. *International Journal of Construction Education and Research*. 3(1), pp. 51–65.

Sturgill, R., Taylor, T.R.B., Ghorashinezhad, S. and Zhang, J. (2014) Methods to Expedite and Streamline Utility Relocations for Road Projects. *Kentucky Transportation Center*. Research Report KTC-14-15/SPR460-13-1F. Available at: Methods to Expedite and Streamline Utility Relocations for Road Projects (uky.edu).

Uusitalo, P., Seppänen, O., Peltokorpi, A., and Olivieri, H. (2019). Solving design management problems using lean design management: the role of trust. *Engineering, construction and architectural management. 26 (7)*, 1387-1405.

Vilventhan, A. and Kalidindi, S.N. (2018) Utility relocation management in highway projects. *Built Environment Project and Asset Management 8 (2)*, pp. 171-182.

Wondimu, P.A., Hosseini, A., Lohne, J., Hailemichael, E., and Lædre, O. (2016) Early Contractor Involvement in Public Infrastructure Projects. In: *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, Boston, MA, USA, pp. 13–22.

Lohne, J., Drevland, F., and Lædre, O. (2021). "Agency problems as a driver for crime in the AEC-industry" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 383–392, doi.org/10.24928/2021/0123, online at iglc.net.

AGENCY PROBLEMS AS A DRIVER FOR CRIME IN THE AEC-INDUSTRY

Jardar Lohne[1], Frode Drevland[2], and Ola Lædre[3]

ABSTRACT

The paper seeks to outline agency problems as a fundamental driver for crime occurring in the AEC industry. The investigation uses Principal/Agent-theory to articulate how specific industry mechanisms serve as structural drivers of crime and how they can be counteracted.

This paper is conceptual, based on former empirical investigations—the approach springs from industry knowledge, extensive literature reviews and empirical research.

The research reveals that little discussion has been carried out concerning the root causes of criminal activity within the AEC industry. Widespread theoretical insights from economics and criminology can explain significant parts of the challenges. Production control efforts seem to be an auspicious path for combatting crime.

Being under-analysed to such a degree as identified, the theoretical conditions for criminal activity within the AEC industry needs more in-depth consideration. This need for further exploration especially concerns the implications of criminal activity on advanced process-driven production systems approaches. Establishing effective countermeasures depends heavily on such an understanding.

KEYWORDS

Process, supply chain management, production control, illegal actions, principal-agent theory.

INTRODUCTION

The threat posed by criminal activity – in its many forms, such as corruption, money laundering, and false materials – to the AEC (Architecture, Engineering, Construction) industry is underlined in several publications within the context of the Lean Construction (LC) community. Corruption results in – for example – reduced quality of the built facility, prolonged project delivery duration and increasing project prices (Rizk et al. 2018). False materials – known to exist in, for example, load-bearing systems (Kjesbu et al. 2017) – can have serious consequences. In addition, criminal activity can be difficult to detect (Thameem et al. 2017). While the threat is well documented, the drivers of such activity are less understood, to the extent of constituting a hole in the general understanding of

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the industry. The extent of the problem accentuates the need to understand these drivers as a prerequisite to forming effective countermeasures.

Estimating the level of shadowy activity within a field – be it an industry or a country – is notoriously tricky (Locatelli et al. 2020). Certain attempts have nonetheless been made. A recent report mapping criminal activity in the Norwegian AEC industry estimates that such activity involves turnover figures of approximately NOK 28 billion (Eggen et al. 2017). This number represents more than 5 % of the total turnover for the industry, which for 2017 was NOK 558 billion according to Statistics Norway (2019). However, Eggen et al. (2017) do not include fraud and other criminal activities within the materials supply chain in their analysis, a figure CII (2014) estimated to a further approximately 10 % of total turnover within the US context. Considering the AEC industry's international connectivity, it seems likely that the figures witnessed within the US context resemble those in Norway. Recent explorative studies indicate that Norwegian materials supply chains are subject to significant fraudulent behaviour (Engebø et al. 2016; Kjesbu et al. 2017a). Conservatively, it seems likely that criminal activity within the Norwegian context encompasses a two-digit percentage of the industry's total turnover. This number amounts to a typical national defence budget for Norway – for 2017 – 51 billion NOK, according to the Norwegian Ministry of Defence (2016).

Based on reports from public agencies (e.g. Ministry of Labour and Social Affairs, 2015; Office of the Auditor General of Norway, 2015-16a; Office of the Auditor General of Norway, 2015-16b; Norwegian Ministries, 2017), industry reports (e.g. Sletteböe et al. 2003), and research analyses (e.g. Andersen et al. 2014), the common opinion seems to be that present control efforts towards countering crime do not stop an escalation of criminal activity in the Norwegian AEC industry. Recent research indicates that the criminal activity takes place in fields outside the present scope of the Norwegian control authorities (e.g. Engebø et al. 2016; Kjesbu et al. 2017a; Kjesbu et al. 2017b; Lohne et al. 2015; Lohne et al. 2017; Lohne et al. 2020; Richani et al. 2017; Skovly et al. 2017). These fields include supply chain management, use of false identities, and building process challenges, such as those occurring in the design and handover phases (Lohne et al. 2017; Lohne et al. 2020; Svalestuen et al. 2015).

This paper aims to articulate the relationship between acknowledged industry characteristics and the potential for criminal activity through the lens of Principal/agent (P/A) theory and to propose further crime-combatting measures based on this. These insights are neither ground-breaking nor very innovative, but we have not seen a thorough discussion of their implications for production-oriented approaches such as Lean Construction. This paper addresses the following three research questions:

1. What are the structural drivers for criminal activities in the AEC industry?
2. To what extent do findings from the Norwegian context correspond with these theoretical insights?
3. Based on the above, what measures can be envisaged for countering the criminal activity identified?

METHODOLOGY

This conceptual paper springs from empirical research carried out under the project «Mapping opportunities for criminal behaviour in the Norwegian AEC-industry», supported by Project Norway (projektnorge.no/krim). Over the years 2014-2020, the project has investigated the Norwegian construction industry, thereby permitting for research-based synthesis. The methods employed here are analytic in nature, and the approach is based on industry knowledge and earlier empirical research within the research project. Much of the analysis is based on a scoping literature review of criminal activities in the AEC industry reported in Lohne et al. (2019a). A narrow review of the specific challenges analysed in this paper was carried out September-December 2020. The main search engine used was Google Scholar. In addition, the library database Oria was used. Search terms included "principal agent", "construction industry", "AEC-industry", "agency problems", "building process", “crime”, and “supply chain management”. The individual search terms returned more hits than possible to investigate; however, they returned manageable numbers of hits when combined.

So far, more than 220 semi-structured interviews and a major survey among Norwegian contractors have been carried out within this research project. A list of publications stemming from the project can be found on prosjektnorge.no/krim. When using findings from these interviews and this survey, a research limitation is that they were not solely about agency problems as drivers for criminal activity. While the paper is conceptual in nature, the conclusions presented here are nevertheless grounded in practical research.

DRIVERS OF CRIME IN THE AEC-INDUSTRY

A certain comprehension of what mechanisms drive criminal activity in the AEC industry appears to be widespread among practitioners in the form of tacit knowledge, as first described by Polanyi (1966). Among the studies concerned with crime, corruption has received the most attention. Interestingly, the very nature of AEC projects has arisen as a driver. For instance, Rizk et al. (2018) outline how “the complexity of the project and organisations involved coupled with scarce sanctions on corrupt activities” is a factor leading to corruption. However, much of this effort has described weaknesses in tendering processes, undue political involvement, insufficient sanctions, and similar matters. Little research document and analyse the conditions for criminal activity theoretically. Failing to do so leaves the understanding of crime at the level of symptom healing. In particular, few authors have addressed how industry characteristics serve as structural drivers for crime from a theoretical perspective. Understanding this is crucial for developing effective countermeasures.

STRUCTURAL CHARACTERISTICS OF THE AEC-INDUSTRY

The AEC industry is generally considered an industry of – in lieu of more subtle words – low moral standing. Based on contributions from Ballard and Howell (1998) and Vrijhoef (2011), the research presented in this paper considers the following elements to such a reputation. These are generic and not referenced extensively. Firstly, there is a:

- A low technological entry point for industry actors

Actors barely possessing formal qualifications can enter the industry’s value chains. Get a hammer, you’re in construction! Secondly, the industry carries out the production of:

- Unique products («One-off’s»)

Construction projects are typically highly complex products delivered to serve a particular purpose. Therefore, non-standard solutions are common. Products being unique implies that control over the end-product is complex. This implication is underlined by, thirdly:

- A significant number of clients within the industry are single-project clients

Being a single-project client renders the demand for control over the procurement and production processes highly challenging, especially when the project commissioned is not easily comparable to other projects. The lack of standardised production/standardised products increases the burden for single-product clients. Fourthly, there is:

- On-site production

One principal character of buildings is that they are – with very few exceptions – stationary. Correspondingly, the production of buildings must take place in outdoor conditions. On-site production typically creates a lack of transparency concerning work conditions and other factors more easily controlled within fixed production conditions. Fifthly, AEC projects have:

- Unique project teams

Very rarely are project teams continued from project to project. New teams pose a significant challenge to the production process. The level of trust in such altering conditions is generally challenging since the potential to establish long-term relationships – on which trust typically depends – is limited. Finally, the AEC industry has:

- Complex, non-stable materials value chains

The number of different materials entering the building site has increased exponentially over the last century. Over the last decades, the internationalisation of trade – the materials' value chains are now truly international – has added to the complexity represented by an increasing number of building components. Also, the materials value chains are not stable, in that the particularities of each project typically introduce alterations to the former value chain. In sum, these concerns imply that controlling what materials enter the building site is inherently complex – and getting more so by each year. The research literature mostly ignores the importance of this insight. Exceptions from this general conclusion are, for example, Engebø et al. (2016), Engebø et al. (2017), Kjesbu et al. (2017a), Kjesbu et al. (2017b), Minchin et al. (2013) and CII (2014).

In sum, the AEC-industry a) has unique projects that b) are not easily measurable, c) are governed by inexperienced clients, d) with highly specific production sites, e) where the team changes from project to project, and f) where little efficient control is effectuated over the material value chains. These characteristics combined serve – we would argue – as drivers for crime in the AEC industry. In the following, we propose to utilise insights from P/A-theory to capture more precisely what is at stake.

STRUCTURAL CHARACTERISTICS IN LIGHT OF PRINCIPAL-AGENT THEORY

P/A-relationships occur when the "agent" (person or entity) make decisions or take actions on behalf of the "principal" (another person or entity) to advance the principal's goals (Milgrom and Roberts 1992). Examples of such relationships abound at least from early modernity in both fiction (e.g. the relationship between Othello (principal) and Iago (agent) in Shakespeare's *Othello* (Shakespeare, 1604 (1988)) and in non-fiction (e.g. the theoretical discussions in Machiavelli's *The Prince* (Machiavelli, 1532 (2011)) on the relationship between the ruler and his subjects). However, the challenges involved in such relationships seem first to have been labelled by their contemporary proper name by

Jensen and Meckling (1976); most important within the analysis carried out in this paper is 1) goal incongruity, 2) information asymmetry, and 3) contract design.

Goal incongruity in the P/A-interaction arises when the agent and the principal have different or conflicting interests. As exemplified in Solheim-Kile et al. (2019), the agent's preference (wants as much payment as possible) regarding the performance of services does not correspond to the principal's preferences (wants it as cheap as possible).

Information asymmetry (in the context we are discussing) arises where agents possess information superior to that available to principals – concerning aspects such as own abilities and capabilities, financial situation, and local conditions. Information asymmetry exists when the principal and the agent have divergent interests, and the agent possesses information not available to the principal. Then the principal cannot assure that the agent is always acting in their (the principal's) best interest. This issue causes so-called agency costs (Bebchuk and Fried, 2004).

As Pouryousefi and Frooman (2019) have explained, the implications of these mismatches can prove problematic, given that it is the principal and not the agent that typically determines *contract design*. The principal is supposed to define the terms of the interaction between the parties involved in the contract. Still, both the goal incongruity and the information asymmetry hinder the transparency of the required interaction from the principal's perspective. If interest diverges, even if the principal makes contractual agreements with the agent, it is not sure that the agent delivers what she promises. Several contract tiers can increase interest divergence, for example, when the contractor select contractual arrangements with sub-contractors that diverge from the client's contract design. Then, the agent is likely to act contrary to the principal's interests. This interest typically results from asymmetrical incentive structures amongst the actors.

Agency Problems within the Norwegian AEC-Industry

The majority of design and build contracts carried out within the Norwegian AEC industry include some variant of the standard "NS 8407 General conditions of contract for design and build contracts". This standard regulates contractual relations when one agent (the design and build contractor) takes on all or a substantial proportion of the design and execution of building or civil engineering works (including construction, new build, maintenance, repair, and alterations) for a principal (the client).

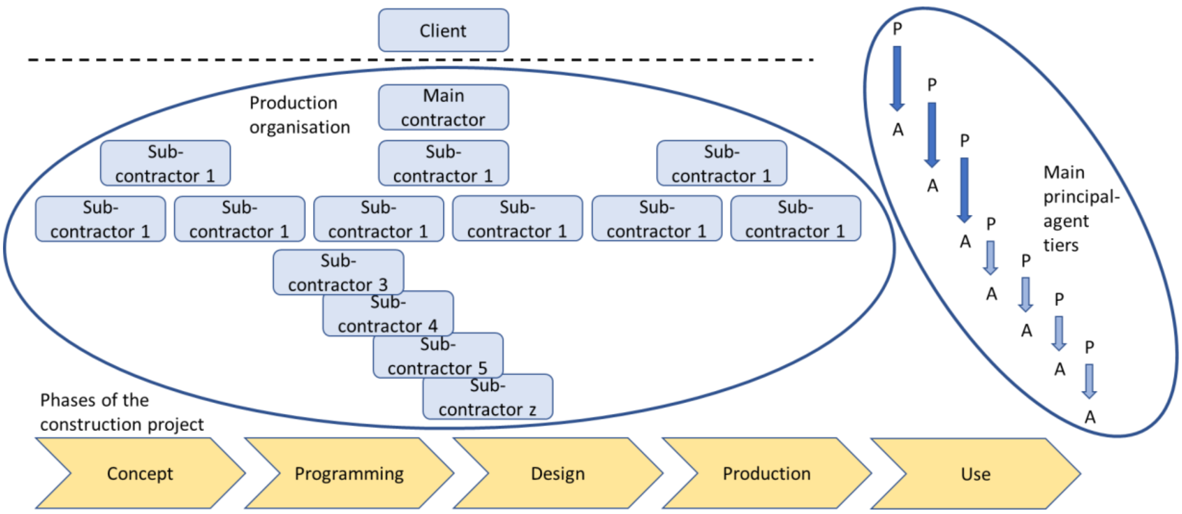

Figure 1: Outline of the production organisation of a typical construction project using NS 8407, with principal-agent tiers illustrated based on a generic phase structure.

The Norwegian AEC industry relies heavily on the standard NS 8407. As illustrated by the dotted line in Figure 1, a prominent characteristic of the contract design is transferring risk from the client to the main contractor. This relationship represents the first of the P/A-tiers involved in such contracts. Further, the general tendency within the industrial context of Norway is to involve a series of sub-contractors to carry out the actual work on the project – these sub-contractors again typically employ sub-contractors, who in turn employ their own sub-contractors. The use of NS 8407 does not hinder the use of multiple layers of sub-contractors. The room for manoeuvre this leaves for criminal elements among sub-contractors is explored in Evjen et al. (2019).

Figure 1 illustrates the typical resulting situation, with multiple layers of sub-contractors carrying out work. An extensive fragmentation of production organisation follows. According to the general outline of P/A-theory outlined above, this means that 1) there will probably be a lack of goal alignment between the sub-contractors and the project client; 2) that there will be a severe information asymmetry problem due to the organisational form of the project and that 3) this will probably mean that the client (dependent on the number of levels of sub-contractors involved) will have little to no information of what actually happens at the level of the organisation where actual physical work is carried out – including being aware or not of criminal activity. Gunnerud et al. (2019) explore opportunistic behaviour from project managers following such an analysis. As Lohne et al. (2019b) illustrated, this fuzzy landscape can serve project clients quite well – they benefit from criminal activity that they do not know of.

Skovly et al. (2017) present an interesting counterargument to this general statement within the Norwegian context. Their analysis clearly illustrates that the client has significant potential for rendering the sub-contractors' accountability transparent through active crime-preventive measures. However, such initiatives are rare in Norway, and the literature review conducted in preparing the research presented in this paper indicates that such measures are also rare internationally. The effort needed to carry out this initiative equally illustrates another general insight from P/A-theory, notably that of information as a commodity, leading to that principals "can invest in information systems in order to control agent opportunism" (Eisenhardt, 1989:64).

MEASURES FOR COUNTERING CRIMINAL ACTIVITY

At least three lines of measures can counter the drivers for criminal activities: 1) precautions in the contract, 2) control efforts – possibly carried out by a third party, and 3) production control.

Firstly, it is possible to adjust *contract design and manage contracts* to reduce agency problems occurring. Initiatives in Norway have explored the consequences of reducing the project organisation's complexity by allowing the main contractor to have a maximum of two subcontractor tiers. Such adjusted contract design – with only subcontractors and sub-sub-contractors – are explored in Aure et al. (2020). The main challenge to their efficiency seems to be the challenges of reducing project organisations' complexity, given the endeavour's complexity, see Haugen et al. (2017). Gunnerud et al. (2019) found that even though the contracts intend to restrict the possibilities for criminal activities, project managers have substantial room for manoeuvre for criminal activities.

Secondly, within the Norwegian context, a significant weight has been put on *legislation and control efforts* targeting criminal activities in the AEC industry. Legislation in general and control efforts initiated by official agencies have concentrated almost exclusively on the last tier of subcontractors. Few efforts envisaged rendering main contractors or clients responsible for criminal activity has so far been observed. The research project has conducted a series of explorative attempts (reported on at prosjektnorge.no/krim) to assess the legislation's actual effectiveness and corresponding measures. However, it has proved challenging to understand to which degree – if at all – these have had any real impact. The interest in governance measures witnessed over the last years can potentially indicate that control efforts are taken seriously by both clients and contractors. So far, Skovly et al. (2017) concluded that even though the Norwegian authorities have introduced new legislation at the same time as both clients and contractors show interest on governance level, there is still substantial room for manoeuvre.

Thirdly, *production control* can help project clients and main contractors to achieve predictability and transparency in their projects. Within standard P/A-theory, such measures fall under the heading *information systems*. As Eisenhardt maintains, "the more programmed the task, the more […] information about the agent's behaviour is more readily determined. Very programmed tasks readily reveal agent behaviour" (1989:62). A very high level of tasks programming is readily observable within the LC literature, especially at the production level. LC contains sets of production control tools, such as the Last Planner® System, Takt planning and IPD. These tools, which rely on project planning, increase predictability and – most notably within this context – transparency in projects. Further, again from Eisenhardt, "it seems reasonable that when principals and agents engage in a long-term relationship, it is likely that the principal will learn about the agent […] and so will be able to assess behaviour more readily" (*ibid.*). The call for long-term P/A-relationships stands out as a true leitmotif within the LC literature. These insights, in sum, enables us to conclude with Eisenhardt that "since information systems inform the principal about what the agent is actually doing, they are likely to curb agent opportunism because the agent will realise that he or she cannot deceive the principal" (1989:60). Programmed tasks lead to transparency and thus potentially reduces the level of deceitful actions.

DISCUSSION AND CONCLUSION

In this paper, we have addressed structural drivers for criminal activities within the AEC industry, examined to what extent findings from the Norwegian context correspond with these theoretical insights and outline three lines of measures for countering the criminal activity identified. The analysis indicates that Norwegian AEC projects share characteristics with internationally recognised issues concerning technological entry point, uniqueness of projects etc. As previously discussed, the persistence of these traits is underlined by the common use of NS 8407, leaving much room for manoeuvre for subcontracting. Resulting from this conjuncture of product specificities and (contractual) organisation is significant, inherent agency problems. Such problems lead to a situation where it is very difficult for the client to know with any certainty what the last-tier subcontractor is doing. This situation appears to leave the room for manoeuvre for criminal actors wide open.

The three lines of measures discussed for countering criminal activities in the AEC industry are 1) contract design and contract management, 2) laws and control efforts, and 3) production control. The two first have room for manoeuvre that rotten apples can exploit. Project managers can surpass the current contract management regime's parts targeted at combating criminal activities initiated by clients. Likewise, project managers that want to do so can surpass legislation and the corresponding control efforts initiated by official agencies. Thus, measures related to contract design and contract control are insufficient to combat criminal activities in the AEC industry. As long as rotten apples in the industry consider criminal activities to pay off, they will use the possibilities caused by characteristics such as low technological entry point, unique products, single product clients, and on-site production. Production control achieved through Lean Construction tools such as LPS, Takt planning, and IPD can increase project transparency.

REFERENCES

Andersen, R.K., Eldring, L. and Roed Steen, J. (2014). Privatmarkedet i byggenæringen – Usynlig arbeidsmarked i de tusen hjem. FAFO, Oslo.

Aure, B., Lædre, O., Lohne, J. (2020). “Experiences from Allowing Maximum Two Contract Tiers in the Vertical Supply Chain”. Proc. 28th Annual conference IGLC, Berkeley, 613-624.

Ministry of Labour and Social Affairs (2015). Strategi mot arbeidslivskriminalitet. Oslo. https://www.regjeringen.no/contentassets/4f7ae70171bd480682b8dafddadaf311/strategi_mot_arbeidslivskriminalitet.pdf, consulted 24.02.21.

Ballard, G. and Howell, G. (1998). “What kind of production is construction?”. Proc. 28th Annual conference IGLC, Guaruja, Brazil.

Bebchuk L. and Fried, J. (2004). Pay Without Performance: The Unfulfilled Promise of Executive Compensation. Harvard University Press, Massachusetts.

CII (2014). Mitigating threats of counterfeit materials in the capital projects industry. CII Research Report No. 307-11, Austin, Texas.

Eggen, F.W., Gottschalk, P., Nymoen, R., Ognedal, T. and Rybalka, M. (2017). Analyse av former, omfang og utvikling av arbeidslivskriminalitet. Rapport nr. 69-2017, Samfunnsøkonomisk analyse AS, Oslo.

Eisenhardt, K. M. (1989). “Building theories from case study research”. Academy of Management Review, 14(4) 532-550.

Engebø, A., Lohne, J., Rønn, P-E. and Lædre, O. (2016). “Counterfeit Materials in the Norwegian AEC-Industry”. Proc. 24th Annual conference IGLC, Boston, p. 13-22.

Engebø, A., Kjesbu, N., Lædre, O., and Lohne, J. (2017). “Perceived consequences of counterfeit, fraudulent and sub-standard construction materials”. Procedia engineering, 196, 343-350.

Evjen, S., Gunnerud, G., Lædre, O., Søfting, R. and Lohne, J. (2019). “Sub-Contractors’ Perception of Contracting: The Case of Crime”. Proc. 10th Nordic Conference on CEO. Emerald Group Publishing Limited, 59-67l.

Green, SD and May, S.C. (2003). “Re-engineering construction: Going against the grain”. Building Research and Information, 31(2) 97-106.

Gunnerud, G., Evjen, S., Søfting, R., Lædre, O., Kjesbu, N.E. and Lohne, J. (2019). “Project Managers: Gatekeepers or Inside Men?”. Proc. 10th Nordic Conference on CEO. Emerald Group Publishing Limited, 69-75.

Jensen, C. and Meckling, W. (1976). “Theory of the firm: Managerial behaviour, agency costs and ownership structure”. *Journal of Financial Economics*, 3(4) 305-360.

Haugen, A., Wondimu, P., Lohne, J. and Lædre, O. (2017). “Project delivery methods in large public road projects – a case study of E6 Jaktøyen-Sentervegen”. Procedia Engineering, 196, 391-398.

Kjesbu, N.E., Engebø, A., Lædre, O. and Lohne, J. (2017a). “Counterfeit, Fraudulent and Sub-Standard Materials: The Case of Steel in Norway”. Proc. 25th Annual conference IGLC, Crete, Greece, 805-812.

Kjesbu, N.E., Engebø, A., Lædre, O. and Lohne, J. (2017b). "Countering counterfeit, fraudulent and sub-standard materials in construction: Countermeasures to avoid the use of counterfeit, fraudulent and sub-standard steel materials in the Norwegian construction industry". Proc. 30th Annual conference IPMA, Kazakhstan, 103-110.
Locatelli, G., Geraldi, J., Konstantinou, E. and Sainati, T. (2020). "The Dark Side of Projects: Uncovering Slavery, Corruption, Criminal Organisations, and Other Uncomfortable Topics". Special issue, call for papers, Project Management Journal. *https://journals.sagepub.com/pb-assets/cmscontent/PMX/SI%20Dark-PMJ-LONG(3).pdf*, accessed 24.02.21.
Lohne, J., Shirkavand, I., Firing, M., Schneider, K., Lædre, O. (2015). "Ethics in Commissioning in Construction". Procedia Economics and Finance, 21, 256-263.
Lohne, J., Svalestuen, F., Knotten, V., Drevland, F. and Lædre, O, (2017). "Ethical behaviour in the design phase of AEC projects". International Journal of Managing Projects in Business, 10 (2) 330-345.
Lohne, J., Kjesbu, N.E., Engebø, A., Young, B. and Lædre, O. (2019a). "Scoping literature review of crime in the AEC industry". Journal of Construction Engineering and Management, 145 (6) 1-14.
Lohne, J., Drevland, F. and Lædre, O. (2019b). "Who Benefit from Crime in Construction? A Structural Analysis". Proc. 10th Nordic Conference on CEO. Emerald Group Publishing Limited, 163-170.
Lohne, J., Engebø, A. and O. Lædre (2020). "Ethical challenges during construction project handovers". International Journal of Project Organisation and Management, 12(1) 31-53.
Machiavelli, N. (1532 (2011)). The Prince. Penguin Classics, UK.
Milgrom, P. and Roberts, J. (1992). *Economics, organisation and management*. Prentice Hall, Upper Saddle River, USA.
Minchin, R. J., Cui, S., Walters, R., Issa, R. and Pan, J. (2013). "Sino-American Opinions and Perceptions of Counterfeiting in the Construction Supply Chain". Journal of Construction Engineering and Management, 139, 1-8.
Norwegian Ministries (2017), Strategi mot arbeidslivskriminalitet, https://www.regjeringen.no/contentassets/17f35b6ba95f4da2a7ac4682b0a052af/no/pdfs/revidert-strategi-mot-arbeidslivskriminalitet-2021.pdf, consulted 24.02.21.
Norwegian Ministry of Defence (2016). Prop. 1 S (2016 –2017). Proposisjon til Stortinget. https://www.regjeringen.no/contentassets/186c695600eb4db085dfcf2ca6825e49/no/pdfs/prp201620170001_fddddpdfs.pdf, accessed 14.01.21.
Pasquire, C., Sarhan, S. and King, A. (2015). "A Critical Review of The Safeguarding Problem in Construction Procurement: Unpicking the Coherent Current Model". Proc. 23rd Annual conference IGLC, Perth, Australia, 309-318.
Polanyi, M. (1966). The tacit dimension. Peter Smith Publisher, Gloucester, England.
Pouryousefi, S. and Frooman, J. (2019). "The consumer scam: an agency-theoretic approach". Journal of Business Ethics, 154 (1) 1-12.
Office of the Auditor General of Norway (2015-16a). Riksrevisjonens undersøkelse av myndighetenes arbeid mot sosial dumping ved offentlige anskaffelser. Dokument 3:14 (2015−2016), https://www.prosjektnorge.no/wp-content/uploads/2017/11/sosialdumping-krim-BAE.pdf, consulted 24.02.21.
Office of the Auditor General of Norway (2015-16b). Riksrevisjonens undersøkelse av myndighetenes innsats mot arbeidsmiljøkriminalitet. Dokument 3:15 (2015−2016),

https://www.prosjektnorge.no/wp-content/uploads/2017/11/arbeidsmiljokriminalitet-krim-BAE.pdf, consulted 24.02.21.

Richani, Y., Klakegg, O.J., Lohne, J. (2017). "Drivers and consequences of identity abuse in the AEC-industry". Procedia Computer Science, 121, 337-344.

Rizk, R., Sobh, D., Abou Yassin, A. and Hamzeh, F. (2018). "Studying the mindset of corruption in the construction industry- A Lean Perspective." Proc. 26th Annual conference IGLC, Chennai, 316-325.

Sarhan, S., Pasquire, C.L., Manu, E. and King. A. (2016). "Are Tier-one contractors making their money out of wasteful procurement arrangements?" Proc. 24th Annual conference IGLC, Boston, 83-92.

Shakespeare, W. (1604 (1988)). Four Tragedies: Hamlet, Othello, King Lear, Macbeth. Bantam Books, UK.

Shirkavand, I., Lohne, J. and Lædre, O. (2016). "Defects at handover in Norwegian construction projects". Procedia Social and Behavioral Sciences, 226, 3-11.

Skovly, M., Mørenskog, A.R., Engebø, A., Lædre, O. and Lohne, J. (2017). "Measures to counteract work-related crime – airport developments in Norway". Procedia Computer Science, 121, 664-671.

Slettebøe, A., Buseth, H., Gangås, B., Wold, E., Mo, N., Melleby, S. and Anskau, E. (2003). Seriøsitet i byggenæringen. FAFO, Oslo.

Solheim-Kile, E., Lædre, O. and Lohne, J. (2019). "Public-Private Partnerships: Agency Costs in the Privatisation of Social Infrastructure Financing". Project Management Journal, 50(2) 144-160.

Statistics Norway (2019). Strukturstatistikk for bygge- og anleggsvirksomhet, 2017. https://www.ssb.no/stbygganl, consulted 14.01.2021.

Svalestuen, F., Lohne, J., Knotten, V. and Lædre, O. (2015). "Ethics of the Design Phase – a Descriptive Approach". Proc. 23rd Annual conference IGLC, Perth, Australia, 609-618.

Thameem, M., Rybkowski, Z. K. and Smith, J. P. (2017). "Delivery Methods and Social Network Analysis of Unethical Behavior in the Construction Industry." Proc. 25th Annual conference IGLC, Crete, Greece, 453-461.

Vrijhoef, Ruben (2011). Supply chain integration in the building industry - The emergence of integrated and repetitive strategies in a fragmented and project-driven industry. Delft University Press.

Asadian, E. and Leicht, R. M. (2021). "Lean Teams and Behavioral Dynamics: Understanding the Link" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 393–402, doi.org/10.24928/2021/0125, online at iglc.net.

LEAN TEAMS AND BEHAVIORAL DYNAMICS: UNDERSTANDING THE LINK

Elnaz Asadian[1] and Robert M. Leicht[2]

ABSTRACT

The emphasis of lean thinking on eliminating waste and improving production makes it easy to relate to the construction domain to have more successful projects. Several tools and techniques have been introduced to simplify lean adoption. However, the human side of lean has not yet seen the emphasis it deserves. Interdisciplinary teams are the implementers of lean practices within projects. Therefore, this study seeks to shed light on the nature of lean teams within construction projects. The human dynamics are mapped to the lean principles to investigate the link between these constructs and lean initiatives implementation. To support the alignment of team enablers with lean principles, eight constructs from the A_B_C framework of team psychology have been identified through the literature search, including openness, trust and psychological safety, cohesion, team viability, collaboration and communication, conflict, information sharing, and knowledge exchange. The findings highlight that organizations should consider the behavioral side of lean in a team context if they want to realize the full benefits of lean transformation. By emphasizing the importance of lean foundations within the organizational culture and team member behavior, construction teams will be able to develop the link necessary between team members' interactions and lean principles adoption.

KEYWORDS

Team dynamics, lean construction, collaboration, trust, culture.

INTRODUCTION

Lean philosophy, which emerged in automotive manufacturing, is a production method to achieve better outcomes, such as improved efficiency. The paradigm of continuous improvement gained popularity in other industries, namely construction, as a way to develop more productive environments. The term lean construction (LC), an overarching concept, encompasses the design and construction phases of a project, is defined as *"a way to design production systems to minimize waste of materials, time, and effort with an aim to generate the maximum possible amount of value"* (Koskela et al. 2002 p. 211).

Since the introduction of lean principles, several studies have discussed the concept's fundamentals. Despite the ample literature on the theory behind the lean philosophy, we have witnessed many failed efforts. According to Aslam et al. (2020), the construction industry is struggling to adopt the full benefits of lean either due to the lack of awareness or complex strategies. Moreover, most of the prior research studies have generally

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targeted lean instruments and application of new technologies. Low emphasis has been assigned to project participants, leaving aside organizational and human issues (Pavez and Alarcón 2006). Simply implementing the best lean methods does not guarantee success. Understanding the culture of lean is needed to assist organizations in successfully adopting and sustaining lean strategies. In this respect, some research studies have tried to identify behavioral dynamics that constitute a thriving lean culture (Van Dun and Wilderom 2012). Most of them focus on manufacturing and other businesses, rather than construction. Therefore, there is a dearth of studies within the construction domain.

This paper aims to identify how lean principles align with the design of teams in a construction context. To determine the links between lean theory and teams, this research will explore literature on team attributes, behavioral dynamics, and sociocultural indicators that underpin lean teams' performance. Ultimately, we seek to understand how team dynamics influence the way lean teams operate.

A subset of lean principles is briefly introduced in this paper, followed by describing the “lean team” concept in construction. Lastly, by linking the human dynamics with lean principles, a comparison of lean principles and ideas with the internal dynamics of effective lean teams was investigated to understand how construction team efforts could be supported more effectively. The study's findings will serve as the initial development of a framework to capture the human side of lean implementation, which must be considered by construction companies if they want to realize the full benefits of lean transformation. By emphasizing the importance of lean foundations within the organizational culture and team member behavior, construction teams will be able to create the necessary human conditions for adopting and sustaining lean principles.

LITERATURE REVIEW

LEAN PRINCIPLES AND IDEAS

In 1992, Koskela proposed eleven principles for flow process design and improvement. These principles are: reduce the share of non-value-adding activities, increase output value through systematic consideration of customer requirements, reduce variability, reduce the cycle time, simplify by minimizing the number of steps and parts, increase output flexibility, increase process transparency, focus control on the complete process, build continuous improvement into the process, balance flow improvement with conversion improvement, and benchmark. He highlighted that approaches to the new production philosophy have originated around one central principle, even if they usually acknowledge other principles. Therefore, many principles are closely related but not on the same abstraction level. Some are more fundamental, while others are more application-oriented (Koskela 1992). Subsequently, Koskela and Leikas (1997) added “focus on the whole processes and optimize the whole” as an overarching lean principle.

Womack and Jones (1997) established five principles of lean: value, value stream, flow, pull, and perfection. In the same year, Melles, in his book, *What do we mean by lean production in construction*, listed seven basic principles of lean production, including multifunctional task groups, simultaneous engineering, kaizen, just-in-time deliveries, co-makership, customer orientation, and information, communication and process structure (Melles 1997). In 2005, Pinch pointed out the following principles as LC principles: establishing integrated teams and collaboration, combining project design with process design, stopping production rather than releasing a faulty product into construction, decentralizing decision-making and empowering project participants, making the process transparent, and requiring a simple, direct handoff between tasks (Pinch 2005). These are only some of the previous studies discussing lean principles. Although each scholar presented different terms, similarities are apparent in the principles. Some principles, such as continuous improvement, perfection, customer orientation, decentralizing decision-making, and optimizing the whole, will be discussed in this paper to investigate the relationship between team dynamics and lean principles.

CONSTRUCTION TEAMS AND TEAM-ORIENTED APPROACH

Teams are the appropriate unit for high complexity tasks with many interdependent subtasks, like construction activities. Katzenbach and Smith (2015) defined a *"True Team"* as a small group of people with complementary skills committed to a common purpose. They also commit to an approach for which they hold themselves mutually accountable.

The team concept was first employed as a management practice for organizations that wanted to become more flexible and harness employees' creative capacities. This practice showed numerous benefits, including higher productivity, improved quality, and increased employee morale (Johnson et al. 2000). In the context of work team applications, four broad categories were proposed: advice and involvement, production and service, projects and development, and action and negotiation. Under the production team category, teams use technology to generate products or services, such as teams in construction. (Sundstrom et al. 1990). Considering construction as team-based production can explain the linkage between team dynamics with production theory, namely lean.

Several scholars have highlighted the vital role of teamwork in construction activities. Spatz (2000) claimed that *"if any industry should appreciate the importance of teamwork, that is the construction industry."* Based on his study, teamwork can be traced back to construction projects' foundation and cultural heritage. In addition, the complex social and technical aspects of construction projects require teamwork to allow specialized individuals to work collaboratively at the job sites or during the project's design phases.

Teamwork initiatives in construction projects generally focus on improving how people interact. This is in accordance with what Liker (2004) emphasized as the two pillars that support lean implementation: *"Continuous Improvement"* and *"Respect for People."* Likewise, Shah and Ward (2007) defined lean production as an integrated socio-technical system that eliminates waste by minimizing supplier, customer, and internal variability. Therefore, the attention to the social aspect of lean production, in parallel with the technical processes, necessitates the study of LC's human dimension.

CRUCIAL ROLE OF LEAN TEAMS IN CONSTRUCTION

Although lean thinking in both construction and manufacturing applies the same principles, there are some differences. One of the distinctions is the complicated interface among multiple entities in construction projects (Fahmy 2020). In construction, these parties have distinct organizational motivations and goals. However, in manufacturing, uncertainties can be almost eliminated by clearly defining the end product. Therefore, while lean manufacturing targets processes to achieve product goals, the lean approach in construction should address peoples' and entities' alignment with the overall project goals.

Van Amelsvoort and Benders (1996) also emphasized the role of lean teams when they called the team a hallmark of lean production, stating *"teams emerge as the heart of the lean factory."* Moreover, companies have realized that their major problems hindering the successful implementation of lean practices are driven by human, cultural, and organizational issues (Pavez and Alarcón 2006). The development of the team aspect of the lean approach is more complicated than merely adopting lean tools. Establishing and maintaining a productive team dynamic is one of the biggest challenges.

Team dynamics describe how unconscious psychological forces affect the behavior of groups of people working together (Wakeman and Langham 2018). Put simply, team dynamics define how team members interact (Gomez et al. 2020). According to Van Dun and Wilderom (2012), these dynamics include interaction behavior between team members and the leader, which were considered invisible to those working outside the team. They defined these internal interactions as the mediating or moderating factors that transform external inputs into collective team outcomes. Considering that the cornerstone of the lean approach in construction is the operations of the construction team, understanding and identifying the dynamics within the project team that helps align team outputs with project goals will ultimately increase the likelihood of project success.

RESEARCH METHODOLOGY

This paper explores theoretical foundations to establish the link between lean and teamwork in the construction domain. To do so, a systematic literature search using Google Scholar and ScienceDirect was conducted. Different combinations of general terms of lean, teams, culture, behavior, combined with dynamics, human side, and organization, were explored within the two search engines. All publications with the search terms in the title or keywords were extracted in the initial step, resulting in 74 articles. The 29 articles that concentrate on the construction industry's organizational settings were then selected for an in-depth study. Following this filtering, the selected papers' abstracts were then used to further narrow down the sample to the studies focused on lean teams in construction. In the final step, nine papers served as the analysis for the purpose of this study. A brief description of these papers is summarized in Table 1.

Table 1: Title, authors, and venue of papers analyzed in the research study

Title	Authors	Publication
Lean, psychological safety, and behavior-based quality: a focus on people and value delivery	(Gomez et al. 2020)	IGLC
Lean Principles Implementation in Construction Management: A One Team Approach	(Fahmy 2020)	CIC 2020
Towards a lean behavior evaluation system in Latin American construction	(Salvatierra et al. 2020)	IGLC
Building a lean culture into an organization	(Kalyan et al. 2018)	IGLC
Building a Lean culture	(Hackler et al. 2017)	IGLC
Behavioral factors influencing lean information flow in complex projects	(Phelps 2012)	IGLC
Understanding lean implementation: perspectives and approaches of an American construction organization.	(Chesworth et al. 2011)	ARCOM Conference
An empirical study of information flows in multidisciplinary civil engineering design teams using lean measures	(Tribelsky and Sacks 2011)	Archit. Eng. Des. Manage.
Qualifying people to support lean construction in contractor organizations	(Pavez and Alarcón 2006)	IGLC

A-B-C FRAMEWORK

Salas et al. (2008) developed the A-B-C framework to establish a practical and concise means to understand teamwork. They proposed the framework to depict three essential aspects: Attitudes, shared Behaviors, and Cognition of the individuals that make up the team. These aspects define the local dynamics, which exist within a team's context.

Team dynamics contribute to the engagement processes of team performance. What team members do can be described by shared behaviors. What team members believe or feel can be portrayed by attitudes, while cognitions consist of what team members think or know. In this respect, the following constructs can be recognized (Delice et al. 2019):

- **Attitudes:** openness, trust, cohesion, team viability,
- **Behaviors:** collaboration, communication, conflict, leadership, and
- **Cognitions:** information and knowledge sharing, shared mental model.

In this paper, the A-B-C framework is employed due to its ability to capture the elements that shape effective team dynamics. It should be noted that more team constructs exist that can be investigated; however, due to space limitation, the authors concentrate on eight identified dynamics, specifically: openness, trust, cohesion, team viability, collaboration, communication, conflict, information and knowledge sharing. While leadership is one of the most important constructs, we do not have sufficient space for it to be fully considered. Similarly, shared mental models are an extensive topic and are not discussed in this paper. In the following section, the eight constructs will be discussed. These constructs are expanded upon and linked to construction literature, developing an initial understanding of the alignment of team dynamics with lean production principles.

FINDINGS AND DISCUSSION

This section investigates the association between team constructs and lean principles. The authors aim to introduce the relationships and discuss how lean teams are linked to the eight constructs from the A-B-C framework to investigate how lean principles support lean team constructs. Each construct is first introduced, then a comparison of lean principles and ideas with this team dynamic is presented.

LEAN TEAM DYNAMICS

Openness

The value of organizing work into teams is that each member does not need to be capable of doing everything on their own. Instead, they can have access to a broader pool of skills and ideas. In this context, the way people accept new ideas, actions, and values or react to them matters. Openness is defined as the degree to which teammates openly share and receive information. This construct can be used to recognize whether individuals will be able to trust one another and communicate differing opinions in the context of their team throughout the developmental stages of a team (Delice et al. 2019).

With “respect for people” as one of the main pillars of lean philosophy, team members are encouraged to be less dogmatic and rigid in their ideas. Instead, they are encouraged to consider different opinions in new situations. In the pursuit of continuous improvement, new concepts are frequently considered for activity improvement. Hence, it is necessary for lean teams to be open to the potential value of new practices. In construction projects, stakeholders come together from various organizations. Therefore, they should be open to ideas from project participants from other organizations to fully realize project benefits.

This notion conforms with another lean principle, “optimize the whole,” highlighting that companies should consider the entire supply chain process to satisfy their end customers’ needs rather than concentrate only on their own work processes.

Moreover, as Van Dun and Wilderom (2012) described, lack of team openness can impair team members' communication and information sharing. Accordingly, a lower level of openness hinders the team’s ability to generate innovative solutions, which is one of lean team pursuits under continuous improvement. Therefore, under the principles of respect for people, continuous improvement, and optimize the whole, a lean team is expected to possess sufficient openness to embrace different perspectives. Thus, openness acts as an underpinning dynamic for teams to effectively use lean principles in projects.

Trust and Psychological Safety

To date, no definition of trust has been universally accepted. However, “positive expectations towards the behavior of others” and “the willingness to become vulnerable to others” are consistently recognized as critical elements of trust. Trust is considered a psychological state influenced by the complex interrelations between expectations, intentions, and dispositions (Costa et al. 2018). Trust is often initially affected by an individual’s openness to other team members to reduces ambiguity. In this environment, team members are open to taking risks and enhancing collaboration and cooperation. Moreover, trust can contribute to a psychologically safer environment, where team members feel comfortable discussing their opinions and viewpoints freely.

Trust between team members plays a pivotal role in the formation of lean teams and can be recognized as an enabler that supports the employee’s contribution towards improving work practices. For example, Van Dun and Wilderom (2012), in their paper about lean teams in the manufacturing industry, reflected on two findings:

- With higher mutual trust, team members are more accepting of mutual monitoring.
- Mutual trust supports information sharing among team members.

Thus, they concluded that high team performance within teams requires members feeling psychologically safe to discuss errors or suggest improvements. Simultaneously, when team members feel responsible for maintaining and co-creating a high level of psychological safety, this may lead to increased team performance.

In one of the most comprehensive studies on psychological safety in the lean construction realm, Gomez et al. (2020) highlighted theoretical concepts to describe how lean principles and psychological safety are connected in a people-centered approach to improve value delivery. Based on this study, awareness of people’s level of psychological safety can nurture lean principles, such as respect for people. As a result, under the culture of trust and within a psychologically safe environment, lean practices can be implemented more effectively to support project outcomes. A well-coordinated Last Planner meeting can be an excellent example of this type of trust.

Due to the high dependency of construction projects on teams, emphasis on trust and psychological safety support communication and idea-sharing to overcome project challenges. As a result, people’s mindsets can be shifted towards pursuing learning and improvement. Quality expectations will be more likely to be met, and safety will become a priority for all (Gomez et al. 2020). Thus, a higher level of trust and psychological safety is supportive of lean teams' efforts to optimize the whole project.

Cohesion

In its classic definition, cohesion refers to a field of forces making team members stay together. Since this early definition, a multidimensional view of cohesion has emerged to describe how various factors may affect team members to work together and remain united. For instance, a categorization of cohesion, including social cohesion, task cohesion, and group pride, was proposed. While social cohesion refers to a shared appeal to the team, i.e., interpersonal attraction and emotional friendship, task cohesion relates to a team's shared commitment to the team tasks to coordinate their efforts to achieve common work-related goals (Chiocchio and Essiembre 2009).

One of the lean principles is the consideration of customer requirements. Considering that team members serve as internal customers within the process, each member tries to coordinate their efforts to answer the work-related requests of their teammates. Previous studies confirmed this notion, suggesting that in the lean context, developing a cohesion level over a certain threshold is needed to become a lean team, and the team cohesiveness may grow over time. During the initial steps of adopting lean philosophy, teams may struggle to change things in their non-value-adding tasks, resulting in a lower team cohesiveness. However, at the more advanced stages of lean implementation, the team's cohesiveness level would be increased (Van Dun and Wilderom 2012). Thus, with respect to customer orientation, cohesion can be considered a key construct in lean teams.

Team Viability

Bell and Marentette (2011) defined team viability as a team's capacity for growth, which is required for success in future performance. It is sometimes viewed as a team members' willingness to remain in the team. Teams with higher social integration and cohesion experience higher member satisfaction, perform better at coordinating tasks and show higher team viability. However, team viability is understudied despite the importance of this construct for examining team maturity (Delice et al. 2019). Little has been done to develop the construct since the inclusion of team viability in team effectiveness models.

None of the previous studies on lean teams have explicitly emphasized this attribute. However, in terms of the links to lean principles and ideas, team viability is in close conformity with the principles of seeking perfection and continuous improvement. Additionally, in lean philosophy, a long-term vision has been emphasized as a lean management component. It is in line with organizational research that the social processes used should sustain team members' ability to work together on subsequent tasks (Bell and Marentette 2011). Yet, the temporary nature of construction project teams may inherently complicate the drive toward viability. Thus, the concept of team viability needs greater attention if the construction organization seeks lean principles. This could be achieved through building relationships across projects and the supply chain.

Collaboration and Communication

Collaboration is referred to the joint effort of two or more agents trying to achieve a common goal where members construct judgments and act based on them. Collaboration occurs when a group of autonomous stakeholders engages in an interactive process by using shared rules, norms, and structures to decide on issues related to a problem domain (Wood and Gray 1991). When team members collaborate, they bring different perspectives to handle complex problems, the resulting information processing capacity is increased. In this context, communication, the act of transferring information from one place to another, is key to effective collaboration and team functioning.

Collaboration and communication play pivotal roles in completing a construction project. Melles (1997) highlighted information, communication and process structure as lean principles. In addition, Pinch (2005) pointed out establishing integrated teams and collaboration, and decentralizing decision-making and empowering project participants as lean principles. Similarly, according to Fahmy (2020), lean can be considered as a set of processes that allow project teams to collaborate efficiently to eliminate waste and maximize value. Hence, principles such as pull have been introduced to address collaboration across fragmented organizational boundaries of project teams. With these lean principles, it can be concluded that the stakeholders' collaboration and communication are a prerequisite of lean teams.

Conflict

Conflict is inherent in any team that even the most homogeneous groups cannot avoid. Conflict is recognized as a multidimensional construct involving tasks or relationships. In this respect, relationship conflict represents the individual’s perception of the incompatibility of their teams. In contrast, task conflict is a disagreement among team members about their collective task decisions and ideas. However, with moderate levels, task conflict can be used constructively to enhance team performance (Delice et al. 2019).

The impact of conflict management on lean teams has been identified in previous studies. For instance, Van Dun and Wilderom (2012) showed that if a lean team is well-structured, members are more likely to learn from work experiences, including conflict. Effective conflict resolution within teams is employed to secure issues, with lean teams extending this into learning and continuous improvement. Though conflict may arise, members will be open to each other’s ideas within a healthy and safe team environment. Teams that effectively manage differences in personality and style have been more flexible by considering the team's good instead of focusing on their own achievement. This is in close correlation with the lean principle of optimizing the whole. When team members concentrate on the ultimate goal of having a better project, individual viewpoints will enable constructive conflict to benefit the overall project.

Information Sharing and Knowledge Exchange

Teams with systems for information sharing and knowledge exchange have been shown to manage conflicts more effectively and experience better performance outcomes. Information sharing is exchanging ideas amongst members, and knowledge exchange can be defined as sharing task-relevant ideas and information among members (Delice et al. 2019). These constructs hold great importance in the progression of team performance.

Van Dun and Wilderom (2012) showed that well-structured lean groups tend to share more information, affecting a team’s learning orientation. This team construct is closely associated with “increase process transparency,” where the process is made observable through the public display of information. Based on this lean principle, proper information sharing can make the production process transparent and visual, facilitating control, identifying waste, and enabling improvement. Hence, the increased process transparency supports the information sharing construct within lean teams.

CONCLUSIONS

Developing and sustaining effective lean teams is more challenging than merely adopting lean tools. Therefore, identifying what dynamics influence how lean teams operate can help align team constructs with lean principles. This paper applied the A-B-C framework to extract team constructs and map them to lean principles to find the links between them.

The findings revealed that team constructs, including openness, trust and psychological safety, cohesion, team viability, collaboration and communication, conflict, information sharing, and knowledge exchange, are closely aligned with the implementation of lean principles, namely respect for people, continuous improvement, perfection, optimizing the whole, customer orientation, increase process transparency, pull, and decentralizing decision-making. The study also revealed that although some of these team constructs have been emphasized in lean construction literature, some of them, namely team viability, have been neglected in previous studies. This suggests the need for a holistic framework of teams and lean principles to fill the gap of overlooking these fundamental team constructs. The findings of this study can help construction organizations to understand team dynamics to provide related training and coaching efforts. Further, as construction projects are often limited in their time and resources, the alignment of lean principles to improve production with improving the effectiveness of teams may help align and reinforce the implementation of both.

Although remarkable signs of progress have been made in adopting lean principles in construction, there is still much to learn about aligning the adoption of principles in the implementation of construction teams. To continue the study and refine links introduced here, we intend to study lean teams' formation and development during the life of projects.

REFERENCES

Aslam, M., Gao, Z., and Smith, G. (2020). “Exploring factors for implementing lean construction for rapid initial successes in construction.” *J. Cleaner Prod.,* 277, 123295.

Bell, S. T., and Marentette, B. J. (2011). “Team viability for long-term and ongoing organizational teams.” *Organ. Psychol. Rev.,* 1(4), 275–292.

Chesworth, B., London, K., and Gajendran, T. (2011). “Understanding lean implementation: perspectives and approaches of an American construction organization.” *27th Annual ARCOM Conference,* 321.

Chiocchio, F., and Essiembre, H. (2009). “Cohesion and Performance: A Meta-Analytic Review of Disparities Between Project Teams, Production Teams, and Service Teams.” *Small Group Research,* 40(4), 382–420.

Costa, A. C., Fulmer, C. A., and Anderson, N. R. (2018). “Trust in work teams: An integrative review, multilevel model, and future directions.” *J. Organ. Behav.,* 39(2), 169–184.

Delice, F., Rousseau, M., and Feitosa, J. (2019). “Advancing Teams Research: What, When, and How to Measure Team Dynamics Over Time.” *Front. Psychol.,* 10, 1324.

Fahmy, M. (2020). “Lean Principles Implementation in Construction Management: A One Team Approach.” *Qatar University Press.*

Gomez, S., Ballard, G., Arroyo, P., Hackler, C., Spencley, R., and Tommelein, I. D. (2020). “Lean, Psychological Safety, and Behavior-Based Quality: A Focus on People and Value Delivery.” Proc. 28thAnnual Conference of the International Group for Lean Construction (IGLC28), Berkeley, California, USA, 97–108.

Hackler, C., Byse, E., Reed, D., and Alves, T. (2017). “Building a Lean culture.” Proceedings for the 25th Annual Conference of the International Group for Lean Construction (IGLC25), 309–316.

Katzenbach, J. R., and Smith, D. K. (2015). “The Wisdom of Teams: Creating the High-Performance Organization.” *Harvard Business Review Press.*

Kalyan, V., Pratap, V., and Singh, S. C. (2018). "Building a lean culture into an organization." 26th Annual Conference of the International Group for Lean Construction (IGLC26).

Koskela, L. (1992). "Application of the new production philosophy to construction." Citeseer, Stanford: *Stanford University.*

Koskela, L., and Leikas, J. (1997). "Lean manufacturing of construction components." *Lean construction*. Alarcón, L.(ed.). AA Balkema, Rotterdam, 263–271.

Koskela, L., Howell, G., Ballard, G., and Tommelein, I. (2002). "The foundations of lean construction." *Design and Construction: Building in value,* 291, 211-226.

Johnson, P. R., Heimann, V. L., and O'Neill, K. (2000). "The wolf pack: team dynamics for the 21st century." *Journal of Workplace Learning,* MCB UP Ltd, 12(4), 159–164.

Liker, J. K. (2004). "The Toyota Way: 14 management principles from the world's greatest manufacturer." *McGraw-Hill,* New York, 109–111.

Melles, B. (1997). "What do we mean by lean production in construction." *Lean Construction,* AA Balkema Rotterdam, 1, 11–16.

Pavez, I., and Alarcón, L. F. (2006). "Qualifying people to support lean construction in contractor organizations." Proc. 14th Annual Conference of the International Group for Lean Construction, 513–524.

Phelps, A. F. (2012). "Behavioral factors influencing lean information flow in complex projects." Proceedings of the 20th annual conference of the international group for Lean Construction, Citeseer.

Pinch, L. (2005). "Lean construction." *Construction Executive,* 15(11), 8–11.

Salas, E., Cooke, N. J., and Rosen, M. A. (2008). "On Teams, Teamwork, and Team Performance: Discoveries and Developments." *Human Factors,* 50(3), 540–547.

Salvatierra, J. L., García, A., and Aracena, P. (2020). "Towards a lean behaviour evaluation system in Latin American construction." IGLC, Berkeley, California, USA.

Shah, R., and Ward, P. T. (2007). "Defining and developing measures of lean production." *J. Oper. Manage.,* 25(4), 785–805.

Spatz, D. M. (2000). "Team-Building in Construction." *Pract. Period. Struct. Des. Constr.,* 5(3), 93–105.

Sundstrom, E., De Meuse, K. P., and Futrell, D. (1990). "Work teams: Applications and effectiveness." *American psychologist,* 45(2), 120.

Tribelsky, E., and Sacks, R. (2011). "An empirical study of information flows in multidisciplinary civil engineering design teams using lean measures." *Archit. Eng. Des. Manage.,* Taylor & Francis, 7(2), 85–101.

Van Amelsvoort, P., and Benders, J. (1996). "Team time: a model for developing self-directed work teams." *Int. J. Oper. Prod. Manag,* 16(2), 159–170.

Van Dun, D. H., and Wilderom, C. P. M. (2012). "Human dynamics and enablers of effective lean team cultures and climates." *International review of industrial and organizational psychology,* 27, 115–152.

Wakeman, D., and Langham, M. R. (2018). "Creating a safer operating room: Groups, team dynamics and crew resource management principles." *Seminars in Pediatric Surgery,* 27(2), 107–113.

Womack, J. P., and Jones, D. T. (1997). "Lean thinking—banish waste and create wealth in your corporation." *J. Oper. Res. Soc.,* Taylor & Francis, 48(11), 1148–1148.

Wood, D. J., and Gray, B. (1991). "Toward a comprehensive theory of collaboration." *The Journal of applied behavioral science,* 27(2), 139–162.

Bou Hatoum, M., Nassereddine, H., and Badurdeen, F. (2021). "Reengineering Construction Processes in the Era of Construction 4.0: A Lean-Based Framework." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 403–412, doi.org/10.24928/2021/0126, online at iglc.net.

REENGINEERING CONSTRUCTION PROCESSES IN THE ERA OF CONSTRUCTION 4.0: A LEAN-BASED FRAMEWORK

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ABSTRACT

Industries around the world continue to be reshaped, and the construction industry is no exception. Being one of the oldest industries, construction did indeed undergo major transformations over the years. However, for the past few decades, traditional business-as-usual in construction has reached a stagnation point, adding pressure on organizations to rethink their current processes. Two major transformations changed and continue to change the landscape of the construction industry: Lean Construction and Construction 4.0. While Lean has taken a hold of construction, Construction 4.0, a counterpart of Industry 4.0, is a growing transformation that leverages the power of technology. While the importance of Construction 4.0 has been highlighted, the "how" component of achieving a Construction 4.0 state has not been yet discussed. A process reengineering methodology is needed to assist construction companies in adopting technologies, especially since the existing construction processes have been mostly designed before current technologies became available. Therefore, this paper proposes a holistic conceptual framework to reengineer construction processes in the Construction 4.0 era. The proposed Construction 4.0 Process Reengineering (CPR4.0) framework, which embodies the Futures Triangle methodology, is inspired by Kurt Lewin Change Management Model, and consists of three phases that build on existing reengineering methodologies, people-process-technology methodology, and Lean principles.

KEYWORDS

Lean construction, process reengineering, Construction 4.0, futures triangle, lean framework.

BACKGROUND

Different businesses across major industries are constantly undergoing significant changes. Driven by the growing global competition, increased complexity of business environments, added pressure from customer expectations, and the emergence of new technology, businesses are changing existing processes to be more dynamic and responsive (Adesola and Baines 2005). As a result, various methodologies to reengineer processes were developed and the concept of business process reengineering (BPR)

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emerged. BPR is defined as "the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service, and speed" (Hammer and Champy 2009). The major phases of BPR can be summarized in a five-step-continuous-improvement-like cycle: (1) *Initiation* of the reengineering or improvement process, (2) *Diagnosis* through analyzing the current state and finding areas of improvement, (3) *Design* of the future state, (4) *Implementation* of the future state, and finally (5) *Evaluation* and continuous assessment of the new process (Adesola and Baines 2005; Widodo et al. 2020).

The construction industry is no exception to the array of industries and businesses that are constantly facing a dynamic environment. It has been well documented that the traditional business-as-usual in the construction industry has reached a stagnation point – there is a pressing need to increase productivity, improve project performance, address the labor shortage, reduce fragmentation, introduce standardization, address resistance to change, and increase collaboration (Barbosa et al. 2017; Bou Hatoum and Nassereddine 2020; Lau et al. 2019; Mellado and Lou 2020; Nassereddine 2019; Sawhney et al. 2020a). Such needs provide a call for action, leading academicians and practitioners to examine other industries for opportunities to innovate for the construction industry. One industry that has been considered the treasure trove of innovation for construction is manufacturing. Two of the major transformations that have taken hold in manufacturing, namely "Lean" and "Industry 4.0", have been examined and have shown great promise in the construction industry. Consequently, the terms "Lean Construction" and "Construction 4.0" emerged in the construction body of knowledge.

Lean construction emerged as a new concept in the mid-1990s that introduced a novel theory-based approach to the construction industry with a kit of tools and methods adopted from Toyota's Lean production (Koskela et al. 2002). Lean construction is also a "respect- and relationship-oriented production management-based approach to project delivery" which changes the traditional of way of designing, building, supplying, and delivering construction projects (Seed 2015). While Lean challenges the traditional management practices, the recent Construction 4.0 transformation leverages the power of technology. Modeled after Industry 4.0 (or the fourth industrial revolution), Construction 4.0 is inspired by the convergence of trends and technologies to plan, design, deliver, and operate projects more effectively and efficiently (Sawhney et al. 2020b). The European Construction Industry Federation (FIEC) defines Construction 4.0 as a "significant transformation for the construction industry which includes revolutionary approaches such as digitalization and automation" (FIEC 2020). Construction 4.0 has four major design principles: (1) interconnection and interoperability to support effective communication and coordination among stakeholders, (2) information transparency, (3) decentralized decision making, and (4) technical assistance for construction personnel (Hossain and Nadeem 2019; Noran et al. 2020). Technologies enabling Construction 4.0 include big data, virtual reality (VR), augmented reality (AR), sensors, robotics, artificial intelligence (AI), 3D printing, drones, and integrated Building Information Modelling (iBIM), in addition to currently used software tools such as Computer-Aided Design and Drafting (CAD), Enterprise Resource Planning (ERP), and Customer Relationship Management (CRM) (Bou Hatoum et al. 2020; Noran et al. 2020; Rastogi 2017).

While volumes have been written on Lean Construction, the exploration of the path towards Construction 4.0 is on the rise. Researchers have investigated Construction 4.0 technologies and their potential associated benefits. However, an important topic that has not been discussed yet is the absence of a construction process reengineering methodology that accounts for the proper integration of the technologies (Oesterreich and Teuteberg 2016). Existing construction processes have been mostly designed before current technologies became available, and thus, cannot undergo transformations without being reengineered (El Jazzar et al. 2020). While technology integration is at the core of the needed process reengineering methodology, focusing solely on technology has the potential to fail in the construction industry (Love et al. 1996). For this methodology to be a recipe for success, it should be three-pronged and combine technology, human, and organizational aspects (Love et al. 1996). Additionally, the methodology should leverage and be supported by existing transformations to maximize the expected value. Therefore, this paper, which is part of an ongoing study, proposes a holistic conceptual framework that leverages on Lean construction to reengineer construction processes in the era of Construction 4.0. The framework, named “Construction 4.0 Process Reengineering” or “CPR4.0”, is developed for construction companies to assist them in their Construction 4.0 reengineering efforts.

METHODOLOGY

The methodology adopted to develop the framework follows a design science approach that can be summarized in four tasks: (T1) reviewing the existing research corpus to understand construction industry transformations and highlight gaps in existing process reengineering methodologies, (T2) presenting a new framework to reengineer construction processes, (T3) verifying the framework with subject matter experts through interviews and surveys, and (T4) validating the framework through applying it on a real-life construction process. This paper will be limited only to T2, where an initial draft of the framework will be presented, and its lean aspect will be discussed.

PROPOSED FRAMEWORK

RATIONAL AND VISION BEHIND CPR4.0

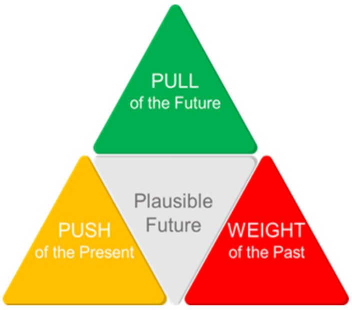
The growing need for change and improvement has led the construction industry to embrace technologies to shape its future. Therefore, the proposed CPR4.0 framework is envisioned as a vehicle that can assist in moving the construction industry towards its future. CPR4.0 provides a holistic framework to reengineer construction processes while properly and effectively integrating technology. In the discourse about the future, the “Futures Triangle” methodology was put fore to map the anticipated future. Developed by Inayatullah (2008), the Futures Triangle (as illustrated in the left of Figure 1) maps the competing dynamics between the past, present, and future contexts. Each dimensions represent a set of drivers or factors that interact to contribute to the plausible future.

When considering CPR4.0, the equilibrium between the three dimensions is crucial for reaching the plausible future. The three dimensions labelled as weight of the past, push of the present, and pull of the future are described below:

The weight of the past, or the hindsight into the past, is represented by the resistance to change that is embedded in the construction industry and hesitance to adopt new technologies. The industry still relies on its traditional and conventional methods and processes resulting in a poor performance record as compared to other industries. Thus, the proposed framework will thoroughly understand the current state of the process to remove all constraints that may hinder the desired future process.

The push of the present, or the insight into present day, is represented by the current trends and quantitative drivers that are pushing for reengineering the construction processes. Examples of these trends include industry fragmentation, labour shortage, aging workforce, low productivity, and cost and schedule overruns. These drivers describe the current landscape of the construction industry, provide momentum for the future, and need to be carefully examined and accounted for in CPR4.0.

The pull of the future, or the foresight about the future, is envisioned as the enhanced image of the construction industry powered through Construction 4.0. This image of the construction future should empower people and embrace the use of technology in the industry to enable Construction 4.0 potential benefits. Thus, the proposed framework should not only result in a reengineered process that utilizes current technology, but also provide the reengineered process with enough room to adopt change and continuously improve with time.



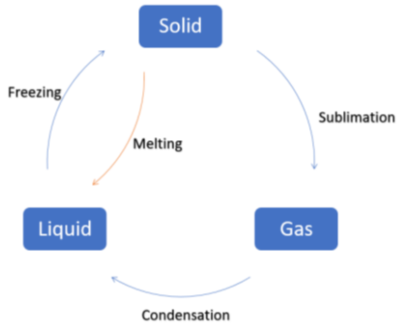


Figure 1: To the left, Futures Triangle reproduced from Inayutallah (2008); To the right, Schematic Diagram of CPR4.0

FRAMEWORK INSPIRATION

Lewin (1951) developed a three-stage model for change known as unfreezing-change-refreeze model. The model called the Kurt Lewin Change Management Model is a method to approach change management: (1) find the motivation to change and unfreeze the process, (2) change what needs to be changed to move to a new stage, and (3) refreeze the process and make the change permanent (Wirth 2004). Inspired by this model and the science behind the state of matter, CPR4.0 can be mapped onto the distinct forms in which a matter can exist. As illustrated in Figure 2, reengineering transforms an existing process from its solid state to gas through sublimation, from gas to liquid through condensation, and then from liquid to solid through freezing which marks the beginning of a new cycle of the reengineered process. Within this external cycle, an internal melting-freezing cycle is also introduced to account for continuous improvement. These phases are aligned with the various process reengineering methodologies developed for the construction industry (Cheng and Tsai 2003; Mao and Zhang 2008; Mendonça and McDermott 2000; Serpell et al. 1996) where reengineering is described as a cycle that begins by first selecting the process to change, diagnosing the process by understanding its current state, designing the future state, implementing the designed future state, and continuously evaluating and improving the process. The CPR4.0 phases are explained in the following section, and the detailed elements of the proposed framework are shown in Figure 2.

The schematic diagram of the proposed CPR4.0 illustrates the cycle of fundamentally rethinking and radically redesigning a construction process, an act that has its root in Lean production. In his book about The Toyota Way, Liker identified 14 principles that explain Toyota's unique approach to Lean management and noted that principles are valuable insights that can be applied to any process. Skaar (2019) noted that when reengineering a process, Lean thinking needs to be first promoted and supported before pushing Lean tool into the reengineered process. Imposing Lean tools on process participants may clash with know-how causing resistance to change (Skaar 2019). The focus on the tools rather than the thinking can also misguide the purpose of the reengineering initiative (Skaar 2019). Therefore, Lean thinking and Lean principles need to be instilled into any construction process reengineering effort. Additionally, researchers have indicated that Lean can support Industry 4.0 (Buer et al. 2018; Pagliosa et al. 2019), thus, highlighting that Lean principles must be inculcated into a Construction 4.0 process reengineering methodology. The proposed CPR4.0 framework is discussed in the following section, followed by the integration of the Lean principles across its phases where Sublimation is referred to as Phase I, Condensation as Phase II, and Freezing/Melting cycle as Phase III.

FRAMEWORK PHASES

A review of the existing reengineering methodologies coupled with the people-process-technology methodology formed the basis for developing the CPR4.0 framework. Researchers noted that any process reengineering methodology that focuses only on technology has the potential to fail in the construction industry; therefore, combining human, process, and technology aspects was a core idea for building the holistic framework (Love et al. 1996). Thus, each phase of the proposed CPR4.0 framework is discussed in terms of people, process, and technology as detailed in Figure 2. A prerequisite for employing CPR4.0 is for the construction company to choose a process to reengineer. The process is assumed to be in its current solid state having its fixed tasks, participants, end-users, information, technology, and its interactions with the external environment. It should be noted that the selection of the process is outside the scope of this paper.

Once a selection has been made, the chosen process needs to be first understood. Thus, the process is broken down into its smallest particles (i.e., components) to understand its status quo. This breakdown changes the state of the process form solid to gas, and the process is hence called sublimation. The understanding of the process will allow us to map it out for diagnosis and reengineering. The understanding happens at three levels: people, process, and technology.

Then, after mapping out and diagnosing the process, the status quo needs to be changed and the future state envisioned. At this point, the process is being transformed into its liquid state, where the company can control and mold the flow of the process: it can add, modify, reorder, change, and/or remove any of the components of the existing process as the future process is being established. This step is thus called condensation, where the reengineering process moves the existing process from its gas to its liquid state.

After that, once the future state is mapped out and all constraints are removed, the future state process can be implemented. Implementing the new process means fixing its components, so the liquid state is now frozen to a new solid-state process.

Finally, the process needs to be monitored for success. If the success metrics are not achieved, the process is melted again to the liquid phase for changes. The process can also be melted for improvement, or if external factors such as the rise of new technology can impact the process. This melting/freezing cycle is thus a representation of the continuous improvement cycle.

MAPPING OF LEAN PRINCIPLES

Principle 1 – “Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals” (Phases I, II, and III): Basing decisions on a “long-term philosophy" should be applied throughout the entire framework. Every decision taken in any phase should not hinder the tasks or the work happening in the subsequent phases.

Principle 2 – "Create a continuous process flow to bring problems to the surface" (Phase II): Creating continuous flow when designing the future state of the process is crucial. This can be achieved by removing waste and creating an uninterrupted flow of materials and information needed for the different tasks of the process (Intrieri 2018). Once this is achieved in Phase II, it will automatically be implemented in Phase 3 where the envisioned process is continuously evaluated and improved.

Principle 3 – "Use pull systems to avoid overproduction" (Phase II): Using the "pull" system is essential in Phase II. When envisioning the future state of the process, information for example should be provided to people or technology when needed (Liker 2004). In other words, it is important to pull information from later phases to be used earlier in the framework.

Principle 4 – "Level out the workload, i.e. heijunka" (Phase II): Levelling out the workload (Heijunka) is important in Phase II when envisioning the future process. For example, roles and responsibilities should be distributed between people in a manner that keeps them focused on performing added-value work without being overburdened (Intrieri 2018; Kilpatrick 2003).

Principle 5 – "Build a culture of stopping to fix problems, to get quality right the first time" (Phases II and III): Building a culture to stop and fix problems (Jidoka) is applicable to Phases II and III. When envisioning the future state, people should be trained to detect problems and quickly solve them and provide countermeasures. Technologies being considered should also assist in doing so (Intrieri 2018). Applying this principle can reduce rework and detect errors to eliminate or mitigate them early (Nikakhtar et al. 2015).

Principle 6 – "Standardized tasks and processes are the foundation for continuous improvement and employee empowerment" (Phases I and II): Standardizing tasks can be of great help in Phases I and II. This would help those involved in the reengineering effort to understand all the necessary tasks and their requirements. It would also help detect waste and creating the process blueprints. Additionally, standardizing the thought process can ensure buy-in from and alignment among all involved parties.

Principle 7 – "Use visual control so no problems are hidden" (Phases I, II, and III): Using visual control is extremely important through the entire phases of the framework. It can facilitate discussing ideas, solving problems, standardizing tasks, mapping processes, and reporting progress.

Principle 8 – "Use only reliable, thoroughly tested technology that serves your people and processes" (Phases II and III): Using technology that will not disturb the process is key to a practical reengineering effort. Technology should be reliable, predictable, and able to serve both the people and the process (Liker 2004).

Principle 9 – "Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others" (Phases I, II, and III): Empowering leaders or "champions" who advocate for the use of technology and motivate people to change is essential for the reengineering process (Andipakula 2017). A strong champion would be able to motivate co-workers to overcome their hesitance, try new things outside their comfort zone, and direct the efforts towards achieving the common objective(s) (Shohet and Frydman 2003).

Principle 10 – "Develop exceptional people and teams who follow your company's philosophy" (Phases I, II, and III): Developing exceptional people and cross functional teams that work together in all three Phases is a must for a seamless transfer of knowledge and implementation of the premise of framework.

Principle 11 – “Respect your extended network of partners and suppliers by challenging them and helping them improve” (Phases I, II, and III): Respecting the extended network of partner and suppliers is important through ought the entire reengineering process. The needs of stakeholders affected by the process should be investigated in both the current and future stat. Moreover, the reengineered process should aim to empower and assist the external entities affected by the future state process. For example, a contractor implementing a certain technology can assist the subcontractors in adopting that technology as well, especially if it serves projects and enhances the work.

Principle 12 – “Go and see for yourself to thoroughly understand the situation” (Phases I, II, and II): Go and see for yourself (Genchi Genbutsu) must be practiced throughout the three Phases. Those involved in the process and those impacted need to be engaged in the reengineering effort to ensure that the process is being improved for the greater benefits of everyone (Intrieri 2018).

Principle 13 – “Make decisions slowly by consensus, thoroughly considering all options and then implement rapidly” (Phase II): Making decisions slowly and implementing them rapidly (Nemawashi) can be leveraged in Phase II. People responsible for change should take their time in analysing the current state and making decisions for the future ones. Once all decisions are taken carefully and thoroughly, implementing the new process should be rapid.

Principle 14 – “Become a learning organization through relentless reflection and continuous improvement” (Phases I, II, and III): Using reflection (Hansei) and continuous improvement (Kaizen) should be an integral part of the framework from beginning to end. People participating in the reengineering initiative should continuously reflect on their work and asses their progress to learn from mistakes and improve their future performance.

CONCLUSIONS AND FUTURE WORK

Achieving a plausible future for the construction industry is a long journey. Lean Construction and Construction 4.0 are two major transformations that play a central role in rethinking existing construction processes to empower construction personnel and leverage the power of technology. While the importance of Construction 4.0 has been highlighted, the “how” component of achieving a Construction 4.0 state has not been yet discussed. A process reengineering methodology is needed to assist construction companies in adopting technologies. This paper is a first step of an ongoing effort to meet the need of the construction industry. This paper proposes a holistic conceptual framework to reengineer construction processes in the Construction 4.0 era. The proposed Construction 4.0 Process Reengineering (CPR4.0) framework, which embodies the Futures Triangle methodology and is inspired by Kurt Lewin Change Management Model, consists of three phases that build on existing reengineering methodologies, people-process-technology methodology, and Lean principles. Each phase of CPR4.0 consists of several tasks which, collectively, lead to a reengineering a process through the lens of Construction 4.0. The work presented in this paper is conceptual and will be expanded on in two future steps: verify the framework through structured interviews with subject matter experts and validate the applicability of CPR4.0 through an implementation in action case study.

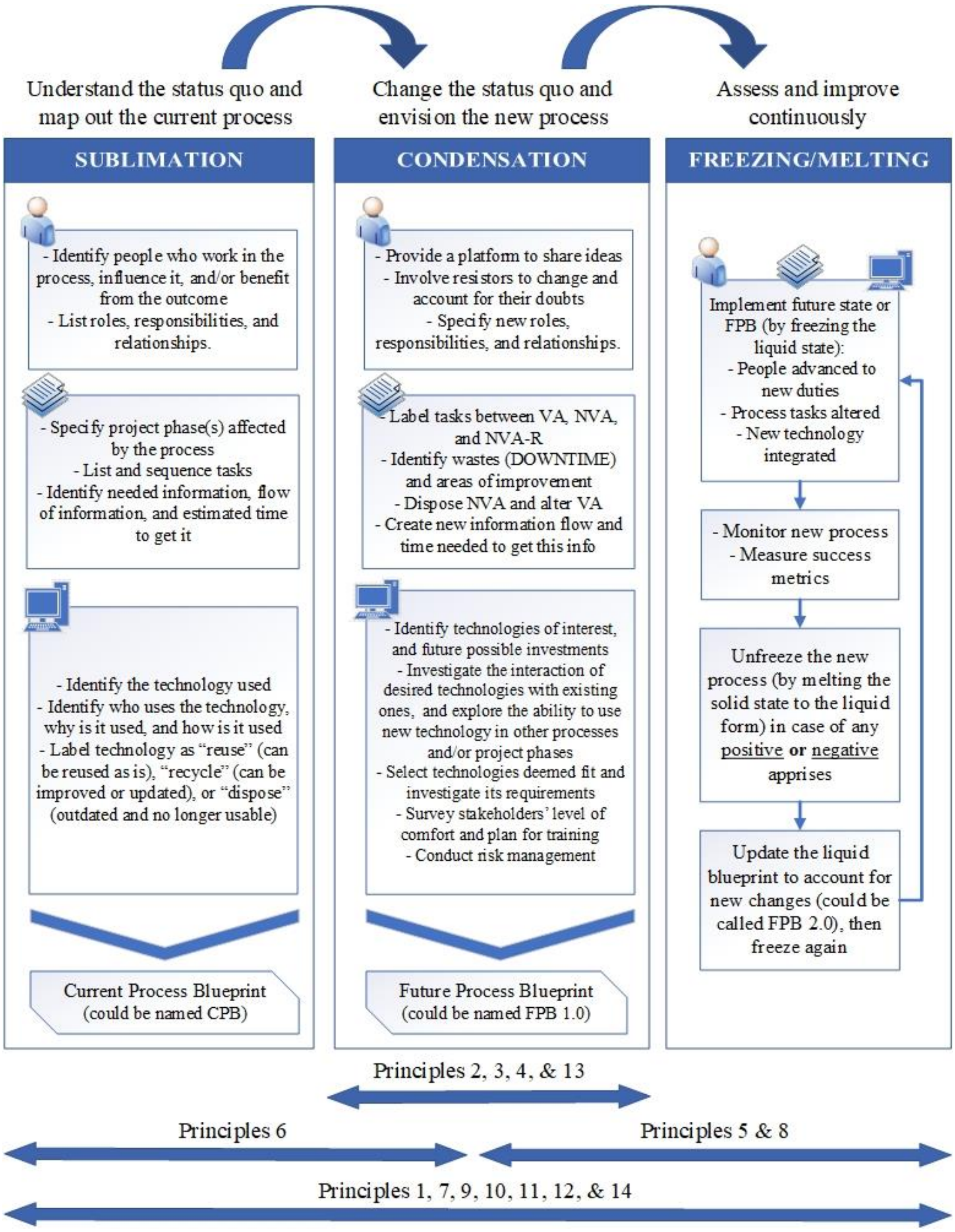


Figure 2: Proposed CPR4.0 Framework

REFERENCES

Adesola, S., and Baines, T. (2005). "Developing and evaluating a methodology for business process improvement." *Business Process Management Journal*, Emerald Group Publishing Limited, 11(1), 37–46.

Andipakula, T. (2017). "Case study of barriers inhibiting the growth of information and communication technology (ICT) in a construction firm, A." PhD Thesis, Colorado State University.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., Bertram, N., and Brown, S. (2017). *Reinvinting Construction: A Route to Higher Productivity*. McKinsey Global Institute.

Bou Hatoum, M., and Nassereddine, H. (2020). “Developing a Framework for the Implementation of Robotics in Construction Enterprises.” *EG-ICE 2020 Proceedings: Workshop on Intelligent Computing in Engineering*, Germany, 453–462.

Bou Hatoum, M., Piskernik, M., and Nassereddine, H. (2020). “A Holistic Framework for the Implementation of Big Data throughout a Construction Project Lifecycle.” *Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC)*, Kitakyushu, Japan, 1299–1306.

Buer, S.-V., Strandhagen, J. O., and Chan, F. T. (2018). “The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda.” *International Journal of Production Research*, Taylor & Francis, 56(8), 2924–2940.

Cheng, M.-Y., and Tsai, M.-H. (2003). “Reengineering of construction management process.” *Journal of construction engineering and management*, American Society of Civil Engineers, 129(1), 105–114.

El Jazzar, M., Urban, H., Schranz, C., and Nassereddine, Ha. (2020). “Construction 4.0: A Roadmap to Shaping the Future of Construction.” *Proceedings of the 37th International Symposium on Automation and Robotics in Construction*, Kitakyshu, Japan, 1314–1321.

FIEC. (2020). “Digitalisation, Construction 4.0 and BIM.” *European Construction Industry Federation Priorities*.

Hammer, M., and Champy, J. (2009). *Reengineering the Corporation: A Manifesto for Business Revolution*. Zondervan.

Hossain, M. A., and Nadeem, A. (2019). “Towards digitizing the construction industry: State of the art of construction 4.0.” *Proceedings of International Structural Engineering and Construction ·*, ISEC Press.

Inayatullah, S. (2008). “Six pillars: futures thinking for transforming.” *Foresight*, Emerald Group Publishing Limited, 10(1), 4–21.

Intrieri, C. (2018). “14 Principles of Lean Toyota Production System (TPS).” *Flevyblog*.

Kilpatrick, J. (2003). “Lean Principles.” *Utah Manufacturing Extension Partnership*, 68(1), 1–5.

Koskela, L., Howell, G., Ballard, G., and Tommelein, I. (2002). “The foundations of lean construction.” *Design and construction: Building in value*, Oxford, UK: Butterworth-Heinemann, Elsevier, 291, 211–226.

Lau, S. E. N., Zakaria, R., Aminudin, E., Saar, C. C., Abidin, N. I. A., Roslan, A. F., Abd Hamid, Z., Zain, M. Z. M., and Lou, E. (2019). “Identification of roadmap of fourth construction industrial revolution.” *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 012029.

Lewin, K. (1951). *Field theory in social science: selected theoretical papers (Edited by Dorwin Cartwright.)*. Harpers.

Liker, J. K. (2004). *The Toyota Way: 14 Management Principles drom the World’s Greatest Manufacturer*. McGraw-Hill.

Love, P. E. D., MAcSporran, C., and Tucker, S. N. (1996). “The Application of Information Technology by Australian Contractors: Toward Process Re-Engineering.” *4th Annual Conference of the International Group for Lean Construction*, Birmingham, UK.

Mao, X., and Zhang, X. (2008). “Construction process reengineering by integrating lean principles and computer simulation techniques.” *Journal of construction Engineering and Management*, American Society of Civil Engineers, 134(5), 371–381.

Mellado, F., and Lou, E. C. (2020). "Building information modelling, lean and sustainability: An integration framework to promote performance improvements in the construction industry." *Sustainable Cities and Society*, Elsevier, 61, 102355.
Mendonça, L. V., and McDermott, P. (2000). "Lean Design Management Applied to Concrete Structures for Retaining Aqueous Liquids: A Redesign Process Model to Portuguese Design Companies." Brighton, UK.
Nassereddine, H. M. (2019). *Design, Development and Validation of an Augmented Reality-Enabled Production Strategy Process for the Construction Industry*. The University of Wisconsin-Madison.
Nikakhtar, A., Hosseini, A. A., Wong, K. Y., and Zavichi, A. (2015). "Application of lean construction principles to reduce construction process waste using computer simulation: a case study." *International Journal of Services and Operations Management*, Inderscience Publishers, 20(4), 461–480.
Noran, O., Romero, D., and Burchiu, S. (2020). "Exploring the Path Towards Construction 4.0: Collaborative Networks and Enterprise Architecture Views." *IFIP International Conference on Advances in Production Management Systems*, Springer, Sad, Serbia, 547–556.
Oesterreich, T. D., and Teuteberg, F. (2016). "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry." *Computers in industry*, Elsevier, 83, 121–139.
Pagliosa, M., Tortorella, G., and Ferreira, J. C. E. (2019). "Industry 4.0 and Lean Manufacturing: A Systematic Literature Review and Future Research Directions." *Journal of Manufacturing Technology Management*, Emerald Publishing Limited, ahead-of-print(ahead-of-print).
Rastogi, S. (2017). "Construction 4.0: The 4th Generation Revolution." *Indian Lean Construction Conference*, ILCC 2017, C288–C298.
Sawhney, A., Riley, M., and Irizarry, J. (2020a). *Construction 4.0: an innovation platform for the built environment*. Routledge, Abingdon, Oxon ; New York, NY.
Sawhney, A., Riley, M., Irizarry, J., and Pérez, C. T. (2020b). "A proposed framework for Construction 4.0 based on a review of literature." *EPiC Series in Built Environment*, EasyChair, 1, 301–309.
Seed, W. R. (2015). *Transforming Design and Construction: A Framework for Change*. Lean Construction Institute.
Serpell, A., Alarcón, L. F., and Ghio, V. (1996). "A general framework for improvement of construction process." *Annual Conference of the International Group for Lean Construction*.
Shohet, I. M., and Frydman, S. (2003). "Communication patterns in construction at construction manager level." *Journal of construction engineering and management*, American Society of Civil Engineers, 129(5), 570–577.
Skaar, J. (2019). "The Power of Lean Principles." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*, Dublin, Ireland, 393–404.
Widodo, S. M., Astanti, R. D., Ai, T. J., and Samadhi, T. M. A. A. (2020). "Seven-waste framework of waste identification and elimination for computer-based administrative work." *The TQM Journal*, Emerald Publishing Limited, ahead-of-print(ahead-of-print).
Wirth, R. A. (2004). "Lewin/Schein's change theory." Citeseer.

Prado, G. (2021). "Challenges of Virtual Design and Construction implementation in public projects." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 413–422, doi.org/10.24928/2021/0129, online at iglc.net.

CHALLENGES OF VIRTUAL DESIGN AND CONSTRUCTION IMPLEMENTATION IN PUBLIC PROJECTS

Guillermo Prado Lujan[1]

ABSTRACT

The Peruvian AEC industry has started implementing VDC and BIM in public projects due to recent regulations that state the progressive adoption of BIM (as a methodology) in public construction. Regardless of the benefits of these new approaches, some challenges to VDC implementation have emerged as a response to the resistance to change of the Peruvian AEC industry, which is stronger in the Peruvian public sector. The aim of this paper is to present the challenges found in the author´s VDC implementation experience in a public project, as part of the third VDC Certificate Program in Lima lead by CIFE from Stanford University. These challenges will be identified based on a schema, constructed by the literature review. The results show that the main challenges found are the lack of commitment and the lack of collaboration between stakeholders. These results suggest the need to overcome this resistant-to-change environment by focusing on training programs and conducting capability assessments within public institutions before start implementing VDC, so more benefits will be achieved by the Peruvian public institutions.

KEYWORDS

Process, collaboration, commitment, challenges, VDC.

INTRODUCTION

The Peruvian Architecture, Engineering and Construction (AEC) industry has inherent problems to deal with, which affect both private sector projects and public sector projects. The drawbacks of the public sector projects are caused by poor management of the stages of planning and execution (design and construction), lack of government control, inherent fragmentation of the state contracting methods, financial obstacles, and incomplete basic engineering studies (Arnao, 2011). Therefore, the current problems are presented as project delivery delays, overbudget, and mistrustfulness from the stakeholders involved in this kind of projects.

Consequently, new project management approaches and tools have been introduced to the Peruvian AEC industry, Ghio (2001) concluded on the need to apply Lean Construction principles and 3D visualization tools to the infrastructure projects of Peru as a result of low productivity rates. Moreover, as a mean to improve the productivity and quality of the work, since 2012 selected Peruvian construction companies started to learn the Virtual Design and Construction (VDC) methodology, which is defined as "The use

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of integrated multi-disciplinary performance model and design-construction projects to support explicit and public business objectives" (Kunz and Fischer, 2012).

On the public sector side, since 2018 several Peruvian laws have established the adoption of Building Information Modeling (BIM) to enhance the delivery of public infrastructure. In this context, Peruvian public institutions have started to implement VDC and BIM to trigger the AEC industry to the next level, which involves high levels of collaboration between stakeholders, use of technology, and constant control of the project production throughout metrics (Kunz and Fischer, 2009). Although, the idiosyncrasy presented in the Peruvian public sector generates a strong rejection to this new project management approach.

This research uses a literature review to identify the challenges presented during VDC implementations in the AEC industry, sets up a classification on these challenges, presents one case study as part of the third VDC certificate program in Lima, in which the author implemented VDC in a Peruvian public project. Then, the challenges found in this VDC implementation experience will be determined based on the classification identified in the literature. The research results will encourage the wider implementation of VDC in the Peruvian public sector by knowing the challenges that need to overcome before or during the VDC implementation process.

LITERATURE REVIEW

Virtual Design and Construction (VDC) is defined by Stanford University Center for Integrated Facility Engineering (CIFE) as "The use of integrated multi-disciplinary performance model and design-construction projects to support explicit and public business objectives" (Kunz and Fischer, 2009). These business objectives are both: client and project objectives; which provides an alignment between VDC and Lean Construction practices as it focuses on fulfilling the client's objectives. Khanzode et al. (2006) stated VDC as an enabler of Lean Project Delivery System (LPDS), as the tools, technologies, and methods of the VDC framework provide the best toolset to accomplish the ideals of the LPDS. In addition, VDC requires people to collaborate to reach measurable objectives they establish. It is integrative by nature and can be learned and mastered. Everything people do within the VDC framework allows them to integrate systems, processes, their organization and information so they can deliver high-performing buildings (Rischmoller et al., 2018).

Heymaker and Fischer (2001) found several technical challenges in the construction of the 4D-BIM models (which are part of VDC) including geometry and scheduling issues, and the linking of the geometry and the schedule. Gilligan and Kunz (2007) conducted a VDC Use Survey, which results showed a shift in the nature of limitations of VDC implementation: in the past difficulties were encountered more with technical issues or contractual terms between the parties involved in the project. But, by the year of the study, the limitations were more related to the lack of qualified people and the kind of training that needs to be provided. Kunz and Fischer (2012) present important limitations regarding the wide implementation of VDC in the AEC industry, which includes: lack of owner request or willingness to use VDC in its projects, the culture of minimizing cost in the AEC industry, lack of learning from experience and not-easy-to-use VDC modeling and analysis tools.

Khanzode et al. (2008) found challenges related to the VDC implementation in The Camino Medical Office Building (MOB) case study, focused on MEP coordination. These challenges include determining how to organize the project team and structure the coordination process to best utilize the VDC tools, how to set up the technical logistics, and how to perform the coordination in a Big Room. Teixeira (2014) found challenges in the VDC implementation of transport infrastructure projects: lack of infrastructure BIM software, the employment of an "open file format", the reduction of the opportunities for collaboration between stakeholders due to the design-bid-build delivery method, and the lack of involvement of contractors in the design process.

Several pieces of literature are focused on the limitations, barriers and challenges of BIM implementation in the AEC industry, which uses the term "VDC" as a synonym of "BIM". Regardless of the origin of the difference between these terms, which exceeds the limits of this study, the author considers relevant the outcomes of this literature due to the similarities between the implementation process of both VDC and BIM. Azhar et al. (2008) classified the industry implementation challenges on technical reasons and managerial reasons; Chan et al. (2014) focused on the designer´s opinions on the barriers that affect the BIM or VDC implementation in the projects; Sun et al. (2017) proposed five factors that limitate the BIM or VDC implementation: technology, cost, management, personnel, and legal; and Criminale et al. (2017) classified the BIM or VDC implementation challenges by the association with project, organization or both.

As it was presented, previous research has shown the challenges found in various VDC implementation experiences based on case studies, usually, from the contractor or designer perspectives, and VDC implementation challenges at the industry level have been presented too. Despite the results shown in the previous studies, there is no study that addresses the VDC implementation challenges from the public client perspective and no study has analyzed the VDC implementation process in the Peruvian public sector. Therefore, the main objective of this research is to fill this research gap by identifying the challenges in the VDC implementation of Peruvian public projects.

METHOD

The aim of the study was to determine the challenges found in the VDC implementation of Peruvian public projects. Therefore, the research procedure consists of three steps:

The first step is collecting relevant studies in order to create a ´schema´ for the challenges in VDC implementation. Two search conditions are used: the terms in the first search condition are "Virtual Design and Construction" or "VDC" or "BIM"; the terms in the second search condition are "challenge" or "barrier" or "obstacle" or "limitations". The material collected by the search is analyzed and classified based on a criterion, which defines the types of challenges in the VDC implementation.

The second step is studying the monthly reports of the Peruvian public project presented to the Stanford professors by the author throughout the conference calls. The measured metrics will be used to describe the outcomes of the VDC implementation in this Peruvian public project.

The third step is applying the same criteria used in the schema presented in step one to determine the challenges of the VDC implementation of the Peruvian public project analyzed in step two.

RESULTS

SCHEMA FOR THE CHALLENGES IN VDC IMPLEMENTATION

The implementation of VDC is beneficial to the AEC industry, but its methods are still undergoing theoretical development and in an industry that appropriately values risk mitigation, the changing theoretical foundation provides a handy and often an appropriate excuse to avoid the use of the methods (Kunz and Fischer, 2009). Table 1 shows a summary of the challenges found in the literature review based on the criterion that defines the type of challenge.

Table 1: Schema for the challenges of VDC implementation

Type of challenge	Challenge	Reference
Legal issues and contracting methods	Define the scope of the implementation of VDC while the project is being developed because it was not defined in the requirements documents (EIR, contracts, etc.)	Teixeira 2014; Kunz et al. 2012
	Define the responsibility of licensed professionals in this multi-contributors environment	Criminale et al. 2017
	Require the participation of the general contractor since the design stage of the project, despite the contract does not allow it	Khanzode, et al. 2008; Sun et al. 2017; Teixeira 2014
	Use data from BIM models produced during the VDC implementation to take decisions during the project, despite the contract does not state it	Criminale et al. 2017; Chan 2014
Culture of the organization	Develop plans, protocols, standards, etc. before starting the VDC implementation	Criminale et al. 2017; Chan 2014; Sun et al. 2017; Azhar et al. 2007
	Promote and create the proper environment for the involvement and collaboration between stakeholders (subcontractors, end-users, etc.) in the VDC implementation	Khanzode, et al. 2008; Criminale et al. 2017; Sun et al. 2017; Azhar et al. 2007; Teixeira 2014; Kunz et al. 2012
	Involve all the departments of the institution in the VDC implementation process lead by the general managers of the institution	Criminale et al. 2017; Sun et al. 2017; Kunz et al. 2012
	Consider the whole lifecycle of the project looking for integration between its stages	Khanzode, et al. 2008; Sun et al. 2017; Kunz et al. 2012
	Promote the use of digital format documents and data instead of continuing working with printed documentation	Azhar et al. 2007
People	Capacitate the professionals from the stakeholders (client and providers) in a short period of time to implement VDC in the project	Criminale et al. 2017; Chan 2014; Sun et al. 2017; Kunz et al. 2012
	Break the resistance to change from the professionals involved in the project to implement VDC	Criminale et al. 2017; Sun et al. 2017; Teixeira 2014; Kunz et al. 2012

It is very important to notice that the criterion used for classifying the challenges does not include technology nor cost-related factors as the purpose of this schema for challenges in VDC implementation is to use it later to find the challenges in the VDC implementation of the Peruvian public project, which will show only the types of challenges presented in the schema of Table 1.

VDC IMPLEMENTATION IN A PERUVIAN PUBLIC PROJECT

The Peruvian public project selected to implement VDC was the Centro de Emergenia Mujer (CEM), which consists of the design of a module inside a police building and the client was the Ministry of Interior (MININTER). The delivery method of this project was Design-Bid-Build (DBB), and the legal framework used involved the State Contracting Law of Peru and the National System of Multi-year Programming and Investment Management INVIERTE.PE. In this context, the design stage of this kind of project is divided into a specific number of "deliverables" (usually three) that also are considered as milestones for schedule and payment purposes; and is developed by two teams: "team A" that produces the design, and "team B" that assess the design produced by "team A". In the CEM project, "team A" was a design company and the "team B" was a team of architects and engineers (structural, electrical, plumbing and mechanical) formed by MININTER. The process and flow of one deliverable are shown in Figure 1.

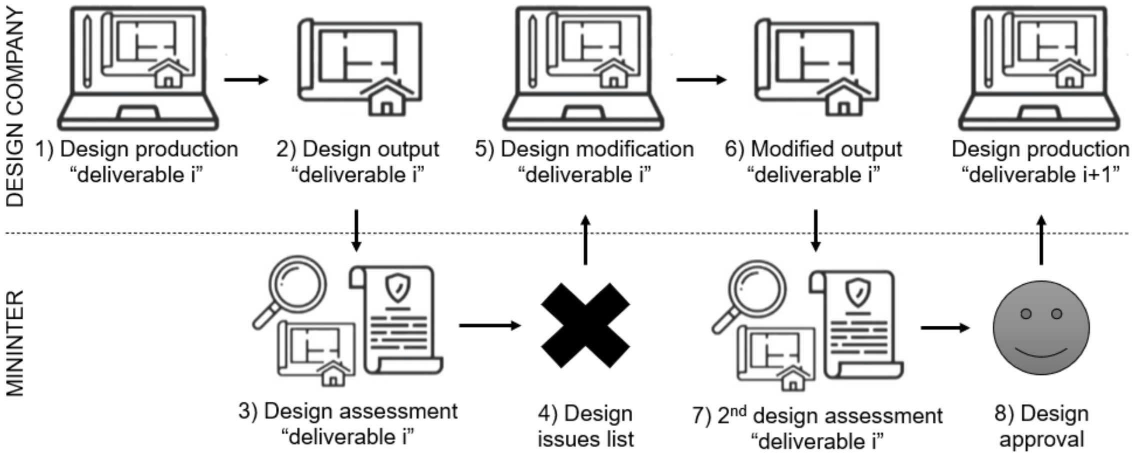

Figure 1: Design production and design assessment of one "deliverable"

The contractual documentation (Employer´s information requirement, technical requirements, etc.) considered several BIM uses, Integrated Concurrent Engineering (ICE) sessions, and metrics to measure the production of the design company. MININTER conducted VDC training sessions with the members of the design company in order to share the expectations regarding the participation of this company in the project and the VDC implementation. However, each of the parties (MININTER and the design company) develop their work isolately due to the restrictions stated by the State Contracting Law, which does not allow the public institutions to participate directly in the project unless one contractual milestone is reached and the "deliverable" is presented formally (printed), as its shown in Figure 1. In addition, there was no internal VDC implementation in MININTER as the objective of implementing VDC was restricted to the CEM project.

The VDC implementation of this project was focused into finalize the design stage in four months. The production metrics measured were: PPC (Percent Plan Complete), assessment time per deliverable (production of review), # of issues in the BIM models, % of drawings produced by the BIM models, % of achieved goals during ICE sessions, and % of people (designers) involved in the solutions during ICE sessions. Unfortunately, the design of the project did not finalize as expected, but some of the mentioned metrics will provide the mean for finding the challenges in this VDC implementation.

During the monthly reports of the VDC implementation, the BIM metrics show these results: the ´# of issues in the BIM models´ showed a significant decrement between each version of the BIM models, and nearly 60% of the design drawings were produced from the BIM models. Regarding the ICE metrics, nearly the 70% of the ICE sessions (15 out of 22) reached a 100% of achieved goals during ICE sessions; but no ICE session had a 100% in the metric ´% of people (designers) involved in the solutions´. The Project Production Management (PPM) metrics showed no good results during the last monthly report of the VDC implementation: the PPC reached almost 70% and the metric ´assessment time per deliverable (production of review)´ indicates nearly 1 month periods for the assessment of one deliverable of design.

CHALLENGES IN THE VDC IMPLEMENTATION

Challenges related to legal issues and contracting methods

One of the most important challenge to overcome in the VDC implementation was to involve a general contractor in the project design, despite the CEM project was delivered by the DBB method, which does not allow the involvement of contractors in early stages of the project. It causes fragmentation through the development of the stages of the project: the design company will not be commited with the construction stage and, the expertise of the general contractor will not be considered in the design of the project, therefore any constructibility proposal cannot be considered due to the obligation to follow exactly the design output. Unfortunately, the State Constracting Law of Peru states restrictions for applying other delivery methods (Design-Build) and most of the public institutions have to use DBB, which does not allow to implement VDC as it should be: collaboratively.

Another challenge was to deal with the contractual conditions between MININTER and the members of the assessment team hired by this institution. Most of the architects and engineers hired by MININTER did not even have a contractual obligation of being located inside the MININTER offices, which caused delays in developing the assessment of the design and lack of feedback shared with the design company. Additionally, the conditions of these contracts allowed them to be hired by other institutions, which lead them to not being fully focused on the CEM project.

Challenges related to the culture of the organizations

The lack of a collaborative working approach inside the institutions is a big challenge experienced. The PPM metric ´assessment time per deliverable (production of review)´ shown in the figure 2 helps to understand this challenge.

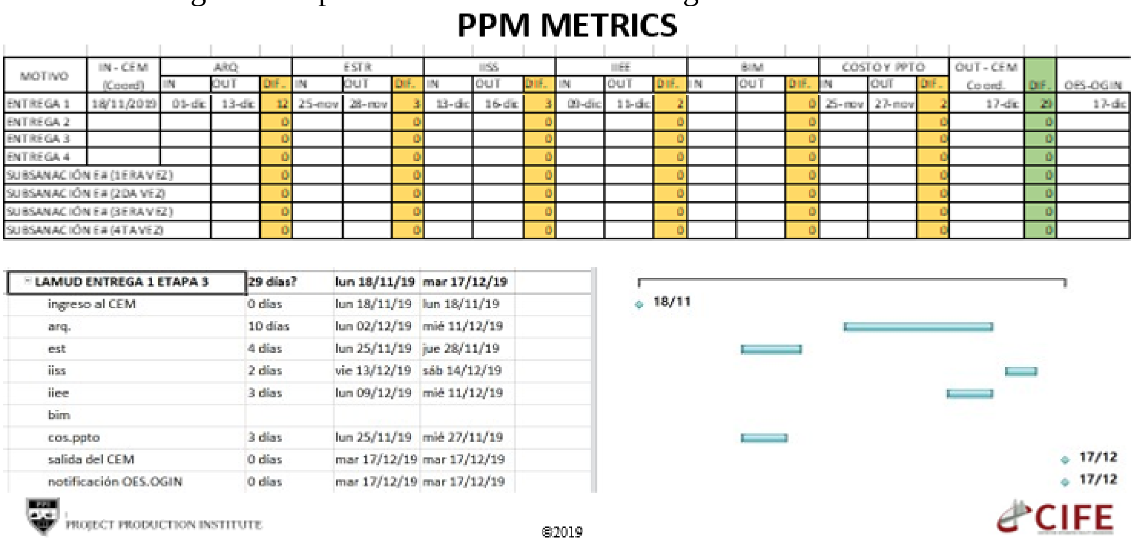

Figure 2: Isolated work between professionals

Despite that the team members of MININTER can assess the design output all together concurrently, each architect and engineer took their time without any order and these activities were developed almost sequencially, as its shown in the Figure 2. This causes delays on providing feedback to the design company about the design output, and promotes no-concurrent work between stakeholders, which is inherently embedded in the culture of the organitzations involved in Peruvian public projects.

Another challenge was the lack of knowledge of the internal procedures and current status of MININTER, which lead us to produce process maps with almost all the departments of MININTER as its managerial documents did not show the information flow between the departments inside this institution. This situation caused that during the development of the CEM project, information and documents were lost as a result of no clear path to follow or workers with no idea of what to do with the documentation delivered. In addition, it caused delays in processing documentation and uncertainty regarding the current status of the project.

Challenges related to the people

The ICE metric ´% of people (designers) involved in the solutions´ shown in figure 3 represents the lack of commitment of the designers (hired by the design company) to develop proper solutions to the technical issues addressed during the ICE sessions as no ICE session was fully attended by the designers. This situation caused that the solutions stated by the assistants of the ICE sessions could be changed later, as at least one discipline was not involved in that solution. In this context, the main challenge is to form a design team of committed people, that understand the project´s objectives and the relevance of their participation in the implementation of VDC.

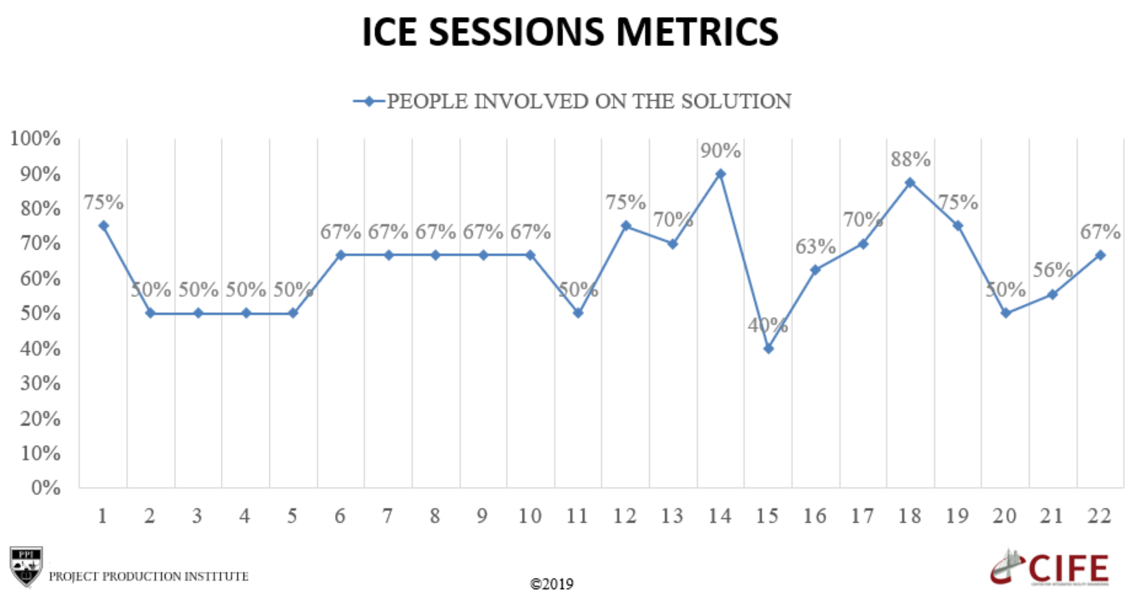

Figure 3: People involved on the solutions of the problems throughout ICE sessions

Also, the lack of VDC capabilities and misconception of this method from the team members of MININTER and from the design company affected negatively the project. The team members of the design company argued that they believed that BIM was a 3D model that can produce the drawings “rapidly” without any additional effort. In this context, the main challenge is to capacitate the team members of the public institution and require trained professionals in the project teams of the private providers, which has to be explicitly stated in the requirement documents during the bidding stage of the project.

DISCUSSION

The types of challenges defined in Table 1 provided criteria for organizing the data collected during the monthly reports (metrics) of the VDC implementation in order to use it for explaining the challenges found during this VDC experience. Despite that the metrics showed in this VDC experience were mainly focused on the design assessment process, the understanding of these metrics is believed to be benefitial for continuous improvement (Belsvik et al., 2019), as they gave insights about the limitations and challenges for implementing VDC inside MININTER.

The challenges related to legal issues and contracting methods (DBB) are clearly affecting the outcomes of the project and the origin of these challenges is the legal framework used in most Peruvian public projects. The State Contracting Law of Peru promotes fragmentation and states restrictions for using collaborative delivery methods that would be beneficial for these projects. In this context, this legal framework seems to be an uncontrollable factor for the project managers of Peruvian public institutions; therefore, there is no production metric to use in order to track the possible outcomes of the project. This lack of control happens when Peruvian public institutions contract: design providers, general contractors, and professionals (architects and engineers); which leads us to an uncertain situation regarding the impossibility to control it unless there is a structural change in the legal framework mentioned. Unfortunately, this is the most common contracting method (DBB) for infrastructure projects in Peru.

The challenges related to the culture of the organizations show that there is no worry about the current status of the projects of the Peruvian public institutions and the lack of a collaborative working approach between the team members of the stakeholders involved in the project. Also, this no-collaborative culture makes that public managers take the least risky and easiest decisions, and there is no concern for planning long-term goals. This situation might explain the reason for no developing managerial documents to understand the information flow and continuously waste time searching for the next step of one single repetitive internal process, nor making structural changes in the public institutions in order to be more efficient.

The challenges related to the people reveal no commitment of the people involved in the projects, which leads to delays in the project and other drawbacks too. This challenge has been studied previously, as all the team members of the project are required to be committed to the accomplishment of the objectives stated (Rischmoller et al., 2018) in the VDC implementation. Also, a central aspect to the VDC implementation has been to fully commit to those who want to change (Fosse et al., 2017), so to overcome this challenge a new team that believes in this approach may be established in order to implement VDC collaboratively. Regarding the misconception of the concepts related to VDC and BIM, the effort needed to work with BIM models properly had been underestimated by the design company and its use was not well planned, which introduced inefficiencies in their use (Mandujano et al., 2015). In this situation, is necessary to implement capacitation plans and capabilities assessment for the people involved in the project in order to reach its objectives.

CONCLUSIONS

The VDC implementation experience in MININTER provided insights into the type of challenges that need to be overcome in order to accomplish the objective of the project. The types of challenges are related: the legal framework applied in this kind of project generates fragmentation throughout the development of the project and between the parties involved in it. The parties involved in the project lack collaboration, partially due to the legal framework and the inherent resistant-to-change culture of the Peruvian AEC industry, which generates a lack of commitment between the people involved in the project and misunderstanding of the concepts and implications of VDC. The metrics, an essential component of VDC, showed crucial information related to the production of the project, which provides a better understanding of the VDC implementation challenges presented in this research.

The outcomes of this study can be used to represent a wider and generalized problem of the Peruvian public institutions as the legal framework applied is the most commonly used in this kind of project. The implementation of VDC makes transparent inherent problems related to the management of Peruvian public projects, as the production metrics provide data to control times and demonstrate that the implementation of VDC has to overcome several challenges, not only in the project and people level, but in the organizational and legal framework level too. Moreover, the problems presented in this study are hidden in the Peruvian public institutions, or maybe the public managers ignore their existence, but by implementing VDC they can be displayed in order to propose countermeasures against these problems.

Regardless of all the challenges stated in this paper, the enhancement of the AEC industry through VDC is imminent. In consequence, the public institutions should start with the development of a capability assessment and find an implementation plan that enables collaborative implementation of VDC in order to reach their respective goals.

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REFERENCES

Arnao Rondán, R. (2011). La eficiencia en la gestión pública: "El caso de la gestión de inversión pública local en el Perú” [The efficiency in the public management: "The case study of local public investment in Peru"]. Lima: Serie de investigaciones 6: Universidad Católica Sedes Sapientae. [In Spanish].

Azhar, S., Hein, M., & Sketo, B. (2008). *Building Information Modeling (BIM): Benefits , Risks and Challenges*. Proc., 44th Associated Schools of Construction National Conference, Auburn, AL.

Belsvik, M.R., Lædre, O., and Hjelseth E. (2019). “Metrics In VDC Projects.” In: *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC), Pasquire C. and Hamzeh F.R. (ed.),* Dublin, Ireland, pp. 1129-1140. DOI: https://doi.org/10.24928/2019/0167. Available at: IGLC.net.

Chan, C. T. W. (2014). Barriers of Implementing BIM in Construction Industry from the Designers’ Perspective: A Hong Kong Experience. *ISSN Journal of System and Management Sciences Journal of System and Management Sciences*, *4*(2), 1816–6075.

Criminale, A., and Langar, S. (2017). Challenges with BIM implementation: a review of literature. In *Proceedings of 53rd Associated School of Construction International Conference, Seattle, WA, April*, 329–335.
Fosse, R., Ballard, G., and Fischer, M. (2017). "Virtual Design and Construction: Aligning BIM and Lean in practice". In: *LC3 2017 Volume II - Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC), Walsh, K., Sacks, R., Brilakis, I. (eds.)*, Heraklion, Greece (pp. 499–506). DOI: https://doi.org/10.24928/2017/0159. Available at: IGLC.net.
Ghio Castillo, V. (2001). Productividad en obras de construcción: Diagnóstico, crítica y propuesta [Productivity in construction works: diagnosis, criticism and proposal]. Lima. Pontificia Universidad Católica del Perú, Fondo Editorial, 2001. [In Spanish].
Gilligan, B. and Kunz, J. (2007). *VDC use in 2007: Significant use, dramatic growth, and apparent business opportunity*. *CIFE Working Paper 103.* Stanford, CA: Center for Integrated Facility Engineering (CIFE), Stanford University.
Haymaker, J., and Fischer, M. (2001). *Challenges and Benefits of 4D Modeling on the Walt Disney Concert Hall Project. CIFE Working Paper 64*. Stanford, CA: Center for Integrated Facility Engineering (CIFE), Stanford University.
Khanzode, A., Fischer, M., Reed, D., and Ballard, G. (2006). *A Guide to Applying the Principles of Virtual Design & Construction (VDC) to the Lean Project Delivery Process. CIFE Working Paper, 93*. Stanford, CA: Center for Integrated Facility Engineering (CIFE), Stanford University.
Khanzode A., Fischer M., Reed D. (2008). "Benefits and Lessons Learned of Implementing Building Virtual Design and Construction (VDC) Technologies For Coordination Of Mechanical, Electrical, and Plumbing (MEP) Systems On A Large Healthcare Project", *ITcon*, 13, 324 - 342.
Kunz, J., and Fischer, M. (2009). *Virtual Design and Construction: Themes, Case Studies and Implementation Suggestions. CIFE Working Paper 97 (Version10)*. Stanford, CA: Center for Integrated Facility Engineering (CIFE), Stanford University.
Kunz, J., & Fischer, M. (2012). *Virtual Design and Construction: Themes, Case Studies and Implementation Suggestions. CIFE Working Paper 97 (Version14)*. Stanford, CA: Center for Integrated Facility Engineering (CIFE), Stanford University.
Mandujano, M.G., Alarcón, L.F., Kunz, J., and Mourgues, C. (2015). Use of Virtual Design and Construction, and its Inefficiencies, From a Lean Construction Perspective. In: Proc. 23rd Annual Conference of the International. Group for Lean Construction (IGLC). Perth, Australia, July 29-31, pp. 836-845, available at IGLC.net.
Prado, G. (2019) VDC December 2019, Report VDC Certificate Program.
Rischmoller, L., Reed, D., Khanzode, A., and Fischer, M.(2018). "Integration Enabled by Virtual Design and Construction as a Lean Implementation Strategy" In: Proc. 26th Annual Conference of the International. Group for Lean Construction (IGLC), González, V.A. (ed.), Chennai, India, pp. 240–249. doi.org/10.24928/2018/0521.
Sun, C., Jiang, S., Skibniewski, M. J., Man, Q., & Shen, L. (2017). A literature review of the factors limiting the application of BIM in the construction industry. *Technological and Economic Development of Economy*, *23*(5), 764–779. doi.org/10.3846/20294913.2015.1087071
Teixeira, H. (2014). *VDC implementation in transport infrastructure projects*. Master´s thesis. Department of civil and transport engineering, Norwegian University of Science and Technology.

Mourão, C.A.M.A., Miranda Filho, A.N., Nogueira, R.N., Barros Neto, J.P., and Costa, J.M. (2021). "Using Storytelling to Understand a Company's Lean Journey." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 423–432, doi.org/10.24928/2021/0140, online at iglc.net.

USING STORYTELLING TO UNDERSTAND A COMPANY´S LEAN JOURNEY

Carlos Alexandre M. do A. Mourão[1], Antonio N. de Miranda Filho[2], Rebeca Nara Nogueira[3], José de P. Barros Neto[4], and Jorge Moreira da Costa[5]

ABSTRACT

Lean implementation has become a recurring topic in literature. Scholars have studied lean tools, implementation barriers and proposed strategies, audit tools, and maturity models to overcome such barriers. However, despite the importance of these methods, over the years, researchers have realized that "best practices" emerge from a combination of contextual factors and coherent strategic choices affecting workforce management, supplier relationship, and other "soft" factors. Therefore, through exploratory research structured according to business storytelling fundamentals, the authors describe a company's lean journey along a timeline to provide an overview to understand the strategic choices and even the underlying rationale aligning strategic, tactical, and operational level decision-making. Findings suggest that lean implementation is a never-ending journey, which requires organization-wide changes for achieving success. Furthermore, strategic choices enhancing organizational stability and predictability seem to have played a crucial role in the company's success in lean implementation, knowledge retention, and capability development.

KEYWORDS

Lean implementation, organizational stability, strategic choices, business storytelling.

INTRODUCTION

Nearly twenty years have passed since the day a construction manager heard from an employee a comment that would start a paradigm shift within his company. While talking to a group of workers about the importance of getting everybody involved in construction planning, one foreman stepped up and said: "Thinking ahead is asking too much from individuals that spent most of their young lives in poverty and grew up not knowing what they would have for breakfast the next morning. Getting them to contribute beyond their job description is a hard task when they are not even sure if they will still be employed when the project is over". That construction manager now recalls that that was when it became clear that short-term thinking was a major constraint to workforce commitment

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and effective lookahead planning. It made people in the company realize that lack of predictability and stability were problems that needed to be tackled to reduce short-term thinking amongst employees and subcontractors.

Time passed, that manager progressed to become a Senior Director while the company embarked on a journey to become a lean construction practitioner. This paper tells the company's story depicting relevant events and lean implementation stages along a timeline through a qualitative research approach. This case study can provide a deeper understanding of implementation details and decision patterns to answer the following research questions: What strategic choices fostered its successful lean journey? What was the common rationale behind structural and infrastructural decisions made during the journey? The main objective is to show an overview of implementation steps and strategic choices along the timeline. Although findings from a single case study should not be generalized, the story presented seeks to bring awareness to strategic choices to create organizational stability and predictability for broader lean implementation.

LEAN IMPLEMENTATION IN CONSTRUCTION PROJECTS

Although lean implementation is a recurring topic in literature, research efforts are often focused on isolated tools. This focus is mainly because of barriers to a more comprehensive adoption of lean principles and practices. Throughout the years, studies were conducted to assess factors affecting lean implementation like lack of theoretical understanding, poor top management support, absence of knowledge sharing, and inappropriate culture, to mention a few (Buch and Sander 2005; Torp et al. 2018). To overcome such barriers, academics and consultants have proposed implementation strategies, audit tools, and maturity models (Serpell et al. 1996; Comelli et al. 2019). But despite the importance of these methods, they are sometimes too prescriptive and based on scholar´s interpretations of what is needed.

Another problem is that lean construction has been mostly approached from a project management perspective and not as often from an organizational one. Researchers put much effort into finding the perfect resource and task match to accomplish project schedules. Consequently, the development of project production systems has been focused on structural decisions, such as resource capacity, facilities, equipment, and technology. Nevertheless, in the last years, there has been an increasing realization that true "best practices" mainly emerge from the combination of contextual factors and infrastructural decisions affecting organizational culture, quality control, workforce management, and other "soft" factors. These aspects are less noticeable and frequently overlooked because they involve top management decision-making and cause impacts that extend beyond project boundaries. Acknowledging infrastructural decisions within production strategy helps understand the multiple, equally effective ways organizations can achieve environmental and internal fit to compete within a particular industry (Christiansen et al. 2003). It also helps understand the importance of an organizational approach to the coherent adjustments needed at various levels on a lean journey.

METHODOLOGY

This paper presents well-documented exploratory research to draw lessons from a construction company´s experience. A qualitative approach involving open-ended interviews was used to provide an in-depth account of events, contextual conditions, and challenges. Initially, a timeline was formed with five people who were interviewed, including former employees who directly worked with lean implementation. Internal reports, publications, and other sources were also consulted to recall specific details and dates. Nevertheless, one of the authors has worked in the company for more than two decades, playing an active role in much of the implementation effort.

This paper is structured according to storytelling fundamentals to allow a narrative account of events. The storytelling method's suitability for exploratory research comes from the fact that stories are narrative since they understand events and construct their reality. By binding facts and ideas coherently, stories follow a succinct organization to convey the core message and help readers absorb it. Consequently, business storytelling is a process involving chronology and causality that needs to have a clear goal or core message established before moving forward (Denning 2005). Stories also need a situational context, describing the particular time and place (Escalas 2004). Fog et al. (2005) add that there are four elements in storytelling: the message (or goal), the conflict (or problem), the characters (or persons), and the plot (or timeline).

THE JOURNEY TOWARDS LEAN

Founded in 1977, this case study company worked for many years as a contractor for private investors before becoming a developer and builder of luxury high-rise residential and commercial building projects in Fortaleza, Brazil. Product flexibility, quality, and delivery are the three important performance criteria in the firm's market segment, while internally continuous improvement has always been another criterion. This can be observed in the words of its CEO and founder: "We want to be the locomotive moving the construction industry and setting the pace of innovations. Not just another wagon being pulled by inevitable changes". The company's strive for excellence in a never-ending lean journey is described in the timeline below.

1998

This year can be considered a landmark in the company's journey towards higher stability and predictability. The company was then a well-respected general contractor known for delivering projects on time and budget. However, engaging in different projects in various places hindered the company from obtaining more competitive prices and schedules. This problem was partially due to difficulty in establishing long-term cooperation with subcontractors and suppliers. Uncertainty in customer demand made forecasting difficult and pressured its financial return. To reduce such variation sources, the company made the strategic level choice to gradually focus more on developing its residential projects in the town of Fortaleza. On the operational project level, the company began implementing the ISO9001, aiming to certify that it was applying consistent business processes and establishing procedures that would enhance the stability of all critical processes.

2004

By this time, the foreman's words echoed across the organization. Moreover, it became clear that the Quality Management System alone would not fulfill the expectations of enhanced process stability and performance. This was because ISO9001 was originally conceived to help relatively steady organizational systems control and continuously improve performance. So, the company searched for new ideas to further reduce variation sources. Consequently, the company sent employees to a local conference called CONENX, where the focus was on lean construction theory and practice. There, the company staff not only had their first contact with the topic of lean thinking but also met members of the INOVACON Building Technology Program, which aims at transferring the state of the art technology from various fields of the AEC industry to the participating firms, including innovative production principles and practices. The INOVACON members were in distinct stages of implementing the same bundles of lean practices and were openly sharing their knowledge. That year, the company joined the Program hoping, as discussed by Christiansen et al. (2003), that a strategic group membership would give the company a better understanding of which bundles of practices to implement. This strategic decision was quite handy due to resource constraints. The 5S approach was the company's first experiment with lean tools and was used for planning the construction site in terms of defining fixed storage areas and pathways for materials and personnel.

2005

The company proceeded with its journey by setting up a library consisting of proceedings from previous IGLC conferences and books on project management. The objective was to motivate and facilitate the study of lean thinking in the company. Simultaneously, two top managers began to pursue a Master's Degree with its support. At the operational level, the company continued testing other lean tools in its ever-increasing effort to pursue stability and predictability. The Last Planner System (LPS) provided a disciplined approach to short-interval planning, allowing influence over factors upstream and reducing workflow variations. In addition, a Heijunka box with Kanban cards and mortar batch identification gadgets was installed near the mortar mixing machine. It was possible to enhance lateral relations between work teams and reduce inflow variations in terms of production orders and material delivery to work stations. Moreover, different Andon systems were devised to improve communications between specialists and management teams, using visual aids and color codes to show ongoing operations on different floors and prevent possible workplace disturbances. Lean also raised awareness on waste generation. Therefore, the company started to implement cleaner production and end-of-pipe technologies that mitigate production's environmental burden.

2006

The company maintained its commitment to employee development by supporting those pursuing a Master's qualification. It also paid for them to attend conferences in their field. That same year, the company presented for the first time one paper at the IGLC (Kemmer et al. 2006), demonstrating developments made in terms of Andon systems and construction planning methods. The company also hired a Master's Degree holder to work as a Lean Coordinator to coordinate developments and further implement lean thinking. As a result, the company moved on to implement Poka-Yoke devices in construction processes. The company also began to use procurement strategies promoting relational contracting with subcontractors to create what can be described as project partnering. These partnerships were seen as the starting point to creating proximity between firms in terms of work methods, standards, language, business mores, and policies, which among other things, would ultimately enhance overall predictability and stability.

2007

The company had then wholly shifted from being a contractor to becoming a full-time builder and developer and made the strategic choice to focus on building high-rise skyscrapers in the city of Fortaleza. By focusing on a specific customer segment and particular geographic area, the company aimed to reduce exposure to unknown factors, thereby further improving stability. Underlying this strategic orientation was the notion that a system cannot achieve management goals nor be improved if it is not stable. This year also marked the beginning of the company´s A3 usage history, which employees from *different hierarchical levels* used for problem-solving, knowledge recording, and strategic planning. The company continued to support employees in postgraduate courses and pay for them to attend or speak at conferences. The knowledge acquired from internal developments was also shared through a paper published in IGLC (Kemmer et al. 2007).

2008

Even though the company´s lean journey had full support from top management, things did not always go as planned, and there was resistance to change. By this point, managers and workers left the company after disagreeing with implementation efforts. To establish a lean mindset amongst employees, the company continued to offer lectures on Hansei and Kaizen to build consciousness on the need to acknowledge problems and improve continuously. The company started to make Hansei and Kaizen events for each construction site, in which the employees share knowledge and identify opportunities to improve the processes. These events happen at the end of each milestone for construction, and a final Hansei event happens to summarize all the lessons learned. That year, two top managers obtained their Master´s Degrees, while others received financial assistance to undertake undergraduate and postgraduate courses. Staff members continued to attend or speak at conferences. Furthermore, the company published papers in conferences (Kemmer et al. 2008) and a book about solid waste management was released.

2009

Employee welfare became a big concern, and the company started offering dental and health insurance plans apart from their regular salary and profit-sharing to enhance the employee's well-being and connection to the organization. The company continued to support employee development by offering training sessions. Managers were also encouraged to attend industry, and academic events, such as the Greenbuilding Int'l. Conf. & Expo of USGBC in Phoenix, USA. A paper reporting lean thinking in the company's head office was published (Kemmer et al. 2009). A practical guide to environmental management and waste management written by staff members was also published. That year, research was conducted to develop a supply method based on the milk run and just-in-time principles. The company also started an Environmental Sustainability Program, hoping to become more socially responsible while maintaining economic vitality. The company launched its "Green Commitment" program, in which for each square meter of land purchased, the company plants and takes care of a tree in a public space in Fortaleza.

2010

A Research and Development (R&D) team was formed to work alongside the Lean Coordinator on rethinking and improving existing business processes. Their first task was to study a way of putting lean philosophy into the Quality Management System, thereby creating a "Lean Quality System." Another study aimed to apply lean practices for customization while maintaining flow and low inventory levels. Staff members continued to exchange knowledge and experience by presenting papers (Kemmer et al. 2010). Meanwhile, Laboral Gymnastics was included to reduce stress and physical discomforts caused by postural problems and repetitive strain and improve employee welfare.

2011

The next challenge was knowing how much lean thinking was embedded in the organization. Thus, internal audit checklists were revised to make people in the company think about customer satisfaction and work more effectively and efficiently. The main objective was to reinforce a culture of continuous improvement. In parallel, the company continued to build a stable workforce by offering a private pension plan to employees.

2012

Benchmarking started being used to compare the company's success in terms of lean implementation against direct competitors and companies in other industries. Internal benchmarking was also adopted within the company's construction sites to identify best practices and improvement opportunities. As a result, an internal study group was formed to write a Lean Guidebook to retain organizational knowledge and provide instructions for future construction projects. Other study groups aimed to learn and share insights on trending topics such as BIM and Lean & Green. Company managers continued to regularly attend or speak at relevant conferences. They also presented a paper on lean monitoring and evaluation at the IGLC (Valente et al. 2012).

2013

The company was already a well-established lean practitioner and getting significant international attention. Lean practitioners and academics worldwide had the remarkable opportunity to see up close its improvements during the IGLC held in Fortaleza, where the company performs its activities. The visit to one of the company's construction sites during Industry Day was a highly attended event. R&D team members authored four papers (Costa et al. 2013; Valente et al. 2013; Valente et al. 2013a; Rocha and Kemmer 2013) detailing improvements. In the following months, one of the study groups worked on revising and updating the Lean Guidebook. A second group assembled a collection of papers on Lean & Green written by the company's R&D team. A third group offered introductory training sessions on BIM.

2014

The continuous effort to increase stability and plan reliability led to establishing work standards in terms of objectives, methods employed, team size, work pace, and work paths. First Run Studies began to be used early on to identify constraints and incorporate improvements, leading to a better adjustment between product and work content. Pursuing standardized work also led to acquiring technology for Virtual Gemba Walks to gather continuous improvement ideas. Openness to sharing these and other results led staff members to publish another paper (Valente et al. 2014) and attend conferences. Furthermore, the company's growing commitment to sustainability began to pay off with Brazil's first LEED-certified residential project.

2015

The search for sustainable methods was viewed as another step of the lean journey; hence the company made an effort towards sustainable practices by controlling some environmental metrics and searching for innovative and technological constructions methods to reduce these environmental metrics by diminishing waste production, water usage, and greenhouse gases emissions. The R&D team prepared a management report with guidelines based on sustainability reporting standards proposed by the GRI (Global

Reporting Initiative). The company soon started working on reducing carbon emissions and undertaking carbon offset projects to complement internal initiatives. Staff members attended the Greenbuilding Brasil Conferência Internacional & Expo, and sustainability was the topic of one the papers published that year (Saggin et al. 2015).

2016

The company took another step towards higher stability and predictability, adopting the BIM capabilities related to time (4D BIM) and cost management (5D BIM). The objective of adding these dimensions was to enable better-planned and more cost-effective construction and better manage the effects of change orders by identifying possible reworks before making any changes. The company also started a Total Productive Maintenance (TPM) Program focused on proactive and preventive techniques for improving equipment safety and reliability. Cranes, racks, and pinion elevators used to transport working materials and people were the major concerns. During that time, the company´s R&D team published papers (Fernandes et al. 2016) and spoke at IGLC, CONENX, and Lean Summit conferences.

2017

The company created a Lean Committee composed of managers from different functional areas to make decisions concerning lean progress as a group and ensure that all views are looked at. Concern regarding sustainability practices was also pushed forward. A study group was formed to perform a Life Cycle Assessment (LCA) on the cumulative impacts and emissions to the environment derived from energy and materials required across the company's value chain. As an initial result of the LCA study, the company launched its plan to plant forty thousand trees in a local state park. Staff members also attended the BATIMAT and the IGLC, where they published another paper (Saggin et al. 2017).

2018

After a few years of waiting, the company finally received an invitation to visit Toyota's manufacturing facility in Brazil. To get the most out of the day, staff members took the guided tour with the clear objective of observing lean processes at work and learning firsthand how they get things done. No other Brazilian construction company had ever done this before. Searching for new insights and technologies, one of the company's top managers participated with other members of the INOVACON in a commercial and academic mission to Silicon Valley. Company managers continued to attend conferences, where they did a paper presentation on workforce well-being (Dantas Filho et al. 2018). Meanwhile, the LCA study advanced, and a company's residential projects received from the local government the first ever-granted Green Factor Certification.

2019

Inspired by observations made during the visit to Toyota's manufacturing facility, the company's R&D team started to study the fundamentals of Karakuri Kaizen. They began to look for moving objects automatically using gravity, counterweights, and the force of equipment already used in construction sites. The R&D team also prepared a second edition of the management report based on sustainability reporting standards proposed by the GRI. Company managers traveled to Germany to attend Bauma 2019, the world's largest construction machinery trade fair. Moreover, one of the company's top managers, alongside members of the INOVACON, participated in an academic mission to Columbia University, USA.

2020

The COVID-19 pandemic impacted the company's performance and plans. Maintaining employee welfare and developing a workplace safety plan to help workers stay healthy and safe at work became the most crucial thing. Moreover, even though coronavirus-related restrictions imposed social distancing, staff members continued to seek knowledge and exchange experience by publishing one paper (Valente et al. 2020) and attending the virtual CONENX conference.

DISCUSSION

The company's efforts to acquire and maintain knowledge are noticeable. Employees got support to get their post-graduate degrees and attended conferences such as Lean Summit, CONENX, ENTAC, ENEGEP, and IGLC. The publication of papers by employees to share and consolidate knowledge and experience was encouraged, and the R&D team detailed the company's experience on the various papers published over the years. As a result, the company was recognized four times as the Best Builder and Developer in Ceará, alongside other awards such as the New Millenium Award (Paris), Social Responsibility Award (Brazil), and the Int'l. Diamond Prize for Excellence in Quality (European Society of Quality Research). Furthermore, representatives of the company were continuously invited to speak at conferences and events, such as Industry Day (Salford University, UK) and the Conference of the Parties (COP 23), which demonstrates its international recognition as a consolidated lean practitioner.

CONCLUSIONS

Every business has a story to tell and lessons to share. This paper used a story structure to give visibility to two messages. The first message is to understand better underlying strategic choices and how they impact lean implementation. The second message is to capture the rationale behind decision-making and strategic alignment. This comes from the fact that the most successful organizations have a good environmental fit and internal coherence between business strategy, functional strategies, and operational practices. The notion that true "best" practices emerge from several organizational adjustments points to the importance of carefully aligning strategic choices in production strategy, be they structural or infrastructural, with one another and with those in other functional areas like marketing, finance, and human resources.

Under this notion, the company in this case study used an organization-wide perspective while pursuing a new production model. It initially changed the business strategy to gradually develop and build its projects in a specific geographic area, reducing uncertainties regarding consumer behavior, product development, local regulations, and other possible unwanted variation sources. Changing the strategic orientation allowed the company to devise partnering strategies with local subcontractors and suppliers to improve collectively and create more behavioral predictability in the value chain. Moreover, it permitted important infrastructural decisions regarding employee welfare to maintain a skilled and stable workforce. As a result, the company built other explicit strategies for preserving institutional memory and making accessible the knowledge and capabilities developed. Creating organizational commonality in language, culture, and work standards was another way of preventing disturbances. These and other strategic choices indicate that the search for predictability and stability was the underlying rationale for creating coherent decision-making throughout its lean journey.

The story presented indicates that stabilizing the work environment requires more than implementing the Last Planner System and other operational level practices from the lean toolbox. In a dynamic environment like the construction sector, understanding the implications of individual or combined strategies can be crucial to shielding production from upstream variation and enhancing project performance. As shown in this business case, the strive for excellence starts with the formalization of strategic choices in production strategy. Although commonly overlooked by lean construction literature, if carefully chosen and made explicit, the strategies applied alongside lean practices can help create a project production system where methods and outputs are less uncertain.

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REFERENCES

Buch, S. and Sander, D. (2005). “From Hierarchy to Team – Barriers and Requirements in Relation to a New Organization of Building Sites.” Proc. 13th Ann. Conf. Int’l. Group for Lean Construction, Sidney, Australia.

Christiansen, T., Berry, W.L., Bruun, P., and Ward, P. (2003). “A Mapping of Competitive Priorities, Manufacturing Practices, and Operational Performance in Groups of Danish Manufacturing Companies.” Int’l. Journal of Operations & Production Management 23 (10), 1163-1183.

Comelli, M. L., Carvalho, Y. M. V., Marinho, R. C., Candido, L. F., Barros Neto, J. P. (2019). "Assessing the Level of Implementation of Lean Construction: an Audit Protocol." Proc. 27th Ann. Conf. Int’l. Group for Lean Construction. Dublin, Ireland.

Costa, H.M., Silva, M.V.V., Mourão, A., Valente, C.P, and Laércio, F. (2013). "Redesigning Administrative Procedures Using Value Stream Mapping a Case Study" Proc. 21th Ann. Conf. Int’l. Group for Lean Construction. Fortaleza, Brazil.

Dantas Filho, J.B.P., Barros Neto, J.P., Mourão, A., Rocha, A.B., Luccas, A.V., and Saggin, A. (2018). “Respect for People’s Well-Being: Meditation for Construction Workers.” Proc. 26th Ann. Conf. Int’l. Group for Lean Construction. Chennai, India.

Escalas, J. E., (2004). "Imagine Yourself in the Product: Mental Simulation, Narrative Transportation and Persuasion. Journal of Advertising, Summer 2004.

Denning, S. (2005). "The Leader’s Guide to Storytelling. Mastering the Art and Discipline of Business Narrative." Jossey-Bass. A Wiley Imprint. San Francisco.

Fernandes, N.B.L.S., Valente, C.P., Saggin, A.B, Brito, F.L., Mourão, C.A.M.A., and Elias, S.J.B. (2016). “Proposal for the Structure of a Standardization Manual for Lean Tools and Processes in a Construction Site.” Proc. 24th Ann. Conf. Int’l. Group for Lean Construction.

Fog, K., Budtz. C., Yakaboylu, B. (2005). "Storytelling – Branding in Practice". Springer-Verlag, Berlin, Heidelberg.

Kemmer, S.L. , Saraiva, M.A. , Heineck, L.F.M. , Pacheco, A.V.L. , Novaes, M.V. , Mourão, C.A.M.A. & Moreira, L.C.R. (2006), 'The Use of Andon in High Rise Building” Proc. 14th Ann. Conf. Int’l. Group for Lean Construction Santiago, Chile.

Kemmer, S.L., Heineck, L. F.M., Novaes, M.V., Mourao, C.A.M.A., and Alves, T.C.L. (2007). “Medium-Term Planning: Constributions Based on Field Application.” Proc. 15th Ann. Conf. Int’l. Group for Lean Construction, Michigan, USA.
Kemmer, S.L., Heineck, L.F.M., and Alves, T.C.L. (2008). “Using the Line of Balance for Production System Design.” Proc. 16th Ann. Conf. Int’l. Group for Lean Construction, Manchester, UK.
Kemmer, S. L., Alves, T. C., Macedo, M., Novaes, M. V., and Neto, J. P. B. (2009). "Lean Office at a Construction Company." Proc. 17th Ann. Conf. Int’l. Group for Lean Construction, Taipei, Taiwan.
Kemmer, S. L., Rocha, C. G., Meneses, L., Pacheco, A. V. L., Formoso, C. T. (2010). "Application of Lean Principles to Manage a Customisation Process". Proc. 18th Ann. Conf. Int’l. Group for Lean Construction.
Mohan, S.B. and Iyer, S. (2005). “Effectiveness of Lean Principles in Construction.” The 13th Ann. Conf. Int’l. Group for Lean Construction, Sidney.
Rocha, C. G. da, and Kemmer, S. L. (2013). “Managing the Information Flow in Customised Apartment Building Projects.” Proc. 21th Ann. Conf. Int’l. Group for Lean Construction, Fortaleza, Brazil.
Saggin, A. B., Valente, C. P., Mourão, C. A. M. A., and Cabral, A. E. B. (2015). “Comparing Investments in Sustainability With Cost Reduction From Waste Due to Lean Construction.” Proc. 23rd Ann. Conf. Int’l. Group for Lean Construction.
Saggin, A. B. , Mota, T. R. , Brito, F. L. & Mourão, C. A. M. A. (2017). "Standardized Work: Practical Examples in a Brazilian Construction Company." Proc. 25th Annual Conference of the International Group for Lean Construction. Heraklion, Greece.
Serpell, A., Alarcón, L. F., Ghio, V. (1996). ”General Framework for Improvement of the Construction Process”. Proc. 4th Ann. Conf. Int’l. Group for Lean Construction, Birmingham, UK.
Torp, O., Knudsen, J. B., Ronneberg, I. (2018). “Factors Affecting Implementation of Lean Construction.” Proc. 26th Ann. Conf. Int’l. Group for Lean Construction, Chennai, India.
Valente, C.P., Novaes, M.D.V., Mourão, C.A.M.D.A., Barros Neto, J.D.P. (2012). "Lean Monitoring and Evaluation in a Construction Site: A Proposal of Lean Audits." Proc. 20th Ann. Conf. Int’l. Group for Lean Construction. San Diego, USA.
Valente, C. P., Montenegro, G. A., Brito, F. L., Biotto, C. N., Mota, B. P., and Schramm, F. K. (2013). "Benefits of Batch Size Reduction: A Case Study in a Residential Project." Proc. 21th Ann. Conf. Int’l. Group for Lean Construction. Fortaleza, Brazil.
Valente, C.P., Mourão, C.A.M.A., and Barros Neto, J.D.P. (2013). "Lean and Green How Both Philosophies Can Interact on Strategic, Tactical and Operational Levels of a Company." The 21th Ann. Conf. Int’l. Group for Lean Construction. Fortaleza, Brazil.
Valente, C.P., Montenegro, G.A., Brito, F.L., Biotto, C.N., and Mota, B.P. (2014). “Guidelines for Developing a Line of Balance for Non-Repetitive Areas (Common Areas) at a Vertical Residental Building.” Proc. 22nd Ann. Conf. Int’l. Group for Lean Construction.
Valente, C.P., Mourão, C.A.M.A., Saggin, A.B., Barros Neto, J.P., and Costa, J.M. (2020). "Achieving Excellence in Lean Implementation at Construction Companies - A Case Study From Brazil." Proc. 28th Ann. Conf. Int’l. Group for Lean Construction, Berkeley, California, USA.

Retamal, F., Salazar, L.A., Alarcón, L.F., and Arroyo, P. (2021). "Monitoring of Linguistic Action Perspective in Online Weekly Work Planning Meetings." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 433–442, doi.org/10.24928/2021/0142, online at iglc.net.

MONITORING OF LINGUISTIC ACTION PERSPECTIVE DURING ONLINE WEEKLY WORK PLANNING MEETINGS

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ABSTRACT

There is a need to improve construction productivity through project planning and control. In this study, the authors measured and analyzed the Key Indicators for Linguistic Action Perspective (LAP) in the Last Planner® System (LPS) through the Lean Implementation Plan (LIP) research method. This research was carried out for four high rise construction projects in different Colombian cities. Some of the most notable results were that the positive LAP indicators increased in three of the four projects during the first five weeks of intervention. In addition, there was a positive trend for all the projects regarding the LAP indicators in the long term. Furthermore, the percentage of plan completed (PPC) stabilized in all projects, improving the level of LPS maturity. The research was successful even though it was performed using online intervention due to the COVID-19 pandemic. Finally, the authors propose future research that focuses on finding other patterns, adding additional variables to the study, and analyzing projects with different characteristics and in other countries.

KEYWORDS

Linguistic action perspective, Last Planner® System, lean implementation, case study.

INTRODUCTION

The construction industry has not increased their productivity factor, as other industries have (Eastman, Teicholz, Sacks, & Liston, 2011). Therefore, it is essential to improve the planning and control of projects by standardizing and strengthening the technical and operational capacities of workers (McKinsey & Company, 2009). As part of the philosophy of Lean Construction, the Last Planner® System (LPS), developed by Glenn Ballard and Gregory Howell in the 1990s (Ballard & Tommelein, 2016), is the most widely used methodology for the planning, design, and construction of buildings and infrastructure (Babalola, Ibem, & Ezema, 2019).

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BACKGROUND

LAST PLANNER® SYSTEM AND LINGUISTIC ACTION PERSPECTIVE

The Last Planner® System is a planning and commitment control methodology based on the principles of Lean Construction and seeks to increase the reliability of planning and the performance of construction projects (Ballard & Tommelein, 2016). According to Goldratt & Cox (2013), reliability depends on the effectiveness of controlling dependencies and fluctuations between project activities. Therefore, the management and control of commitments become relevant, primarily in weekly work planning meetings (Salazar, Ballard, Arroyo, & Alarcón, 2018). For this purpose, Macomber & Howell (2003) propose the Linguistic Action Perspective (LAP), also called "language action," as a way to improve commitment management in construction projects. This perspective, developed by Flores (2015), is based on the application of the speech act theory (Austin, 1971; Searle, 1969). Flores (2015) states that there are four stages involved in "conversation for action" or "commitment management," which are 1) the preparation of a request; 2) negotiation and agreements; 3) the execution and declaration of compliance; and 4) the acceptance and declaration of satisfaction (Salazar et al., 2018).

Consequently, Salazar et al. (2018) carried out an initial proposal of indicators to measure and control the management of commitments in construction projects, applying the principles of LAP. Later, after several iterations, Salazar, Arroyo, & Alarcón (2020) proposed a system of key LAP indicators that measure and control the management of commitments. However, there are still not enough case studies to analyze the relationship between these indicators ant the percentage of plan completed (PPC) and construction project performance.

RESEARCH METHODOLOGY

The authors selected the case study methodology because of the research questions it asks, how and why (Yin, 2003). Furthermore, this study did not represent a "sample", and therefore a controlled experiment was ruled out (Retamal, Salazar, Herrera, & Alarcón, 2020). In this case, the authors performed a longitudinal-multiple-holistic case study because this research aims to extend and conceptualize theories through an analytical generalization of causal relationships, both simple and complex, through the verification of the proposed theory (Yin, 2003) and is not a statistical generalization (Yacuzzi, 2005).

SELECTED PROJECTS

The authors selected four projects for participation in this research. These projects were all located in Colombia, but in different cities: Barranquilla (Project A), Bucaramanga (Project B), and Bogota (Project C and Project D).

These projects had the same characteristics (tall building type), and they were measured in the same eight weeks. Measurement for each project started on October 13th, 2020, and ended on December 08th, 2020.

Weekly work planning meetings were held in person, with adequate social distancing. Additionally, the meetings were held outdoors, and all participants wore masks. In some cases, a megaphone was used so that all meeting participants were aware of when it was their turn to participate. Only the authors who performed the interventions were remotely located.

LEAN IMPLEMENTATION PLAN

The authors used the Lean Implementation Plan (LIP) research method. This method is based on the art and practice study, with 5 phases of implementation (Gómez-Cabrera, Salazar, Ponz-Tienda, & Alarcón, 2020).

According to Gómez-Cabrera et al. (2020), the first step is the project's characterization, i.e., the authors must understand the project's state prior to implementation. The next phase is to make a diagnosis using KPIs, establishing a baseline for the project. Third, the authors select tools from Lean Implementation to apply to each project. Finally, the project is evaluated, and is considered to have started an improvement process. Figure 1 shows the process implemented in this research.

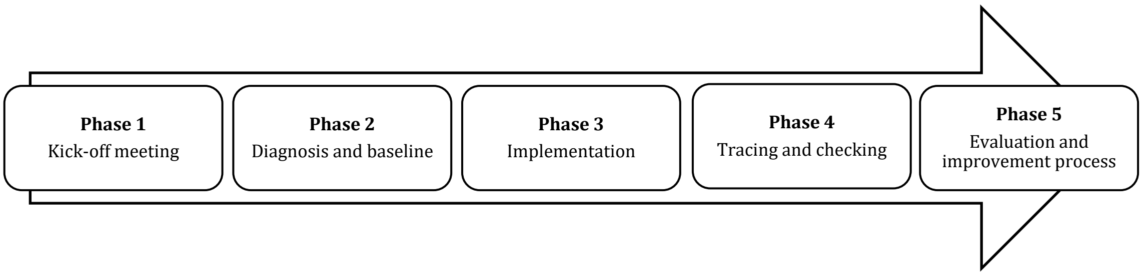

Figure 1: Lean Implementation Plan process (LIP) (Figure 2 in Gómez-Cabrera et al., 2020)

SELECTED INDICATORS

Last Planner® Maturity

The level of maturity is defined as the level of depth at which a tool is implemented. This measure depends on the implemented tool type (Vujica Herzog & Tonchia, 2014).

The Center of Excellence in Production Management (GEPUC) developed a worksheet that measures the level of implementation and maturity of the LPS. This worksheet measures key aspects of the Last Planner® System and allows users to track the level of implementation as well as the different practices involved in this methodology (Baladrón Zanetti, 2017). Figure 2 shows an example of the worksheet used to measure the level of maturity in the LPS. The average of these indicators is the percentage of LPS maturity, and the red color corresponds to a low level of maturity, yellow corresponds to a medium level, and green corresponds to an advanced level of LPS maturity.

MATURITY OF THE LAST PLANNER®			
Project	**PROJECT A**		
Researcher	**XXXX**		
Date	**23-10-2020**		
Initial Plan		**Is it?**	**Quality**
38%	Master Plan exists	Yes	Regular
	It is checked periodically	Yes	Regular
	It is updated	Yes	Poorly
	It is published	Yes	Regular
	There is a milestone plan, and it is published	No	Poorly
	It is complemented with the layout	NA	
	It is complemented with a shopping program	NA	
	It is sustainable, the standards of the company are met	Yes	Regular
Look ahead			
33%	Lookahead exists	Yes	Regular
	It is reviewed weekly	Yes	Regular
	Crossover with milestones and programming goals	No	Regular

Restrictions Management			
50%	Record of restrictions exists	Yes	Good
	It is measured	Yes	Regular
	It is tracked	Yes	Regular
	There is an indicator for managing restrictions for noncompliance	No	
Weekly Work Planning Meeting			
52%	Be prepared before the meeting	Yes	Regular
	The structure of the meeting is followed	Yes	Good
	There is the active participation of the Last Planners	Yes	Poorly
	It takes place weekly	Yes	Regular
	The goal is clear	Yes	Poorly
Causes of noncompliance analysis			
75%	CNC exist in the meeting	Yes	Regular
	Accumulated CNC are recorded	NA	
	Weekly CNC are recorded	Yes	Good
	Weekly analysis of CNC	Yes	Regular
	CNC are published	Yes	Good
Corrective actions			
77%	Corrective actions exist in the meeting	Yes	Good
	Corrective actions are recorded	Yes	Good
	Its impact is monitored	Yes	Poorly
Reliable commitments			
20%	Commitment by the Last Planner	Yes	Poorly
	There is analysis of quantities and resources necessary to achieve the proposed goal	Yes	Poorly
	Responsible comes with their own plan proposal	No	
Visual management			
0%	Visual management exists in the meeting	No	
	It is updated	No	
Phase plan			
40%	It is done	Yes	Good
	It is updated	Yes	Regular
	Commitments are recorded	Yes	Regular
	It is monitored periodically	No	
	Visible panel	No	
Measurement and control of indicators			
19%	Attendance Control Record	No	
	Concrete Advance Curve Chart	No	
	Key Items Yield Curve Chart	No	Regular
	Graph of Yield Curves of Key Items by subcontract	No	
	Graph of Compliance with Progress Commitments (PPC)	No	
	Causes of Noncompliance Chart	Yes	Regular
	Updated indicators	Yes	Regular
	They are published	Yes	Regular
Last Planner meetings			
35%	Weekly meeting	Yes	Regular
	Punctuality	Yes	Poorly
	It is done constantly	Yes	Regular
	Adequate space	Yes	Regular
	The use of radios, cell phones, and computers within the meeting is respected	Yes	Poorly
	There is a coffee or cookies for comfort f the participants	No	
Participants			
50%	All participants attend in the meeting	Yes	Good
	There is support in case of staff rotation to take up the subject (inductions, procedures, formats, etc.)	No	

Figure 2: Example of LPS Maturity worksheet. (Annex A in Baladrón Zanetti, 2017)

Linguistic Action Perspective Indicators

The authors analyzed LAP indicators, following the methodology proposed by Salazar et al. (2018), later updated by Salazar et al. (2019) and Salazar et al. (2020), known as Weekly Work Planning. The methodology measures positive and negative LAP actions, defined by Retamal et al. (2020). The average of these indicators corresponds to LAP (+) and LAP (-).

Table 1: Positive and negative linguistic action perspective (LAP) indicators (Table 3 in Retamal et al., 2020)

LAP indicator	Positive or Negative indicator
Arrives on time	Positive
Take notes	Positive
Check mobile phone	Negative
Mobile phone rings	Negative
Talk by mobile phone	Negative
Leave the room	Negative
Walkie talkie rings	Negative
Talk by walkie talkie	Negative
Does not speak in the meeting	Negative
Does not look at the person who is speaking	Negative

Notebook for Last Planners

Video recordings were used in previous research to measure Linguistic Action Perspective (LAP) indicators, but they turned out to be very invasive for the meeting participants. Salazar et al. (2020) propose a way to simplify the measurement of LAP indicators by assigning participants a notebook. This notebook, together with a checklist used by the facilitator, allows researchers to analyze the engagement of the meeting participants, avoiding the use of video recordings. Figure 33 shows the Notebook for Last Planners.

NOTEBOOK FOR LAST PLANNERS												
Name:				Measurement start date:			/ /2020		Measurement end date:		/ /2020	
Position:				Symbology		-- (Very low)		- (Low)	0 (Mean)	+ (High)	++ (Very High)	
Company:						W: Well		N: Normal			P: Poor	
Week 1								Week 2				
Who asks for it	Activity and / or Task	(%)	Sector	Day (AM or PM)	Task Priority	Clarity in the Petition (request)	Negotiation and Agreement	% Completed	PPC	Declaration of compiance	Declaration of satisfaction	Comments (CNC)
Name and / or Position					--, -, 0, +, ++	W - N - P	W - N - P	%	Does it comply?	Yes - No	Yes - No	
Administrator	Floor slab installation -1	80%	Quadrant A and B	Tuesday (AM)	-	W	N	70%	NO	YES	NO	bla bla bla
Week 2								Week 3				
Who asks for it	Activity and / or Task	(%)	Sector	Day (AM or PM)	Task Priority	Clarity in the Petition (request)	Negotiation and Agreement	% Completed	PPC	Declaration of compiance	Declaration of satisfaction	Comments (CNC)
Name and / or Position					--, -, 0, +, ++	W - N - P	W - N - P	%	Does it comply?	Yes - No	Yes - No	

Figure 3: Notebook for Last Planners. (Appendix B in Salazar et al., 2020)

RESEARCH TASKS

Due to the COVID-19 pandemic, the authors participated in Weekly Work Planning meetings via videoconference for each project. These meetings were held every week for a total of 10 weeks. In weeks 1 and 8, the researchers measured the LPS maturity level to analyze the evolution of the project, using the LIP implementation strategy detailed below.

1. **Kick-off meeting:** A kick-off meeting was held to detail the scope of the research for the selected projects. In each project, a field facilitator was defined, while the researcher participated via videoconference. The role of the facilitator was to support the implementation tasks that the researcher assigned during the kick-off videoconference. Specifically, the field facilitator was provided with the necessary materials, problems with the internet connection were resolved, and, in the case that the facilitator does not understand all simulations, they were explained. In addition, every Friday for the next 10 weeks, the researcher met with all project facilitators by video call to check on the progress of each project and explain the activities to be carried out in the following week.
2. **Diagnosis and baseline:** Information regarding each project's history was collected to determine the context. During the first week, the level of LPS maturity and LAP indicators were initially evaluated, and the information about the PPC was collected prior to the intervention to serve as a point of comparison with the implementation.
3. **Implementation:** During weeks 1 to 5, three simulations with the planners were run online. In addition, each week, a short presentation was made on LAP. These presentations did not last more than ten minutes per week to avoid interfering with the meeting times. The agenda for each of the first five weeks is shown in Tabl; agendas were chosen so that the simulations share a common thread with that week's presentations.

Table 2: Timeline of intervention in the first five weeks

Measure	Week 1	Week 2	Week 3	Week 4	Week 5	Week 8
Intervention	What does LAP mean?	Importance of Commitment Management	Moods	Team Work	Conditions of Satisfaction and background of obviousness	
Simulation		Dice Game		Nasa on the Moon	Dictation Drawing	
Measurement	PPC / LPS Maturity		PPC			PPC / LPS Maturity

4. Tracing and checking: During weeks 6 to 8, each Last Planner participant entered their information in the LAP notebook. In addition, the researcher was present in each meeting via videoconference to receive an update regarding how the commitments were developing. In week 8, the LPS maturity level was measured again to establish metrics before and after the intervention.
5. Evaluation and improvement process: The evaluation was carried out by analyzing the evolution of the LPS maturity level, the increase in commitment management when using LAP, and the PPC stabilization. Finally, a new method for performing interventions online was established, with only facilitators being allowed in the field because of the constraints of the pandemic.

RESULTS AND ANALYSIS

Due to the pandemic, the authors held a videoconference each week to see how the commitments were being carried out. The facilitators then printed an LPS notebook for each of the workers who were at the LPS meeting.

With the LPS notebook, the following results were obtained in weeks 1, 5, and 8 for each project, detailing information about the indicators proposed by Salazar et al. (2020). The positive and negative LAP indicators were measured by the field facilitators because the researchers' webcam did not capture all the people in the meeting. These positive (+) and negative (-) LAP indicators are described in Table 1.

In addition, the level of maturity was measured by the authors, using their expertise, to prevent the facilitators from reporting subjective opinions. Table 33 shows the results obtained and the slope of the trend line from the four projects that were measured in these eight weeks.

Table 3: Results of indicators in each project

Project	Indicator	Week 1	Week 5	Week 8	Slope
A	PPC	72.73%	65.91%	88.89%	2.7%
	LAP (+)	63.33%	70.59%	81.25%	1.1%
	LAP (-)	0.83%	5.88%	7.81%	0.8%
	LPS	43.00%	-	64.00%	3.0%
	% of fulfillment of a request	67.42%	56.25%	83.33%	2.0%
	% of compliance negotiation and agreements	56.06%	62.50%	83.33%	3.8%
	% of declaration of compliance with the commitment	38.33%	50.00%	-	2.9%
	% of fulfillment declaration of satisfaction	53.33%	25.00%	-	-7.1%
B	PPC	64.41%	89.36%	81.63%	2.8%
	LAP (+)	90.00%	86.36%	100.00%	2.7%
	LAP (-)	11.67%	9.09%	5.83%	-0.9%
	LPS	68.00%	-	76.00%	1.1%
	% of fulfillment of a request	86.51%	77.78%	94.61%	1.0%
	% of compliance negotiation and agreements	52.38%	70.37%	94.76%	6.0%
	% of declaration of compliance with the commitment	75.79%	90.29%	98.33%	3.2%
	% of fulfillment declaration of satisfaction	75.79%	88.29%	98.15%	3.2%
C	PPC	55.00%	59.25%	58.00%	-0.2%
	LAP (+)	56.25%	65.63%	67.65%	1.4%
	LAP (-)	2.34%	7.81%	5.88%	0.7%
	LPS	59.00%	-	71.00%	1.7%
	% of fulfillment of a request	57.41%	66.67%	66.67%	1.4%
	% of compliance negotiation and agreements	49.07%	50.00%	50.00%	0.1%
	% of declaration of compliance with the commitment	59.44%	100.00%	91.67%	4.9%
	% of fulfillment declaration of satisfaction	51.11%	100.00%	91.67%	6.1%

Project	Indicator	Week 1	Week 5	Week 8	Slope
D	PPC	71.88%	77.78%	75.68%	-0.6%
	LAP (+)	86.67%	100.00%	84.62%	-0.1%
	LAP (-)	3.33%	0.83%	0.00%	-0.5%
	LPS	47.00%	-	73.00%	3.7%
	% of fulfillment of a request	62.50%	75.00%	60.71%	-0.1%
	% of compliance negotiation and agreements	50.00%	63.54%	60.71%	1.6%
	% of declaration of compliance with the commitment	74.31%	90.48%	95.24%	3.0%
	% of fulfillment declaration of satisfaction	74.31%	90.48%	95.24%	3.0%

The results show that during the first five weeks of intervention, there was an increase in LAP (+) in three out of four projects. This is because this intervention begins with LA prompts. However, regarding LAP (-) indicators, we observed different results.

In week 8, we can see that over the long term, the authors suggested continuous improvements during each intervention, which projects may or may not implement. In some cases, the LAP(+) indicators continued to increase, as was the case for projects A, B, and C, who implemented continuous improvements in their projects with respect to better behavior exhibited by workers during the weekly work planning meeting (WWP).

In terms of the indicators proposed by Salazar et al. (2020) regarding the linguistic action perspective, the trend line shows that in the long term, these indicators increased for all projects, demonstrated by their positive slopes. Furthermore, in week 8 for project A, we can see that some indicators were not measured by the workers, causing a -7.1% slope for the percentage of fulfillment declaration of satisfaction. However, in this case, as it does not have three measurements, it is eliminated from the indicator analysis.

In terms of PPC variation, the commitments increased during the weeks that all linguistic action indicators were increased; in other words, the higher the PPC, the higher the results from the LAP. In addition, there was PPC stabilization, preventing large variations in this indicator for each project.

Finally, the Last Planner maturity level was reinforced by the intervention carried out during each of the projects. For all projects, the maturity level increased by 11%, especially in projects A and D. For projects A and D, we also see that an increase in PPC as well as a gradual increase in LAP indicators.

CONCLUSIONS

The intervention during these five weeks led to an increase in the maturity level of the Last Planner® System, creating a new method for performing remote interventions. This method's use of videoconferences was especially effective, since they ensured that those participating in all projects understood the linguistic action process. Furthermore, the interventions were recorded on video so that all projects could access them and the knowledge they contained.

Regarding the positive LAP indicators and the indicators proposed by Salazar et al. (2020), we conclude that by performing remote interventions focused on the linguistic action perspective, it is possible to increase the knowledge of the Last Planners and establish reliable commitments during the eight weeks of monitoring, and that these lessons can be replicated in both the current and future projects. With the LAP notebook, we found that the Last Planners became more involved in the project since, during each weekly work plan meeting, they themselves provide their perception of how different commitments are being carried out.

As this research used a small sample and followed up for eight weeks, it is recommended that the measurements last longer to determine whether there is continuous project improvement.

This research demonstrated that online interventions can be achieved from anywhere in the world, overcoming existing social distancing limitations due to COVID-19 or any other potential cause. By doing so, this study demonstrates a new way of generating value through distance. Nevertheless, the facilitators for each project played an important role in these interventions.

In the future, the authors plan to continue looking for new patterns, both by adding more variables and generating more data; significant sample information regarding the evolution of these projects will produce more reliable results.

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REFERENCES

Austin, J. L. (1971). *Palabras y Acciones*. Paidós. Buenos Aires.

Babalola, O., Ibem, E. O., & Ezema, I. C. (2019). Implementation of lean practices in the construction industry: A systematic review. *Building and Environment*, *148*, 34–43. doi.org/10.1016/j.buildenv.2018.10.051.

Baladrón Zanetti, C. (2017). *Evaluación de impactos de la implementación de metodologías lean en proyectos de desarrollo minero en construcción* (Pontificia Universidad Católica de Chile). Retrieved from https://repositorio.uc.cl/handle/11534/21415.

Ballard, G., & Tommelein, I. (2016). Current Process Benchmark for the Last Planner System. *Lean Construction Journal*, *13*(1), 57–89. Retrieved from https://leanconstruction.org.uk/wp-content/uploads/2018/10/Ballard_Tommelein-2016-Current-Process-Benchmark-for-the-Last-Planner-System.pdf.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. John Wiley & Sons.

Flores, F. (2015). *Conversaciones para la Acción*. Bogotá, D.C., Colombia: Lemoine Editores.

Goldratt, E. M., & Cox, J. (2013). La meta, un proceso de mejora continua. In S. A. Ediciones Granica (Ed.), *Revisada. 12a. Reimp. Granica. México* (Tercera). México D.F.

Gómez-Cabrera, A., Salazar, L. A., Ponz-Tienda, J. L., & Alarcón, L. F. (2020). Lean Tools Proposal to Mitigate Delays and Cost Overruns in Construction Projects. *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC)*, 781–792. doi.org/10.24928/2020/0049.

Macomber, H., & Howell, G. A. (2003). Linguistic Action: Contributing to the theory of lean construction. *Proc. 11th Annual Meeting of the International Group for Lean Construction.* Virginia, USA.

McKinsey & Company. (2009). Productividad como motor de crecimiento: El próximo desafío = Chile X 2. *Presentación Ante La Confederación de La Producción y El Comercio de Chile*, 38. Santiago, Chile.

Retamal, F., Salazar, L. A., Herrera, R. F., & Alarcón, L. F. (2020). Exploring the Relationship Among Planning Reliability (PPC), Linguistic Action Indicators and Social Network Metrics. In I. D. Tommelein & E. Daniel (Eds.), *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC)* (pp. 109–118). doi.org/10.24928/2020/0031.

Salazar, L. A., Arroyo, P., & Alarcón, L. F. (2020). Key Indicators for Linguistic Action Perspective in the Last Planner® System. *Sustainability*, *12*(20), 8728. doi.org/10.3390/su12208728.

Salazar, L. A., Ballard, G., Arroyo, P., & Alarcón, L. F. (2018). Indicators for Observing Elements of Linguistic Action Perspective in Last Planner® System. In V. A. González (Ed.), *Proc. 26th Annual Conference of the International. Group for Lean Construction (IGLC)* (pp. 402–411). doi.org/10.24928/2018/0441.

Salazar, L. A., Retamal, F., Ballard, G., Arroyo, P., & Alarcón, L. F. (2019). Results of indicators from the linguistic action perspective in the Last planner® system. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, 1241–1250. doi.org/10.24928/2019/0148.

Searle, J. R. (1969). *Speech acts: An essay in the philosophy of language* (Vol. 626). Cambridge university press.

Vujica Herzog, N., & Tonchia, S. (2014). An Instrument for Measuring the Degree of Lean Implementation in Manufacturing. *Strojniški Vestnik - Journal of Mechanical Engineering*, *60*(12), 797–803. doi.org/10.5545/sv-jme.2014.1873.

Yacuzzi, E. (2005). *El estudio de caso como metodología de investigación: Teoría, mecanismos causales, validación*. Buenos Aires.

Yin, R. K. (2003). Case Study Research: Design and Methods. In *SAGE Publications* (3th ed.). Thousand Oaks, CA.

Hao X. and Florez-Perez L. (2021). "The effect of classroom environment on satisfaction and performance: Towards IoT-Sustainable spaces" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29), Alarcon, L.F. and González, V.A. (eds.)*, Lima, Peru, pp. 443–453, doi.org/10.24928/2021/0145, online at iglc.net.

THE EFFECT OF CLASSROOM ENVIRONMENT ON SATISFACTION AND PERFORMANCE: TOWARDS IOT-SUSTAINABLE SPACES

Xinyue Hao[1] and Laura Florez-Perez[2]

ABSTRACT

The physical classroom environment includes the overall design and layout facilities that are provided in a classroom. Classroom facilities should be organised to maximise the satisfaction and performance of students. With the increased demand of well-equipped classrooms, upgrades in new high-technology need to be adopted to enable the optimisation of the students' perceptions and behaviours. A number of studies have investigated the impact of classrooms in high schools. However, few studies have investigated the impact of the physical classroom environment in university settings. This paper examines the impact of the physical classroom environment on students' satisfaction and performance in a university setting. A total of 173 responses from students were obtained regarding their perceptions of five physical classroom environment factors, namely, classroom layout, noise, temperature, lighting and colour. The questionnaire results showed that students have different demands for the physical classroom environment. Using the guidance of the person-environment fit theory, a smart IoT-enabled classroom has been proposed. The results of this study could be used by managers who make capital decisions on classroom construction upgrades and facility managers who aim to improve the satisfaction and performance of students in higher education institutions.

KEYWORDS

Process, design science, person-environment fit, internet of things (IoT).

INTRODUCTION

In recent decades, the progress reached in educational theories and paradigms in addition to the advancement of technological development, have served to create new possibilities for the transformation of learning environments in higher education institutions (HEI) (Baum, 2018). Such developments enable the optimisation of physical, technological, and social conditions of university classrooms (González-Zamar et al., 2020), since these spaces for learning must adapt to the needs of multiple students. Throughout the process

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of schooling, students spend the majority of their time inside the classroom where they study (Woolfolk and Margetts, 2007), so it is critical to ascertain the influence of physical classroom environments in HEI to guarantee that students obtain the maximum benefits from these spaces (Puteh et al., 2015).

Steels (1973) defined the word ‘environment’ as the surroundings and conditions which are occupied by humans; each element of which has a different impact on human perceptions and behaviours. It is the primary intention of a learning environment to assist and improve the physical aspects for its users, such as those which are auditory and visual (Kopec, 2018). The classroom environment as an intermediate for learning can be addressed separately as two components, namely physical factors and social factors (Ramli et al., 2014). The physical factors include the facilities which are provided in the classroom (lighting, colour, temperature, noise, classroom layout, amongst others), which collectively form the entire classroom (Earthman, 2002). In contrast, social factors refer to human subjective percpetions which are informed by physical factors (Tanner and Lackney, 2006).

In this context, the physical classroom is not understood as a simple volumetric container of human activities, but this concept goes beyond to an architectural and built environment object (González-Zamar et al., 2020). From a positive perspective, it is often supposed that students who are more satisfied with the physical classroom environment are more likely to get better study outcomes (Kamarulzaman et al., 2011). From a negative perspective, students who are disappointed with perceived physical classroom conditions, tend to become distracted from their studies (Badayai, 2012). Therefore, improving the quality of the physical environment within the classroom design is one of the major objectives in terms of building and developing the education system in HEI (Barrett et al. 2017).

Practical methods and tools for efficient (automated) data collection can act on students’ requirements in a timely manner and provide effective communication and sharing of information (Teizer et al, 2017). Information and communication technologies are in particular beneficial to lean practices when they improve the flow of processes by identifying non-value adding options that can be eliminated. IoT systems can integrate internal and external information, feed this information into a platform and provide perceived information for decision-making. IoT systems can also enhance the interaction between facility managers and students to increase effectiveness. These are the aims of Lean Thinking (Huovila and Koskela, 1998) and in this empirical research the aim is to identify the impact of the physical classroom environment on motivational attributes of students in HEI. In doing so, it will explore whether the design of physical classrooms influences learning satisfaction and performance. The results of this research provide specific design suggestions that contribute to reducing absenteeism, increasing enthusiasm, and forming a good person-environment relationship that continuously satisfies the needs of students. Furthermore, the environmental factors for classroom design that enhance performance and satisfaction have been used to develop an IoT-enabled classroom that can boost the construction of smart spaces and buildings.

LITERATURE REVIEW

PERSON-ENVIRONMENT FIT THEORY

Lewin (1935) and Murray (1938) creatively proposed a theoretical standpoint that identifies both the physical environment and its connection with personal preferences of the individual as potent determinants of human behaviour. Lewin (1951) perfected the definition of the person-environment (P-E) fit model that has been widely adopted and continues to be used. It states that P-E fit refers to the research of behaviour as a consequence of the interaction between the individual and the surrounding physical environment. Chartrand (1965) proposed a core assumption that meaningful differences can be assessed between the individual and the environment and considers that matching individuals to physical environments will expand the likelihood of positive outcomes. The P-E model has been adopted to understand and predict performance in the workplace (Mackinnon, 1962; McDermid, 1965), and it has also been applied in the field of education (Pawlowska et al., 2014). The "E" refers to the physical classroom environment where students learn and expect to be comfortable and safe. The "P" focuses on the students' perceptions, behaviours, and performance that are formed in the environment "E" (Pawlowska et al., 2014).

PERSON-ENVIRONMENT FIT IN CLASSROOM

Fraser (2012) argued that the contemporary physical classroom environment can be either beneficial (encourages communication and increased performance) or detrimental (noisy and with poor privacy). Therefore, the question is how to make a physical classroom environment to play an active positive role? Although there are many physical classroom environment factors, the main ones are: noise, temperature, lighting, colour, and classroom layout (Lewinski, 2015). McCoy (2005) proposed that these five factors play a critical role in improving the happiness of users and constitute the second-largest financial overhead for the majority of organisations when it comes to physical spaces. Regardless of the investment, the allocation of these spatial factors continues to be uncontrolled for many organisations (Lewinski, 2015), so it is necessary to state the impact of these five factors before establishing formal guiding practices for building spaces (Zannin et al., 2012).

Noise and poor classroom acoustics can generate a negative environment for students (Shield and Dockrell, 2003). DiSarno et al., (2002) determined that noise undermines student's reading, writing, and comprehension skills as noise diminishes the level of focus on the task being performed. To respond to these concerns, many countries have introduced guidelines concerning appropriate noise levels to improve acoustic conditions (Shield and Dockrell, 2006). For instance, the ANSI standard S12.60 acoustical performance standard has noise guidelines for schools in the USA (ANSI, 2002), and the Department for Education and Skills (DfES) in the UK (DfES, 2003). The noise inside a classroom can be owing to several reasons such as external noise (adjoining classrooms and street), building services noise (heating, lighting, and ventilation systems), noise from teaching aids (computers), and noise from the students (Shield and Dockrell, 2004).

Temperature may also impact the classroom environment. An inappropriate temperature can have physiological problems on people and make them exert more effort and prone to making more mistakes (Halstead, 1974). Haverinen-Shaughnessy and Shaughnessy (2015) claimed that students who study in a classroom with an unsuitable temperature showed a decreasing trend in the achievement of high marks. The classroom climate should be cautiously managed not only to ensure comfort, but also to act as a positive environment in the learning process by increasing attention and concentration (Wargocki and Wyon, 2013). Although there is no ideal temperature for a classroom, Earthman (2002) proposed a comfort indoor temperature between is 23°C to 26°C.

The visual lighting environment also affects the capability of students in perceiving visual stimuli (Philips, 1997). Fenton and Penney (1985) found that children are more likely to engage and concentrate in classroom activities, and achieve good academic results with fluorescent light. Heschong and Knecht (2002) found significant positive correlations between learning satisfaction and lighting, that is, the better the use and artificial controls of fluorescent light and natural daylight, the greater the satisfaction of students.

Colour is a design element that induces physiological and psychological responses (Gaines and Curry, 2011). For the physiological factors, Engelbrecht (2003) proposed that colour affects children's blood pressure, eye strain, and even brain development. For psychological considerations, findings have shown a relationship between colour preferences and the participants' performance and satisfaction (Verghese, 2001). Torice and Logrippo (1989) noted colour characteristics in the classroom design since colours have different effects on social environment factors. It was found that active students prefer cool colours and passive students are more comfortable with warm colours.

Classroom layout and spatial arrangements with well-defined spaces positively impact the interactions between students and teachers and on-task behaviours (Budge, 2000). There are many forms of seating arrangements in a classroom such as U-shape, V-shape, Hollow square, Boardroom, Oval and Top tables, which share functional similarities (Burgess and Kaya, 2007). Fuhrer et al. (1999) determined that students in the U-Shape and V-Shape arrangements asked more questions than in the traditional classroom arrangement. Classrooms with traditional seating configurations improve the student's ability to concentrate on the lesson and focus on their work (Budge, 2000).

IoT and Smart Classroom

Internet of Things (IoT) devices have been widely applied to improve noise, lighting, and temperature conditions in diverse environments (Uzelac et al., 2015). The basic key features of IoT are sensing, communicating, networking, and producing new information. IoT can support organisations to advance the quality of learning and teaching by offering a more affluent learning experience, as well as real-time actionable insight into students' performance and satisfaction (Dawndasekare and Jayakody, 2017). It has the potential to create a smart learning environment in which students can customize environmental variables to their preferences. IoT applications (tablets, sensors, fitness bands, virtual reality headsets) are being used in education to track the performance of students (Asseo et al., 2016). Smart classrooms can measure and analyse the effect of different parameters in the physical environment like noise, CO2 level, temperature on students' attention (Gligoric et al., 2015) and decide in real time whether to the physical environment is enhanced to make the most of students' ability to focus on a task (Dawndasekare and Jayakody, 2017).

RESEARCH METHOD

This study assesses the influence of HEI classroom design on students' performance and satisfaction. Satisfaction refers to students' subjective feelings with the physical classroom environment. A physical classroom environment may be constituted by several dimensions such as noise, lighting, temperature, interior colour etc. that have a considerable positive or negative impact on behaviour, perceptions, attitudes and the performance of students (Ashkanasy et al., 2014). From a positive perspective, it is often supposed that students who are more satisfied with the physical classroom environment have better work outcomes (Kamarulzaman et al., 2011) and when emotionally engaged are actively eager to learn and work with higher grades (Mouratidis et al. (2009). From a negative standpoint, an inappropriate physical classroom environment will affect students' perceptions. Obviously, the subjective satisfaction level of students will have an impact on the objective grade. To explore the satisfaction and performance of students in HEI, data was drawn from a University in the UK. A survey questionnaire was conducted in order to solicit opinions and preferences from students on the factors that need to be considered for designing good quality classroom environments. The questionnaire was designed and a mix-method approach was used for analysis, where samples were drawn with the adoption of both random and purposive sampling. According to the research results, a smart classroom system based on IoT devices will be built to meet their specific needs.

DATA COLLECTION

A web-based questionnaire was sent to students since the goal was to learn about the opinions of students about classroom environments in HEI. According to the research hypotheses (see Table 1), the first part of questionnaire was designed to collect opinions on impact: "do you think that classroom noise/temperature/lighting/colour/ layout has an impact on your learning performance and satisfaction?", on a 5-point Likert scale in which: 1-strongly disagree and 5-strongly agree". In the second part, respondents were asked to answer open-ended questions: on what they think is the most: "influential noise source?"; "suitable temperature for university classroom?"; "suitable colour for the classroom?"; "favourite classroom layout?" and "comfortable light source?".

Table 1: Research Hypotheses

No.	Hypotheses
H1:	Classroom design influences learning performance and satisfaction
H1a:	Noise influences learning performance and satisfaction
H1b:	Temperature influences learning performance and satisfaction
H1c:	Lighting influences learning performance and satisfaction
H1d:	Colour influences learning performance and satisfaction
H1e:	Classroom layout influences learning performance and satisfaction

Participants

An email was sent to University students, requesting voluntary and anonymous participation responding to the questionnaire. About 283 emails were sent (randomly from the list of all students) and a total of 173 were returned with valid responses. The minimum age of respondents was 18 years of age. Of the total number of students, 45 were undergraduate, 100 postgraduate, 20 Ph.D., and 8 visiting (other) students.

Factor Analysis

Cronbach's coefficient alpha was used to measure internal consistency among the various factors. Cronbach's values were 0.765 (performance) and 0.791 (satisfaction), which were higher than the 0.50 threshold and indicate reliability at the 5% significance level. The collinearity diagnostic test was used to test the multi-collinearity among physical classroom factors. Prior to applying this method, the variance inflation factor (VIF) test was conducted. As for tolerance (=1/VIF), the less and closer that this value is to 1.0, the weaker collinearity relationship exists. All the tolerance values obtained were less than 1.0 and VIF values were less than 10. All data analysis was performed using IBM SPSS version 27.0.

RESULTS

Table 2 shows the survey results. The relationship between the independent variables (classroom design) and dependent variables (student satisfaction and performance) were examined by adopting Pearson correlation analysis.

Table 2: Pearson Correlation Analysis

Factors	N	T	L	CO	CL	CD	S	P
Noise (N)	1	.758	.715	.251	-.284	.785	.678	.723
Temperature (T)	.758	1	.711	.176	-.210	.871	.563	.475
Lighting (L)	.715	.711	1	.218	.170	.653	.325	.506
Colour (CO)	.251	.176	.218	1	.185	.567	.287	266
Classroom layout (CL)	-.28	-.210	.170	.185	1	.325	.752	692
Classroom design (CD)	.785	.871	.653	.567	.325	1	.610	.753
Satisfaction (S)	.678	.563	.325	.287	.752	.610	1	.785
Performance (P)	.723	.475	.506	.266	.692	.753	.785	1

For instance, the Pearson value for classroom design and students' satisfaction was 0.610 (p-value <0.001). This value suggests that there is a moderate positive correlation ([0.5, 0.8]) between students' satisfaction and classroom design. Similarly, the Pearson value for students' performance and classroom design was 0.753 (p-value <0.001), suggesting that there also exists a moderate positive relationship between these two variables ([0.5, 0.8]).

To investigate the influence of explanatory variables ("E" factors) on dependent variables ("P" factors), a regression analysis was conducted. The satisfaction model refers to the impact of "E" factors on satisfaction, and the performance model refers to the impact of "E" factors on performance. As shown in Table 3, the satisfaction model explained 58.2% of the variance in student satisfaction (dependent variable). Note that the model strength is 0.565 (p-value<0.05). Additionally, the results suggest that the better the physical design of the classroom, the higher satisfaction of students. The performance model explained 72.7% of the variance in students' performance and its strength is 0.725 (p-value<0.05). These results indicate that classroom design has a positive relationship with performance, that is, the better the physical design of the classroom, the better performance of students. Therefore, research hypotheses H1 were accepted.

Table 3: Classroom Design and Student's Satisfaction and Performance

Model	R	R^2	Adj. R^2	F	Sig.	B	T	Sig.
Satisfaction Model	.763	.582	.565	386.82	.00	.592	11.328	.000
Performance Model	.853	.727	.725	571.65	.00	.786	20.586	.000

Furthermore, a linear regression was employed to investigate the impact of classroom design on students' learning satisfaction and performance. Table 4 shows the results. Note that noise and classroom layout explain most of the variance (67.2% and 62.1% individually) in students' satisfaction. Similarly, noise and classroom layout explain most of the variance (71.5% and 68.5% individually) in students' performance.

Table 4: Classroom Design on Student's Satisfaction and Performance

Independent variables (Dependent variables)	R	R²	F-value	B	T
Noise (Satisfaction)	.819	.672	544.869	.685	13.248
Noise (Performance)	.845	.715	615.686	.752	18.156
Temperature (Satisfaction)	.716	.513	366.112	.603	12.597
Temperature (Performance)	.711	.506	347.861	.587	10.418
Lighting (Satisfaction)	.563	.318	175.498	.416	9.142
Lighting (Performance)	.702	.493	326.134	.565	10.113
Classroom layout (Satisfaction)	.788	.621	496.358	.638	14.956
Classroom layout (Performance)	.827	.685	579.625	.711	16.844
Colour (Satisfaction)	.514	.265	101.432	.395	7.354
Colour (Performance)	.492	.243	82.366	.316	8.743

Additionally, note that both noise and classroom layout have a positive relationship with performance and satisfaction. However, colour explains the least variance in performance (24.3%) and satisfaction (26.5%). From the results, it can also be concluded that the influence of temperature is greater than lighting. Specifically, temperature affects satisfaction (51.3%) slightly more than performance (50.6%), while lighting shows an opposite trend. From the results of regression analysis results, the research hypotheses H1a, H1b, H1c, H1d, and H1e were accepted. Accordingly, the conditions of the physical university classroom environment and its related characteristics can have a considerable impact on students' performance and satisfaction and the data support the possibility of a positive correlation of environmental factors on performance and satisfaction.

DISCUSSION

Quantitative research results show that the physical classroom environment has a particularly prominent impact on students' performance, followed by students' satisfaction. At a more micro level, every environmental factor will have an impact on students' performance and satisfaction. From the regression analysis, the influence rankings can be obtained for both performance and satisfaction: noise >layout>temperature>lighting>colour. Through the open questions, it was found that the demand for classroom environment shows a diversified trend. However, commonalities were found. For instance, the majority of students prefer natural daylight in the classroom and a temperature between 23°C to 25°C in the summer. Noise coming from outside the window affects students the most, yellow was found to be the students' favourite colour, and flexible seating arrangements such as V-shape and U-shape are enjoyed most by students.

To meet their diverse but common needs, an IoT-enabled smart classroom could be developed. IoT networks have a master control dashboard and have been used in various industries, including education (Meola, 2016). IoT campus developed by Abuarqoub et al. (2017) contains four applications (smart buildings, renewable and smart grid application, smart learning application and waster and water management). IoT-enabled services monitor environmental factors such as pressure, temperature, humidity. Sensors control the supply of hot water in radiators, turning them off and saving around 50-60% of energy for heating. The second advantage is that maintenance can be automated, with sensors attached to IoT devices that monitor status of equipment and when action is required maintenance staff can respond instantly. The third advantage is smart devices provide security. With Computer Vision (CV) algorithms, smart classroom can recognise entering students based on face recognition and give permission to pass. The fourth advantage is students' attendance can be done automatically through the use of biometric parameters. The fifth benefit is occupancy detection and tracking. IoT services can point out to students available study spaces. Lastly, the experience of users can be enhanced through intelligent equipment (sensi ng lights, automatic temperature adjustment). A wireless acoustic sensor network is presented by Segura et al. (2016), which evaluates the functional architecture of IoT prototype to produce noise maps. If the noise exceeds the standard, the system will automatically issue an alarm. A PIR Sensor is a motion-sensing device integrated with the controller to detect occupants in the room by sensing infrared fluctuations to trigger the lights from turning On/Off. PIR sensors are commonly used to detect human presence to monitor occupation and to save energy (Twumasi et al. 2017). IoT temperature controls allow for customisation from room to room, and temperature settings can be scheduled for certain times of day. Present scenes allow these environment adjustments to occur with just one click. Based on the above theoretical and practical research, an IoT-based automatic control system has been proposed for university classrooms (see Figure 1).

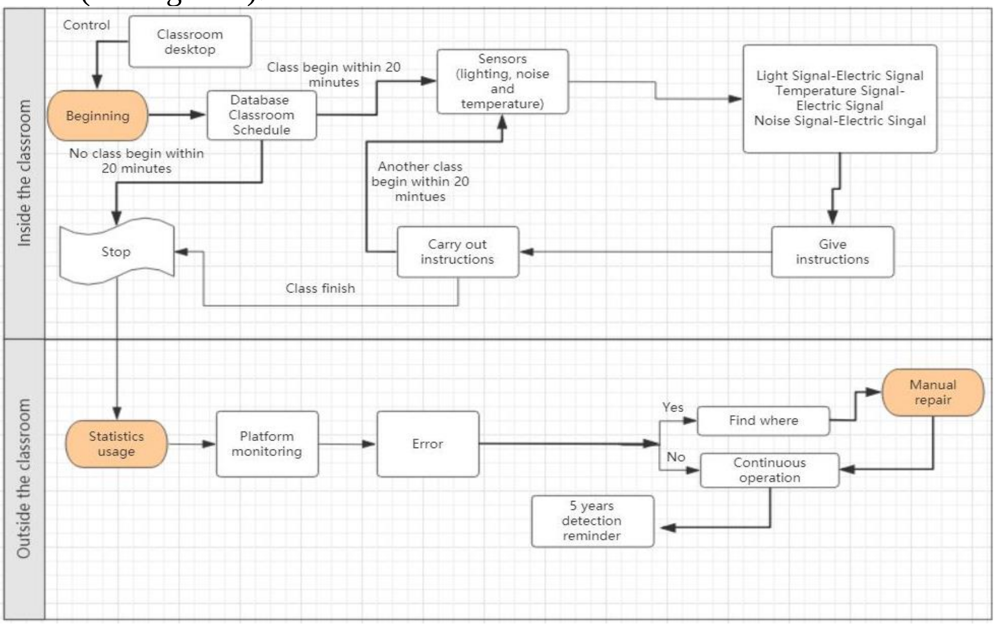

Figure 1: Classroom Automation Control System

For inside the classroom, lighting, noise and temperature sensors can be installed. Before sensors work, a database will check if a class will take place in the next 20 minutes, if so, sensors will be turned on. Otherwise, sensors will not operate. Lighting sensors will convert the light information into electrical signals. When natural light is insufficient (assuming that the curtains are closed), classroom lights will be turned on automatically. Additionally, when noise exceeds 60 dB, sensors will recognise and memorise the noise level. When temperature sensors determine the temperature is either too high or too low, the electric signal will automatically adjust the temperature of the air conditioner. The system will automatically operate the stated conditions after a class is finished. If another class will take place within 20 minutes from the previous class ending, sensors will continue to work. Otherwise, sensors will stop working. All the character strings will be transmitted to the platform system outside the classroom. If the operation is wrong, the alarm will be activated and the monitor platform will report the location where errors have occurred. It is expected that such a system can operate for 5 years, after which a large-scale maintenance needs to be scheduled. Note that the platform monitoring has permission to control all classroom sensors.

CONCLUSIONS

With the results from the person-environment analysis conducted in this study, a smart classroom based on IoT devices, flexible design, and higher quality building components has been proposed. This IoT-based smart classroom may ensure good working conditions for HEI environments that will satisfy the needs of its users. IoT devices integrating sensors, signal conversion, and intelligent processing mechanisms can efficiently ensure appropriate temperature and lighting conditions. When it comes to classroom layout, flexibility in the use of elements such as tables and chairs can be provided by allowing multiple configurations that promote collaboration between students and facilitate the interaction between students and teachers. Poor acoustics in classrooms have been recognised for years (Shield, 2011). For this reason, the DfES incorporated the Building Regulations for acoustic design for classrooms (DfES, 2003). School designs have to meet criteria for noise, reverberation and sound insulation. Specifically, acoustic insulation can be external and internal walls to meet the requirements (Shield and Richardson, 2018). Noise level in the classroom is monitored using several microphones. The data collected using IoT devices can be analysed and results presented in real-time. If a lecturer notices a higher noise than the standard, the current activity can be changed. This smart classroom system will decide in real-time whether acoustics are enhanced to make the most of student’s ability to focus. Results show that the colour of the university classroom has little influence on student’s performance and satisfaction, but the students prefer white and yellow. By improving the university classroom environment, the results of this study suggest that the performance and satisfaction of students may be enhanced. With such results and supported by IoT, the future of the classroom environment in which digital and physical objects can be connected by means of suitable information and communication technologies, a range of applications and services can be developed.

REFERENCES

Abuarqoub, A., Abusaimeh, H., Hammoudeh, M., Uliyan, D., Abu-Hashem, M. A., Murad, S., & Al-Fayez, F. (2017, July). A survey on internet of things enabled smart campus applications. In *Proceedings of the International Conference on Future Networks and Distributed Systems* (pp. 1-7).

Ashkanasy, N. M., Ayoko, O. B., & Jehn, K. A. (2014). Understanding the physical environment of work and employee behavior: An affective events perspective. *Journal of Organizational Behavior, 35*(8), 1169-1184.

Asseo, I., Johnson, M., Nilsson, B., Chalapathy, N., & Costello, T. J. (2016). The Internet of things: Riding the wave in higher education. *Educause review*, *51*, 11-33.

Backman, Y., Alerby, E., Bergmark, U., Gardelli, Å., Hertting, K., Kostenius, C., & Öhrling, K. (2012). Improving the school environment from a student perspective: Tensions and opportunities. *Education Inquiry, 3*(1), 19-35.

Badayai, A. R. A. (2012). A theoretical framework and analytical discussion on uncongenial physical workplace environment and job performance among workers in industrial sectors. *Procedia-Soc. and Behav. Sci.*, *42*, 486-495.

Barrett, P., Davies, F., Zhang, Y., and Barrett, L. (2017). The holistic impact of classroom spaces on learning in specific subjects. *Env. and Behave.*, *49*(4), 425-451.

Baum, E. J. (2018). Learning space design and classroom behavior. *Intl J. of Lear., Teach. and Educ. Res.*, *17*(9), 34-53.

Budge, D. (2000). Secret is in the seating. *Times educational supplement*, *4396*, 26-27.

Burgess, B., and Kaya, N. (2007). Gender differences in student attitude for seating layout in college classrooms. *College Stu. J.*, *41*(4), 940-947.

Chartrand, G. (1965). The existence of complete cycles in repeated line-graphs. *Bulletin of the American Mathematical Society*, *71*(4), 668-670.

Dawndasekare, D. M. S. P. K., & Jayakody, A. (2017). IoT Based Framework to Increase Student Success in the Classroom of Tertiary Education in Sri Lanka: The Smart Classroom. In *24th Annual technical conference of iet Sri Lanka network* (p. 57).

Department for Education and Skills (DfES) (2021). Every child matters https://www.gov.uk/government/organisations/department-for-education/everychild.

Earthman, G. I. (2002). School facility conditions and student academic achievement.

Engelbrecht, K. (2003). The impact of color on learning. NeoCON2003.

Fenton, D. M., and Penney, R. (1985). The effects of fluorescent and incandescent lighting on the repetitive behaviours of autistic and intellectually handicapped children. *Australia and New Zealand J. of Develop. Disab.*, *11*(3), 137-141.

Fraser, B. J. (2012). *Classroom env.* (Vol. 234). Routledge.

Gaines, K. S., and Curry, Z. D. (2011). The inclusive classroom: The effects of color on learning and behavior. *J. of Family & Consumer Sci.*, *29*, 1.

Gligoric, N., Uzelac, A., Krco, S., Kovacevic, I., & Nikodijevic, A. (2015). Smart classroom system for detecting level of interest a lecture creates in a classroom. *Journal of Ambient Intelligence and Smart Environments*, *7*(2), 271-284.

González-Zamar, M. D., Ortiz Jiménez, L., Sánchez Ayala, A., and Abad-Segura, E. (2020). The impact of the university classroom on managing the socio-educational well-being: A global study. *Intl J. of Env. Res. and Pub. Health*, *17*(3), 931.

Great Britain. School Buildings, & Design Unit. (2003). *Acoustic Design of Schools* (Vol. 93). Stationery Office.

Halstead, T. K. (1974). Proton NMR studies of lanthanum nickel hydride: Structure and diffusion. *J. of Solid State Chemistry*, *11*(2), 114-119.

Haverinen-Shaughnessy, U., and Shaughnessy, R. J. (2015). Effects of classroom ventilation rate and temperature on students' test scores. *PloS one*, *10*(8), e0136165.

Heschong, L., and Knecht, C. (2002). Daylighting Makes a Difference. *Educ. Facility Planner*, *37*(2), 5-14.

Kamarulzaman, N., Saleh, A. A., Hashim, S. Z., Hashim, H., & Abdul-Ghani, A. A. (2011). An overview of the influence of physical office environments towards employee. *Procedia Engineering*, *20*, 262-268.

Kopec, D. A. (2018). Environmental psychology for design.

Lewin, K. (1935). *Dynamic Theories of Personality*. New York: McGraw-Hill.

Lewin, K. (1951). *Field theory in social science*. New York: Harper.

Lewinski, P. (2015). Effects of classrooms' architecture on academic performance in view of telic versus paratelic motivation: a review. *Frontiers in Psych.*, *6*, 746.

MacKinnon, D. W. (1962). The nature and nurture of creative talent. *American Psych.*, *17*(7), 484.

Martínez-Otero, V., & Pérez, V. M. O. (1997). *Los adolescentes ante el estudio: causas y consecuencias del rendimiento académico* (Vol. 213). Editorial Fundamentos.

Marx, A., Fuhrer, U., and Hartig, T. (1999). Effects of classroom seating arrangements on children's question-asking. *Learning Environ. Res.*, *2*(3), 249-263.

McCoy, M., and Evans, W. (2005). Physical work environment. *Handbook of work stress*, 219-245.

McDermid, C. D. (1965). Some correlates of creativity in engineering personnel. *J. of App. Psych.*, *49*(1), 14.

Meola, A. (2016). How IoT in education is changing the way we learn. *Business Insider*.

Mouratidis, A., Vansteenkiste, M., Lens, W., & Auweele, Y. V. (2009). Beyond positive and negative affect: Achievement goals and discrete emotions in the elementary physical education classroom. *Psychology of Sport and Exercise*, *10*(3), 336-343.

Murray, H. (1938). *Explorations in Personality*. Boston, MA: Houghton Miffl.

Pawlowska, D. K., Westerman, J. W., Bergman, S. M., and Huelsman, T. J. (2014). Student personality, classroom environment, and student outcomes: A person–environment fit analysis. *Learning and Ind. Differences*, *36*, 180-193.

Phillips, R. (1997). Educational facility age and the academic achievement of upper elementary school students. *Unpublished PhD. Dissertation.* University of Georgia.

Puteh, M., Che Ahmad, C. N., Mohamed Noh, N., Adnan, M., and Ibrahim, M. H. (2015). The classroom physical environment and its relation to teaching and learning comfort level. *Intl. J. of Social Sci. and Humanity*, *5*(3), 237-240.

Ramli, N. H., Ahmad, S., Taib, M. Z. M., and Masri, M. (2014). Principals' perception on classroom physical environment. *Procedia-Social and Behav. Sci.*, *153*, 266-273.

Segura Garcia,J.,Perez Solano,J.,Cobos Serrano,M.,Navarro Camba,A., Felici Castell,S., Soriano Asensi,A., & Montes Suay,F. (2016). Spatial statistical analysis of urban noise data from a WASN gathered by an IoT system: Application to a small city. *Applied Sciences*, *6*(12), 380.

Shield, B. M. (2011). Acoustic design of schools-Where are we now. In *Proceedings of the Institute of Acoustics, Acoustics 2011 Conference* (Vol. 33, No. Pt 2, pp. 1-17).

Shield, B. M., and Dockrell, J. E. (2003). The effects of noise on children at school: A review. *Building Acoustics*, *10*(2), 97-116.

Shield, B., & Richardson, R. (2018). Regulation of school acoustic design in the UK: recent revision of Building and School Premises Regulations and their application.

Steele,F.I.(1973). Physical settings and organization development.Addison Wesley Publishing Company.

Tanner, C. K., and Lackney, J. A. (2006). Educational facilities planning: Leadership, architecture, and management. Allyn & Bacon.

Teizer, J., Wolf, M., Golovina, O., Perschewski, M., Markus Propach, M., Neges, M., & König, M. (2017). Internet of Things (IoT) for Integrating Environmental and Localization Data in Building Information Modeling (BIM). In *Proceedings of the* International Symposium on Automation and Robotics in Construction (pp. 603-609).

Torrice, A. F., and Logrippo, R. (1989). *In my Room: Designing for and with Children.* Fawcett.

Twumasi, C., Dotche, K. A., Banuenumah, W., & Sekyere, F. (2017). Energy saving system using a PIR sensor for classroom monitoring. In *2017 IEEE PES PowerAfrica* (pp. 347-351). IEEE.

Uzelac, A., Gligoric, N., and Krco, S. (2015). A comprehensive study of parameters in physical environment that impact students' focus during lecture using Internet of Things. *Computers in Human Behav.*, *53*, 427-434.

Verghese, P. (2001). Visual search and attention: A signal detection theory approach. *Neuron*, *31*(4), 523-535.

Wargocki, P., and Wyon, D. P. (2013). Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Building & Env.*, *59*, 581-589.

Woolfolk, A., and Margetts, K. (2007). Education psychology. *Boston: Pearson Edition*.

Zannin, P. H. T., Passero, C. R. M., and Zwirtes, D. P. Z. (2012). Assessment of acoustic quality in classrooms based on measurements, perception and noise control. *Noise Control, Reduction and Cancellation Solutions in Eng*.

Peltokorpi, A., Seppänen, O., Lehtovaara, J., Pikas, E., and Alhava, O. (2021). "Developing a framework for systemic transformation of the construction industry." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 454–463, doi.org/10.24928/2021/0154, online at iglc.net.

DEVELOPING A FRAMEWORK FOR SYSTEMIC TRANSFORMATION OF THE CONSTRUCTION INDUSTRY

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ABSTRACT

In the era of customer-driven and digitalized businesses, the construction industry has still demonstrated inadequate performance development. This research aims to disentangle the industry's current problems and present justified paths toward sustainable improvement. Following the design science research approach, the paper develops a conceptual framework about the path toward the systemic transformation of the construction industry. We first argue how current efforts to improve construction system are often limited to changes in sub-systems, namely in a) products, b) processes, c) organizing and people, d) information systems, or e) value creation models, therefore lacking a systemic approach needed for significant and sustainable improvements. We then propose a framework that underlines the need to simultaneously develop all the identified five sub-systems to achieve successful transformation. Three cases are presented as partial solutions to such systemic innovations. The paper provides new insights into how a systemic approach could be utilized when transforming the construction industry. More specifically, takt production is identified as one key driver for systemic change. The theoretical contribution lies in the identified five sub-systems and their parallel development as a source for sustainable transformation. However, the paper is conceptual and limited to three partial cases. More empirical research is needed to validate the framework and to specify the most effective transformation paths.

KEYWORDS

Systemic innovation, transformation, construction industry, design science approach.

INTRODUCTION

The construction industry has been criticized for its lack of innovation and future-oriented investments. This has led to slow development of the whole sector and lagging behind other industries, for example, in terms of productivity (e.g., Barbosa et al. 2017). Many

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contractors have had enormous project management problems in recent years, which has traditionally been the general contractors' capability. Together with quality issues, these problems raise the question about the sector's systemic challenges: are there some fundamental reasons why in the era of customer-driven and disruptive digitalized businesses, the construction industry has demonstrated an inadequate and unsatisfactory development?

Systemic innovations form a way of overcoming these persistent challenges. Systemic innovations are industry-defining, mold-breaking changes that diffuse across companies and specialties, often resulting in fundamental changes in how companies operate within the industry (Taylor and Levitt 2004). Systemic innovations often call for an extended, collaboratively coordinated cross-company effort that requires commitment from several actors in the supply network (Lavikka et al. 2020), making the implementation burdensome and less likely to succeed than incremental innovations that fit within the predefined boundaries of the industry. Within construction, the industry's fragmented and risk-averse nature sets barriers for employing systemic innovations (Sheffer 2011): fragmentation hinders long-lasting collaboration in innovation activities, and risk aversion leads to low R&D investments in general. However, when successful, systemic innovations often offer superior and long-lasting performance benefits compared to incremental innovations (Hall and Lehtinen 2015).

This paper aims to disentangle the construction sector's current problems and then present justified paths toward systemic improvement. The contribution to knowledge is not in addressing individual issues or solutions but in emphasizing systemic and integrated solutions to the known challenges. In practice, this means that multiple sub-systems should be simultaneously developed to radically and sustainably improve the sector's performance.

Regarding the sub-systems, we would not refer directly to different roles or professionals in the construction ecosystem as they often mirror the ongoing practices. Instead, we follow the logic of Nightingale (2000) about the product–process–organization relationships in complex development projects and argue that innovation in construction is most likely successful when these different focuses of development, such as products and processes, are developed simultaneously in an integrated manner. These sub-systems have traditionally been managed by different actors, such as clients, designers, contractors, and product suppliers, client or general contractor often acting as a system integrator. Consequently, a systemic transformation likely requires changes in the actors' roles and responsibilities and increased collaboration between stakeholders.

In practice, this paper develops a conceptual framework about the path toward systemic innovations in the construction sector. We utilize the design science approach (e.g., Ravitch and Riggan 2012; Torraco 2016) first to describe the status of the construction system and then to progress on developing a solution framework that is informed by systemic innovation thinking. In each phase, when identifying the most relevant sub-systems, when describing the status of the system, and when developing a framework as a consequence of the status and the systemic thinking, the authors' insights are discussed and validated in a group of 20 CEOs representing various AEC companies of the Finnish construction ecosystem. In the end, we present three existing partial solutions in which the logic of systemic innovation and transformation is implemented in practice.

This paper is organized as follows: We first present a current construction practice diagnosis, highlighting five broken sub-systems. Next, we provide principles to help understand the root causes for the breakage of these sub-systems. We then conceive a solution framework that emphasizes appropriate combinations of sub-system improvements. Next, we present partial solutions using examples from actual cases to help pave the sector's progress toward systemic transformation. Finally, we conclude by discussing on implications of findings on research and practice.

DIAGNOSIS: FIVE BROKEN SUB-SYSTEMS

We argue that solving issues and symptoms one-by-one is not sufficient for the construction sector's sustainable development. Following Bertelsen's (2003) research, the view of complex adaptive systems (CAS) should be in focus when discussing new management paradigms in construction. In other words, to manage the inherent complexity of construction, a holistic understanding of multiple sub-systems and their interconnected problems is needed.

In this paper, we focus on the five broken sub-systems: 1) product, 2) process, 3) people and organizing, 4) information, and 5) value creation. The first three sub-systems, product, process and organizing, originate from the key elements of the complex development projects (Nightingale 2000) and the three types of innovation (Boer and During 2001). The CEO group suggested to add the people aspect in organizing to emphasize the role of individuals and professional groups in innovating and disseminating innovations. Then, information systems were separated from other processes, as they are more suitable for technological developments and benefit from field-specific standards. Finally, value creation aspect was added to underline customer value as a fundamental objective of any lean system.

1. BROKEN PRODUCT

Buildings are complex products with a large variety of incompatible sub-products and materials. Parts must fit geometrically and support the system's function as a whole. Unfortunately, the lack of systematic study and evaluation of design alternatives leads to incompatibility issues. The sub-products have complex interfaces, and there are often coordination issues between the sub-products. There are large and unaligned engineering tolerances in building structures and products. This all means, that product development, such as innovating pre-fabrication solutions, is often hindered by existing project processes, fixed roles of professionals, and disruptions of innovations to some actors' existing business models (e.g., Lavikka et al. 2021).

2. BROKEN PROCESS

Although lean construction aims to improve the process, most projects are built based on ad hoc processes and practices. There is a lack of integration of value chains and limited engagement and integration of stakeholders. Limited communication and collaboration lead to a lack of flow in design and production processes. Decision-making is often not systematic, and typically continuous learning from project to project is limited. Recent advancements, e.g., in adopting takt production, have improved the processes (Lehtovaara et al. 2021). However, successful takt production implementation on-site often requires simultaneous product development (Chauhan et al. 2018), new organization and collaboration methods (Kujansuu et al. 2019), and management of logistic processes (Tetik et al. 2019a).

3. Broken Organizations and Management of People

In most projects, clients still prefer traditional procurement and contracting models, such as Design-Bid-Build, which have led to underdeveloped relationships and distrust. Organizations tend to work in silos in both design and construction. These silos originate from the systems and cultures in which construction managers and design disciplines are educated. Other stakeholders, for example, users and material suppliers, are not integrated into the process. Having multiple different professionals and actors in the joint innovation effort has promised to result in remarkable transformations (Lavikka et al. 2020).

4. Broken Information Systems

In construction projects, information is located and distributed in different and incompatible information systems. There is no adequate information management standard that could formalize the information from the construction process. A gap exists for linking the on-site construction operation information with the supporting processes (Zheng et al. 2020). The lack of interoperable systems hinders the development of a real-time understanding of the current state. Furthermore, most of these systems rely on manual data entry and updating. There are technical, organizational, and cultural barriers to sharing data and information between actors and processes in the projects.

5. Broken Value Creation

Contractors and designers lack customer-driven business models and services. Most of the actors use precisely the same business model to win new business and complete projects profitably (Pekuri et al. 2015). The business models are based on outdated financing instruments and asset-dependence, especially among developers. There is no real business connection between the project delivery and building operation phases. Project actors tend not to have a holistic—but rather a piecemeal—understanding of the customer's requirements and targets.

The consequences of the current practices are that actors have a single-project mindset leading to a lack of scalability in products and production and a lack of learning and continuous improvement. With the current mindset and roles, lifecycle investments are not seen profitable. Contractors' business models are vulnerable and asset-based, in which surprises destroy value. Down-side risks are higher than upside opportunities. In summary, there is no systemic sector-wide development and scalable businesses.

PRINCIPLES FOR SOLUTION

After diagnosing the construction industry's status, we next present principles in finding solutions for existing challenges. Following the generic lean principles (Liker 2004), the first principle is not only fixing visible and obvious problems but identifying root causes for symptoms and acting on them. This requires asking multiple times "why" to question the existing conventions and practices. Although existing practices may not be completely ineffective, their historical origins mean they may no longer be relevant when applied to current circumstances. The following are examples of such questioning:

- Instead of controlling production on-site, we should ask why these activities are done on-site.
- Instead of solving quality issues on site, we should ask why the issue emerged and was not detected in earlier stages.

- Instead of managing multi-specialty teams, we should ask why we have so many professions with siloed cultures and languages.

In addition to those questions about the "big picture" of construction practices, more specific problems and their origins should be continuously challenged. For example, regarding the products:

- Instead of solving tolerance problems, we should ask why product tolerance requirements are that loose in construction.
- Instead of solving problems with the drying of products on site, we should ask why we have wet products.

The second principle is to look for solutions that exist at the boundaries of the sub-systems. For example, suppose we would like to improve the product. In that case, we should think about what kind of new organizing modes, such as industry actors' roles and contracts, and processes are needed to support the transformation. Similarly, sharing real-time information between the actors within and between projects might be a crucial trigger for a holistic understanding of the projects, and simultaneously, the path to a common language and culture.

FRAMEWORK FOR SYSTEMIC TRANSFORMATION AS A SOLUTION

Based on the principles mentioned above, we present a framework about the solutions at the sub-system level and systemic and synergistic solutions that integrate simultaneous developments in multiple sub-systems. Figure 1 presents our conceptual framework. Many of these solutions have already been suggested in previous research; however, they are mostly isolated from each other and focused on individual existing problems. Focusing only on a specific sub-system, such as product, process, or information, leads to compromises, poor implementation, and partial solutions.

The most remarkable innovations are systemic, in which multiple challenges are solved simultaneously. For example, integrated design, product, process, and use data (information system), together with modular product architecture (product system) would enable developing integrated or even cyber-physical design and construction capabilities that utilize parametric and algorithmic design and engineering (e.g., Tetik et al. 2019b). These systems' development requires that multiple existing professionals, including architects, engineers, production specialists, and owners, work together for an extended period. By systematically collecting data from the use phase, these solutions can be further developed for new customers. Additional value-adding services and products can be provided during the building's lifecycle.

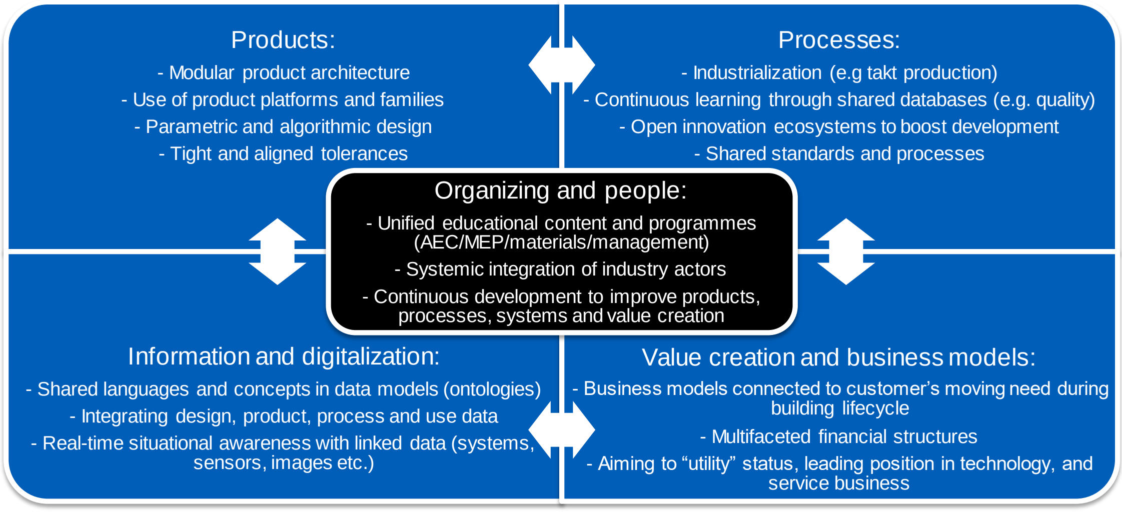

Figure 1: Conceptual framework of integrating sub-system solutions for construction industry transformation.

INTEGRATED PARTIAL SOLUTIONS: CASE EXAMPLES

We next present three existing solutions which fully or partially follow the logic of systemic innovation and integration of the sub-system solutions.

PROJECT FROG: ECOSYSTEM AROUND DIGITAL DESIGN CONFIGURATOR

Project Frog is located in California, USA; the company has developed a construction ecosystem that integrates product platforms, mass customization, offsite fabrication, systematic processes, and digital technologies to manufacture building components in a controlled environment, transport them to their final location, and assemble them on site. The value proposition to their clients is the speed and scalability from design through manufacturing and construction. Benefits include lead time reduction from project inception to handover, automation of processes, and improved schedule, cost, and quality planning and control.

The critical part of their solution is a building configurator known as a Kit-of-Parts platform. The main idea is that buildings are treated as product platforms, wherein building components are developed, iterated, and reused in the design process to enable a wide variety of buildings. Criteria in designing and developing these components are manufacturability and ease of assembly. This is otherwise known as Design for Manufacturing and Assembly (DfMA). Other criteria include flexibility, automation, and reusability.

This approach relies on interconnected data-centric cloud technology to enable data management at scale. The technology supports the design and engineering with real-time feedback on cost and schedule and enables data flow management from planning and design through manufacturing and construction. This has been achieved by developing interoperable digital systems related to products and processes.

Using Kit-of-Parts and data-centric approaches have enabled the company to automate manufacturing processes. For example, the flow of design information to manufacturing equipment, also known as BIM (building information model) to CAM (computer-aided manufacturing), reduces manual work to process the product and manufacturing information. In addition to automating manufacturing processes, greater automation in the design phase can be achieved. With proper templates, product catalogs, property sets, and knowledge catalogs, the development of intermediate information products, including, for example, drawings, specifications, engineering calculations, and detailing, can be automated extensively. Currently, these activities consume a lot of skilled labor hours.

In summary, using a system architecting and building strategy, the company has developed an ecosystem where different sub-systems work together. This has allowed them to develop a new business model with high-quality services to clients and end-users. Over time, more such examples will likely emerge, such as Katerra, which is also located in California.

BRYDEN WOOD: PLATFORM APPROACH TO CONSTRUCTION

Bryden Wood is a technology-led design company in the UK, bringing together a broad range of specialists from various industries with a vision to deliver high quality sustainable architecture. They aim to close the gap between construction and manufacturing. Today they are considered the UK leader in offsite and advanced construction techniques. At the heart of Bryden Wood's business models is their platform-based approach to construction. Without compromising aesthetic integrity, Bryden Wood seeks to build more quickly, more economically, and with a greater whole life value.

They have used the analogy of platforms from the software and manufacturing companies and adapted it to the context of the built environment. For Bryden Wood, the platform represents a design system, turned into a construction system in factory conditions through standardized routines. The platform comprises a set of standardized components with well-defined interfaces (kits of parts). Yet, components and interfaces are flexible to design, produce, and assemble a great variety of buildings.

This is achieved by breaking down buildings into spaces to identify commonalities across building sectors. For example, based on their analysis, schools, apartments, and healthcare facilities have similar structural spans and ceiling heights. At Bryden Wood, they have defined two common platforms, including small-scale residential and large-scale buildings.

The critical part of their business model is software development of building and product configurators used by clients and the general public. The objective is to give users access to configure buildings in hours rather than in weeks using their platform and kits of parts. But the digitalization does not end with the configurator apps. Detailed models can be generated from the configurator apps and taken as input to design, manufacture, and assembly processes. That is, models can be imported to BIM applications to develop designs further. Then information for computer-aided manufacturing can be extracted and fed into manufacturing equipment. The gap between the construction and manufacturing is reduced because of standardized processes and common data platforms.

DIGITAL TAKT PRODUCTION

Despite primarily serving as a process-based innovation, takt production can be viewed as one key driver for systemic change; with increased maturity, takt planning and control touches almost all aspects of a project system (Lehtovaara et al. 2020). It can be argued that when reaching the highest maturity levels, effective takt production process development is linked to product development (pull-based design management, constructability of designs), value creation (production pacing is matched with client's needs), information flow and digitalization (real-time situational awareness aided with digital tools) and learning of organizations and people (a collaboration between actors, continuous improvement, and holistic understanding on how effective project systems operate). Social aspects of location-based systems, such as takt production, can be further enhanced by integrating the Last Planner System© to improve the utilization of tacit knowledge of stakeholders and to provide structure to continuous improvement (Frandson et al. 2014).

Even though takt production can be successfully implemented without digitalization, recent studies (e.g., Alhava et al. 2019) suggest that digital tools can greatly enhance real-time situational awareness, which is necessary to excel with fast-paced takt production control (Lehtovaara et al. 2021). Transparent and up-to-date progress information helps production stakeholders plan and control their actions proactively and collaboratively, enabling efficient flow of processes and operations and effective flow of information (Uusitalo et al. 2019) and material (Tetik et al. 2019a) flows.

In addition to offering the potential for more efficient takt production control and short-term improvement, digitalization can also help to improve long-term learning. As takt production increases in maturity, effective learning from project to project—including the process steps from upstream design to downstream use phase—is needed to reach full potential of takt production while driving for systemic transformation. The concept of digital twin construction (DTC; Sacks et al. 2020) has recently captured broad interest, being a potential contributor in forming a comprehensive model for construction management and enabling data-driven management and learning through iterative control loops. In addition to achieving efficient information flow within a single production system, vertical and horizontal utilization of DTC would also greatly enhance information flow through projects and organizations.

CONCLUSIONS

This paper presents a conceptual framework of integrating sub-system solutions for sustainable construction industry transformation. The proposed framework can be utilized both among researchers and practitioners when developing and implementing new practices in the construction industry. The presented examples suggest that innovation may originate in a specific sub-system, such as in processes (takt production), digital information systems (Project Frog), or products (Bryden Wood). Still, to achieve a genuinely sustainable transformation, modifications are also needed in other sub-systems. Simultaneous improvements in multiple sub-systems require additional investments and resources. However, they may lead to more disruptive innovations and create a competitive advantage that other firms and networks cannot easily imitate.

From a process point of view, one remarkable finding is that takt production could work as a key driver for many systemic changes in the construction ecosystem. Successful implementation of takt production requires that product design, individuals' capabilities, information flow, and value creation among the project actors are aligned. On the other hand, takt production can also be used as a catalyst for innovations in other sub-systems. Collaborative contracts, such as Alliance and Integrated Project Delivery (IPD), have had a similar role in enabling innovations. However, contracts are often project-specific, and therefore their innovation potential for the whole industry is limited. Takt production as a strategic choice of a general contractor could better lead to project-to-project improvements and finally to sustainable transformation.

This research contributes to existing knowledge about systemic innovations in construction, underlining the need for a holistic approach and integration of sub-systems' development when transforming the industry. The theoretical contribution lies in the identified five sub-systems and their parallel development as a source for sustainable transformation.

This research is conceptual and limited to three partial cases. Three cases were investigated that are mostly designer-contractor-supplier led, and customer organizations had only a minor role in the innovation teams. It could be argued that customer has a major role in enabling industry transformation, e.g., through collaborative models or by setting new requirements for projects and products. However, more research is needed on customer's possible role in owning the innovation and being responsible for its continuous development. Further conceptual and empirical research is needed about real-life innovation efforts and nuanced mechanisms behind successful transformations and innovations. Comparative studies on successful and failed innovation efforts could also reveal additional insights on the transformations and their implementation.

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REFERENCES

Alhava, O., Rinne, V., Laine, E. & Koskela, L. (2019). "Can a Takt Plan Ever Survive Beyond the First Contact With the Trades On-Site?" In: Proc. *27th Annual Conference of the International Group for Lean Construction* (IGLC). Dublin, Ireland, 3-5 Jul 2019. pp 453-464.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., Bertram, N. & Brown, S. (2017). *Reinventing construction through a productivity revolution*. McKinsey Global Institute.

Bertelsen, S. (2003) "Construction as a Complex System" In: *11th Annual Conference of the International Group for Lean Construction*. Virginia, USA, 1-.

Chauhan, K., Peltokorpi, A., Seppänen, O. & Berghede, K. (2018) "Combining Takt Planning With Prefabrication for Industrialized Construction". In: *26th Annual Conference of the International Group for Lean Construction*. Chennai, India, 18-20 Jul 2018. pp 848-857.

Hall, D. M., and T. Lehtinen. (2015). "Agile cost shifting as a mechanism forsystemic innovations". InProc., *Engineering Project Organization Conference*, 1–15. Edinburgh, Scotland: The Univ. of Edinburgh.

Kujansuu, P; Lehtovaara, J; Grönvall, M; Seppänen, O; Peltokorpi, A. (2019) "Comparison of Collaboration and Trade Partner Commitment in Takt Implementation Cases", *27th Annual Conference of the International Group for Lean Construction*, Dublin Ireland.

Lavikka, R., Seppänen, O., Peltokorpi, A., & Lehtovaara, J. (2020) "Fostering process innovations in construction through industry–university consortium". *Construction Innovation*, Vol. 20 No. 4, pp. 569-586.

Lavikka, R., Chauhan, K., Peltokorpi, A. and Seppänen, O. (2021) "Value creation and capture in systemic innovation implementation: case of mechanical, electrical and plumbing prefabrication in the Finnish construction sector", Construction Innovation, ahead-of-print. doi.org/10.1108/CI-05-2020-0070.

Lehtovaara, J., Heinonen, A., Lavikka, R., Ronkainen, M., Kujansuu, P., Ruohomäki, A., Örmä, M., Seppänen, O. & Peltokorpi, A. (2020) "Takt Maturity Model: From Individual Successes Towards Systemic Change in Finland" In: Proc. *28th Annual Conference of the International Group for Lean Construction* (IGLC). Berkeley, California, USA, 6-10 Jul 2020. pp 433-444.

Lehtovaara, J.; Seppänen, O.; Peltokorpi, A.; Kujansuu, P.; Grönvall, M. (2021). "How takt production contributes to construction production flow: A theoretical model." *Constr. Manag. Econ*., 39, 73–95.

Liker, J. K. (2004) *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. McGraw-Hill.

Nightingale, P. (2000) "The product–process–organisation relationship in complex development projects". *Research Policy*, Vol 29, Iss 7–8, pp. 913-930.

Pekuri A, Pekuri L & Haapasalo H (2015) Business models and project selection in construction companies. *Construction Innovation: Information, Process, Management* 15(2): 180–197.

Ravitch, S.M., Riggan, M. (2012) *Reason & Rigor: How Conceptual Frameworks Guide Research*. SAGE Publications.

Sheffer, D. A. (2011). *Innovation in modular industries: Implementing energy-efficient innovations in US buildings*. Ph.D. thesis, Dept. of Civil and Environmental Engineering, Stanford University.

Taylor, J. E., and R. E. Levitt. (2004). "A new model for systemic innovationdiffusion in project-based industries". InProc., *PMI Research Conf.*: Innovations. Newtown Square, PA: Project Management Institute.

Tetik, M. Peltokorpi, A; Seppänen, O; Viitanen, A; Lehtovaara, J. (2019a) "Combining Takt Production With Industrialized Logistics in Construction", *27th Annual Conference of the International Group for Lean Construction*, Dublin Ireland.

Tetik, M., Peltokorpi, A., Seppänen, O., Holmström, J. (2019b) "Direct digital construction: Technology-based operations management practice for continuous improvement of construction industry performance". *Automation in Construction*, Vol. 107, November 2019.

Torraco, R.J., 2016. Writing integrative literature reviews: Using the past and present to explore the future. *Human resource development review* 15, 404–428.

Uusitalo, P., Seppänen, O., Lappalainen, E., Peltokorpi, A., Olivieri, H. (2019). "Applying Level of Detail in a BIM-Based Project: An Overall Process for Lean Design Management". *Buildings*, Vol. 9, Issue 5, p. 109-121.

Zheng, Y., Tetik, M., Törmä, S., Peltokorpi, A., Seppänen, O. (2020) A Shared Ontology for Logistics Information Management in the Construction Industry. *37th International Symposium on Automation and Robotics in Construction* (ISARC 2020).

Frantz, L., Hanau, A., Budau, M. R.-D., Haghsheno, S., Väth, C., Schmidt, J.-S. (2021). "Trust and Control in the Context of Integrated Project Delivery." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 464-473, doi.org/10.24928/2021/0158, online at iglc.net.

TRUST AND CONTROL IN THE CONTEXT OF INTEGRATED PROJECT DELIVERY

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ABSTRACT

Project delivery models with a high level of integration of the involved partners like "Project Alliancing" (e.g. in Australia and Finland) and "Integrated Project Delivery" (IPD) (e.g. in the US and Canada) have been used successfully for many years. These models differ from traditional models particularly by integrating key project participants at an early stage and offer incentive models based on the success of the project. In this article the term “Integrated Project Delivery” (IPD) is also used as a generic term for project delivery models with a high level of integration.

The successful implementation of these models requires a high degree of trust between the partners. At the same time a certain level of control can be beneficial or even required. The following article examines the question which elements in an IPD project influence the level of trust between the partners and to what extent control is required in turn. Therefore elements of IPD that require trust are identified and their configuration depending on the level of trust is analysed.

KEYWORDS

Trust, control, integrated project delivery, IPD.

INTRODUCTION

"Integrated Project Delivery" (IPD) has been used successfully worldwide for many years. This project delivery model differs from traditional models in particular by the early integration of key project participants, incentive models geared to project success, and increased use of lean methods. (AIA California Council 2014) In the meantime, this approach is also being applied in pilot projects in Germany. Due to the lack of experience with this approach in Germany, among other things the role of trust and control within these projects have not yet been conclusively defined. Trust is the prerequisite for

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collaborative teamwork and is seen as a success factor for projects (Schön 2020a). The factors that influence trust between project participants and the relationship between control tasks and trust are not yet clearly known.

Within the framework of a research project, the authors investigated which roles are necessary for successful project execution and how much control is appropriate or permissible for this success by the respective roles. It was thus investigated by which elements the degree of trust between the partners in an IPD project is influenced and to what extent control is required.

In the following, first results of this research project are presented. For this purpose, in the first step the terms trust and control are discussed. In the next step a framework is developed to explain the releationship between trust and control. This framework serves as the basis for the further research. Finally the relationship between trust and control is exemplified by discussion of three selected trust issues and control tasks.

THEORETICAL BACKGROUND

TRUST

There is no universally valid and unambiguous definition for the term trust. (Schön 2020a p. 34, b pp. 1-3) The term trust is defined differently depending on the scientific field, such as psychology, sociology and economics. Different definitions of trust are presented below and finally a definition relevant for this research is derived. However, this article does not contain a fully comprehensive discussion of the term trust.

Duden (2021) describes trust as a firm conviction of the reliability of a person or thing. According to Rousseau et al. (1998), trust is a psychological state that involves the intention to accept vulnerability, based on positive expectations about another's intentions or behavior. (Rousseau et al. 1998) Schön (2020a p. 43) defines trust as follows: Trust is the confidence that another person will act predictably in the common interest.

The various definitions show that trust represents a positive expectation (Duden 2021; Mayer et al. 1995a; Rousseau et al. 1998; Schön 2020a) of the future and can build up between a person (Trustor) and one or more other persons or a thing (Trustee). Moreover, some definitions imply that trust involves risk in the form of a breach of trust (Mayer et al. 1995a; Petermann 2013; Rousseau et al. 1998).

Based on this in this article trust is defined as follows:

"Trust is the positive expectation from a person, organization, or system with confidence that they will behave predictably in the common interest and do not pursue their personal interest."

Depending on whether trust arises in relation to one person, several persons or a system, a distinction can be made between the two types of "personal trust", referred to below as „individual trust“, and "system trust". (Luhmann 2014; Schön 2020a p. 44)

Individual trust" refers to the perception and interaction of two actors. The individual trust of the trustor is formed on the one hand by the perception of the personally conditioned actions of the trustee as well as by the repeated fulfillment of the given trust. Thereby, the more often trust has been confirmed, the higher is the individual trust. (Luhmann 2014 p. 47 ff) The trustor thereby gives less "effort" at the beginning (with previously unconfirmed trust) and thus risks less damage through an abuse of trust (Luhmann 2014 p. 56).

Luhmann (2014 p. 60 ff) describes "system trust" as trust in the functioning of systems. Everyday examples of system trust are people's trust in the value and function of money as a medium for transactions and trust in science. In system trust, a person relies on a system having enough control to ensure the system's functioning and thus forgoes further information and performance reviews (Luhmann 2014 pp. 27, 69). System trust also develops through ongoing experience in using the system. However, unlike personal trust, system trust degrades less through individual disappointments. (Luhmann 2014 p. 64,75; Wong et al. 2008)

The establishment of trust depends on various further factors: lived experiences with the trustee (Kramer 1999; Luhmann 2014; Mayer et al. 1995b; Müthel 2006); reputation (Kenning 2002; cf. Kramer 1999 pp. 576-577), skills, goodwill, integrity (Mayer et al. 1995b p. 715), commitment, organizational culture of the trustee (Walker and Rowlinson 2020) and the willingness to trust and risk-taking of the trustor (Müller 2019). The presence of trust can in turn have a positive impact on the project. For example, trust has a positive effect on the working atmosphere in the team and on the team's performance (Edmondson 1999; Lindskold 1978). It therefore makes sense to establish a certain level of trust for the sake of the project outcome.

CONTROL

The term control is also viewed and defined differently in the literature. Das and Teng define control as a process of regulating and monitoring to achieve organizational goals (Das and Teng 2001 p. 258). Green and Welsh (1988) define that control is always goal-directed and thus regulates a system so that the system fulfills a conscious or unconscious purpose. (Green and Ann Welsh 1988 pp. 298-291) Consequently, control can be understood as the process of monitoring and achieving organizational goals, as well as the outcome in terms of power and domination over one or more persons or a thing.

Das and Teng (1998, p. 501) distinguish between formal and social control. The main difference between these two elements is that formal control is an evaluation of performance, while social control refers to the way people are treated. Here, formal control uses specific rules, objectives, procedures, and regulations to monitor and promote desired performance. Formal control can thereby control either processes (behavioral control) or specific outcomes or performance goals (output control). The implication of formal control is that stakeholders cannot make fully autonomous decisions. In this context, inappropriate formal control in particular is negatively related to trust. (Das and Teng, 1998, p. 501,2001, p. 259) Social control relies on normative considerations to influence the behavior of others. Social control induces desired behavior through "soft" measures, such as interactions and training. The influence here takes the form of shared goals, values, and norms. Social control requires more trust and mutual respect because there is no direct constraint on the behavior of the participannts. Thus, in social control, a certain level of trust in the abilities and competence of the participants is necessary. (Das and Teng, 1998, p. 502)

In addition, control can be divided into the elements “control mechanisms” and “control level”. Control mechanisms describe the organizational arrangements that determine and influence the behavior of organizational members and serve to increase the predictability of the achievement of certain goals. The level of control is the direct result of the control process, i.e. the degree to which one believes that the correct behavior of the other party is ensured. Because control mechanisms increase the predictability of goals, when used effectively, they can help generating trust. (Das and Teng, 1998, p. 493)

In the literature, there is no prevailing opinion regarding possible interactions between the elements of trust and control. On the one hand, a complementary relationship between trust and control is assumed. On the other hand, it is assumed that trust and control are not mutually exclusive, but can also exist simultaneously. (Das and Teng 2001)

INTEGRATED PROJECT DELIVERY

According to Lahdenperä, the origins of "integrated project delivery" can be traced back to the oil industry in the 1990s. (Lahdenperä 2012) There, offshore projects were successfully managed through the formation of a project alliance. These successes led to the introduction and increasing application of these approaches in the Australian construction market, particularly in the infrastructure sector, under the name "project alliancing". (Schlabach 2013)

Another approach, called IPD, was first mentioned in the USA in the early 2000s (Lahdenperä 2012). IPD and "project alliancing" are also called collaborative delivery methods. Trust, in turn, is the foundation for collaborative and cooperative work (Engebø et al. 2019 p. 779; Schöttle et al. 2014 p. 1271; Zhang and Qian 2016 p. 1889). True collaboration enables project teams to accomplish challenging tasks (Hartman 2000; Robbins and Judge 2011; Smith et al. 2014). Trust leads to effective communication (cf. Hartman 2000) and information sharing between the people in a project (cf. Robbins and Judge 2011).

OVERVIEW OF THE INVESTIGATION

FRAMEWORK

The framework presented in Figure 1 serves as the basis for the investigations. The framework was derived from theoretical considerations on trust and control (see above) based on a literature review and was validated with the help of expert interviews. A total of 77 references were analyzed and four people with experience in IPD and Alliance projects were interviewed. The keywords of the research were combinations of the terms: Trust, Control and IPD.

The framework divides trust into two types: "individual trust" and "system trust". Both types of trust are state variables, which can change in the course of an IPD project. At the beginning of an IPD project (at time t=0) there is an initial trust between the individuals or organizations and in IPD as a system. The initial trust is based on perceived or experienced trustworthiness. Over the course of an IPD project, both types of trust can then increase or decrease depending on the external influences as well as the control tasks. Trust can thus be seen as a varying state variable, which can increase as well as decrease depending on experience.

In the context of this article, a control task comprises, on the one hand, the verification of a person or organization, e.g. in the form of a check of claimed or assumed and real states. On the other hand, a control task includes the comparison of planned and realized variables. The degree of control (high or low) or by whom the control task is performed depends on the respective trust level (individual and system trust) and external requirements. The interactions between the level of trust and the degree of control are presented in the following chapters.

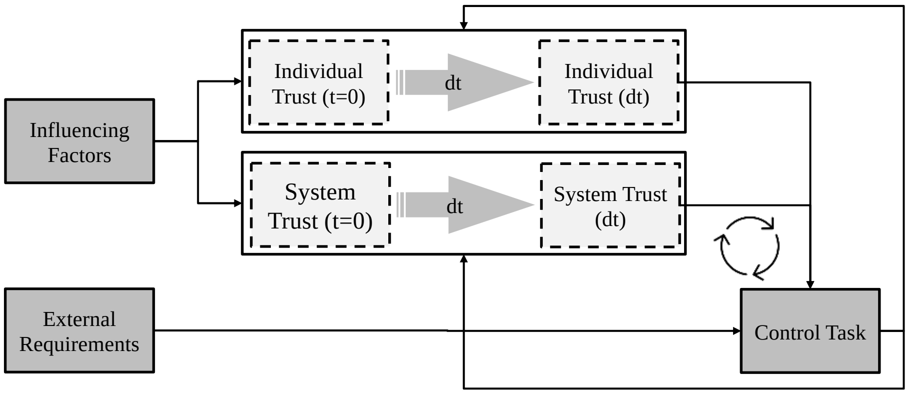

Figure 1: Framework for illustrating the interactions between trust and control

IDENTIFICATION OF TRUST ISSUES AND INTERDEPENDENCIES

The methodological approach for identifying control tasks and the trust issues and their interactions in the context of integrated project delivery is presented below. A comprehensive literature review and evaluation was conducted to identify possible control tasks in the context of integrated project delivery. Different types of literature, such as contracts, guidance documents, case studies, and general literature, were evaluated and possible control tasks were extracted. The literature review was conducted using a keyword search. This was followed by the development of trust issues. Trust issues are subject areas in which trust and control are relevant. Either the current level of trust has an impact on a trust issue or the way it is structured has an impact on it. The following chapter will explicitly deal with three selected trust issues listed in Table 1.

Table 1: Selected trust issues

Key word	Description
Team Selection	Participation in an IPD project requires, in addition to specific capabilities, special soft skills to maintain good cooperation and collaboration and to create innovative solutions. A special care must be taken when selecting participants to ensure that the parties coming into the project have the qualities and skills necessary for an IPD project.
Definition of Target Costs	Establishing the target costs is an important point in the course of the project. Since the partners' remuneration depends on this, the partners must be able to trust that each partner has calculated its costs in accordance with the specifications and is not pursuing any self-interest.
Remuneration of IPD Partners	Remuneration under IPD is essentially based on the costs incurred by the individual partners. Here, trust is important in several respects. For example, transparency is necessary and the disclosure of cost parameters requires trust.

In addition to the trust issues identified in Table 1 the following issues were also identified: Insurance Program, Contracting, Shared Decision Making, Conflict Resolution, Managing Teams, Performance Management, Company Metrics, Opportunity and Risk, Collaboration, Establishing and Sustaining Team Culture, IPD Experience.

Building on the compilation of trust issues and control tasks in the context of IPD, the various effect relationships according to the framework presented between the degree of trust and the design of the control task were investigated and recommendations for actions were derived based on the authors' experience and, where necessary, validated and supplemented with results from the literature and the expert interviews. The results are presented below exemplified for the trust issues mentioned in Table 1. According to the expert surveys, these aspects represent neuralgic points in the course of an IPD project.

SELECTED TRUST ISSUES AND CONTROL TASKS IN IPD PROJECTS

TEAM SELECTION

In contrast to traditional construction projects, the selection of participants in IPD is not only based on commercial criteria and the technical skills of the applicants. There is usually a comprehensive process in which the applicants are evaluated according to defined criteria. The criteria include commercial criteria and technical ability as well as necessary soft skills and collaborative skills. (Allison et al. 2020 pp. 30-33; Department of Infrastructure and Regional Development 2015a p. 68; Macdonald and Sc 2011 p. 216f; Pishdad-Bozorgi and Beliveau 2016 p. 158; Schlabach 2013 p. 105f).

In this task, control can be adjusted by checking more or less criteria. In addition, the selection process can be conducted either through one or more interviews or through an assessment center. This control task can increase the system trust, because beside commercial criteria also further abilities of the applicants are examined. The interviews also confirm that individual trust can be increased because the project participants get to know each other earlier in a comprehensive selection process and the project participants can assume that the partners for the IPD project are capable and can work collaboratively.

Additional consultants may be brought in, to monitor the legitimate conduct of the selection process, to verify the commercial and technical procedure and performance of the applicants, and to verify their capabilities to work collaborativly. These other control tasks can additionally increase system trust by ensuring the fairness of the selection process and allowing partners to assume applicant ability and suitability for the IPD project. Due to the interaction between system trust and individual trust, system trust can positively transfer to individual trust to a certain extent.

Some applicants attend training prior to the selection process on the skills required for IPD. This shows commitment and motivation and can increase individual trust. These and other relationships and their effects on trust are shown schematically in Figure 2.

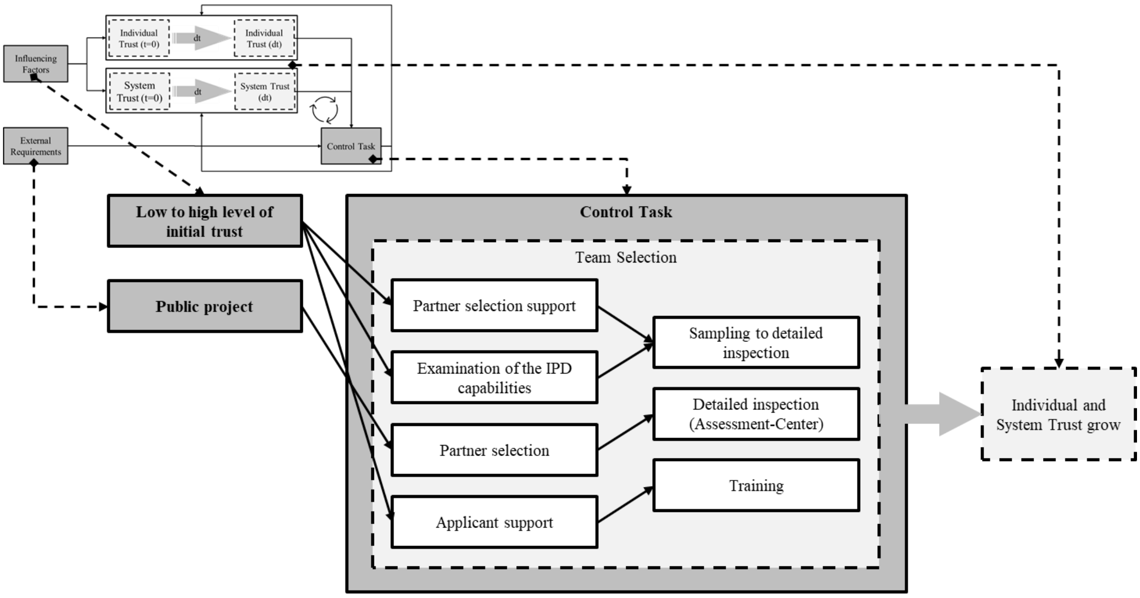

Figure 2: Trust issue "Team Selection"

DEFINITION OF TARGET COSTS

The process of defining the target costs requires a high degree of cooperation. However, this is usually not sufficient to obtain an economical target cost. For this, there must also be sufficient technical expertise in the project. (Walker 2016) In addition, the use of external consultants is also sometimes recommended, either to review the cost estimation that has been carried out (Department of Infrastructure and Regional Development 2015b) or to develop a further cost estimate (Macdonald 2011). The conducted interviews indicated that performing these two tasks is often recommended regardless of the level of trust. This is particularly recommended for public projects (Department of Infrastructure and Regional Development 2015b). Regardless of the reason for performing these inspection tasks, the interviews showed that performing them usually increases the level of trust.

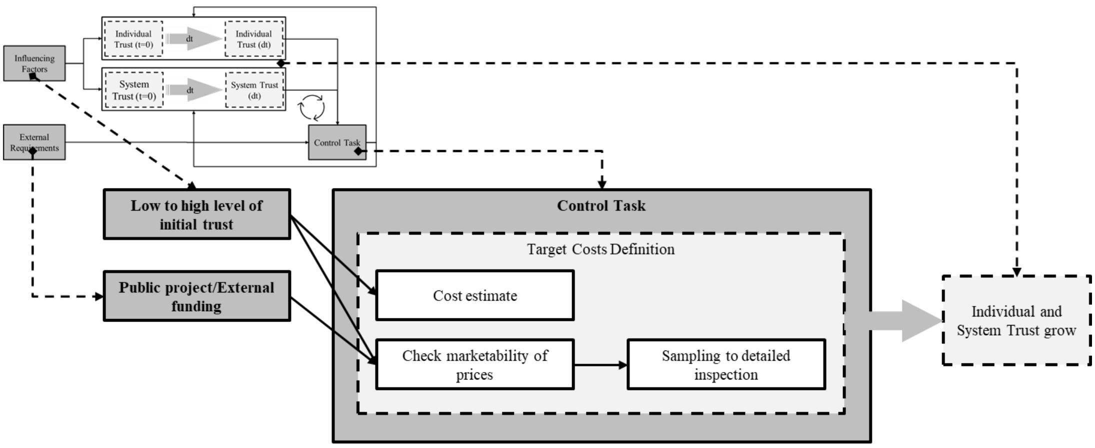

Figure 3: Trust issue "Target Costs Definition"

REMUNERATION OF IPD PARTNERS

Remuneration under IPD is essentially based on the costs incurred by the individual partners. A high level of transparency is important. The resulting control tasks are necessary project tasks but their design depends on the level of trust. As one of the control tasks audits reveal the accrued costs which will be refunded and therefore allow fair fees for the team members. Here an audit can vary regarding its intensity, e.g. it is possible to just do a plausibility check, if the level of trust is really high, or on the contrary to verify every detail, if the level of trust is quite low. Knowing that there are the same regulations for every participant increases the system trust. Whereas successful checks without mistakes also increase the individual trust.

Another task is the review of accounting and calculation either through the IPD team or through an external auditor. This decision does not only depend on the level of trust but also on the competence and capacity of the IPD team. Partly participants will be in favour of a third party as not every team member gets a detailed look into their accounting this way. These rules will also lead to a growth of the individual and system trust because the participants know that the other parties are acting as promised.

Another control task is the continuous cost tracking which includes a comparison between the target and the actual costs. This monitoring enables the team to be aware of deviations at a very early stage so that they can find solutions together and therefore improve. Furthermore this task confirms the capability of the team and strengthens them in their collaborative behaviour.

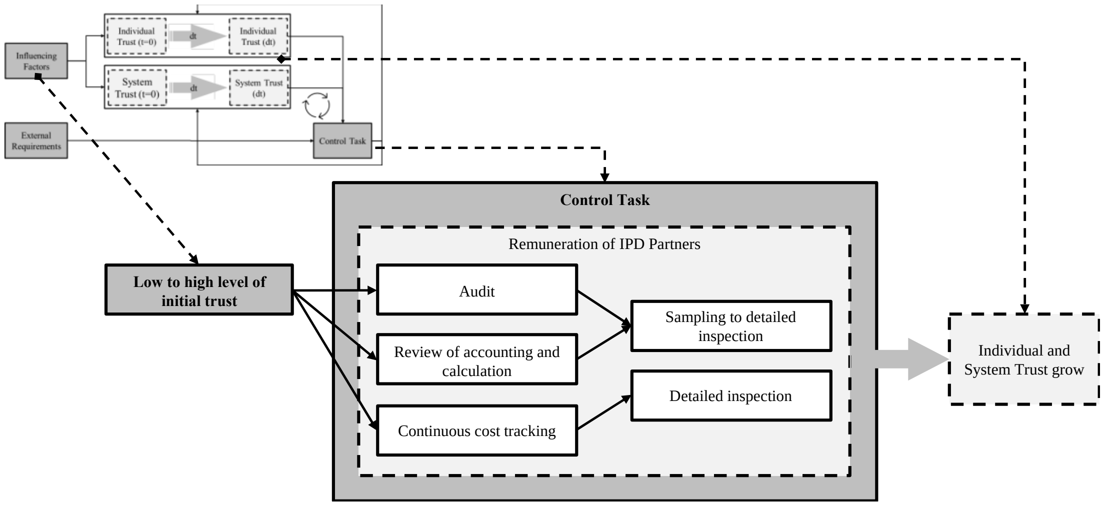

Figure 4: Trust issue "Remuneration of IPD Partners"

CONCLUSIONS

This article discussed the relevance of trust and control in the context of IPD. A distinction must be made here between trust between the participants and trust in the system. However, so-called control tasks are also required for the system to function. These control tasks interact with the different types of trust in the project. On the basis of so-called trust issues it was shown that the execution of one of these control tasks can also increase the trust level. However, this does not mean that there is a direct correlation between trust and control. Project execution is a very complex system in the context of which control tasks can have very divergent effects on trust in the project. This interplay was shown by focusing on three trust issues.

This article contains parts of the results of a research project. This project has not yet been completed. But even beyond this project, the interplay between trust and control must be further investigated in order to increase the understanding of IPD and thus further improve acceptance and project performance.

REFERENCES

AIA California Council. (2014). "Integrated Project Delivery : an Updated." *American Institute of Architects*, 1–18.

Allison, M., Ashcraft, H., Cheng, R., Klawans, S., and Pease, J. (2020). *Integrierte Projektabwicklung Ein Leitfaden für Führungskräfte Deutsche Übersetzung*.

Das, T. K., and Teng, B. S. (2001). "Trust, control, and risk in strategic alliances: An integrated framework." *Organization Studies*, Walter de Gruyter and Co., 22(2), 251–283.

Department of Infrastructure and Regional Development. (2015a). *National Alliance Contracting Guidelines - Guide to Alliance Contracting*.

Department of Infrastructure and Regional Development. (2015b). *National Alliance Contracting Guidelines - Template 1 - Project Alliance Agreement*.

Duden | Vertrauen. (2021). "Duden | Vertrauen | Rechtschreibung, Bedeutung, Definition, Herkunft." https://www.duden.de/rechtschreibung/Vertrauen (Jan. 20, 2021).

Edmondson, A. (1999). "Psychological safety and learning behavior in work teams." *Administrative Science Quarterly*, 44(2), 350–383.

Engebø, A., Skatvedt, Å., and Torp, O. (2019). "Soft elements in collaborative project delivery methods." *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, The International Group for Lean Construction, 773–784.

Green, S. G., and Ann Welsh, M. (1988). *Cybernetics and Dependence: Reframing the Control Concept*. *Source: The Academy of Management Review*.

Hartman, F. T. (2000). "The role of TRUST in project management." *PMI® Research Conference 2000*, Project Management Institute, Paris, France.

Kenning, P. (2002). *Customer Trust Management*. *Customer Trust Management*, Deutscher Universitätsverlag.

Kramer, R. M. (1999). *TRUST AND DISTRUST IN ORGANIZATIONS: Emerging Perspectives, Enduring Questions*. *Annu. Rev. Psychol*.

Lindskold, S. (1978). "Trust development, the GRIT proposal, and the effects of conciliatory acts on conflict and cooperation." *Psychological Bulletin*, 85(4), 772–793.

Luhmann, N. (2014). *Vertrauen*. UVK Verlagsgesellschaft mbH, Konstanz.

Macdonald, C. C. (2011). "Value for Money in Project Alliances".

Mayer, R. C., Davis, J. H., and David Schoorman, F. (1995a). *An Integrative Model of Organizational Trust*.

Mayer, R. C., Davis, J. H., and Schoorman, F. D. (1995b). "An Integrative Model of Organizational Trust." *The Academy of Management Review*, The Academy of Management, 20(3), 709–734.

Müller, M. (2019). *Vertrauen durch Transparenz*. *Vertrauen durch Transparenz*, Springer Fachmedien Wiesbaden.

Müthel, M. (2006). "Erfolgreiche Teamarbeit in deutsch-chinesischen Projekten." *Entscheidungs- und Organisationstheorie*, Deutscher Universitäts-Verlag/GWV Fachverlage GmbH, Wiesbaden.

Petermann, F. (2013). *Psychologie des Vertrauens*. Göttingen.

Pishdad-Bozorgi, P., and Beliveau, Y. J. (2016). "A Schema of Trust Building Attributes and Their Corresponding Integrated Project Delivery Traits." *International Journal of Construction Education and Research*, Routledge, 12(2), 142–160.

Robbins, S. P., and Judge, T. A. (2011). *Essentials of Organizational Behavior*. Prentice Hall.

Rousseau, D. M., Sitkin, S. B., Burt, R. S., and Camerer, C. (1998). “Not so different after all: A cross-discipline view of trust.” *Academy of Management Review*.

Schlabach, C. (2013). “Untersuchungen zum Transfer der australischen Projektabwicklungsform Project Alliancing auf den deutschen Hochbaumarkt.” Kassel University Press.

Schön, W. (2020a). *Vertrauen, die Führungsstrategie der Zukunft*. *Vertrauen, die Führungsstrategie der Zukunft*, Springer Berlin Heidelberg.

Schön, W. (2020b). *Vertrauensorientiertes Projektmanagement Top-10-Erfolgsfaktoren für Projekte und Veränderungsprozesse*. Springer Gabler, Wiesbaden.

Schöttle, A., Haghsheno, S., and Gehbauer, F. (2014). “Defining Cooperation and Collaboration in the Context of Lean Construction.” *IGLC-22*, Oslo, 1269–1280.

Smith, J. P., Rybkowski, Z. K., Bergman, M., and Shepley, M. (2014). “Trust-builder: A first-run study on active trust-building.” *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*, 305–316.

Walker, D. H. T., and Rowlinson, S. (2020). *Routledge Handbook of Integrated Project Delivery*. Routledge Taylor & Francis Group, London, New York.

Walker, D., and Lloyd-Walker, B. M. (2016). “Understanding the Alliance Target Outturn Cost Process and its Implications.” (September).

Wong, W. K., Cheung, S. O., Yiu, T. W., and Pang, H. Y. (2008). “A framework for trust in construction contracting.” *International Journal of Project Management*, 26(8), 821–829.

Zhang, L., and Qian, Q. (2016). “Exploring the Factors for Collaborative Relationships in IPD Projects.” *Construction Research Congress*, ASCE, 1886–1896.

Huaman-Orosco C. and Erazo-Rondinel, A. A. (2021). "An Exploratory Study of the Main Barriers to Lean Construction Implementation in Peru." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 474–483, doi.org/10.24928/2021/0173, online at iglc.net.

AN EXPLORATORY STUDY OF THE MAIN BARRIERS TO LEAN CONSTRUCTION IMPLEMENTATION IN PERU

Cristian Huaman-Orosco[1] and Andrews A. Erazo-Rondinel[2]

ABSTRACT

Lean Construction (LC) has been implemented for 20 years in Peru in different types of projects: buildings, sanitary works, mining, sports infrastructure, and for the development of people, finding significant benefits after its implementation. However, some barriers make complicated Lean Construction from being applied in many projects in Peru. This research aims to identify and classify the obstacles that lead to poor implementation of Lean thinking. First, the study started with a literature review and consultation with six experts with more than ten years of experience in the implementation of Lean Construction in different types of projects, identifying thirty-two barriers to Lean Construction implementation, dividing the barriers into four types: culture barriers, technology barriers, lean philosophy, and other barriers. One hundred and twenty-four engineers from various projects are surveyed, and the main obstacles to Lean Construction implementation are ranked. The findings identified that "lack of government policies," "lack of alliances between academy and organizations," and "high use of time and cost with no return" are the main barriers related to the implementation of Lean. Research is the basis for generating a roadmap and lines of research.

KEYWORDS

Lean construction, challenges, barriers, Peru, Latin America.

INTRODUCTION

Lean Construction has been implementing since 2000 in Peru, with the book "Productivity in construction works" (Ghio, 2001). In this book, Ghio (2001) developed a study of productivity in Peru, and he identified the barriers that generate low productivity in the Peruvian construction sector. This book has served as a reference for various professionals to apply LC in different types of projects in Peru: mining projects (Izquierdo & Arbulú, 2008 y Rosas et al. 2011), buildings (Murguia et al. 2016 y Lazarte, 2020), roads (Cabrera & Li, 2014), sporting infrastructure (Erazo et al. 2020 y Erazo-Rondinel et al. 2020), sanitary works (Flores & Ollero, 2013 and Yoza, 2011); This is how Peru, appears in the 14th position with 19 papers published in the IGLC (Engebø et al. 2017). However, lean implementation has focused heavily on tools such as the Last Planner System. (Murguia 2019), generating that people start using them without really

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understanding the benefits and purpose of Lean thinking. (Almanei et al., 2017); time and cost resources invested in implementation and continue to have problems of poor team coordination, unaligned objectives among project stakeholders, and unreliable planning.

Thus, the following study aims to identify the main barriers that make Lean Construction challenging to implement in Peru. First, a literature review of LC implementation barriers is conducted and validated with the judge experts with more than ten years of experience in LC implementation. After this, we surveyed professionals with 0 to 20 years of experience and with different roles in the industry (planning engineers, field engineers, project managers, technical office engineers, among others); with the data obtained from the surveys, we proceeded to identify the main barriers to LC implementation in Peru. The contribution of the research allows the involvement of the state, universities, and companies to disseminate its implementation in as many projects as possible, help professionals to highlight the barriers, and generate a roadmap to guide organizations.

LITERATURE REVIEW

Lean Construction is everyone's participation in the organization to identify waste and make minor incremental improvements daily, moving everyone in the same direction with common goals. Salvatierra et al. (2015) argue that implementing LC in an organization over the long term requires that people in the organization focus on Philosophy (All must understand lean principles, waste, and customer value). A culture generates social interaction among team members to engage them and adopt the philosophy to the project's complexities and technology that permits apply the philosophy through tools in an iterative process of continuous learning.

The partial or erroneous implementation of Lean Construction results in poor project management, poor coordination with the teams, and unreliable planning, affecting the trust between management and project workers. (Loosemore 2014). Most organizations start by implementing LC using part of the principles or tools (Soren 2014), generating that people implement LC without understanding the philosophy. Also, other organizations suffer in the implementation of LC due to the complexities and many participants in construction projects. These factors lower expectations and are perceived as high use of resources, cost, and time, returning to traditional systems (Okere 2017).

The most recurrent barriers that practitioners face when implementing lean could be indicated as inadequate training of practitioners, lack of top management leadership, long-term LC implementation planning, and people's resistance to change. Alarcón et al. (2002) refer that the full support of top management is required and that the information is available at all levels of the organization. Salvatierra et al. (2015) claim that implementing LC in the short term in temporary projects generates new problems. From the literature, barriers related to people, business, and education are observed. However, little is known about the specific factors that hinder LC deployment in Peru. Also, there is little knowledge about the impact of company size and sector on LC implementation. Understanding these factors would help engineers make better decisions when implementing LC in their projects or organization.

LEAN IMPLEMENTATION BARRIERS

Based on the Literature Review, we identified and classified barriers using the triangle of sustainable Lean practices (Salvatierra et al., 2015). The barriers identified are classified in table 1.

Table 1: Barriers associated with the lean implementation.

Variable	Reference
Barriers associated with the Lean philosophy	
Lack of understanding of the fundamental purpose and rationale for Lean implementation.	(Walter et al. 2020)
Lack of transparent information between team members and management, reducing reliability in Lean.	(Liu et al. 2020)
Local and not global flow optimization	(Almanei et al. 2017)
Lack of information exchange between teams, suppliers, subcontractors, etc.	(Demirkesen et al. 2019)
Lack of long-term thinking in the organization for Lean implementation	(Shang y Sui Pheng 2014)
Lack of clear definition of scope, identifying value and definition from the customer's point of view.	(Sarhan y Fox 2012)
Long duration of the Lean learning curve	(Almanei et al. 2017)
Lack of leadership and empowerment of people in the project.	(Alarcón et al. 2005)
Barriers associated with the lean culture	
Lack of centralized, stored, and shared information to generate a continuous improvement cycle.	(Alarcón et al. 2005a)
Incorrect selection of Lean tools	(Albliwi et al. 2014)
Ease of communication from top management with improvement initiatives.	(Almanei et al. 2017)
Resistance to change of people in the organization	(Murguia 2019)
Barriers associated whit the lean tools	
Lack of self-criticism to learn from mistakes and identify problems	(Alarcón et al. 2005)
Lack of improvement culture throughout the organization	(Walter et al. 2020)
Inability to measure team performance and progress	(Omran y Abdulrahim 2015)
Lack of advance work planning and realistic scheduling using Lean tools	(Cano et al. 2015; Murguia 2019)
Lack of time to implement Lean in ongoing projects	(Soto 2016)
Lack of collaboration of all project stakeholders at all levels and early stages of design and production (suppliers, subcontractors, etc.).	(Shang y Sui Pheng 2014)
People use tools without supporting them with culture and philosophy.	(Salvatierra et al. 2015)
Other barriers related to lean implementation.	
Replicating the Lean strategy of another organization	(Albliwi et al. 2014)
Lack of top management commitment to the implementation	(Demirkesen et al. 2019)
Lack of knowledge and experience of implementers	(Soren 2014)
Lack of collaborative work between academia and the construction industry	(Tsao et al. 2012)
High cost of implementation	(Bashir et al. 2015)

RESEARCH METHOD

To better understand the study phenomenon, the authors conducted a literature review of Lean implementation barriers, followed by expert feedback and validation. The mixed-method was used to take a "snapshot" of the study phenomenon (Cresswell, 2014), integrating qualitative and quantitative questions. Research starts with a literature review; later Lean Experts are selected for exploratory interviews and validation of the barriers. Finally, the mass survey is taken (See Figure 1).

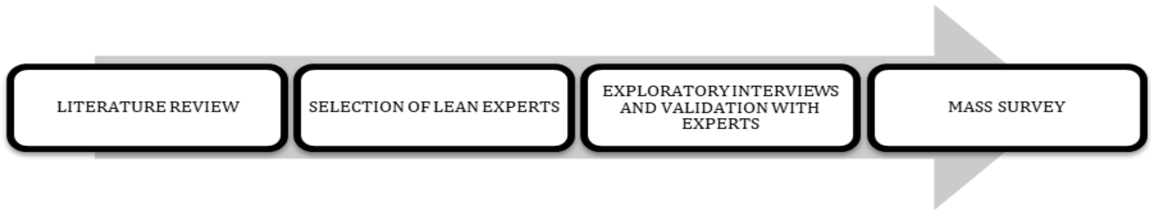

Figure 1. Research methodology.

LEAN EXPERTS SELECTION

Nine expert professionals are targeted to be part of the research to align the objectives of the study; only six experts are selected based on the following characteristics:

- Civil Engineer with more than twelve years of experience implementing lean.
- Professionals with teaching experience, published articles and at least a master's degree.

The interview with the experts are based on general and structured interviews; the following results are obtained in the three stages of the interview:

Table 2: Expert interview results.

Stage	***Structure***	***Results***
I	General data, experience in its implementation, results obtained in its implementation and difficulties.	Served as a criterion for the selection of the expert. To know the expert's profile. Preliminary overview of the study phenomenon and alignment of the study goal.
II	Questions related to the type of project for each expert. Preliminary review of barriers according to literature references.	Emphasis on barriers according to the type of project. Readjustment of the negative syntax to positive or neutral, to avoid influencing and sympathizing with the respondent. Priority was given to 32 barriers out of 78 identified in the literature.
III	Review of questions to achieve objectives. Validation of barriers through the experience of each expert.	Final survey. Identification of patterns of barriers and the study population. A section was incorporated to survey university students.

After stage two, the experts identied the next new barriers: (1) Contracts do not require the use of Lean, leaving it to the company's choice. (2)Low capacity of people to recognize waste. (3) Lack of government policies to incentivize the use of Lean. (4) People in meetings do not respect the opinion of others and impose their ideas. (5) The low empowered capacity of people in the organization delays decision making. (6) Low organizational commitment. (7) Do you agree that universities provide sufficient lean training to perform in the labor market.

SAMPLING, PROFILE AND RESPONDENT ETHICS

In this study, accidental non-probability sampling has been performed based on the researchers' knowledge, experts, and the study objectives. The characteristics of the respondents are Peruvian civil engineers with at least two years of experience working under the Lean philosophy or participating in a project implemented with Lean. Ethical issues were related to the confidentiality and data protection of the survey. Respondents are aware that they could leave the questionnaire at any time.

INSTRUMENTS, DATA SIZES AND DATA ANALYSIS

The survey followed a cross-sectional process to get the most important data and ease of remote response. The questionnaire had 40 open-ended and closed-ended questions. The research team disseminated the survey to Lean organizations, companies, and professionals involved in LC practices through e-mails, social networks, and professional networks. After that, the team sent a total of 1300 mailings. One hundred seventy-four participants complete the survey; 50 are discarded for not meeting the study profile, abandoned surveys, or anomalous data correlation between themselves or about the mean. Barriers are evaluated using a Likert scale of 1 to 5 points, asking respondents to rate which variables they most frequently experienced in their project and are evaluated as "Never=1, Rarely=2, Occasionally=3, Frequently=4 and Very frequently=5". For example, how often does the project team experience reflections on activities carried out and suggestions for good practices? The respondent can choose to rate on a scale of 1 to 5. Thus, the more frequently used, the more common practice among professionals and the less frequently used the practices become barriers that prevent the development of the implementation. The average frequency of use is used to prioritize barriers, where the lower the numerical value, the higher the priority as a barrier. Quantitative data were analyzed and represented with descriptive statistics. The qualitative data served to confirm, corroborate, and have explanations of the barriers. After that, the integration of both data allowed for a better analysis of the study.

JUSTIFICATION OF THE METHOD

The mixed-method is used to have a better understanding of the phenomenon. The mixed method allows a greater variety of perspectives on frequency, generality, complexity, size, and comprehension of the problem. Quantitative to identify the company's size, years of experience, frequency of use of best practices. Qualitative to describe their experiences, personal difficulties, or experiences. Integrating both methods allowed the questionnaire to be improved by the experts. After the pilot plan, new questions are identified and readjusted thanks to the corroboration of qualitative and quantitative data. Non-probabilistic and accidental sampling is used to get as much data as possible conditioned to the study's objectives.

RESULTS AND DISCUSSION

Experts validated the questionnaire and the consistency of 0.95 or 5% error with Cronbach's Alpha(α). Table 3 shows the relevant results of the 124 respondents.

Table 3. Bibliographic characteristics of the survey respondents.

Demographic characteristics	***Frequency***	***Percentage***
Experience		
1-5 years	82	66.39%
6-10 years	24	19.33%
11-15 years	10	7.56%
16-20 years	6	5.04%
More than 20 years	2	1.68%
Experience working with lean.		
1-2 years	51	41.13%
3-5 years	38	30.65%
6-8 years	21	16.94%
9- 10 years	12	9.68%
More than 10 years	2	1.61%
Organization		
Construction	92	73.95%
Consulting and project supervision	9	7.56%
Project formulation and design	8	6.72%
Project logistics and maintenance	4	2.52%
suppliers	2	1.68%
other	9	7.56%
Project Type		
Buildings	59	47.5%
Infrastructure	37	30%
Industrial plants	7	5%
Energy and oil	6	4.17%
Other	15	11.67%
Size of organization		
micro (1 to 10 people)	27	22%
small (10 to 50 people)	32	26%
medium (50 to 250 people)	30	24%
Large (more than 250 people)	35	28%

The main barriers identified are related to the group of other factors and philosophy. The other group is related to policy factors and the public project management system. The understanding of the philosophy is still difficult. Using descriptive statistics, Table 4 shows that "Lack of government policies to encourage the use of Lean" and "Lack of collaborative work between academia and the construction industry" are the most significant barriers. It can be determined that the government and academia play a significant role in generating a Lean system, where builders, designers, suppliers, and subcontractors are quickly integrated into Lean practices. "High cost of implementation" shows that practitioners identify that it requires a high degree of time and financial resources, especially time. "Low empowered capacity of people in the organization delays decision making," "Low knowledge of Lean among university graduates" indicate that professionals have low knowledge of Lean, making it difficult for them to empower themselves and lead Lean implementation. "Lack of top management commitment to implementation" and "Long duration of the Lean learning curve" show that companies do not have top management leadership and do not have labor insertion policies to generate gradual knowledge in Lean implementation. "Lack of knowledge of the fundamental purpose and rationale for Lean implementation" shows that it is still complex for people to understand Lean due to the low number of resources in the language and local studies on the benefits of Lean. "Contracts do not require the use of Lean, leaving it to the company's choice" and "Lack of time to implement Lean in ongoing projects" show that clients are unaware of the benefits of applying Lean in their project and require their builders to use it.

Table 4: Most important barriers to Lean Construction implementation

Variable	***s.d.***	***Mean***	***Rank***
Lack of government policies to encourage the use of Lean.	1.71	2.51	1
Lack of collaborative work between academia and the construction industry.	1.39	2.57	2
High cost of implementation	1.02	2.74	3
Low empowered capacity of people in the organization delays decision making.	0.84	2.95	4
Low knowledge of Lean among university graduates.	0.89	2.95	5
Lack of top management commitment to implementation	1.38	3.04	6
Long duration of the Lean learning curve	1.15	3.04	7
Lack of knowledge of the fundamental purpose and rationale for Lean implementation	0.86	3.17	8
Contracts do not require the use of Lean, leaving it to the company's choice.	1.57	3.18	9
Lack of time to implement Lean in ongoing projects	1.41	3.21	10

The study results show that the lack of government policies to incentivize the use of Lean, many authors consider this as an important barrier (Cano et al., 2015; Demirkesen et al., 2019). Lack of government policies demonstrates the importance of the government to generate lean practitioner environments to engage and empower their organization as the final customer, and the government can demand organizations due to significant investments in public projects. The government needs to change, update, and adapt its project bidding policies to break its traditional project management. The little interaction between academia and industry is corroborated by the few courses dictated on LC in universities, and this point was also mentioned by (Ghio 2001; Tsao 2012). The government and academia oversee disseminating, educating, and training professionals to generate a Lean environment; academy and organization alliances could help solve problems, generate more academic resources in research and create a career line for those involved. The "high resource costs in implementation" are related to the fact that a lot of time effort is required to train project people and a cost with no return due to the temporality of the project; this finding is related to Almanei et al. (2017). This barrier is generated because practitioners still do not understand the benefits of Lean in the long term and focus to a greater extent on the short term. Finally, the "lack of knowledge of Lean in the qualified professionals" is a barrier many implementers agree (Cano et al., 2015; Demirkesen et al., 2019; Walter et al. 2020). Overcoming this barrier will allow the spread of Lean and reduce the impact of other barriers such as: "resistance to change," "the perception of the high cost of implementation," "top management does not support the changes," and others. Lean implementation is not directly related to concepts or techniques but business processes. The implementation must be done at the enterprise level, but it requires management and managing the learning curve.

CONCLUSIONS

Implementing Lean in Peru may be relatively new to many. The study focuses on identifying the main barriers to successful Lean implementation. The information gathered from implementers and the literature reviews used in the study show that the main barriers are: "Lack of government policies," "Lack of collaborative work between academia and business," "High cost of implementation," and "Lack of knowledge of lean in professionals graduated from universities." The barriers identified in the literature review in international research are not reflected in Peru; so, specific barriers are depending on the geographical location, the political context, and the type of industry. Peruvian professionals show a low level of awareness and knowledge about lean. These results evidence the need to focus more on philosophy and technology. It may be easier to start lean implementation by private companies rather than public companies. Finally, understanding, adapting, implementing, and disseminating Lean in Peru requires much effort by all professionals and the commitment of the State, universities, and companies. This study is the basis for proposing a lean implementation roadmap to reduce these barriers.

REFERENCES

Alarcón, L., Diethelm, S., Rojo, O., y Calderon, R. (2005). “Assessing the Impacts of Implementing Lean Construction”. Proc. 13th International Group for Lean Construction Conference, Sydney, Australia.

Alarcón, L. F., Diethelm, S., y Rojo, Ó. (2002). “Collaborative Implementation of Lean Planning Systems in Chilean Construction Companies”. 10th Annual Conference of the International Group for Lean Construction, Gramado, Brazil.

Albliwi, S., Antony, J., Lim, S. A. H., y van der Wiele, T. (2014). “Critical failure factors of lean Six Sigma: A systematic literature review”. International Journal of Quality and Reliability Management, 31(9), 1012–1030.

Almanei, M., Salonitis, K., y Xu, Y. (2017). “Lean Implementation Frameworks: The Challenges for SMEs”. Procedia CIRP, The Author(s), 63, 750–755.

Arbulu, R., y Zabelle, T. (2006). “Implementing Lean in Construction: How to Succeed”. Proc. 14th Annual Conference of the International Group for Lean Construction, Santiago, Chile.

Bashir, A., Suresh, S., Oloke, D., Proverbs, D., y Gameson, R. (2015). “Overcoming the Challenges facing Lean Construction Practice in the UK Contracting Organizations”. International Journal of Architecture, Engineering and Construction.

Cresswell, J.W., (2014). Research Design. Qualitative, Quantitative and Mixed methods approach 4th ed., London: Sage.

Cano, S., Delgado, J., Botero, L., y Rubiano, O. (2015). “Barriers and Success Factors in Lean Construction Implementation Survey in Pilot Contex”. Proc. 23rd Annual Conference of the International Group for Lean Construction, Perth, Australia.

Demirkesen, S., Wachter, N., Oprach, S., y Haghsheno, S. (2019). “Identifying Barriers in Lean Implementation in the Construction Industry”. Proc. 27th Annual Conference of the International Group for Lean Construction, Dublin, Ireland.

Engebø, A., Drevland, F., Lohne, J., Shkmot, N., y Lædre, O. (2017). “Geographical Distribution of Interest and Publications of Lean Construction”. Proc. 25th Annual Conference of the International Group for Lean Construction, Heraklion, Greece.

Erazo-Rondinel, A. A., Vila-Comun, A., y Alva, A. (2020). “Application of the Last Planner® System in a Sports Infrastructure Project in Perú”. Proc. 28th Annual Conference of the International Group for Lean Construction, Berkeley, California.

Erazo, A., Guzman, G., y Espinoza, S. (2020). “Applying BIM Tools in IPD Project in Perú”. Proc. 28th Annual Conference of the International Group for Lean Construction, Berkeley, California.

Flores, G., y Ollero, C. (2013). “Productivity Improvement Applying Production Management in Projects with Repetitive Activities”. Proc. 21st Annual Conference of the International Group for Lean Construction, Fortaleza, Brazil.

Forero, S., Cardenas, S., Vargas, H., y Garcia, C. (2015). “A Deeper Look Into the Perception and Disposition to Integrated Project Delivery (IPD) in Colombia”. Proc. 23rd Annual Conference of the International Group for Lean Construction, Perth, Australia.

Ghio, V. (2001). Construction Site Productivity. Pontificia Universidad Católica del Perú, Lima.

Gutiérrez, F. M. (2020). “Influence of Integrated Teams and Co-Location to Achieve the Target Cost in Building Projects”. Proc. 28th Annual Conference of the International Group for Lean Construction, Berkeley, California.

Izquierdo, J. L., y Arbulu, R. (2008). “Application of Production Management in Industrial EPC and Mining Projects in Peru”. Proc. 16th Annual Conference of the International Group for Lean Construction, Manchester, UK.

Liu, C., González, V. A., Liu, J., Rybkowski, Z., Schöttle, A., Mourgues Álvarez, C., y Pavez, I. (2020). “Accelerating the Last Planner System® (LPS) Uptake Using Virtual Reality and Serious Games: A Sociotechnical Conceptual Framework”. Proc. 28th Annual Conference of the International Group for Lean Construction, Berkeley, California.

Loosemore, M. (2014). “Improving Construction Productivity: A Subcontractor’s Perspective”. Engineering, Construction and Architectural Management, 21(3), 245–260.

Murguia, D. (2019). “Factors Influencing the Use of Last Planner System Methods: An Empirical Study in Peru”. Proc. 27th Annual Conference of the International Group for Lean Construction, Dublin, Ireland.

Murguía, D., Brioso, X., y Pimentel, A. (2016). “Applying Lean Techniques to Improve Performance in the Finishing Phase of a Residential Building”. Proc. 24th Annual Conference of the International Group for Lean Construction, Massachusetts, USA.

Okere, G. (2017). “Barriers and Enablers of Effective Knowledge Management: A Case in the Construction Sector”. The Electronic Journal of Knowledge Management, 15(2), 85–97.

Omran, A., y Abdulrahim, A. (2015). “Barriers to prioritizing lean construction in the Libyan Construction Industry”. Acta Tehnica Corviniensis, (1998), 1–4.

Román, B., y Juárez, G. (2014). “A Lean-Triz Approach for Improving the Perfomance of Construction Projects”. Proc. 22nd Annual Conference of the International Group for Lean Construction, Oslo, Norway.

Rosas, E., Ríos, L., y Carrera, D. (2011). "Implementing Last Planner in Open Pit Mining Projects: Case Study". Proc. 19th Annual Conference of the International Group for Lean Construction, Lima, Peru.

Salvatierra, J. L., López, A., Alarcon, L. F., y Velásquez, X. (2015). "Lean Diagnosis for Chilean Construction Industry: Towards More Sustainable Lean Practices and Tools". Proc. 23rd Annual Conference of the Internatioanl Group for Lean Construction, Perth, Australia.

Sarhan, S., y Fox, A. (2012). "Trends and Challenges to the Development of a Lean Culture Among UK Construction Organisations". Proc. 20th Annual Conference of the International Group for Lean Construction, San Diego, California.

Shang, G., y Sui Pheng, L. (2014). "Barriers to Lean Implementation in the Construction Industry in China". Journal of Technology Management in China, 9(2), 155–173.

Soren, W. (2014). "Lean Construction With or Without Lean Challenges of Implementing". Proc. 22th Annual Conference of the International Group for Lean Construction, Oslo, Norway.

Soto, U. (2016). "Maturity Assessment of Lean Principles in Construction Projects". Pontificia Universidad Católica de Chile.

Tsao, C., Alves, T., y Mitropoulos, P. (2012). "Different Perspectives on Teaching Lean Construction". Proc. 20th Annual Conference of the International Group for Lean Construction, San Diego, California.

Walter, R., Weinmann, M., Baier, C., Oprach, S., y Haghsheno, S. (2020). "A Requirement Model for Lean Leadership in Construction Projects". Proc. 28th Annual Conference of the International Group for Lean Construction, Berkeley, California.

Yoza, A. (2011). "Impact of 'The last planner' Method on Sanitation works". Proc. 19th Annual Conference of the International Group for Lean Construction, Lima, Peru.

Soliman-Junior, J., Awwal, S., Bridi, M.E., Tzortzopoulos, P., Granja, A.D., Koskela, L., and Gomes, D. (2021). "Living Labs in a Lean Perspective" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 484–493, doi.org/10.24928/2021/0176, online at iglc.net.

LIVING LABS IN A LEAN PERSPECTIVE

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ABSTRACT

Living Labs (LLs) consist of social and dynamic environments that enable end-users and stakeholders to collaborate towards an innovation. This paper presents the concept of LLs and analysis on how it can foster communication and collaboration from a lean perspective. Key concepts, such as co-creation, common ground, shared understanding and boundary objects are discussed in relation to LLs. The paper highlights the synergies between LLs and lean, including the focus on users' needs and values, the use of participatory approaches and early inclusion of stakeholders in the decision-making process, for example. There is however lack of clarity in the literature regarding the concept of LLs and, hence, there is a need for future empirical research to enable a better understanding of the synergies between Living Labs and lean.

KEYWORDS

Living labs, co-creation, common ground, shared understanding, boundary objects.

INTRODUCTION

Construction projects involve multiple stakeholders, including end-users and professionals, who have different backgrounds, experiences, knowledge, perspectives and interests. Such differences often lead to misalignments, inhibiting collaboration (Van Geenhuizen 2019), fostering a blame culture (Keeping 2000) and constraining shared knowledge (Pemsel and Widen 2011). Living Labs (LLs) are user-centred initiatives for the development of innovative solutions in real-life contexts through collaborative processes (Leminen and Westerlund 2017). LLs enable all stakeholders to be co-creators in innovation processes, rather than merely observers (Leminen et al. 2012). Users play an active role in the development of a product or artefact (Tang; Hämäläinen 2014), and their willingness to engage in LL activities impacts value creation. Therefore, the added

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value of users' participation in LLs has societal and technological dimensions, such as users accessing products that meet their real needs, the development of creative skilled communities and fostering new employment opportunities (Paskaleva et al. 2015).

Participatory approaches to support design and construction have been already discussed by the lean community (e.g. Sfandyarifard and Tzortzopoulos 2011). Furthermore, Koskela et al. (2016) presented a review of concepts supporting communication and collaboration in construction projects from a lean perspective, including shared understanding and common ground. This paper draws upon the work of Koskela et al. (2016), aiming to conceptually analyse potential synergies between LLs and lean, based on these key concepts. The paper is part of a research project entitled User-Valued Innovations for Social Housing upgrading through Trans-Atlantic Living Labs (uVITAL). This project is being developed through a collaboration between UNICAMP (Brazil), TU Delft (Netherlands), UFZ Helmholtz Centre for Environmental Research (Germany) and The University of Huddersfield (UK). The aim of uVITAL is to advance on user-valued innovations for social housing upgrading through transatlantic Living Labs. This paper is structured as follows: after presenting Living Labs both conceptually and how cases have been reported in the literature, key collaboration and communication concepts are discussed as to how they relate to LLs. A discussion on the synergies between LLs and lean is presented, followed by conclusions and limitations to be addressed in future work.

LIVING LABS

The LL terminology was first introduced in the early 1990s (Nesti 2018), whereas the first largely acknowledged development is attributed to the ‘PlaceLab’ - an initiative from MIT’s professor William Mitchell (Eriksson et al. 2005; Leminen et al. 2012). The initial focus of LLs was on emerging technologies in home-like environments (Bergvall-Kåreborn et al. 2009; Tang and Hämäläinen 2014). Over time, they have been used in different domains, such as energy, mobility, healthcare, urban design and housing (ENoLL 2021), addressing complex social, economic, cultural and political challenges (Claude et al. 2017).

LLs are innovation-driven, whereas value is created by engaging with relevant stakeholders (Bergvall-Kåreborn et al. 2009). They are based on placing users and other value chain actors at the centre of the innovation process (Leminen 2015). This process enables collaboration between the people and organisations that are part of the development of an innovation or are affected by it, such as users, public and private partners, researchers, financial investors, regulators, policy makers, citizen groups, among others (Niitamo et al. 2006; van Geenhuizen 2019). The literature presents multiple definitions for LLs (Bergvall-Kåreborn et al. 2009; Steen and Van Bueren 2017), as highlighted in table 1.

The variety of definitions presented in table 1 indicates a lack of conceptual clarity on LLs, suggesting different ontological assumptions regarding their understanding. The focus on improving collaboration and participation to promote social innovation is key (Almirall and Wareham 2011). Because solutions are created and validated in multi-contextual and real environments (Van Der Walt et al. 2009), LLs foster bottom-up communication and collaboration between stakeholders (Tang and Hämäläinen 2014), especially when it comes to achieving social transformation (Oliveira and Brito 2013).

LLs include user involvement as an intrinsic feature (Eriksson et al. 2005; Niitamo et al. 2006; Tang and Hämäläinen 2014; Leminen 2015). More specifically, they focus on identifying end users' needs and societal problems, hence solutions can be collectively designed, prototyped, validated and refined in real-life contexts (Westerlund and Leminen 2011 *apud* Nesti 2018). As such, they support stakeholders to fully address user's needs (Leminen 2015). This relies on end-users and stakeholders collaborating directly together in LL activities (van Geenhuizen 2019), as in design and prototyping workshops, project meetings and training sessions, playing a co-creation role (Tang and Hämäläinen 2014).

Table 1: Main Living Lab definitions in the existing literature

Reference	Definition	Understanding
Eriksson et al. (2005 p. 4)	*"A user-centric research methodology for sensing, prototyping, validating and refining complex solutions in multiple and evolving real-life contexts"*	Method
Van Geenhuizen (2019 p. 28)	*"Aside from innovation methodology, the term living labs often also refers to the (temporary) organizational structure in which the methodology is implemented"*	Method; Environment
Ballon and Schurmann. (2015 p. 2)	*"An experimentation environment in which technology is given shape in real-life contexts and in which (end) users are considered co-producers"*	Environment
Oliveira and Brito (2013 p. 202)	*"Open ecosystems that engage and motivate stakeholders into an innovation process, encourage collaboration, facilitate and accelerate the creation and sustainability of new markets and business models"*	Ecosystem; Environment
Papadonikolaki; van Oel; Kagioglou (2019 p. 385)	*"User-centred sessions focusing on co-creating meaning with the participants, exploring scenarios and evaluating propositions"*	Sessions

LIVING LAB IN PRACTICE

Even though LLs have common conceptual elements, there are multiple forms of implementation observed in practice (ENoLL 2021). Existing literature is fragmented, with few comprehensive descriptions of LL activities. Reported LL cases usually start from (i) a problem, by getting people together to initiate an endeavour and come up with ideas for a solution; or (ii) with an idea, when partners set up a lab for experimentation, further connecting the idea to a relevant problem (Steen and van Bueren 2017). Examples of LL cases are presented in tables 2 and 3.

LLs are reported as a linear or non-linear process, using standardised or customised tools (Leminen et al. 2012). Tang and Hämäläinen (2014) synthesised LL processes in a four-stage iterative model: (1) requirements; (2) co-design; (3) prototyping; and (4) test and tracking. The model placed end-users at the centre of the process and included an output stage (5) commercialisation. The model proposed by Steen and Van Bueren (2017) focuses on the use of LLs at an urban scale and included six cyclical and iterative stages: (1) plan development; (2) co-creative design; (3) implementation; (4) evaluation; (5) refinement; and (6) dissemination, preceded by (0) initiation and closed with (7) replication. This model provides a generic process in which participants allocate themselves in the LL, supporting activities in a constructive, proactive and efficient way.

As discussed, there is no standard LL process reported by existing research, despite the similarities between models. This is also observed regarding the participants involved, and resources used in LLs, which vary signif|icantly according to their specific contexts and objectives (as seen in tables 2 and 3). This can be due to of the lack of conceptual clarity, as identified in table 1. As a consequence, reported LL cases are diverse and fragmented, presented through different formats and detail levels.

Table 2: Descriptive examples of Living Lab cases

Exhibit 1: Nesti (2018)	Exhibit 2: Johansson and Snis (2011)
Nesti (2018) describes a housing innovation lab that was created in 2015 to provide affordable housing in Boston. The project collaborated with housing experts, community organisations and residents to develop solutions, considering the high living costs in the local area. The lab started with pilot projects relating to density, compact living and alternative housing models. It was followed by exploration, experimentation and evaluation. Initially, housing problems and users' needs were identified by interviewing key residents; then, users' needs were analysed and led to alternative solutions. Through a testing option with residents, feedback was collected, supporting the proposition of recommendations. For example, the "Urban Housing Unit Roadshow" consisted of a compact apartment on wheels. It was placed in different areas of the city. Residents were asked to experiment the apartment and give feedback. The information further helped to define needs and recommendations associated to compact living.	Johansson and Snis (2011) reported empirical results from "The Find Project" developed by the Halmstad Living Lab in Sweden. The purpose was to customise a sender and receiver device to find missing objects and people, fitted to the needs of elderly and demented users. Co-creation activities involved researchers, developers and target users relatives. The project was held in an apartment equipped with tools and artefacts to serve as a real-life context test laboratory. It enabled developers to present statements and questions on workshops to compare the users' needs with the device prototypes. It also consisted of building and designing the prototypes. Participants were asked to be creative and propose design ideas for both receiver and sender devices using sketches or models (e.g. jewellery piece). The activity also included presenting and discussing results with the group.

Table 3: Examples of Living Lab cases

Reference	Living Lab Objective	Participants	Examples of resources and activities
Claude et al. (2017)	Validate refurbishment techniques based on ecological materials through a scientific experiment. Testing materials in the laboratory, but also directly in a real context	Craftsmen, students, local authorities, material producers	Workshops, lab simulations, in-situ sensor monitoring, hardware infrastructure for monitoring empty building before and after
Lockton et al. 2013	Developing devices that help to save energy and enhance comfort in terms of heating	City institute and partner university, advisory board, local and regional housing companies	Visits and interviews, energy displays, Home Energy Hackday, co-creation workshops, monitoring toolkit (tablet for self-reporting), Prototype testing
Boess et al. (2018)	Deliver a scalable zero-energy renovation of outdated multistorey housing	Housing association, construction company, researchers, resident representatives	Invitation letter, discussion sessions, A2 sheets (design), physical components (renovation samples), informal chats, reflection booklets

KEY CONCEPTS: RELATIONSHIP TO LIVING LABS

The following discussion explores communication and collaboration, aiming to understand and identify potential synergies between LLs and lean. This includes four key concepts and their relationship to LLs i.e., co-creation, common ground, shared understanding and boundary objects. These concepts have been discussed as preconditions to communication and collaboration in construction projects (Koskela et al. 2016; Gomes et al. 2016) and can help better understanding LLs under a lean perspective.

CO-CREATION

Co-creation can be understood as an act of collective creativity or "*creativity that is shared by two or more people*" (Sanders and Stappers 2008 p. 6). The referred authors discuss co-creation in the context of participatory design and understand this as a broad definition. Co-creation is intrinsic to LLs (Nesti 2017) and when practised at early stages has a positive impact on its outcomes (Sanders and Stappers 2008). The importance of co-creation is also reinforced in LL definitions, e.g. "*Living labs are user-centred sessions focusing on co-creating meaning with the participants, exploring scenarios and evaluating propositions*" (Papadonikolaki et al. 2019, p. 385).

Although collaboration is fundamental to achieve co-creation, endeavours might differ on how stakeholders collaborate and co-create artefacts (Schuurman et al. 2013). Depending on how a LL evolves and stakeholders develop relationships, more intensive ideation and co-creation activities can be achieved (Leminen et al. 2019). This reflects the nature of collaborative design, which is based on collective creative processes and multidisciplinary project actors deliberately co-creating design solutions over time (Papadonikolaki et al. 2019). It also suggests that co-creation depends on common ground and shared understanding, whereas a LL environment helps achieving them in practice.

COMMON GROUND

Common ground can be defined as a presumption of awareness (Clark 1996), being achieved when people share the same knowledge and beliefs (Holtgraves 2002; Stalnaker 2002). However, Holtgraves (2002) argues that common ground exists regardless of people's awareness of it. Koskela et al. (2016) explain common ground as a concept derived from classical rhetoric, which plays a vital role in effective communication and collaboration (Geurts 2018). Common ground is the primary basis for successful communication and it is the starting point to persuade the speaker and the audience to understand mutual grounds (Kecskes and Zhang 2009). This highlights that common ground can act as a starting point towards mutual understanding between the interlocutors and stakeholders involved in a process (Geurts 2018; Feurstein et al. 2008).

According to Feurstein et al. (2008), stakeholders should be directly connected to mitigate risks in design. In a LL, all relevant stakeholders are identified and engaged at the start of the process (Van Der Walt et al. 2009), and communication strategies to support initial interactions are proposed to overcome likely conflicts and boundaries (Pemsel and Widén 2011). As the common ground is the primary basis for successful communication (Geurts 2018; Kecskes and Zhang 2009), it has a direct impact on LLs not only from a process perspective but also considering their social character.

SHARED UNDERSTANDING

Shared understanding can be defined as "the ability of multiple agents to exploit common bodies of causal knowledge for the purpose of accomplishing common (shared) goals"

(Smart et al. 2009, p. 2). Gomes et al. (2016, p. 70) further state that shared understanding is an "ability to be collectively developed", being dynamic and influenced by the context of the project and its social aspects. The same authors argue that this process involves two abilities: one of collective action for sense-making; and the other of collective coordination of interdependent perceptions between team members.

Valkenburg (1998) states that the absence of shared understanding creates miscommunication, potentially delaying the design process. As LLs are based on collaborative efforts (Almirall and Wareham 2011), achieving shared understanding is key to enabling LLs through a social, context-based and collective effort.

BOUNDARY OBJECTS

Star (1989) describes Boundary Objects (BOs) as an analytical concept for objects that can coexist between different social worlds and satisfy individuals' information needs. Those objects can be abstract or physical artefacts, and they incorporate multiple meanings, while sharing a common structure which allows interaction by maintaining coherence across different knowledge areas (Star and Griesemer 1989). BOs can be artefacts such as timelines, drawings, 3D models, among others (Koskela et al. 2016). Generally, BOs are seen as tools that create common understanding between participants allowing collaboration even with a lack of consensus (Kjølle and Blakstad 2014).

LLs involve a network of stakeholders requiring mediating activities and translating different interests and understandings. This leads to the construction of BOs that are both meaningful and acceptable between participants (Paskaleva et al 2015). Existing research on LLs addressed BOs in multiple forms: (a) as a way to transpass communication boundaries (Paskaleva et al. 2015); (b) as the materialisation of ideas and concepts during co-creation (Johansson and Snis 2011) and (c) as both physical and imaginary artefacts that connect stakeholders coordinate participants (Engels and Münch 2015).

DISCUSSION: LIVING LABS AS A LEAN APPROACH

The previous discussion demonstrates that LL's outcomes are impacted by how effectively stakeholders communicate, collaborate and co-create artefacts while considering end-users' needs. The LL process, therefore, depends on many of the preconditions for communication and collaboration discussed by the lean community, such as those explored by Koskela et al. (2016). In a LL context, participatory approaches support the co-creation of not only innovative artefacts but also of meaning between different stakeholders (Papadonikolaki et al. 2019). This highlights the role of LLs to support shared understanding. Furthermore, the synthesis presented in this paper demonstrates that LLs do not necessarily refer to a 'place' or a 'specific setting', but to a social, context-dependent and dynamic environment that enables stakeholders to better communicate and collaborate towards a user-driven innovation.

Nevertheless, a starting point for such understanding can be associated with the steering user-driven approach in Living Labs. In practice, it has been recognized that collaborative design interactions will lead to compromises, where different needs and interests are negotiated and balanced across project stakeholders influenced by aspects of power and interest. Because end-users and other stakeholders are fundamental actors engaged in the Living Lab from the start, their needs should be key project drivers. The early involvement of stakeholders and team initiation create opportunities for the collective exchange of opinions, ideas and analysis of trade-offs, supporting collaborative decision-making and facilitating the elicitation of potential misalignments. This integration of project stakeholders is also an essential element of Integrated Project Delivery (IPD) projects. In this context, LLs could complement IPD projects in a way as to achieve even more benefits, acknowledging the main focus of LLs on their end-users.

Multiple participatory approaches reported in lean research relate to prototyping, mock-ups, focus groups and co-design workshops. As observed in table 3, they are also part of many LLs, usually highlighted as BOs that support the development of common ground and shared understanding. Additionally, because of the way LLs enable iterative processes, there is an opportunity for accelerated feedback loops, suggesting a synergy between lean and Living Labs. A summary of the potential synergies between LLs and lean is presented in table 4, also highlighting their related lean principles (Koskela 1992).

Table 4: Key synergies between Living Labs and lean

Synergy	Description from LLs	Lean Principles
Focus on users' needs and values	LLs are user-driven initiatives aiming to address their specific needs and values. There is a clear link between LLs and value generation	Increase value
Participatory approach;	LLs are based on participatory approaches through co-creation. These include the development of both physical artefacts such as prototypes, often used as BOs, but also abstract artefacts to support collective sense-making.	Increase value
Early stakeholder involvement; **Team forming and initiation**	In LLs, stakeholders are identified and engaged from the beginning of the process, whereas communication strategies support initial interactions to overcome potential conflicts and boundaries.	Increase value; Increase transparency
Environment that supports collaboration, transparency	LLs provide an experimentation environment in real-life context, supporting the development of common ground and shared understanding through increased transparency and collaboration between stakeholders (as per tables 2 and 3).	Increase transparency
Iterative process	LL cases are usually reported as iterative processes with multiple evaluation points and feedback loops, suggesting a link to continuous improvement both in the process, but also in the innovation under development.	Continuous improvement
Feedback loops	The iterative process in LLs enables accelerated feedback loops (as evidenced by, contributing to the reduction of cycle times.	Reduce cycle times

Table 4 is limited to the conceptual analysis presented in the paper. It needs to be further supported with empirical data, given the real-life character of LLs and due to the lack of clarity in existing research related to concepts, processes and activities associated with LLs, as presented in Tables 1 and 2. The contexts in which LLs have been used and the scale of the projects reported in cases are varied. Applications range from urban to housing scales, and from major sustainable programmes to the development of specific mobile devices. Despite the plethora of uses reported in existing research, LLs have been typically applied to improve value generation through collective sense-making. Interestingly, many of the situations in which participatory approaches have been used and reported by lean research relate to healthcare projects (e.g., Sfandyarifard and Tzortzopoulos 2011), whereas these have not been explored with similar emphasis in LLs.

CONCLUSIONS

The theoretical discussion here presented show that LLs should be understood not as a 'place' where stakeholders meet and co-create solutions, but as a social, context-dependent and dynamic environment that enables end-users and stakeholders to better communicate and collaborate towards an innovation. Also, lean construction practices as described in the previous section could be further enhanced by using a LL approach. This paper demonstrates that key lean concepts and practices are also part of LLs, highlighting potential synergies between LLs and lean, suggesting that lean projects could benefit from LLs and vice-versa. Whereas the impact of LLs in lean tends to be as an approach to improve construction projects further; the use of lean can help LLs in a greater and broader sense. There is an opportunity to incorporate multiple lean tools and approaches related to stakeholders and value management, collaboration and continuous improvement, which have not been explored in the LL context yet.

The analysis here described relates to early research findings and is solely based on literature review, meaning that no empirical data has been collected yet. Furthermore, the lack of conceptual clarity on LLs suggests that the initial concept proposed in the 1990s might have diverged over time and LLs have been understood differently from an ontological perspective in practical implementations. Nevertheless, there is still a conceptual gap associated with LLs' definition, to be addressed in future research.

Even though the potential synergy between LLs and lean (table 4) suggests some commonalities emerging from reported LL approaches, activities and project contexts, further investigation in practice is needed. This represents a limitation of the paper due to the convoluted theoretical background associated with LLs. This also means that framing LLs as a lean approach, and investigating the benefits and limitations of such practical interplay demands further empirical and theoretical investigation.

ACKNOWLEDGEMENTS

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REFERENCES

Almirall, E., and Wareham, J. (2011). "Living Labs: arbiters of mid- and ground-level innovation." *Technology Analysis & Strategic Management*, 23:1, 87-102.

Ballon, P., Van Hoed, M., and Schuurman, D. (2018). "The effectiveness of involving users in digital innovation: Measuring the impact of living labs." *Telematics and Informatics*, 35(5), 1201–1214.

Bergvall-Kåreborn, B. H. M. S. A., Hoist, M., and Stahlbrost, A. (2009). "Concept design with a living lab approach." *42nd Hawaii Int. Conf. on Syst. Sciences* (pp. 1-10). IEEE.

Boess, S., Silvester, S., De Wal, E., and De Wal, O. (2018). "Acting from a participatory attitude in a networked collaboration." *ACM Int. Conf. Proceeding Series*, 2, 1–6.

Claude, S., Ginestet, S., Bonhomme, M., Moulène, N., and Escadeillas, G. (2017). "The Living Lab methodology for complex environments" *Energy Research & Social Science*, 32, 121–130.

Clark, H. (1996). "*Using language*." Cambridge: Cambridge University Press.

ENoLL. (2021). "About us" *Enoll*, https://enoll.org/about-us/ (Jan. 27, 2021).

Engels, F., and Münch, A. V. (2015). "The micro smart grid as a materialised imaginary within the German energy transition." *Energy Research & Social Science,* 9, 35–42.

Eriksson, M., Niitamo, V. P., & Kulkki, S. (2005). "State-of-the-art in utilizing Living Labs approach to user-centric ICT innovation", Lulea University of Technology

Feurstein, K., Hesmer, A., Hribernik, K. A., Thoben, K. D., & Schumacher, J. (2008). Living Labs: a new development strategy. In: *European Living Labs-a new approach for human centric regional innovation*, Verlag Berlin, 2008, pp. 1-14.

Geurts, B.(2018)."Convention and common ground."*Mind & Language*,33(2),115–129.

Gomes, D., Tzortzopoulos, P., and Kagioglou, M. (2016). "Collaboration Through Shared Understanding in Early Design Stage." In: *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, Boston, MA, USA, sect.7 pp. 63–72.

Holtgraves, T. M. (2002). "*Language as Social Action: Social Psychology and Language Use*." Mahwah NJ: Lawrence Erlbaum.

Johansson, L. O. and Snis, U. S. (2011). "The dynamics of interaction: exploring a living lab innovation process from a community of practice perspective." In: *Proceedings of Pacific Asia Conference on Information Systems (PACIS).*

Kecskes, I. and Zhang, F. (2009). "Activating, seeking, and creating common ground: A socio-cognitive approach." *Pragmatics & Cognition,* 17(2), 331–355.

Keeping, M. (2000). "What about demand? Do investors want 'green buildings'?" In: Sustainable Building. Int'l. Conf. Sustainable Building. The Netherlands.

Kjølle, K. H., and Blakstad, S. H. (2014)."Architects and end users:Boundary objects in participatory briefing and design."*Nordic Journal of Architectural Research*,1, 20.

Koskela, L. (1992). "*Application of the new production philosophy to construction"* (Vol. 72). Stanford: Stanford University.

Koskela, L., Pikas, E., Gomes, D., Biotto, C., Talebi, S., Rahim, N., and Tzortzopoulos, P. (2016). "Towards shared understanding on common ground, boundary objects and other related concepts." In: *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, Boston, MA, USA, sect.1 pp. 63–72.

Leminen, S. (2015). "Q&A. What Are Living Labs?" *Technology Innovation Management Review*, 5(9), 7.

Leminen, S., Nyström, A.-G., and Westerlund, M. (2019). "Change processes in open innovation networks – Exploring living labs." Industrial Marketing Management.

Leminen, S., Westerlund, M., and Nyström, A.-G. (2012). "Living Labs as Open-Innovation Networks." Technology Innovation Management Review, 2(9): 6-11.

Lockton, D., Greene, C., Brass, C., and Gheerawo, R. (2013). "SusLabNWE : Integrating qualitative and quantitative data to understand people's everyday energy behavior." In: *Behavior, Energy & Climate Change 2013 conference.*

Niitamo, V., Kulkki, S., Eriksson, M. and Hribernik, K. A. (2006). "State-of-the-art and good practice in the field of living labs." 2006 IEEE International Technology Management Conference (ICE), Milan, pp. 1-8.

Nesti, G. (2018). "Co-production for innovation: The urban living lab experience." Policy *and Society*, 37:3, 310-325.

Oliveira, Á., de, and Brito, D., A., de. (2013). "Living Labs: a experiência Portuguesa." CTS: Revista iberoamericana de ciencia, tecnología y sociedad, 8(23), 201–229.

Papadonikolaki, E., van Oel, C., and Kagioglou, M. (2019). "Organising and Managing boundaries: A structurational view of collaboration with Building Information Modelling (BIM)." *International Journal of Project Management*, 37(3), 378–394.

Paskaleva, K., Cooper, I., Linde, P., Peterson, B., and Götz, C. (2015). "Stakeholder Engagement in the Smart City: Making Living Labs Work." In: *Transforming City Governments for Successful Smart Cities* (p. 115–145). Springer International.

Pemsel, S., and Widén, K. (2011). "Bridging boundaries between organizations in construction." *Construction Management and Economics,* 29(5), 495-506.

Sanders, E. B. N., and Stappers, P. J. (2008). "Co-creation and the new landscapes of design." *Co-design*, 4(1), 5-18.

Schuurman, D., Mahr, D., De Marez, L., and Ballon, P. (2013). "A fourfold typology of living labs: an empirical investigation amongst the ENoLL community." In: *2013 Int. Conf. on Engineering, Technology and Innovation (ICE)* (pp. 1-11). IEEE.

Sfandyarifard, E. and Tzortzopoulos, P. (2011). "Supporting Value Generation in Children's Hospital Design Through Participatory Approaches" In: Rooke, J. & Dave, B., *19th Ann. Conf. of the Int. Group for Lean Construction.* Lima, Peru, 13-15 July.

Smart, P. R., Mott, D., Sycara, K., Braines, D., Strub, M., and Shadbolt, N. R. (2009). "*Shared understanding within military coalitions: A definition and review of research challenges.*" Southampton.

Stalnaker, Robert C. (2002)."Common ground."*Linguistics and Philosophy* 25: 701-21.

Star, S. L. (1989). "The Structure of Ill-Structured Solutions: Boundary Objects and Heterogeneous Distributed Problem Solving." *Distr. Artific. Int.*, 37–54.

Star, S. L., and Griesemer, J. R. (1989). "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39." *Social Studies of Science*, 19(3), 387–420.

Steen, K., and Van Bueren, E. (2017). "*Urban living labs. A living lab way of working.*" Amsterdam: Amsterdam Institute for Advanced Metropolitan Solutions.

Tang, T., and Hämäläinen, M. (2014). "Beyond Open Innovation: the Living Lab Way of ICT Innovation." *Interdisciplinary Studies Journal*, 3(4), 15.

Valkenburg, R. C. (1998). "Shared understanding as a condition for team design." *Automation in Construction,* 7(2–3), 111–121.

Van de Ven, A. H., and Zahra, S. A. (2016). "Boundary Spanning, Boundary Objects, and Innovation." *Managing Knowledge Integration Across Boundaries*, OUP.

Van Der Walt, J. S., Buitendag, A. A., Zaaiman, J. J., and Van Vuuren, J. J. (2009). "Community living lab as a collaborative innovation environment." *Issues in Informing Science and Information Technology*, 6(1), 421-436.

Van Geenhuizen, M. (2019). "Applying an RRI filter in key learning on urban living labs' performance." *Sustainability*, 11(14).

Sosa, A. A. and De La Torre, J. R. (2021). "Feasibility of Stakeholder Management to improve Integration and Communication using Big Room, Lean Construction, PMBOK and PRINCE2 in Multifamily Projects in Times of Change." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 494–503, doi.org/10.24928/2021/0180, online at iglc.net.

FEASIBILITY OF STAKEHOLDER MANAGEMENT TO IMPROVE INTEGRATION AND COMMUNICATION USING BIG ROOM, LEAN CONSTRUCTION, PMBOK AND PRINCE2 IN MULTIFAMILY PROJECTS IN TIMES OF CHANGE

Alvaro A. Sosa[1] and Jorge R. De La Torre[2]

ABSTRACT

The purpose of this article is to corroborate the feasibility of stakeholder management for multifamily projects using Big Room as the main tool and Lean Construction, PMBOK6 and PRINCE2 as management methodologies. In Peru, multifamily projects have a great lack of integration and communication between stakeholders in all phases of execution. For this purpose, a survey was conducted among engineers with expertise in construction project management with emphasis on stakeholder management and a comparative technical analysis to highlight the best of each methodology. Finally, a stakeholder management proposal was developed taking into account these changing times due to the pandemic.

KEYWORDS

Lean construction, big room, integration, management.

INTRODUCTION

Multifamily housing construction requires a well-structured management strategy by all stakeholders for the success of the project. Therefore, the problems that arise from inefficient construction project management are innumerable and must be detected and corrected in a timely manner. In addition, the paralysis of the construction sector due to the pandemic symbolized an economic downturn that was detrimental to all stakeholders involved (Zhang, X., Hou, H., Fu, Q. and Zhang, Y. , 2020). This refers to the group of people who are impacted by the company's decisions. Its management is very scarce in the construction of multifamily projects in Peru, and many reports point out that part of the problem is due to the fact that a specific plan is not prepared for the stakeholders (Vacanas, Y., Danezis, C, 2021) to know what each one is looking for and to set common objectives for the success of the project.

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Although there are many processes involved in a multifamily project and multiple conditions that one may face, it is essential to practice good management from the beginning, as well as strict control and methodical planning based on the concepts of different institutions (Matos, M., 2018).

The objective of this article is to elaborate a stakeholder management proposal to improve integration and communication using Lean Construction, "Project Management Body of Knowledge" (PMBOK 6) and "Projects in Controlled Environments" (PRINCE2) by implementing the Big Room and adapting to the stages of the construction of a multifamily project considering the limitations and health constraints that have been established in Peru due to the pandemic with the following study methodology (Figure 1).

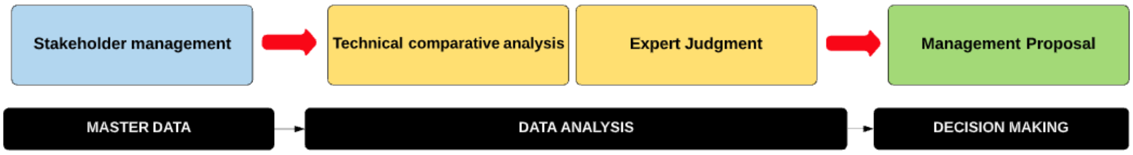

Figura 1: Study methodology flowchart.

STUDY METHODOLOGY

MASTER DATA

The information was gathered from three main sources: Lean Construction, PMBOK6 and PRINCE2. To begin with, Lean Construction has two integrative techniques that is based on how stakeholders work for project delivery which means a new method of designing and constructing buildings and infrastructure (Pons, J., and Lezana, E. 2014). On the other hand, PMBOK 6, latest edition of PMI knowledge guide (PMI, 2017), provides great inputs on management strategies. Finally, PRINCE2 is one of the most important methodologies of the APM, a British institution specialized in the accreditation or certification of organizations in the field of project management (Pico, O., 2016). Figure 2 shows the stakeholder management structure of each one.

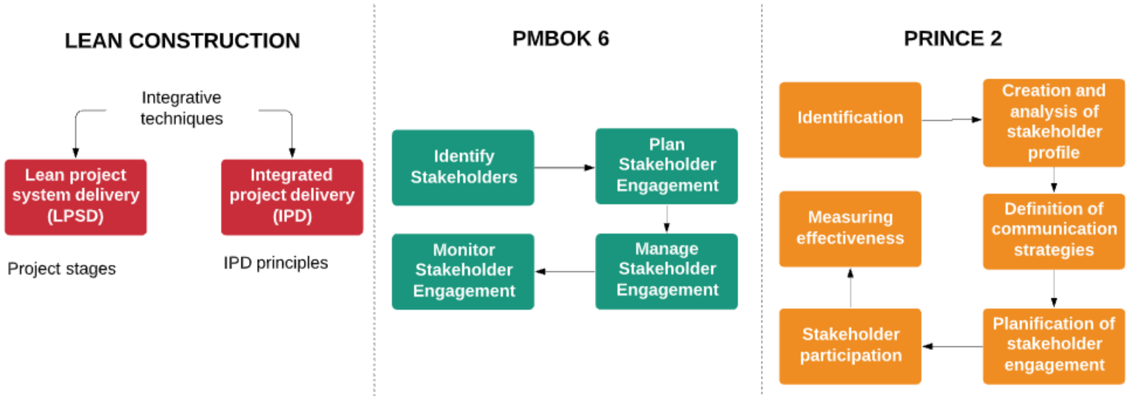

Figure 2: Stakeholder management structure of Lean Construction, PMBOK 6 and PRINCE2.

DATA ANALYSIS

A technical comparative table was made to see what each one contributes to stakeholder management. For this occasion, the table (Table 1) was prepared based on the research proposal that consists of three phases, which are as follows:

1. Identification of stakeholders
2. Stakeholder management planning
3. Execution of stakeholder management

Table 1: Technical comparative analysis

Phase	Lean Construction	PMBOK 6	PRINCE 2
1	LPSD **concisely defines** the client's propositions and the interests of all stakeholders	The **charter project** is a source of information that identifies and analyzes the impact of each stakeholder on the project.	The identification, **creation and analysis of profiles** is where the roles and responsibilities of each person are defined.
2	The **IPD principles** are promoted for good communication between each of the stakeholders. In addition, the organizational structure is planned in a **manner consistent** with the needs and constraints of each stakeholder.	The **project management plan** is presented in which approaches are developed using techniques and tools to involve stakeholders in their needs, expectations and interests.	**Stakeholder participation** is planned here by defining communication methods and strategies to encourage the involvement of all stakeholders.
3	An efficient communications plan and **the practice of IPD principles** is fundamental to the involvement of all stakeholders.	Incidents, changes, lessons learned **are addressed** to encourage **appropriate participation** by everyone	The communication and stakeholder involvement plan is **carried out** at all stages of **project implementation.**

Finally, a survey was conducted among experienced engineers and experts in the field of project management in buildings to analyze the problem in Peru and corroborate the feasibility of the research topic. Given the pandemic we are going through, this expert judgment (Figure 3 & 4) was adapted as a virtual tool using the QuestionPro platform. Expert judgment is one of the most requested and used tools in construction project management, since it allows me to corroborate all kinds of information with a certain degree of uncertainty through the opinion and support of at least 10 experts for the validity of a problem (Galicia, L., Balderrama, J. and Edel, R., 2017), so a technical survey was conducted to the experts who are 14 civil engineers.

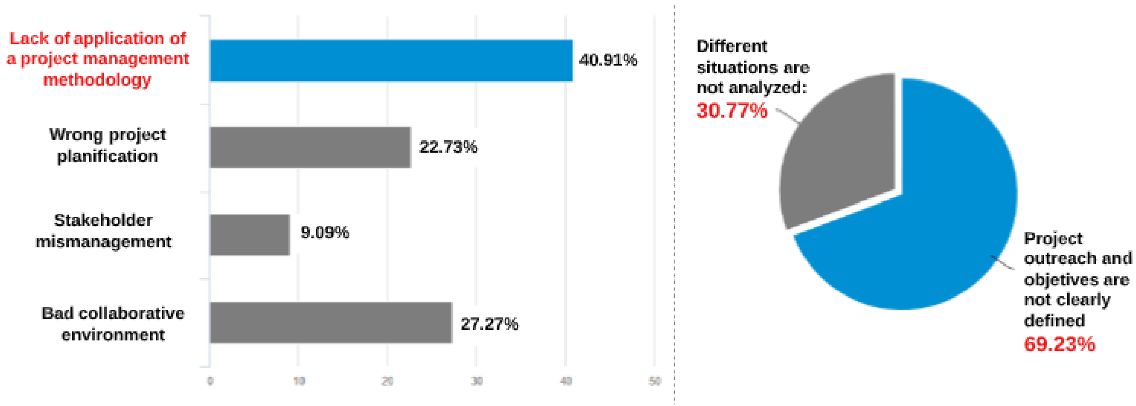

Figure 3: Most recurrent causes of inefficient multifamily project management and main problems in project planning in Peru. Adapted from QuestionPro.

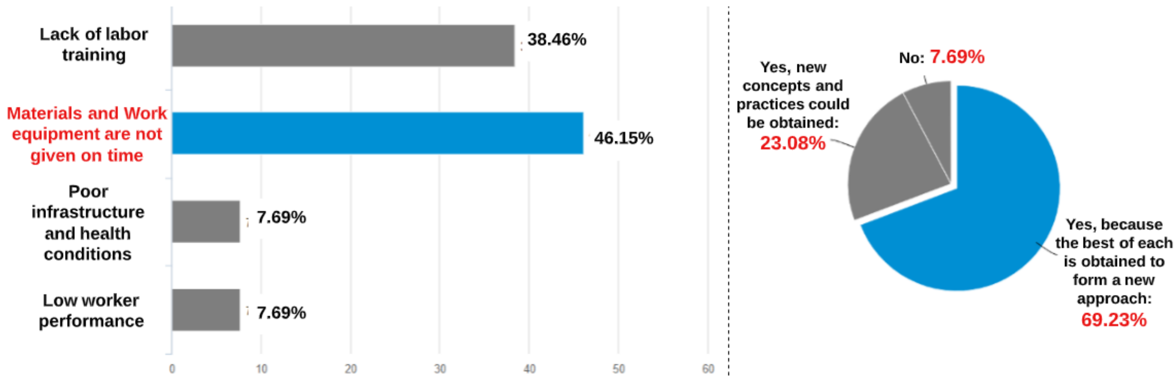

Figure 4: Reasons for poor on-site execution in multifamily projects in Peru and the percentage of feasibility of the subject of this article. Adapted from QuestionPro.

It is worth mentioning that the technical survey consisted of 16 questions, but, for the purposes of this article, only four of the most important questions were selected.

DECISION MAKING

The stakeholder management proposal is aimed at multifamily projects. Therefore, the stages of this type of projects are shown (Figure 5).

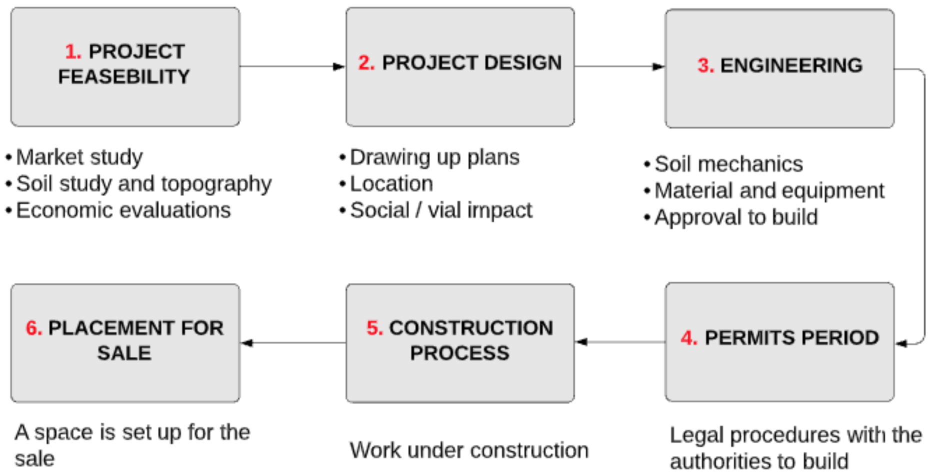

Figure 5: Stages in the construction of a multifamily project.

The following is a detailed explanation of the proposal that focuses on stakeholder management with the integration of the aforementioned study methodologies.

1. Stakeholder identification

Figure 6 shows the structure of the initial phase, which consists of the activities or documents to be carried out. For that, some techniques and tools are used to fulfill everything structured and move on to the next phase.

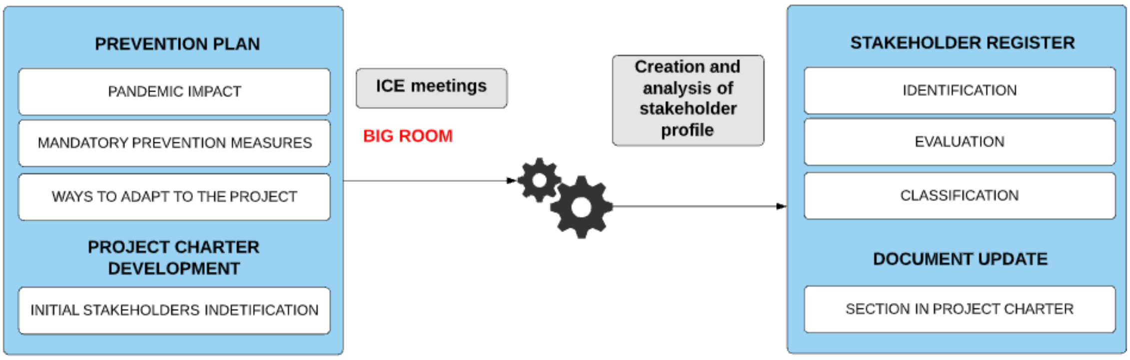

Figure 6: Structure of the stakeholder identification phase.

This phase is very important before starting with the feasibility stage of a multifamily project, since before any type of study is carried out, it is necessary to know who the team members are and what their intentions and expectations are within the project. For that, it is established to have a specific section in the project charter about the interested parties and to discuss about the new prevention measures that one has to comply with in order to work with the lowest possible risk, since the world is facing a pandemic with a very high mortality rate.

To achieve a correct registration of stakeholders, it is established to implement ICE meetings, since one of the objectives of Lean Construction is to improve the levels of collaboration. Therefore, integrated concurrent engineering (ICE) is a method that gives us an effective and reliable development of any type of engineering or design. Now, due to the pandemic, it is recommended, for this phase, to make use of the "Big Room" type of ICE meeting (Kunz, J. and Fischer, M., 2020).

Big Room is a large and orderly space that fosters a good collaborative environment. This is where the training and the elaboration of a profile of each interested party will take place, reflecting their knowledge, communication methods and their interest in the project.

2. Stakeholder management planning

An on-site prevention plan containing all of the components, shown in Figure 7, should be established to avoid any risk of pandemic infection.

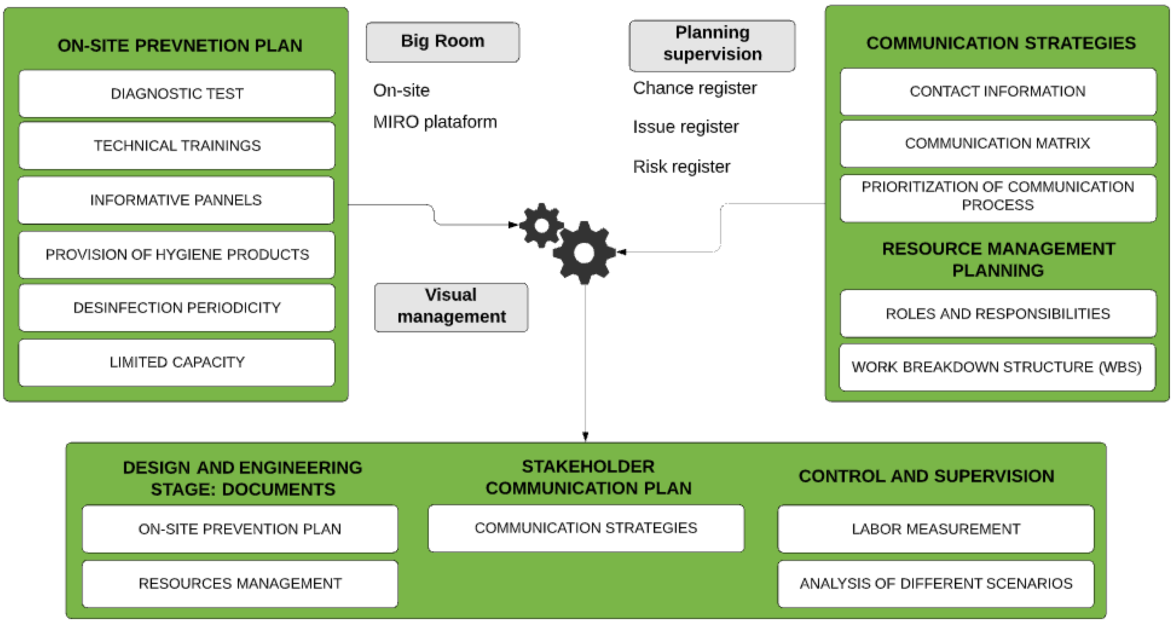

Figure 7: Structure of the stakeholder management planning phase.

For this, the organizational structure is elaborated, where it is seen who responds to whom and under what measures to avoid unnecessary meetings that raise the risk of contagion at work. Therefore, communication strategies must be defined (Figure 8), which contains contact information, a communication matrix and a degree of prioritization that helps the manager to maintain a fluid conversation with the engineer, designer, architect, main contractors and derivatives during the design and engineering stages.

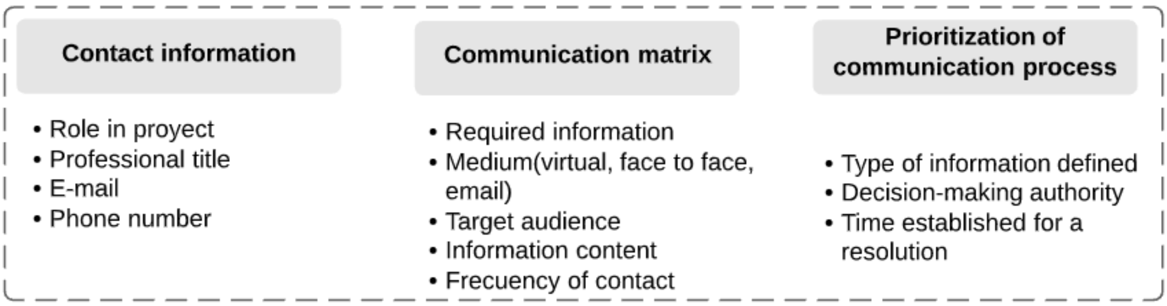

Figure 8: Content of the register of communication strategies among stakeholders.

For the development of the activities of this phase, the progress of the project planning must continue with the practice of the Big room. For strictly necessary cases, it is carried out in person taking all sanitary measures. Otherwise, virtual meetings are implemented using the MIRO platform (Figure 9).

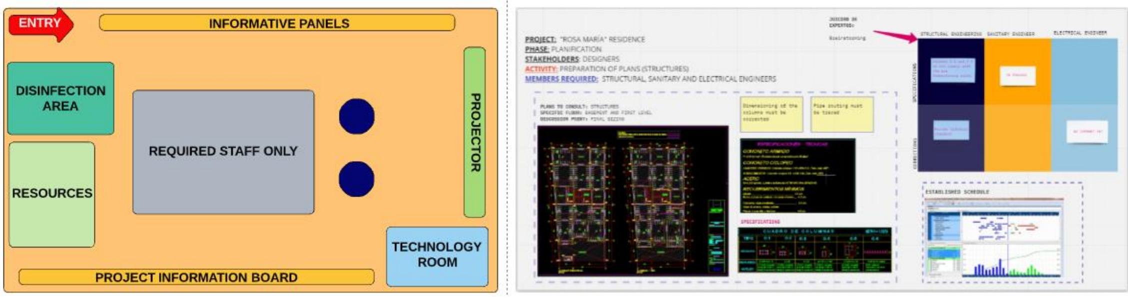

Figure 9: Proposed layout of the on-site Big Room and virtual Big Room using the MIRO platform.

MIRO facilitates the meeting between the design and engineering team to discuss planning decisions for on-site execution. In addition, the service is free, easy to access, and above all encourages the application of visual management, which is a Lean tool that helps clarify processes or other information to be visually appealing and simple to understand.

The novelty of this phase is that a control and follow-up is applied through a series of records mentioned in Figure 7, which helps to measure the work done in order to report any type of incident or risk, and make changes if necessary, taking into account different scenarios.

3. Execution of stakeholder management

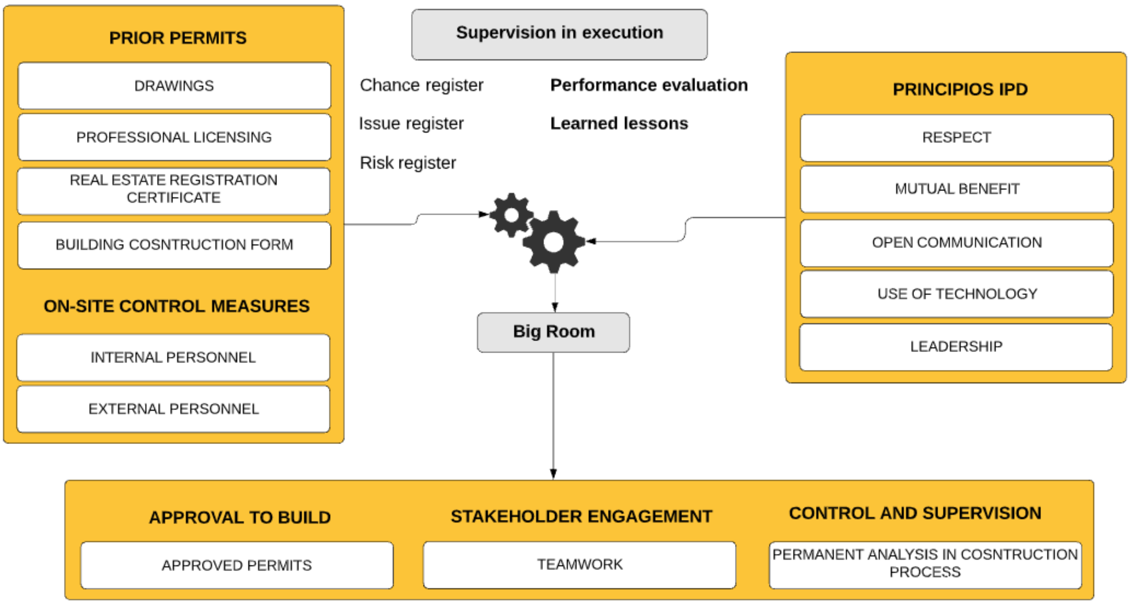

Figure 10: Structure of the execution phase of stakeholder management.

According to Figure 10, all documents must be in order since they must be reviewed by the district municipality of the project location in order to start the construction process without inconveniences.

Integrated Project Delivery (IPD) contains a series of very important principles for the correct execution of a construction project. The engineers interviewed emphasize that the poor collaborative environment that exists in construction companies is synonymous with poor management in Peru. Therefore, these principles help to form leaders regardless of the position one holds. Respect, good communication will foster a good working environment taking advantage of all the tools and technological availabilities mentioned above for a correct progress.

Everything planned in this pahse is put into practice and it is very important to comply with all the limitations set forth. Therefore, before entering the work site, a temperature control must be performed using a laser thermometer. Once this has been checked, the disinfection area must be entered, where water, soap and alcohol are required for hand and body hygiene. Finally, when leaving the disinfection area, latex masks and gloves must be provided, which must be renewed daily.

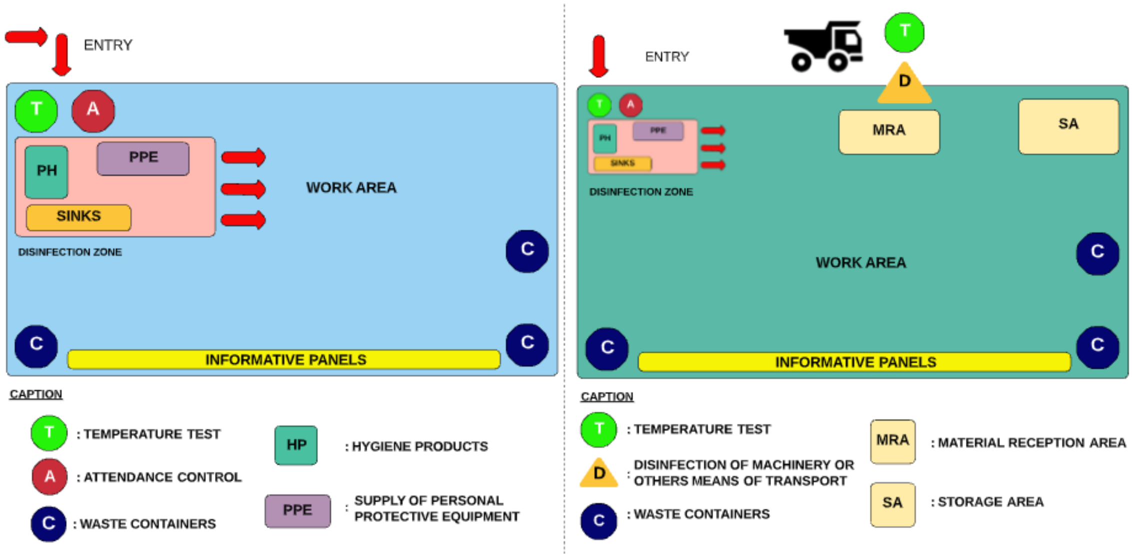

Figure 11: Proposed layout of the work area on site and layout of the materials reception area, applying preventive sanitary measures.

Figure 11 shows the proposed layout for the work areas. Now, for the internal personnel the following is established:

- Establish personnel in charge of disinfecting and cleaning work tools, materials and shared-use equipment.
- Establishment of maximum capacities in the different areas of the construction site.
- Inclusion of informative panels to make workers aware of the danger posed by the pandemic.

In the case of external personnel, the following must be complied with:

- Perform temperature control and ensure that they proceed to hand hygiene.
- Do not allow the entry of people who are not involved in the execution of activities during the working day.
- Encourage all types of documents to be delivered by digital means to ensure social distancing.

For the last stage of the construction process, a Big Room is proposed for the sales area, following the necessary sanitary measures (Figure 12).

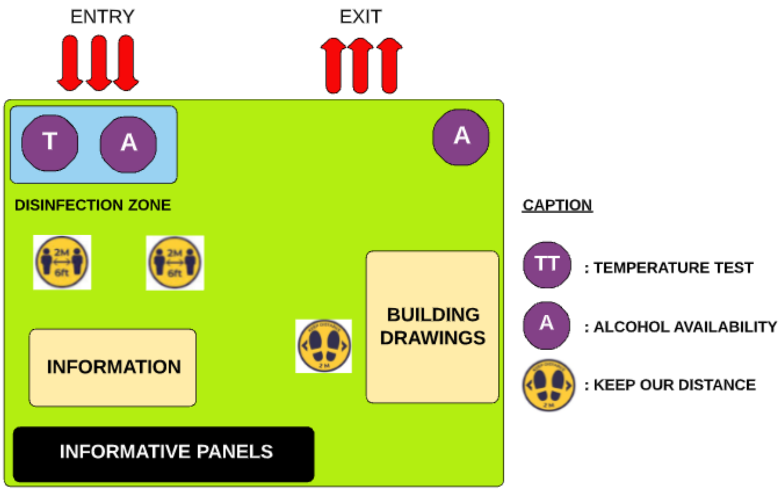

Figura 12: Proposed layout of sales area.

Finally, in this phase, monitoring and follow-up adds two records: Performance Evaluation and Lessons Learned. These reports help to evaluate the performance of the stakeholders and recognize which were the errors in the assigned activity with the objective to improve immediately and take into consideration these records for future planning of other multifamily projects.

CONCLUSIONS

The experts' opinion highlights the management problems in multifamily projects in Peru, mentioning that 68.18% of the causes of inefficient management are due to the lack of application of a project management methodology (40.91%) and a poor collaborative environment (27.27%).

Inefficient planning development and poor execution of a multifamily project in Peru is mainly due to project scope and objectives not being clearly and concisely defined (40.91%) and equipment and work materials not being delivered on schedule (46.15%) respectively.

In the three phases of the proposal, the practice of face-to-face and virtual Big Room (MIRO platform), type of ICE meeting, is established, since it promotes order and speed to make decisions in any situation that may occur during the development stages of a multifamily project.

The constant monitoring of the activities established in the proposal with the established records allows them to analyze the different scenarios during a multifamily project. That is, it helps to identify any type of incident or underperformance of the stakeholder to take corrective action quickly and effectively.

The stakeholder communication plan, shown in phase 2 of the proposal, represents the use of communication strategies in a registry that allow for greater fluidity and integration among each stakeholder.

The feasibility of stakeholder management in multifamily projects in Peru applying the mentioned methodologies and the use of the Big Room as the main tool is 92.31%, since the best of each one is obtained (69.23%) and new concepts and practices are established (23.08%) to formulate a new approach in these times of change as stated in our proposal.

REFERENCES

Galicia, L., Balderrama, J. and Edel, R. (2017). "Validez de contenido por juicio de expertos: propuesta de una herramienta virtual". *Apertura (Guadalajara, Jal.)*, *9*(2), 42-53. doi.org/10.32870/ap.v9n2.993.

Kunz, J. and Fischer, M. (2020). "Virtual design and construction, Construction Management and Economics", doi.org/10.1080/01446193.2020.1714068.

Matos, M. (2018). "Sistema de gestión de proyectos de construcción basado en la filosofía Lean y en el PMBOK para mejorar su productividad". (Tesis de Magister). *Universidad Privada del Norte, Perú.*

Pico, O. (2016). "Los stakeholders como actores estratégico-instrumentales en los proyectos de la nueva gestión pública". (Master interuniversitario en dirección de proyectos). *Universidad de Oviedo, España.*

Pons, J. and Lezana, E. (2014). "*Introducción a Lean Construction"*. Madrid: Fundación Laboral de la Construcción.

Project Management Institute (2017). "La guía de los fundamentos para la dirección de proyectos (Guía del PMBOK)". Newtown Square, PA. PMI sexta edición.

Vacanas, Y. and Danezis, C. (2021). "Determination of effective delay-avoidance practices in cosntruction projects". Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 13(1) doi.org/10.1061/(ASCE)LA.1943-4170.0000438.

Zhang, X., Hou, H., Fu, Q. and Zhang, Y. (2020). "Current Problems and Restructuring Suggestions for Smart City Construction: A Case Study on Fight Agaisnt COVID-19 in Several Chinese Cites". ACM Internacional Conference Proceeding Series, 64-69. doi.org/10.1145/3414752.3414803.

Kallassy, J. and Hamzeh, F. (2021) "Developing a Lean Culture Index in Construction" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 504–513, doi.org/10.24928/2021/0192, online at iglc.net.

DEVELOPING A LEAN CULTURE INDEX IN CONSTRUCTION

Jessica Kallassy[1] and Farook Hamzeh[2]

ABSTRACT

Metrics and indices have become commonly available for construction planners in general, and Lean practitioners in particular, to evaluate and control their projects' performance. Amidst the ample availability of such measures, the fight against specious Lean implementation in different construction firms has been the concern of many researchers. In order to address this issue, and in an attempt to provide practitioners with new methods to assess the Lean culture, this research develops a Lean Culture Index that can be used to measure Lean culture and the readiness of an organization to apply Lean. It presents a comprehensive model to assess Lean culture, and it can be used as a basis for future models of Lean implementation. It also provides practitioners with a diagnostic tool that measures where areas need further improvement. The paper utilizes a thorough literature review to identify features of Lean culture. Then, a survey is conducted to assess the derived features. Analysis of the data revealed that although surveyed construction companies showed some relation to Lean culture such as flexibility and consistency, there is still room for improvement in areas such as training and human focus. The study is capped with recommendations and conclusions.

KEYWORDS

Lean construction index, lean culture, organizational culture.

INTRODUCTION

In a rapidly changing world, predicting upcoming changes is an impossible feat, and researchers believe that the velocity of change will continue to increase exponentially (Cameron 2003). For example, only sixteen out of one hundred large firms listed on Fortune magazine have survived since the early 1900s, which highlights the necessity for companies to update their systems in order to maintain their competency (Cameron and Quinn 2005). Although several companies are introducing new management concepts, most of them fail in implementing them due to their internal culture (Kotter 1996, Wandahl 2014). Therefore, it is important to understand the organizational culture within these companies and reshape them accordingly to embrace implement new systems successfully.

Several companies choose to adopt Lean construction (LC) as a new management concept within their companies. The major benefits of LC according to practitioners are reductions in construction time and overall project cost, increase in productivity,

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improvement in product quality, and increase in customer satisfaction (Bernstein and Jones 2013, Hamzeh et al. 2016). Despite the mentioned benefits of LC implementation, several companies have failed in implementing LC due to the LC concepts being applied in a superficial manner by the company, or the concepts being inconsistent or conflicting with the existing organizational principles. That is why these attempts end up by being just a short-lived fad (Simonsen et al. 2014).

Ettore (1997) illustrated the five life cycle stages of new management concepts. The first phase is the discovery of the new management concept where people become aware of it from publications, advertisement, or other companies. In the second phase, these new management concepts gain momentum and are discussed more frequently among the enterprise. In the third phase, the concepts are further studied, analyzed, and criticized. Accordingly, the number of people interested in these concepts begins to decrease in phase four until only a small group keeps on supporting them towards the fifth phase. The lifecycle of a new management concept varies depending on its popularity and the readiness of the company to implement new management systems (Simonsen et al. 2014). Although companies usually focus on attaining results within a short time period, Emiliani (1998) stated that for an organization to properly achieve Lean behavior, it needs at least five to ten years of continuous work and commitment. Moreover, managerial boards and teams tend to rush the implementation of LC concepts without performing the required cultural changes nor embracing the lean philosophy (Shook 2010).

The goal of this research is to understand Lean culture as the primary step to its successful implementation. Accordingly, a Lean Culture Index (LCI) is developed to reflect the construction firms' Lean culture level. This index is then applied to medium and large-scale construction firms to help in assessing their existing culture and compare it to the Lean culture. After culture assessment, recommendations related to cultural change are given as a foundation for successful lean implementation.

LITERATURE REVIEW

ORGANIZATIONAL CULTURE

The culture of an organization comprises many facets reflected through the adopted leadership style, work procedures, communication languages, and corporate logos and slogans. Additionally, the shared beliefs, values, and assumptions held by members of an organization define its culture, and they are usually the result of unwritten and unspoken rules shared among employees. This common culture is best manifested through people's behavior over the years. When a behavior is rewarded, employees usually repeat it and make it part of the organizational culture (Cameron &Quinn 2005). Schein (2010) divides the organizational culture into three levels. At the surface level are the artifacts, which include all the visible elements that can be seen, heard, and felt. Beneath artifacts lies the second level comprising the firm's espoused beliefs and values. They are the beliefs upon which the company is built and are then developed into its code of conduct. The third level includes the basic underlying assumptions which are the foundations on which a company's culture is based. These assumptions consist of unconscious thoughts, beliefs, perceptions, and feelings; in other words, they reflect the way through which "things are done around here". Because these basic assumptions are neither discussed nor written and are difficult to pinpoint, changing them is extremely difficult.

Several studies have reported that the main reason behind failure when applying changes to an organization or introducing new management systems is the neglect of the organization's culture. The most common organizational changes applied are Total Quality Management (TQM) initiatives, downsizing initiatives, and reengineering initiatives (Cameron 1997). TQM was developed to increase effectiveness by delivering a higher quality product, yet several studies have shown that most firms did not successfully implement this initiative. On the other hand, some companies opt for downsizing initiatives to improve productivity, efficiency, competitiveness, and effectiveness. However, results have shown that the trust, morale, and productivity of personnel suffered after implementing this initiative (Cameron 1997). The same outcomes were observed for the application of reengineering design. Cameron (1997) concludes that the failure of those three initiatives is related to them having the same organizational culture where they focus on applying mere techniques rather than on changing their organization values, direction, goals, and culture.

The reason why organizational culture has been ignored throughout the years is that people remain bound to the definition, underlying assumptions, and unwritten guidelines of a company (Cameron & Quinn 2005). In fact, people usually do not like change; they prefer to stick to their old habits, doing the same thing every day (Zammuto & Krackower 1991). In other words, having the same organizational culture provides stability to employees and implementing any change is faced with rejection and fear.

DIFFERENT TYPES OF ORGANIZATIONAL CULTURE

Organizational culture has taken different attributes and dimensions. Several authors have defined culture but they place their own set of attributes. This large and varying number of attributes is due to the extremely broad and vague set of factors constituting the organizational culture. Cameron and Quinn (2005) have developed a framework that includes the most important factors that define a culture. The main factors are related to people: how they think, interact, and resolve problems based on their values and assumptions. After several studies, Cameron and Quinn (2005) came up with frameworks that include four clusters: adhocracy, clan, hierarchy, and market. Each one of these clusters defines a cultural type. An adhocracy, in a business context, is a corporate culture based on the ability to adapt quickly to changing conditions. A single visionary usually leads the adhocracy culture without a need for formal policies. The glue that holds the organization together is commitment to experimentation and innovation. Therefore, the challenge is to create something new to maintain the competitive edge. That is why leaders are usually creative, entrepreneurial, and risk oriented. When the company grows, its culture starts to resemble a clan culture. Under the clan culture, the company becomes similar to a family-type organization, where employees share the same values and goals and feel a sense of belonging to the company. The main features of a clan are mainly teamwork, employee involvement, and top management support with a main focus on its people. When the organization grows even more, rules and regulations become a must to control the work environment, making the company resemble a hierarchical culture which is usually characterized by formal structures and procedures. The main purpose of formalizing the cultural structures and procedures is to maintain a stable and predictable output. When personnel shift from a clan to a hierarchal culture, they lose the feeling of belonging to a family and, consequently, their personal satisfaction decreases. As the company gets oriented toward external affairs rather than internal ones, it takes the form of a market culture. The main features of a market culture are competitiveness and productivity with the main goal of generating more money. Under this market, leaders are usually competitors and makers (Cameron and Quinn 2005).

METHODOLOGY

The research methodology used in this study is Design Science Research (DSR). DSR offers an alternative approach for understanding, solving practical problems, and evaluating innovative artifacts in construction management as it bridges the gap between theory and practice (Khan & Tzortzopoulos 2018). Since DSR requires the creation of an innovative artifact relevant for both practitioners and academics, the artifact must be well presented, coherent, and internally consistent (Hevner et al. 2004). The research procedure of this study comprises the following steps. First, a thorough literature review is conducted to understand the organizational culture on the one hand, and derive the features of lean culture on the other hand. Then, a questionnaire is designed according to the derived features. Afterwards, the questionnaire is pilot tested before getting administered through structured face-to-face interviews with employees at several construction companies. The resulting data collected from the questionnaires is then statistically analyzed and discussed. Finally, conclusions and recommendations are put forth towards a better implementation of lean culture within construction firms.

QUESTIONNAIRE DESIGN

In order to assess the current organizational culture in Lebanon, a questionnaire was prepared to collect the necessary data for this study. The survey is divided into two main parts; the first part comprises questions aimed at gathering general information, and the second part presents questions that help assess the existing culture at Lebanese construction firms. The survey contains 60 statements which participants must rate, on a Likert scale (1 to 5), the extent of which those statements are adopted in their company. The first draft of the survey was pilot tested and then adjusted accordingly. In the general information part, the questions focus on the role of the participant in the company and years of experience, the company's size and its years spent working under lean principles (if applicable). The focus is to differentiate mainly between the responses of white/blue collar employees and between the company size (medium /large). The second part of the questionnaire contains 60 statements. Each statement targets one or more of the 48 features of Lean Culture shown in figure 1 which derived from the thorough review of research on lean and its applications.

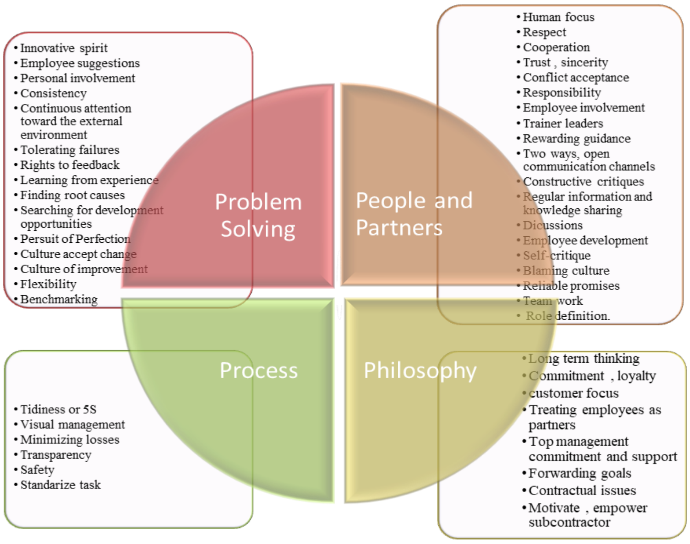

Figure 1: Lean Features according to the 4P model inspired from Liker 2004.

DATA COLLECTION

Structured face-to-face interviews were conducted to administer the questionnaires to employees on construction sites. Twenty construction sites representing twenty different companies were visited in different Lebanese districts. The selected companies include 10 large-scale and 10 medium-scale companies. During the interviews, the purpose of the study was first clearly described, and the anonymity of the survey was continuously emphasized on to avoid any hesitancy in responding. Then, all the survey questions and statements were thoroughly explained to the participants, and the questionnaires were administered in the same manner to all participants to avoid biases. On most sites, the questionnaires were administered in groups of four to five white-collar employees. On the other hand, it was hard to group blue-collar employees, so questionnaires were administered individually. The total number of completed surveys was 109 divided into 77 surveys completed by white-collar employees and 32 completed by blue-collars. The difference in the number of completed surveys between the two groups is due to having less foremen (blue-collar employees) on site than the number of engineers (white-collar employees).

DATA ANALYSIS AND DISCUSSION

COMPARING BLUE AND WHITE-COLLAR EMPLOYEES

The responses given by the blue and white-collar employees that were interviewed were averaged separately. To check for any significant differences between the answers given by the blue- and white-collar employees for each company, the non-parametric Mann-Whitney U-test was applied. The test results showed a clear difference between the responses of the white- and blue-collar employees. In sixteen out of twenty companies, the blue collars tend to score higher than the white-collar employees. This difference could be attributed to the blue-collar employees tending to overemphasize the lean culture or possibly not trusting that the survey is anonymous.

ASSESSING THE FEATURES OF THE LEBANESE CONSTRUCTION CULTURE

Each question in the survey addresses one feature of lean culture as discussed earlier. To assess the current Lebanese construction culture, a box plot was generated for each of the 60 questions. Since the results of the blue-collar employees were inflated and reflected that they overemphasized the lean culture, only the answers given by white collars (77 respondents) were taken into consideration. Additionally, since most of the questions have a median of three, only the questions having high variability, low variability, a median less than three, and a median greater than four were taken into consideration. In order to know which features in the Lebanese construction culture are related to lean culture, the questions that have a median of four and above were considered in addition to those questions having low variability with a median of four. On the other hand, for the purpose of identifying the features that need to be improved for a better implementation of lean construction in Lebanon, questions having a median less than three were considered. Furthermore, questions having large variability were taken into consideration as they reflect the existence or absence of the lean features within the investigated companies. Accordingly, a one-sample sign test was conducted to check if the median values of the questions rank three and above. The p-values and a brief discussion on each question are shown in Table 1. The topic of each question is highlighted in bold in table 1.

Table 1: Sign test for specific questions

	Ques tions	Null Hypothesis	Sign test + p-value	Decision	Topic Discussion
High variability	Q19	Population median of question 19 = 3	p-value = 0.410	Fail to reject H0	**Employee development**: some companies invest in the development of the employees' skills
	Q23	Population median of question 23 = 3	p-value = 0.2	Fail to reject H0	**Pursuit of perfection**: some companies have annual reviews to measure improvement, others do not.
	Q30	Population median of question 30 = 3	p-value = 0.519	Fail to reject H0	**Benchmarking**: some companies benchmark other top performers
	Q31	Population median of question 31 = 3	p-value = 0.081	Fail to reject H0	Only some companies pay **attention to the external environment**
	Q43	Population median of question 49 = 3	p-value = 1	Fail to reject H0	**Self-critique**: not all employees do their own self-evaluations.
	Q49	Population median of question 49 = 3	p-value = 0.220	Fail to reject H0	**Tolerating failures**: some employees try to hide mistakes instead of fixing them.
Low variability	Q28	Population median of question 28 < 3	p-value = 1.957e-10	Reject H0	**Flexibility**: the company can respond rapidly to the changes implemented by the owner.
	Q34	Population median of question 34 < 3	p-value = 2.135e-11	Reject H0	**Treating employees as partners** : people in the organization take pride in the company's products and services.
Median < 3	Q5	Population median of question 5 < 3	p-value = 1	Fail to reject H0	**Trust:** respondents do not trust the promises made by their subcontractors.
	Q14	Population median of question 14 < 3	p-value = 0.997	Fail to reject H0	**Training**: shows the companies' lack of training for their employees.
	Q32	Population median of question 32 < 3	p-value = 0.9818	Fail to reject H0	**Human focus**: respondents agreed that companies do not value employees.
	Q48	Population median of question < 3	p-value = 1	Fail to reject H0	**Blaming culture**: respondents agreed that the culture leans towards blame.
	Q50	Population median of question 50 < 3	p-value = 0.9991	Fail to reject H0	**Tolerating failures**: respondents agreed that employees feel that a shortcoming is someone else's responsibility
	Q59	Population median of question 59 < 3	p-value = 1	Fail to reject H0	**Contracts**: respondents agreed that contracts are written in a way that put the parties in adversarial relationship.
Median > 4	Q16	Population median of question 16 >4	p-value = 5.551e-16	Reject H0	**Consistency**: respondents agreed/ strongly agreed that the company strives to deliver same/better-quality product.

EVALUATING THE DIFFERENCE IN 4P'S

Each question in the survey reflects one of the 4P's of the Toyota Way. 9 questions are related to the Philosophy, 10 questions are related to the Process, 21 questions are related to People and Partners, and 20 questions are related to Problem Solving. A total of 77 averages were calculated for each P. Those averages were statistically analysed to establish if the four Ps are significantly different from each other. The Kruskal-Wallis non-parametric rank sum test was performed, and the test results provided enough evidence to reject that the four Ps are equally ranked. To identify which groups are significantly different from the others, the pair wise Wilcox test with holm as the adjusted p-value was applied. The results showed that Process was significantly higher than Philosophy, People and Partners, and Problem solving with a 90% confidence interval.

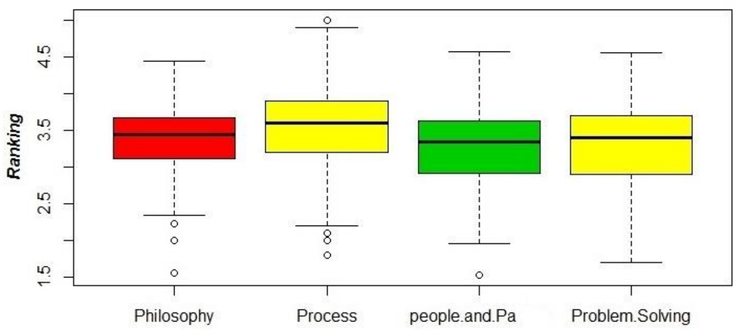

Figure 2: The distribution of the 4P's for white-collar participants

As figure 2 shows, the findings indicate that the interviewed companies tend to focus on the Process more than the other P's because engineers are usually more goal-oriented, believing that they can fix everything related to the process without realizing that the process is founded upon main pillars such as philosophy, people and partners, and problem solving. Liker (2004) states that "it's the people who bring the system to life", reflecting the need for companies to invest in their people by providing employees with the appropriate safe environment not only related to on-site safety, but also where employees feel that they have a secure job. Moreover, companies must value their employees and provide them with a long-term career path alignment along with the necessary training and education. Also, companies must involve employees in decision-making, listen to their suggestions, and implement them. Companies should also provide incentives to their employees to enhance the motivation of the employees who will better contribute to the growth of the company. On the other hand, employees, regardless of their role, seniority, and position, must learn to respect and treat each other equally.

Enhancing the Process facet alone is not enough to bring about the desired change; companies need to constantly upgrade their underlying systems for continuous improvement. Therefore, companies should encourage their employees to innovate and find better ways to deliver a product or service. Firms can also enhance their systems by building a culture where employees learn from failure and see the latter as an opportunity to avoid future mistakes as well as progress their experience rather than placing the blame on others. In addition, standardizing the best practices and continuously improving them can reduce wastes resulting from inefficient systems. Similarly, management and employees should accept and implement constructive feedback received internally and externally towards expanding their horizons and continuously improving their system.

At the core of enhancing both the processes and underlying systems is the need for employees to understand the fundamental philosophy behind them. Based on this premise, companies should work on growing and aligning the whole organization towards a common purpose and a shared view of a desired future state. This purpose and common vision should be clearly understood by and shared among all employees of the organization and lived out over a worth-while period of time. These efforts and endeavors carried out by the company should be favored over monetary gains. Moreover, decisions of firms and their derived methods must be based on a long-term philosophy even if it comes at the expense of short-term financial goals. People, regardless of their hierarchical level and role at the firm, should derive satisfaction and a sense of accomplishment from their involvement and participation at work. Finally, companies must respect their partners and aim towards a continued return business with them.

Although the authors tried to dissect the elements of the 4P's, the elements are highly interrelated. For instance, companies depend on people to reduce waste that results from an inefficient process. Companies also depend on people to identify problems and fix them, which defines the problem-solving process. In fact, none of this can be accomplished without investing in the future of these employees and establishing a shared vision, which embodies the philosophy aspect.

LEAN CULTURE INDEX (LCI)

This research developed a Lean Culture Index (LCI) to assess the readiness or not of any company to implement lean by understanding its culture. For this reason, the survey was tailored to deduce the LCI. Each question in the survey is related to one feature of lean as discussed earlier. For each white-collar respondent, the results of the 60 questions were averaged. Then for each company, the total averaged answers given by its white-collars were averaged to come up with one value representing the company's LCI. The proposed LCI measures the lean culture and the readiness of a firm to apply lean. An LCI scoring model (Table 2) classifies the lean maturity of construction firms.

Table 1: LCI scoring model for classifying lean maturity within Lebanese construction companies

Average Score	Interpretation	Large scale companies	Medium scale companies
<180	Companies are not yet ready to implement lean.	-	N (154.00) O (179.50) P (150.33) S (178.00)
181-210	Excessive changes in the company are needed before implementing lean	A (195.75) B (198.00) C (202.50) E (192.60) F (205.25) G (201.75) H (208.75) J (196.25)	L (194.00) M (203.50) Q (189.50) R (190.50) T (203.67)
211-240	Several improvements in the company are needed before implementing lean	D (235.17) I (224.00)	K (227.70)
241-270	Companies are ready to implement lean	-	-
271-300	Companies are already applying lean well	-	-

As reflected in Table 2, most of the large-scale companies have LCI scores ranging between 181 and 210, so they need excessive system changes before implementing lean. On the other hand, only two companies out of ten need several improvements before implementing lean. For the medium scale companies, most of them scored an average LCI between 181 and 210. Thus, excessive changes in these companies are needed before implementing lean. Furthermore, an alarming 40% of these companies are not yet ready to implement lean. As a conclusion, the results of the conducted questionnaires in the twenty Lebanese construction firms revealed that most of them need excessive changes before they are ready to successfully implement lean and adopt its culture.

RECOMMENDATIONS

Based on the outcomes of studying the existing Lebanese construction culture as per the highlighted results in table 1, some culture-related improvements are hereby provided to guide a better implementation of lean construction in Lebanon. First, employees should receive the necessary training to foster their skills and lean knowledge even if such training programs are time and cost consuming. In fact, their implementation is crucial for continuous improvement and the long-term benefits can outweigh the initial monetary and time investments. Second, engineers and foremen have doubts in the promises made by subcontractors. Without trust, people cannot exercise reliable promises. Therefore, companies must focus on changing the behavior of people, adopting new ways of thinking, and fostering the relationship with subcontractors before implementing the LC tools. This would also help in gaining competitive advantage in the market place. As a third step, companies must invest in, challenge, and retain productive employees. When employees feel valued and engaged, they are more likely to stay within the organization which, in turn, decreases the firm’s turnover rate. Fourth, the most important cultural change is to have a “no blame” culture. This is important when teams are learning from failures. Thus, problems must be seen as learning opportunities to improve conditions instead of placing blames. The project teams must identify the root causes of construction problems and learn from failures to avoid repeating the same mistakes. This will help in reducing of waste and achieving continuous improvement. Fifth, traditional contracts adopted in Lebanon are designed in a manner that puts the involved stakeholders in adversarial relationships. To better apply lean construction, relational contracts should replace the traditional adversarial ones. These types of contracts are based on the relationship of trust between the different involved parties aiming to facilitate the resolution of conflicts (Colledge, 2005). Finally, companies should apply benchmarking strategies to measure the performance of an organization against other similar organizations to achieve higher performance levels. Companies should learn best practices followed by others to introduce breakthrough improvements of their own. Moreover, companies should also be aware of the achievements within their external environment (regional and international companies). This ultimately pushes companies to innovate and continuously improve their systems to maintain their competitive edge within the market.

CONCLUSION

A Lean Culture Index (LCI) is developed to evaluate the lean culture and the readiness of construction companies to apply Lean. The LCI helped in assessing the lean culture in companies and provided a clearer orientation as to where to look at and what aspects to consider for culture-related improvements. Ultimately, assessing the existing culture of firms and highlighting the drawbacks can help bring the necessary changes to better apply lean construction in Lebanon. To achieve the above, it was important to first derive the features of Lean Culture. A questionnaire was then prepared based on the fifty derived features of Lean. After conducting structured face-to-face interviews with employees of several Lebanese construction firms of different scales, the data was collected and analyzed. Some of the obtained results include the fact that Lebanese construction companies show some relation to lean culture such as flexibility and consistency, but there is still room for improvement in areas such as training, trust, human focus, and type of contracts. Furthermore, the Lebanese culture does not tolerate failures and leans towards a blaming culture. Additionally, companies usually focus on the process more than the other P’s of the Toyota Way, since engineers are usually goal oriented and believe that they can fix everything related to the process and operations; however, they fail to realize that behind the process lie the foundation stones of the pyramid: the philosophy, people and partners, and problem solving. Finally, after measuring the LCI, results revealed that most of the large-scale companies need excessive changes in their company before implementing LC. Some culture-related improvements were suggested for better implementation of LC in Lebanon. Companies should invest in the development of employee skills and provide trainings. By doing so, the behavior of people would change, and trust would increase. Furthermore, employees must see failures as an opportunity to learn and improve towards reaching a "no blame" culture. Moreover, companies should use benchmarking and learn from the success of others to introduce breakthrough improvements.

REFERENCES

Bernstein, H. M. & Jones, S. A. (2013). Lean construction: Leveraging collaboration and advanced practices to increase project efficiency. *Intelligence, McGraw Hill Construction, Bedford, MA.*

Cameron, K. S. (1997). Techniques for making organizations effective: Some popular approaches. *Washington DC: National Research Council.*

Cameron, K. S. (2003). Ethics, virtuousness, and constant change. The Ethical Challenge: How to Lead with Unyielding Integrity. Jossey-*Bass, San Francisco, CA, 185-194.*

Cameron, K. S., & Quinn, R. E. (2005). Diagnosing and changing organizational culture: Based on the competing values framework. *John Wiley & Sons.*

Colledge, B. (2005). Relational contracting: creating value beyond the project. *Lean Construction Journal*, 2(1), 30-45.

Emiliani, M. L. (1998). Lean behaviors. *Management Decision,* 36(9) 615-631.

Ettorre, B. (1997), "What's the next business buzzword?", Management Review, 86(8)

Hamzeh, F., Kallassy, J., Lahoud, M., and Azar, R. (2016). "The First Extensive Implementation of Lean and LPS in Lebanon: Results and Reflections." In*: Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, Boston, MA, USA, pp. 33–42.

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research. MIS quarterly, 75-105.

Kenny, M., & Florida, R. (1993). Beyond Mass Production: The Japanese System and Its Transfer to the US New York: Oxford University.

Khan, S. & Tzortzopoulos, P. (2018). Using Design Science Research and Action Research to Bridge the Gap Between Theory and Practice in Lean Construction Research. In *Proceedings of the 26th Annual Conference of the International Group for Lean Construction*, Chennai, India, 209-219.

Kotter, J. P. (1996). *Leading Change*. New York: Harvard Business School Press. 187.

Liker, J.K. (2004). The Toyota Way- 14 Management Principles from the World's Greatest Manufacturer. New York: McGraw Hill.

Schein, E.H. (2010): Organizational culture and leadership, Jossey-Bass Publishers, San Francisco, 4th ed.

Simonsen, R., Thyssen, M.H. & Sander, D. (2014), Is Lean Construction Another Fading Management Concept? In *Proceedings of the 22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway, 85-96.

Shook, J. (2010). How to Change a Culture: Lessons From NUMMI, *MIT Sloan Management Review*, 51(2) 63-68.

Wandhal, S. (2014). Lean Construction with or without Lean–Challenges of implementing Lean Construction. In *Proceedings of the 22nd Annual Conference of the International Group for Lean Construction,* Oslo, Norway, 97-108.

Zammuto, R.F., & Krakower, J.Y. (1991). Quantitative and Qualitative Studies in Organizational culture. *Research in Organizational Change and Development*, 5, 83.

Perez-Apaza, F., Ramírez-Valenzuela A., and Perez-Apaza, J. D. (2021). "The Toyota Kata methodology for managing the maturity level of Last Planner® System" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 514–523, doi.org/10.24928/2021/0194, online at iglc.net.

THE TOYOTA KATA METHODOLOGY FOR MANAGING THE MATURITY LEVEL OF LAST PLANNER® SYSTEM

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ABSTRACT

The implementation of the Last Planner® System (LPS) generates reliable production flows in construction projects and improves the competitiveness of companies that adopt the system. Research shows a greater number of implementations in construction companies and also recognizes that the effectiveness of LPS in projects is not achieved due to partial, short-term implementations, and without continuous feedback. This paper describes a proposal for managing the LPS maturity level with the objective of implementing all the components of the methodology and developing the project organization. It proposes the use of a method based on the LPS maturity model proposed by the Lean Construction Institute and the Toyota Kata methodology, described by Myke Rother, to help organizations achieve improvement actions. The proposed methodology was evaluated in a case study and the results were compared based on literature regarding the level of adoption of the organizations implementing the LPS components. The results and indicators obtained were compared with studies on the implementation of LPS in projects.

KEYWORDS

Last Planner® System, lean construction, continuous improvement, toyota kata, maturity.

INTRODUCTION

The Last Planner® System (LPS) has been successfully implemented in construction to increase planning reliability, improve production performance, and create a predictable workflow (Hamzeh 2009). LPS is also considered as the gateway for the adoption of Lean culture in organizations. (Fauchier et. al 2013).

For Ballard and Tommelein (2016), the LPS is a system of interconnected parts and omitting one of the parts destroys the ability of the system to perform its functions. However, studies by Daniel (2017) and Lagos (2017) show that LPS implementations are short-term and partial with the components with the highest adoption being: Weekly work planning, Analysis of causes of non-compliance, and Percent Plan Complete (PPC). It also requires a human component as described by Fernandez-Solis et al. (2018) in their

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study on challenges in LPS implementation where they mention: lack of training, resistance to change, lack of leadership, and lack of experience in use.

The frameworks to obtain benefits from the implementation of LPS, (e.g. Hamzeh 2011; Ballard 2016; Daniel 2017; Mossman 2017), are divided into three stages: First stage (before the start of the project), in which the seeks to involve the senior managers of the company, configure the LPS for the project and have the necessary resources; second stage (during project execution), start with a pilot test, show the benefits of LPS, involve, train and empower team staff, it is also important to measure the effectiveness of the implementation and improve it; third stage (after project closure), manage knowledge for future projects and contribute to the community by publishing their best practices. During these stages, it is important to perform implementation maturity measurements to make decisions and improve the system (Daniel 2017). In the second stage, the teams initiate the application of LPS in the projects and require methodologies that achieve the success of the implementation.

The methodology for proper implementation should include tools to measure the level of implementation of LPS (Ballard and Tommelein 2016; Daniel 2017). In the literature review, three assessment proposals have been identified: the first, proposed by the GEPUC, which proposes the degree of implementation of LPS based on the Planning Best Practice (PBP) (Lagos 2017); the second, proposed by Daniel (2017), who proposes to use the assessment based on the PBP and assessing the implementation of LPS on projects developed by Lean Project Consulting; the third, proposed by the Lean Construction Institute (LCI 2016), which proposes an assessment of the level of maturity of LPS and other aspects for the adoption of the Lean culture in the organization. It also establishes a measure of progress based on maturity levels, which brings a greater degree of objectivity to the results (Nesensohn 2014).

The LCI has developed the "LCI Lean IPD Health and Maturity Assessment Approach" which measures team performance as well as Lean tools and practices and serves as a line of base propose improvement strategies (LCI 2016). Within this evaluation there is a section dedicated to LPS-LCI that consists of 8 components:

- Project team training: seeks consistency, discipline, coordination, efficiency and performance of the training in the team and in the project;
- Master planning: Long-term plan that seeks to comply with the contractual terms of the project, considering important milestones, in addition to allow to establish the project phases;
- Phase Planning / Pull Planning: Long-term plan of the project phases (the phase can be a period of time or a group of activities that lead to the achievement of a defined objective / milestone that releases a series of new works.), is elaborated based on the master planning in a collaborative way and following the “Pull” thought;
- Make ready planning: Intermediate plan that guarantees that the works can be done as planned, for this the lookahead and the analysis of limitations is executed based on planning by phases;
- Weekly work planning: Short-term plan that involves the last planners in the execution of what is released from the make ready planning.
- Daily commitment management (daily huddle): evaluation of daily commitments, on its compliance and the restrictions that did not allow its compliance;

- Metrics & Reporting: Measurements and displays of the variation of the Percent Plan Complete (PPC), Percent Constraints Removed (PCR), Tasks Anticipated (TA) and Tasks Made Ready (TMR)
- Assessment & Continuous improvement: Team ability to make positive improvements, Proper use of PPC, Variance Pareto, Constraint Log and Root Cause Analysis, plus / delta and maturity models.

Each component of LPS is divided into 6 maturity levels (from level 0 to 5) that describe the conditions that must be met to determine the maturity of the project, the general description of each level is shown in Figure 2: .

Also, a methodology is necessary that incorporates and trains the project team to manage an effective implementation in constant evaluation and improvement (Ballard and Tommelein 2016). The following methodologies were identified: Kaizen events, Plan-Do-Check-Act (PDCA) Rapid Cycles, A3 Thinking, Toyota Kata (TK). These methodologies have a systematic approach to solving problems, unlike the others, TK proposes coaching cycles in which the last executors in the improvements are included, who within the LPS are known as the ultimate planners. Rother (2009) calls the improvement pattern carried out in the Toyota company as TK, it is a methodology that allows a cultural and sustainable change during the application of improvements in search of overcoming a challenge. The TK describes two patterns:

- Improvement Kata: Focused on taking steps to face a challenge, this pattern comprises four steps: (1) understanding the challenge, in which an objective is drawn based on the company's vision; (2) understand the current condition, define the current process metrics; (3) establish the target condition, define improvement metrics for the process; (4) experiment towards the target condition, progressively identifying the obstacles that prevent reaching the objective and executing actions until it is overcome.
- Coaching Kata: Focused on achieving Improvement Kata sustainability through Plan-Do-Check-Act (PDCA) cycles, this pattern includes developing teams through coaching sessions and those who answer these questions: What is my target condition? What is my current condition now? What obstacles prevent you from reaching the target condition? Which one are you turning to now? What's your next step? (Start of next PDCA cycle) When can we go to see the results and learning of that step?

The research seeks to relate the maturity assessment of LPS-LCI and the TK methodology, in order to manage the maturity of LPS. The following describes a proposal that integrates both methodologies. The proposal was tested in an infrastructure project with a budget of 4 million dollars, located in the Peruvian highlands whose scope included the stage of concrete works.

DEVELOPMENT OF THE PROPOSAL

The proposal is based on the synergy of the patterns of the TK methodology and the maturity assessment of LPS-LCI, to describe the proposal, two figures are presented: Figure 1 shows a scheme in which all levels of the company (organization, projects and processes) are aligned with a vision of Lean maturity; while Figure 2 describes the steps to follow to manage the maturity of LPS within a project. The proposal will be described below.

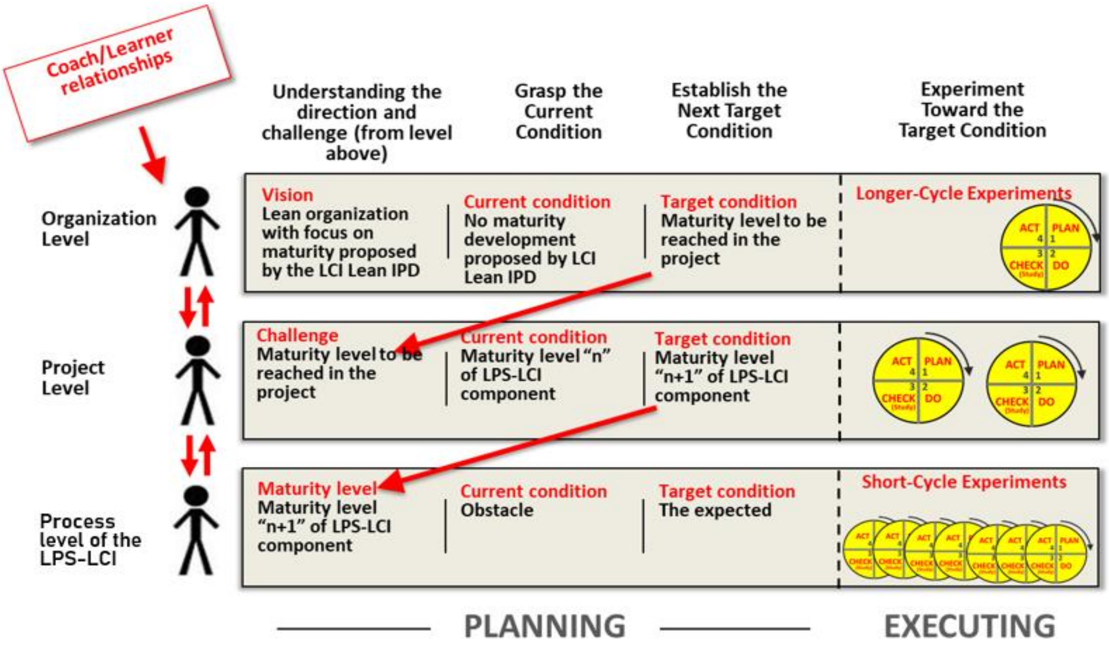


Figure 1: Manage the maturity Lean at all levels of the company

Manage the Lean Maturity of the Company

Step 1: Understand the Vision.

At the organizational level, the vision focuses on business strategy and the adoption of the Lean culture. The three aspects of LCI are considered, which are IPD strategy (commercial), transformation change (organizational), Lean project methods & management (operating system). The vision must be aligned by the leaders of the organization towards the leaders of the project, providing them with support as a coach and providing resources to achieve the objectives.

Step 2: Grasp the Current Condition.

Diagnostics will be made based on the LCI assessment to obtain the current condition of the maturity Lean. The radar chart (Figure 2) will be used to show the current condition. The updating of this condition is also defined based on the results obtained in the evaluation provided by the project leaders.

Step 3: Establish the Next Target Condition.

The target condition should be defined in a "Lean Maturity Assessment" meeting with the participation of organization leaders and project leaders. A target maturity level will be proposed for the projects, this will become the challenge of the leaders of each project.

Step 4: Experiment Toward the Target Condition.

During execution, obstacles are identified and actions are planned to support implementation and provide the necessary resources to the project team.

Manage the Maturity Level of LPS in the Project

Step 1: Understand the Challenge.

At the project level, the target condition proposed at the organization level becomes the challenge. The current and target condition are based on moving from level "n" to "n+1" according to the maturity of LPS. The evolution of the objectives is managed with Table

1. At the process level, the project team executed the implementation by identifying the obstacles that are overcome through the use of the Storyboard and the PDCA cycles. The project leaders are the coaches of the ultimate planners.

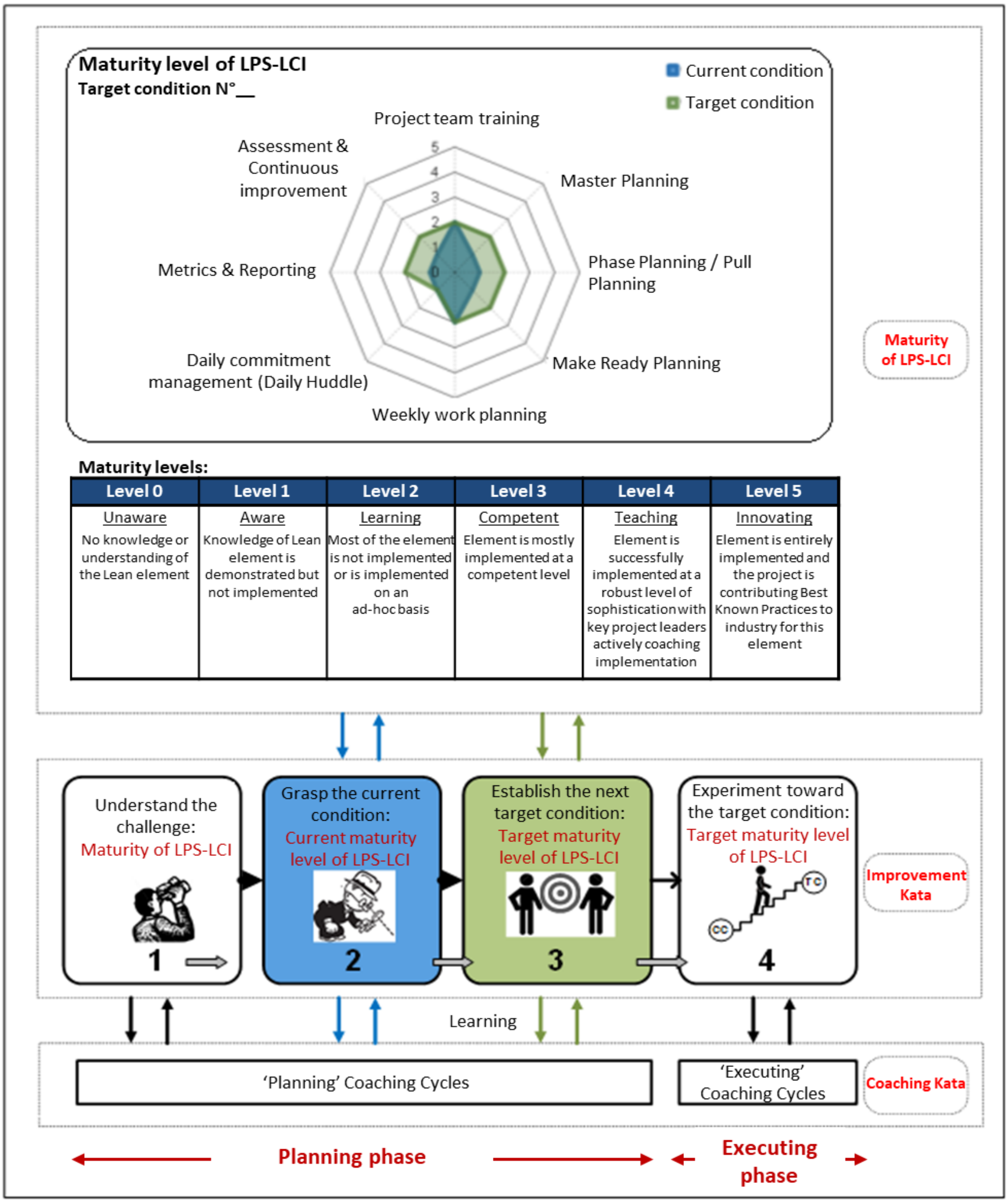


Figure 2: Manage the maturity level of LPS in the project

Manage the Maturity Level of LPS in the Project

Step 1: Understand the Challenge.

At the project level, the target condition proposed at the organization level becomes the challenge. The current and target condition are based on moving from level "n" to "n+1" according to the maturity of LPS. The evolution of the objectives is managed with Table

1. At the process level, the project team executed the implementation by identifying the obstacles that are overcome through the use of the Storyboard and the PDCA cycles. The project leaders are the coaches of the ultimate planners.

Step 2: Grasp the Current Condition.

The first condition of the project is the current maturity level of LPS. While the rest of the current conditions are defined by the last reached maturity level. To assess the maturity level of LPS, evidence is needed, it can be obtained by: conversations with the project team and the last planners, corroborating the use of the tools / methods and evaluating the LPS. Subsequently, a "Maturity Assessment LPS" meeting will be convened, the objective of which will be to analyse the evidence and define the current maturity level of LPS. For a better evaluation, follow the complete guide presented by LCI (2016). The report of this assessment will be presented in a blue radar chart, as shown in Figure 2.

Step 3: Establish the Next Target Condition.

The target condition during the maturity of LPS in the project will be defined by the next level of maturity to be reached. In the aforementioned "Maturity Assessment LPS" meeting, it will be defined which components of LPS will be improve. For a better evaluation, the complete guide presented by LCI (2016). The report of this evaluation will be presented in a green radar chart, as shown in Figure 2. The target conditions that are completed will form the new current conditions.

Step 4: Experiment Toward the Target Condition.

It is based on Kata Coaching, the team is developed through PDCA cycles are executed, defining experiments whose objectives are to overcome the obstacles that arise between the current condition and the target condition of each LPS components, the planned experiments are executed and one learns from what happened. The number of obstacles to overcome, as well as the experiments to overcome them, is unknown. It should be noted that the cycles of the experiments should be short, so that, in case the response or the behaviour of the system deviates from the established direction, it is easy to take actions that can redirect the behaviour of the system. To support the interaction between the team and the coach in the PDCA learning cycles, a Storyboard should be used, documenting the maturity of LPS. The Storyboard must be printed in a minimum A3 format indicating current and target maturity levels. Figure 3 presents the format and application of the Storyboard on the site.

CASE STUDY

The case study in which the management of the maturity of LPS has been done, is a project the construction of a covered coliseum with a budget of 4 million dollars and in a construction area of 4150 m^2. The construction company has experience in buildings, already having several projects executed, its philosophy is focused on the growth of its workers to achieve the delivery of quality projects, in addition the manager has knowledge about Lean Construction, but has not tried to implement. The proposal was followed by the researcher for 17 weeks, due to the stoppage of work due to weather.

MANAGE THE LEAN MATURITY IN THE COMPANY

To understand the vision of Lean maturity, visits and interviews were held with the company manager, in which information was shared about the benefits and success stories of the implementation of LPS, it was also proposed to apply the management proposal of LPS-LCI maturity in a company project. With their approval, the organization leader defined a vision focused on the adoption of the Lean culture based in the "LCI Lean IPD health and maturity assessment" considering: IPD, Methods and Management, Transformational Change, and LPS.

To grasp the current condition, a meeting was held with the leader of the organization and project leader, the Lean maturity assessment were made to the projects, showing low maturity in all aspects.

For the target condition, it was recommended to start with the implementation of LPS since it is a methodology that is the gateway to the Lean culture, the company took on this challenge and proposed to the project that all components have at least a level 3 or competent (in Table 1).

For the experimentation towards the target condition, the organization done follow-ups through the radar chart on a monthly basis. This information is generated by the project team and presented by the project leader. The feedback received by the leader of the organization allowed him to update the target conditions of the organization and the requirement of resources for the development of the implementation.

MANAGE THE MATURITY LEVEL OF LPS IN THE PROJECT

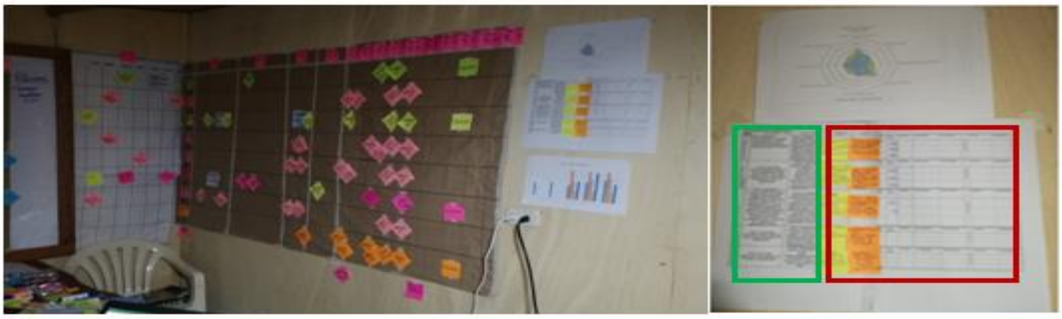
To understand the challenge of maturity of LPS, the organization and the project leader formally communicated the decision to implement the LPS during project implementation. The project team was trained, showing the benefits and successes of LPS, an introduction to the concepts of TK and LPS, and a presentation of the proposed methodology.

To grasp the current condition, evidence was collected on the maturity status of LPS and at the "Maturity Assessment" meeting a common understanding was reached on the maturity level of LPS-LCI components. After that, the agreement is documented in a table and represented in a radar chart.

For the target condition, and being a project in which the intervention was done in full execution, it was decided to follow the implementation framework initially focused on a short-term planning, and then apply an intermediate planning and a long-term planning as recommended by Mossman (2017). This guides the team in the decision to select which component of LPS to improve and lead to a higher maturity level. Four "Maturity Assessment" meetings were hold, these are represented in

Table 1, with the components of LPS in the rows and the target conditions that were done in the project in the columns.

For the experimentation towards the target condition, from the challenge presented and established the current and target conditions, the Improvement Kata and Coaching Kata cycles began to work effectively. Following the methodology, the cycle records are presented according to the target conditions that were defined in the meetings to evaluate the maturity level of LPS. Figure 3 shows the process done to overcome an obstacle identified within the maturity of the Weekly Work Planning, the entire process is documented in a Storyboard located in the Big Room. The table called "Improvement Kata" focuses on the team to meet the target and allows identifying obstacles, while the table "Coaching Kata" allows learning from planned actions based on a dialogue between the project leader and the latest planners.



Improvement Kata		
Challenge: Maturity of the LPS-LCI		
Component	Current condition	Target condition
Weekly Work Planning	Level 0 (Unaware): foreman take instruction from superintendent.	Level 1 (Aware): foreman participate, focus mainly on their own scope.

Coaching Kata					
Target condition #2					
PDCA cycles					
Obstacles		Planned action	What do you expect?	What happened	What we learned
Lack of procedures and lack participation.	PDCA cycle 1	Meeting with foremen and production to indicate the form of work and request that they generate a plan for week 43.	Have a base weekly plan.	The staff met on Monday, however the project still does not have a standardized nomenclature, they proceeded to use construction plans.	It is necessary to use a common language (sectorization) to facilitate the measurement of the weekly plan.
	PDCA cycle 2	The team discusses the planning results for week 43. Plan for week 44.	Raise awareness about the element, through the presentation of the PPC results, and begin to provide solutions from the RNC.	On Saturday a meeting was held to show the results of the PPC (33%). A root cause analysis was performed, the main causes being poor planning and lack of prerequisites. Active participation is observed.	The team is aware of the importance of weekly planning. Show a sense of urgency to learn more about LPS.

Figure 3: Example of Storyboard in the Big Room

RESULTS

Table 1 shows the development of the maturity of LPS components for the three target conditions overcome in the project. It is observed that the challenge posed at the organizational level was not met due to external factors forced the work stoppage. To reach the final maturity shown by the third target condition, it was necessary to detect 44 obstacles and execute 52 improvement actions.

Below is a comparison of the results achieved for each component with respect to the percentage of application of similar components of LPS in the studies by Daniel (2017) and Lake (2017).

- Project team training: evidence that 42% of the cases studied implemented early training; in this research it was implemented to level 3.

- Master planning: evidence that 82% of the cases studied implemented master planning; in this research it was implemented to level 2.
- Phase planning/Pull planning: evidence that 72% of the cases studied implemented planning pull; in this research it was implemented to level 3.
- Make ready planning: evidence that 61% of the cases studied implemented lookahead, 33% implemented constraint analysis and 19% implemented executable work inventory; in this research it was implemented to level 3.
- Weekly work planning: evidence that 85% of the cases studied implemented weekly work planning; in this research it was implemented to level 3.
- Daily commitment management (daily huddle): evidence that 21% of the cases studied implemented daily huddle; in this research it was implemented to level 2.
- Metrics & Reporting: evidence that 68% of the cases studied implemented PPC; in this research it was implemented to level 3.
- Assessment & Continuous improvement: evidence that 39% of the cases studied implemented improvement actions; in this research it was implemented to level 2.

Table 1 Maturity level of LPS components defined in each target condition

Condition / LPS components	Current condition 0	Target condition 1	Target condition 2	Target condition 3
Project Team Training	Level 0: Unaware	Level 2: Learning	Level 3: Competent	
Master Planning	Level 1: Aware		Level 2: Learning	
Phase Planning / Pull Planning	Level 0: Unaware		Level 2: Learning	Level 3: Competent
Make Ready Planning	Nivel 1: Aware		Level 2: Learning	Level 3: Competent
Weekly Work Planning	Level 0: Unaware	Level 1: Aware	Level 2: Learning	Level 3: Competent
Daily Commitment Management (Daily Huddle)	Level 0: Unaware		Level 1: Aware	Level 2: Learning
Metrics & Reporting	Level 0: Unaware	Level 1: Aware	Level 2: Learning	Level 3: Competent
Assessment & Continuous Improvement	Level 0: Unaware	Level 1: Aware		Level 2: Learning

CONCLUSIONS

The methodology uses Maturity Assessment of LPS-LCI to diagnose the level of implementation and determining a current condition, also it allows to know the characteristics of higher levels and to establish a target condition, on the other hand the TK methodology achieves the stated condition , being the IK a guide with ordered steps that manages the improvement actions, while the CK allows a transfer of knowledge in the team members from the actions proposed to overcome an obstacle, this breaks cultural barriers and achieve a configuration of the LPS adapted to the project. The proposed methodology was able to implement all components of the LPS in a project, to achieve the team developed storyboards overcoming 44 obstacles and executed 52 improvement actions.

The use of the LCI Lean IPD Health and Maturity Assessment Tool enabled the organization and the project team to gain insight beyond LPS and assist in the adoption of a lean culture in the organization. Also involve the organizational team in the results of the project, which allows managing the resources necessary for the project. The proposed methodology reached level 3 in five components of LPS and level 2 in two components of LPS. Compared to other studies in which the LPS is partially implemented, with the implementation of the proposal the company achieves an implementation of all the components of the LPS and thus takes advantage of the full ability of the LPS.

For future research, it is recommended to collect data from the use of this proposal to improve measurements and make better decisions. Also update assessment based on new studies on LPS. In addition, it is proposed to use this methodology for the implementation of other fundamental aspects of the lean culture in the organization.

REFERENCES

Ballard, G. and Tommelein, I. (2016). "Current Process Benchmark for the Last Planner® System" *Lean Construction Journal* 2016, 57-89.

Daniel, E. I. (2017). *Exploratory study into the use of Last Planner® System and collaborative planning for construction process improvement*, PhD Dissertation, Nottingham Trent University.

Fauchier, D. and Alves, T.C.L. (2013). "Last Planner® System Is the Gateway to Lean Behaviors" *Proc. Of the 21th Ann. Conf. of the Int'l Group for Lean Construction. Fortaleza, Brazil*.

Fernandez-Solis, J., Porwal, V. y Lavy S. (2018). *Guidelines to Address Challenges Faced by Last Planner Users and Implementers at Organizational and Project Levels.* Construction Science. Accessed March 10, 2021. http://hdl.handle.net/1969.1/166276.

Hamzeh, F. (2009). *Improving construction workflow- The role of production planning and control*, PhD Dissertation, University of California at Berkeley.

Hamzeh, F. R. (2011). "The lean journey: implementing the last planner system in construction" *Proc. Of the 19th Ann. Conf. of the Int'l Group for Lean Construction, Lima, Peru.*

Lagos, C. (2017). *Desarrollo e implementación de herramientas para el mejoramiento de la gestión de la información de last planner*, Master's Thesis, Pontificia Universidad Católica de Chile.

Lean Construction Institute (2016). *LCI Lean IPD Health and Maturity Assessment Tool 1.0.* Accessed March 10, 2021. https://www.leanconstruction.org/pages/learning/tools-and-technologies/.

Mossman, A. (2017). *Collaborative Planning: 5+ 1crucial and Collaborative Conversations for Predictable Design & Construction Delivery.* The Change Business Ltd. https://bit.ly/3wNTtMx (15May21).

Nesensohn, C. (2014). *An innovative framework for assessing lean construction maturity*, PhD Dissertation, Liverpool John Moores University.

Rother, M. (2009). *Toyota Kata: Managing People for Improvement, Adaptiveness and Superior Results.* McGraw-Hill., United State.

Rother, M. (2016). Kata Slides & Graphics v4.1. Accessed May 30, 2021. https://www.slideshare.net/mike734/kata-slides-graphics.

Gordon, E., Rawlinson, K., and Reed, D. (2021). "Assessing Impact of Organizational Change for a Systems Approach to Quality." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 524–533, doi.org/10.24928/2021/0207, online at iglc.net.

ASSESSING IMPACT OF ORGANIZATIONAL CHANGE FOR A SYSTEMS APPROACH TO QUALITY

Elizabeth Gordon[1], Keila Rawlinson[2], and Dean Reed[3]

ABSTRACT

This paper explains what leaders of a change initiative for a new systems approach to Quality did and how they assessed the impact of their work within a large US construction management and general contracting company. All three of the authors were engaged directly or indirectly in the initiative. The research question is to understand what the organizational change agents did to measure the impact of the work contemporaneously and overall. The ideas of three well-known organizational change thought leaders influenced the work of these agents. This paper describes the iterative development of the change initiative over seven years and how leaders used data in combination with participant feedback to assess the impact of the work. Key findings are: the systems approach to Quality was applicable in all five of the organization's core markets, and one-third of all projects by revenue in the five years of data studied attempted to implement the approach.

KEYWORDS

Organizational change, quality, capability, data, impact.

INTRODUCTION

A keyword search of IGLC papers using the keyword "organizational change" finds five, all of which focus on Lean industry transformation. Others are case studies of specific project implementations. This paper follows another published by the IGLC describing the efforts to rethink and implement a new approach to Quality within a large United States (US) Construction Management/General Contractor (CM/GC) organization, characterized as behavior-based (Spencley et al. 2018). This paper focuses on the work and impact of the organizational change efforts to implement that approach, now viewed as a systems approach to Quality (SAQ), from its beginning in 2013 through 2020. The research question is to measure the implementation of this new approach to meeting Quality expectations on the company's projects.

The authors each engaged with the SAQ implementation in one way or another. The first author directly supported the Quality Director and organized dedicated Quality resources and project Quality champions to support project implementations. The second

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author is an Operations Data Business Analyst who uses organizational views of standard work process data to assess and describe organizational behavior and identify organization workflow opportunities for improvement. The third author was a principal advocate and educator for Lean Construction and Integrated Project Delivery.

This paper is limited because it relies on subjective assessments recorded by the first author in notes of meetings and conversations with implementors and presentations made by them. This approach is novel for the industry and the CM/GC, with new language to initiate a change in thinking and behaviors by project sponsors, designers, fabricators and suppliers, construction project managers, and trades-people. The Quality Leadership Team (QLT), those leading the change initiative, and managers have found it challenging to measure project teams' impact and efforts. Although this research incorporates quantitative measurements, the endeavor has only begun using available data not captured for this purpose. This paper's contribution to theory is the design and use of a measurement system using qualitative and quantitative data to understand the implementation maturity of a new systems approach for improving the Quality of built products.

Initially, the QLT based the SAQ launch and implementation on the CM/GC's core values of Integrity, Ever Forward, Uniqueness, and Enjoyment in the pursuit of a Mission, "To build great things" (DPR Construction 2016). The Quality process development team also relied on the Rogers curve for the diffusion of innovations (Rogers 2003). And like many people in the organization, the writings of Jim Collins (Collins 2001) heavily influenced the QLT. Simon Sinek's admonition to first answer the question of, "Why?" rang true to their experience and shaped their work (Sinek 2011). Although the Quality Director and the first author drew respectively on their experiences as Safety Director and Quality Manager, neither had studied W. Edwards Deming, Joseph Juran, or Toyota.

CAPABILITY-BUILDING

INITIATING PROJECT IMPLEMENTATION

Just as this CM/GC recognized their need to approach Quality differently, they entered a multi-billion-dollar joint venture (JV) project, their largest project ever. The Quality Director began testing and integrating this approach to Quality as the project execution strategy. Many conversations with internal and external stakeholder leaders described this Quality vision of creating forums to understand each other's expectations and intentions to identify Distinguishing Features of Work (DFOW) and align on Measurable Acceptance Criteria (MAC) to achieve no surprises (Spencley et al. 2018).

Initially, there was resistance to this type of engagement from many stakeholders. This new way of engaging was different in an industry with long-standing, siloed patterns of common and accepted interactions among fundamental stakeholders: owner, designer, general contractor, and trade partners. To help the team engage differently and execute this shift in behavior, the JV team asked for more tools. The Quality team produced additional tools: a simple checklist of the actions needed before releasing work for bidding, mock-ups, fabrication, and installation; a simple template for documenting conversations about DFOW expectations transparently; workflows for developing MAC; and visual control to track each bid package. Because the Quality team developed these tools and managed the tracking, the cluster teams saw this as additional work, not "the work" to ensure predictable outcomes.

At the same time, the Quality team worked to establish gates in the project workflow, at key hand-offs, when a team member released work to the next phase. These gates prompted stakeholders to have these conversations, identify DFOW, and document their agreements before moving on to the next stage of work. For example, bid packages were not released without an exhibit to determine the initial list of DFOW described by the owner, designer, and CM/GC. This Exhibit forced prompted Project Managers to initiate and document the conversations and provide this information to potential trade partners, also asking for their feedback and plan. What other DFOW did the trade partner see? What was their preliminary plan to achieve this initial list of DFOW?

Just as the benefits of this process were starting to show and this new engagement became routine, the owner dismissed the JV, which dissolved. The pilot project's successes and challenges helped grow the knowledge base and understanding for the leaders who would focus on integrating this approach into the company's DNA. Some of their main takeaways were: focus on building a Quality culture from the beginning; it is never too early to start these conversations; new behaviors take time; putting gates in the system will prompt the team to practice essential behaviors; build upon previous successes.

THE QUALITY DIRECTOR'S PHILOSOPHY OF CHANGE

Following the Mega Project JV pilot, a small Quality Leadership Team (QLT) was formed with three functional leaders from the Risk, Safety, and Quality workgroups who began work to promote the new Quality approach within the company. The time spent planning this change management strategy appeared minimal and informal as the leaders attempted to change the organization. It was not a carefully planned and orchestrated process. Quite the opposite, the Quality Director (QD) had a lot of experience with organizational culture within the company, joining the company within first few years of its founding to leading its safety initiative to build an Injury-Free Environment culture. He believed that engaging those doing the work in the process is more successful, and organic and holistic implementation with simple systems and processes leads to sustainable change because it supports the necessary behavioral change. The QD would often describe the organization as a spider web with strong, flexible connections with which the group could maneuver. He repeatedly cautioned that when someone pushed on one strand of the web, it had unforeseen impacts in other areas.

STEPS BEGIN TO TRANSFORM THE CM/GC CULTURE OF QUALITY

During 2016, *Start with Why* by Simon Sinek (2011) was also a focus at leadership meetings. The QLT spent considerable time refining the message: "Why, How, and What." The leaders consistently engaged with operations leaders and project teams to gain insight and feedback while curating a standard communication flow to support, align, and develop organizational thinking around the initiative. Those innovators formed the organization's change management effort. The "Why" focused on achieving the CM/GC's Purpose of, "We exist to build great things ®" (DPR Construction 2016).

The "How" was a simple framework or mental model to apply to any situation: 1, How am I building from the collective knowledge and information of the project team, the organization, and the industry to identify DFOW, risks, and key hand-offs? 2, How do I understand intentions and DFOW expectations for the project and the processes needed to deliver the work? How am I being understood? 3, How are we aligning and documenting MAC? 4, How am I executing and evaluating work? 5, What did I learn? How can I share and apply that learning?

The "What" was defined by the objective of zero defects and rework. The messaging focused on evoking what Project Executives, Superintendents, Project Managers, and Project Engineers experience: the frustrations, the disappointments, the feelings of being overwhelmed, wondering what was possible, and navigating through these things. It highlighted that this typically requires only a shift in behavior, not a complete transformation. Quality coaches and CM/GC operations leaders needed to speak up if they had reasons why any project team could not integrate this into their work. The Quality mindset appeared to be a shift in individual and organizational understanding, language, and behaviors to solve a systemic problem in the industry that this company faced (Spencley et al. 2018).

Concurrently, the group worked on a simple 1-page Quality Implementation Plan (QIP) to support project teams' experience of "freedom within a framework," as the QLT described it. Following standard organization workgroup collaborations with Preconstruction Managers, Design Integration Managers, and Operations Leaders, the QIP template published in the 4th quarter of 2016 was 5 pages long. This plan clarified the organization's Quality objective: "Being so skilled at understanding and aligning expectations through measurable acceptance criteria that our projects experience zero rework" (DPR Construction QLT, unpublished report, 2016).

REFINING THE MESSAGE

In 2017 the QLT introduced the "Point of Release" (POR) language, which a client representative had coined to identify the point when teams release work for prefabrication or purchase (Digby Christian 2012). POR served as a universal point in the process for understanding Quality expectations. This concept helped teams focus on the dimension of time as it intersects with the flow of information.

The QLT embedded this message into the organization's Design Management Academy (DMA) launch, an organization initiative to grow internal capabilities. This capability growth integrated construction needs into the design process and described actions to frame and focus Quality work during the pre-construction phase of work. The DMA framework was supportive of the effort for a couple of critical reasons: it developed understanding of the importance to begin these conversations at the start of the project and continue during design to prevent rework; and it connected the QLT to other leaders early in the project lifecycle to better understand and strategize how we engage and interact with project stakeholders.

CONSISTENCY

Throughout the first couple of years, the change work was the same: share the vision at all opportunities, find influencers who inspired and aligned their teams, coach teams that needed help, and use project team feedback to guide and inform the initiative. The QLT shared the vision across multiple forums: company-wide network meetings and summits, the 3-day cultural immersion for new hires, local Business Unit (BU) workgroup messaging, and regular open Quality-focused online meetings featuring project teams. In addition, the QLT was consistently meeting with workgroup leaders and project teams as part of their everyday work.

The QLT focused on recruiting those who were inspired and saw value in embracing this new approach. These innovators and early adopters took the vision into daily operations. As Spencley et al. (2018) described, there were various levels of understanding, integration, and application into the CM/GC's project management methods. Some took the concepts and identified key DFOW within specific scopes of work while others focused on architectural feature locations. Some were able to implement this across all project scopes of work. Others internalized the behaviors and recognized this mindset applies to any deliverable and process and developed a "Quality mindset." This approach consistently produced more predictable results. (Spencley et al. 2018).

CREATING A SUPPORT SYSTEM FOR PROJECT IMPLEMENTORS

The weekly online Monday Quality Call began in 2015 and continues to support project implementations. Project teams would relate how they operationalized the shift in behaviors for their project's DFOW and Risk. They would describe the successes and the challenges they were having. They would always be celebrated and challenged to think differently. This forum remains a safe place for practitioners to reflect on what they have done and how we could continue to honor the company's Ever Forward core value. The QLT shared these Quality implementation stories through company communications, setting vivid expectations for the company while inspiring and recruiting others. A key takeaway is implementing the feedback loop: always getting input and hearing the message from those doing the work was critical for understanding adoption and integration of SAQ.

Those that shared on these calls became members of the informal Quality network (QN), the group of practitioners who had implemented SAQ and leaders who were proponents of SAQ. The practitioners became resources and coaches for other projects. In the beginning, the coaching model focused on project kick-off meetings and then workshops with experienced implementors in which they shared their strategy, experiences, opportunities to improve and answered approach and scenario-based questions.

In 2018 the QLT organized a Quality summit for selected project implementors, dedicated BU Quality resources, and other corporate services leaders. While this group wanted a clear roadmap of milestones for execution, what emerged was more discussion on what Quality looked like through the project lifecycle. Different perspectives arose, and practitioners and dedicated Quality resources recognized the need to go back and engage the leaders in their Business Units.

COMMUNICATING EXPECTATIONS

The QLT continued to communicate the Quality vision and its expectations at company-wide meetings and discussions with leaders throughout the company. And internal workgroup adoption became a focus with pre-construction tools integrating DFOW language. The CM/GC's Risk Network group, which looks at project and business unit risk, reinforced the Quality expectations that teams needed to identify DFOW and develop a plan for understanding and aligning measurable expectations. The Contractor-Controlled Insurance Program (CCIP), Corporate Risk Assessments (CRA), and Business Unit Risk Assessments (BURA) all continued to communicate these Quality expectations, and coached teams along the way. Before the CRA, the most senior risk leader would coach the Project Executive on why formalizing the conversation with the stakeholders through the DFOW process was necessary. Similar messages during these process workshops would facilitate connecting project team members with other resources for further coaching.

TRANSITION AND EXPANDING THE QUALITY TEAM

2019 and 2020 marked a time of change for the Quality Initiative. By 2019 the company had experienced tremendous revenue growth, and some of the leadership team transitioned to other roles. The 3-day cultural immersion, a forum to educate and recruit people passionate about the vision and mission, paused in 2019. The QLT piloted an online Quality education program, and this 1-hour per week, 4-week class launched in 2020 in some BUs.

The weekly online Monday Quality Calls became one of the main feedback loops for the group. In 2015 these had the same 5-12 people join regularly. In 2020, 296 different participants attended to listen to stories and ask questions. Many teams had moved beyond sharing how they managed a DFOW list and began describing how the concepts applied to and integrated into how they approached their work. This call engaged all different roles across the company: Regional Leaders, Business Unit Leaders, Corporate Service Leaders, Project Executives, Superintendents, Project Managers, and Project Engineers. As another feedback loop, the organization assigned new members to a parallel support group, increasing Quality focused resources substantially. These leaders worked on providing input into the company's Quality strategy direction.

Throughout these years, the Quality Director challenged the group to measure the results and the initiative's penetration through the organization. In response, the first and second authors began exploring ways to measure the adoption and penetration of these concepts into the organization.

ASSESSING CULTURAL CHANGE

MEASURING ORGANIZATIONAL CHANGE

To understand company-wide implementation, the authors considered ways of assessing organizational adoption. With many incremental iterations along the way, the authors had several different feedback loops: 1, first-hand experience implementing SAQ and coaching project teams; 2, accounts from project teams about their experiences on Monday Quality Calls, accounts from other dedicated Quality resources working with the leaders and project teams; accounts from other leaders within the organization; and 3, through the company data collected about project team performance.

The evidence of implementation seemed rooted in the project team documenting conversations about what was essential to project stakeholders in structured and standard ways to support SAQ implementation. Identifying and documenting DFOW and MAC are key deliverables within SAQ. The first and second author decided to perform keyword searches for the terms "Distinguishing Feature of Work" and "DFOW" in the digital project file repository. Evidence of these documents showed exposure and implementation of SAQ. This methodology collected links to the evidence files to build an organizational knowledge base and identified the quantity of DFOW files generated for each project to explore levels of implementation.

FINDINGS FROM QUALITATIVE NETWORKING

Some influential findings reported through the people participating in the QN include:

- The CRA Manager reported from his sources, at the beginning of 2016, no projects had identified DFOWs before the CRA. By 2018, 30% recognized DFOWs, and by 2020 only a small percentage of teams had not heard about the DFOW process.
- Educating project teams takes many forms, and the impact of project size may influence the data analysis. Onboarding smaller projects may not produce as many files. And as teams learn this new process, efficiency in documentation may occur resulting in fewer files.

FINDINGS FROM MINING PROJECT TEAM DATA

In Table 1 below, the column "Year Project Mobilized" represents an annualized view of the CM/GC projects by the year that the project mobilized, a POR for onsite preparatory construction activities to commence. The associated DFOW project files are assigned to the year that the project mobilized, using an annualized view of project data. The column "Count of Projects with DFOW Files" shows a unique project count to identify how many projects teams initiated the Quality approach. The column "DFOW Projects Revenue as Percent of Annual Sales" shows the contract value of the projects that generated DFOW Files as a Percentage of Annual Sales for the year. The next column "Count of DFOW Files" is the number of DFOW files in the digital repository that had mobilized that year. DFOW Files as a Percent of DFOW Files Total represents the spread of the DFOW file counts over the respective years.

The tables below use an annualized project view based on the year the project mobilized to compare them to the sales in the same year. Annualizing project data helps simplify and standardize the analysis for contract revenues that actualize across multiple years. This annualized sales comparison assigns the project contract revenues to the year the project mobilized. Table 1 shows the organization's number of projects with DFOW files and the quantity of those files shown by the year the project mobilized.

Table 1: Projects with and Quantity of DFOW Files by Year the Project Mobilized

Year Project Mobilized	Count of Projects with DFOW Files	DFOW Project Revenues as Percent of Annual Sales	Count of DFOW Files	DFOW Files as a Percent of DFOW Files Total
2016	3	5%	134	3%
2017	17	29%	392	9%
2018	37	31%	1081	26%
2019	66	42%	1686	41%
2020	67	55%	861	21%
5 Year Total	**190**	**34%**	**4154**	**100%**

Some critical findings seen in this Table 1 data are:

- A steady increase occurs over the five years for implementation as a percentage of annual sales. The QLT and QN efforts resulted in an increased participation rate of 55% of total sales revenue in the five years, after starting with a 5% participation rate in 2016.
- The decrease in the Count of DFOW files in 2020 is consistent with an observation by Quality practitioners, DFOW Files generate over the project lifecycle. The organization data shows that larger projects generate half of their DFOW files in the year of mobilization and half of the files in the year after. Due to the increase

in large projects, this finding shows that more documentation can be expected the following year.

- The decrease in the Count of DFOW Files in 2020 also may reflect impacts from COVID-19 to project lifecycles and project flow with project holds and cancels.

Table 2 below assesses the total five-year period of project revenues as a percentage of Core Market Sales data to evaluate the impact of the organizational change across the portfolio of project types that the CM/GC targets in pursuits.

Table 2: Projects with DFOW Files Sorted by Core Markets

Organization's Core Market Category	Count of Projects with DFOW Files	DFOW Project Revenues as Percent of Core Market Sales
Advanced Technology	34	33%
Commercial	42	41%
Healthcare	37	23%
Higher Education	13	35%
Life Sciences	44	42%
Other	20	24%
5 Year Total	**190**	**34%**

Key findings here include:

- Each Core Market in the organization has implemented this Quality approach in 23% to 41% of its sales volumes.
- This Quality approach appears to have application across all core markets, supporting the view that this approach accommodates diverse requirements.
- Target focus on Healthcare and Other Core Markets indicate knowledge gaps in Quality program awareness or specific Core Market peculiarities that result in lower participation rates than other Core Markets.
- In these five years, 34% of projects by revenue attempted to apply this Quality approach to their projects.

Table 3 below assesses the distribution across distinct geographical regions in the organization. This view highlights the variability in adoption across geography as well.

Table 3: Projects with DFOW Files Sorted by Regions

Organization's Geographical Region	Count of Projects with DFOW Files	DFOW Project Revenues as Percent of Regional Sales
Central	17	24%
Northeast	31	44%
Northwest	60	39%
Southeast	49	36%
Southwest	34	28%
5 Year Total	**190**	**34%**

Key findings from this Geographical view include:

- Each Region in the organization has implemented this Quality approach in 24% to 44% of its sales volumes.

CONCLUSION

NEW INSIGHTS

Both qualitative and quantitative feedback loops were essential to understand the diffusion of SAQ adoption. The DFOW file production counts were not initially collected to measure adoption. This raises the question of whether there may be other quantitative data sources that can be generated or mined to inform the evaluation of SAQ adoption. Also, consistently documenting routine qualitative feedback of Quality implementation accounts was essential to provide context for the quantitative data.

The organizational change efforts experienced to date align in similarities to NUMMI's journey (Shook 2011). Shook describes how NUMMI overcame their Fremont, CA plant's legacy of dysfunction to produce Quality by focusing on 1, what the worker did first instead of starting with focusing on changing what people believe 2, giving workers a means to do their jobs successfully, and 3, changing how problems were experienced as opportunities to improve rather than failures resulting from poor workmanship.

Similarly, this CM/GC's organizational change effort focused on identifying those aligned with the vision and changing the way people worked. The influencers adjusted existing processes and changed the way people interacted, creating new routines and new experiences. These new experiences changed their beliefs:

- From Quality was amorphous, managed by a software program documenting issues after work was put in place that are field operations problems;
- To Quality is how is a result of how builders collaborate with stakeholders.

Without consistent accountability for SAQ, people on projects determine the organizational change. The PORs identified by the project leaders produced the new routines and built capabilities. The templates to do work, without accountability at the project PORs, are not sufficient to create change.

Koskela, Ballard and Howell (2003) do not believe that firms should start with contracts and organization formation to incite change. Instead, the authors believe that change should begin in "the operational processes where the end product is created: design, prefabrication, and site" to learn what should be changed upstream. This CM/GC's change agents also found this to be true. The change in routines at the operational level, where work was done, created new project cultures regardless of project contract type and delivery method.

INTUITIONS AND QUESTIONS

The quantitative data raised other questions such as, Why do some regions have better adoption in count of projects and revenue of projects than other regions? Focused research in the Central and Southwest Regions may reveal knowledge gaps in awareness or specific regional factors that result in lower participation rates than other locations.

As Shook 2003 describes, changing the way leaders and managers viewed and dealt with problems was fundamental for NUMMI providing consistent Quality results and changing the culture. On projects that implemented SAQ, How did the leaders and managers approach problems? How did the project leader's approach to problems contribute to the development of their SAQ and their Quality results?

Leading the Quality vision and accountability for SAQ was a common theme shared by projects on the Monday Quality Calls. The authors wonder how the organization and the QLT can create experiences to encourage and grow those who want to lead these efforts on their projects, and in business units, and regions.

FURTHER STUDY

The authors intend to further study Diffusion of Innovation theory and how it applies to this GC's organizational change efforts (Rogers 2003). Specifically, the authors plan to focus their efforts on understanding the social system and map change agents that influenced their projects and others. By mapping the spread of SAQ adoption, the authors hope to define the leaders' network and social networks that create organizational change to suggest replication models for more effective change.

Furthermore, the authors intend to study how the organization can refine its collection of qualitative feedback from project teams and quantitative data to better understand integration and adoption of SAQ. The authors plan to map the workflows of project implementation accounts shared on Monday Quality Calls to find trends. Also, how information is created, transformed, and transferred through the project lifecycle will be studied to understand and describe SAQ implementation more precisely and based on standard project milestones. This knowledge would allow the organization to monitor SAQ implementation and flag when expected outputs are missing. The authors plan on developing a maturity model for the project files to help further assess SAQ integration. This information would help increase the level of SAQ integration and maturity within projects and within the BUs and Region.

REFERENCES

Christian, Digby. (2012). "Where Ambitious Owners with Ambitious Projects Need Ambitious GC's to Focus." Unpublished presentation.

Collins, J. C. (2001). Good to great: why some companies make the leap... and others don't. Random House, London.

DPR Construction. (2016). "Core Ideology." Who We Are, Communications, https://www.dpr.com/company/culture#mission-2030 (Apr. 12, 2021).

DPR Construction QLT. (2016). "Quality Implementation Plan." Unpublished report.

Koskela, L., Ballard, G., and Howell, G. (2003). "Achieving Change in Construction." 11th Annual Conference of the International Group for Lean Construction, Virginia, USA.

Rogers, E. M. (2003). Diffusion of innovations. Free Press, New York.

Shook, John. (2010). "How to Change a Culture: Lessons From NUMMI." MIT Sloan Management Review, 51(2), 63–68.

Sinek, S. (2011). Start with why: how great leaders inspire everyone to take action. Portfolio, Penguin, New York, NY.

Spencley, R., Pfeffer, G., Gordon, E., Hain, F., Reed, D., and Marosszeky, M. (2018). "Behavior-Based Quality, Case Study of Closing the Knowing-Doing Gap." 26th Annual Conference of the International Group for Lean Construction, Chennai, India, 1170–1181.

Skaar, J. and Kalsaas, B. T. (2021). "The Importance of Alignment" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 534–541, doi.org/10.24928/2021/0211, online at iglc.net.

THE IMPORTANCE OF ALIGNMENT

John Skaar[1] and Bo Terje Kalsaas[2]

ABSTRACT

Illeris learning model for working life claims that learning only happens if both the individual psychological level and the interaction with the surrounding environment is aligned. With an assumption that a principle-based leadership framework can support and maintain lean initiatives, a conceptual walkthrough is conducted by putting the principles-based framework up against Illeris's model for learning in working life. Learning is a fundamental prerequisite for behavioural change, so by discussing how principles can enhance learning in an organization crucial insight is ggained. This insight will further support ongoing fieldwork on action-based research implementing principles within the construction business. A principles-based leadership framework can help align, activate and increase the overlapping area both on work identity and on working practice and therefore be an important contribution for behavioural change in the construction business.

KEYWORDS

Experimental learning, commitment, action research, continuous improvement and leadership.

INTRODUCTION

The construction business is structured around projects (Ballard and Howell 1998) and every project is normally treated as separate reporting and economical subunits. A common way to test implementation of lean is through pilot projects (Kalsaas, Skaar, and Thorstensen 2009; Mota, Mota, and Alves 2008; Dave, Boddy, and Koskela 2013; Lehtovaara et al. 2019) We observe a tendency that even though many of the pilot projects recognize that the lean system, methods and tools implemented in the projects have had a positive effect, we also see that many of the persons involved in the pilots do not continue to use lean if their next project are not defined as another lean pilot project. This means the behavioural change is not transferred to the next project, even though they claim that the last project gained a clear positive effect related to the use of elements from lean construction. Assuming that lean construction is a fruitful path for improvement, what could be a legit reason for this relapse? It seems like many of the possible answers may be captured within Illeris model of learning in working life (Illeris 2009). Among other it can be:

- Lack of confidence to manage lean outside a pilot (Learning process).

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- Individually difficult to change behaviour after limited experience (Learning process).
- Projects specifications and/or conditions becomes barriers for new thinking and methods (Technical-organisational environment).
- The business culture does not make ground for new learning (Socio-cultural environment).

Many academic writings draw on the importance of learning as a foundation for behavioural change. Illeris model for learning in working life (Illeris 2004b) considers both how the work identity and the working practice becomes preconditions for learning. Kalsaas (2012) apply Illeris learning model to conceive the Last Planner System style of planning to understand how processes of learning take place.

This paper is a part of a Phd research project exploring the form and effects of a principle centered leadership framework for supporting and maintaining lean construction initiatives in the construction business. Acknowledging the importance of learning as a foundation for creating and sustaining behavioural change we analyse how principle based leadership can affect the learning ability of individuals.

METHOD AND APPROACH

This paper uses theoretical conceptualization as the main method. We apply learning theory towards a principle-based leadership framework (Stephen R. Covey 2009; Skaar 2019) to analyse where principles spur or discourage learning. A previous and ongoing fieldwork supports the conceptualization, conducted in one Phd project and several master and bachelor studies done with experimental based methodology. The studies test the use of principles in different contexts and using the principles directly or connected to a strategic/tactical discussion either within a lean house (Liker 2003), towards a purpose driven statement (Mackey and Sisodia 2014; Sinek 2014) and/or a vision (Covey 2009). We are in search for actionable knowledge (Tsoukas and Knudsen 2005; Argyris 1996) so the principles are tested within a contractors environment on project level (Skaar 2019), in production (Bøe and Meland 2019), in procurement, in design phase, in early conceptual phase and on department level (Grøtvedt and Haddeland 2020). The research is starting “bottom-up” with ambitions to expand to project owner and top management level.

THEORY

A PRINCIPLE BASED FRAMEWORK

Principles formed prescriptive and with a guiding ability can be interpreted by the individual and spur action adapted to the contextual setting (Skaar et al. 2020). The use of purpose driven principles are even announced to be the next paradigm shift in leadership capabilities by some authors (Mukherjee 1995; S. R. Covey 2001), even though principle based leadership already has a long history especially within the military (Roberts 2018; Szypszak 2016) and later also business (Rodrigues 2001).

Principles act as guides to fulfil the concept they represent. For a company or organization, the main purpose of the business could be explicitly expressed, and it is often done through a purpose, mission and or a vision statement (Arbulu and Zabelle 2006; S. R. Covey 2001; Wallace, Richard, and Jr 1996; Musa, Pasquire, and Hurst 2016; Skaar 2019)(Arbulu and Zabelle 2006). If a company forms explicit principles to support their purpose, they should guide so that if employees act upon the principles with the company's purpose and values in mind it should be in an attempt to advance in alignment with the purpose, the “true north” (S. R. Covey 2001).

Stephen Covey (S. R. Covey 2001) represents a concept where the overall vision and mission statement should be made specific both on the organizational, leadership, interpersonal and individual level.

ILLERIS MODEL FOR WORK LIFE

The model captures the interaction of both the individual aspect of learning and the learning environment. It is a model that combines both work practice and work identity into an overlapping model. The model shows how working practice is filtered through the learners work identity before it is processed to learning (Illeris 2009). The model illustrated in Figure 1shows an area where work identity and work practice overlap, in this area the potential for learning is at its largest. The model moreover conceives the impact from the structure made up of the technical organizational and socio-cultural learning environment on work practice and the impact from cognitive learning and psychodynamic om work identity (Figure 1). The dimension on individual level addressing individual’s history and background is not emphasised in the following, which is also the case for the societal dimension regarding the organizational context.

DISCUSSION ON WORK IDENTITY IN A PRINCIPLE BASED FRAMEWORK

COGNITIVE LEARNING

The arrow between learning content and dynamic (se figure 1), refers to how an individual psychologically acquires learning. Where the dynamic side considers the individual's motivation and emotions, the learning content considers the individual's knowledge and skills. Our ongoing testing of principles show that the framework is not intuitive. The use of principles must be explained, and a purpose, vision and mission seem to have different motivational effects from individual to individual. Our observations indicate that due to the principles often logical and common sense-based character, they can easily be agreed upon, it is though harder to get everybody motivated for daily use. A crucial point in understanding the use of the principles is that they should challenge the status quo continuously, “never accept status quo” is an important principle in itself (Macomber and Davey 2018). So, by thinking of implementation areas and experience with the use of principles a mindset can be built, and knowledge can be gained from the learnings made. Knowledge might in the long run be defined as wisdom, a higher-order tacit knowledge. (Nonaka and Takeuchi 2019)

Knowledge and skills are part of the competence, and the use of principles should be built alongside the trade specific knowledge needed in the work situation. Competence combined with character and integrity forms the prerequisite of empowerment (Covey 2001).

EMOTIONS AND MOTIVATION

Learning is important for behavioural change (Zanone and Kelso 1992; Lim and Yazdanifard 2014). Both knowledge, skills and motivation are important factors for behavioural change among employees. Since the topic in this paper is a leadership framework the motivation for the employees should be spurred and supported by the framework. Research indicates a positive relation between empowerment and motivation (Drake, Wong, and Salter 2007), so a principle cantered leadership framework should seek empowerment as part of the vision (S. R. Covey 2001). Empowerment needs commitment from the employee, and commitment and motivation reach a higher level of intrinsic motivation versus extrinsic motivation (Johnson, Chang, and Yang 2010). An individual and personal commitment to the purpose, might be important for many individuals to create the right alignment. Covey (2001) suggest that mission and vision statements are made on a personal level also in organizations to have a more dedicated personal compass in everyday tasks. Personal vision and mission statements have been tested in different workshops and feedback from this shows an immediate positive reaction, but the long-term effect has not been tested yet.

DISCUSSION ON WORK PRACTICE IN A PRINCIPLE BASED FRAMEWORK

THE TECHNICAL-ORGANIZATIONAL LEARNING ENVIRONMENT

A principle centred leadership framework will directly be a part of the organizational environment when implemented. But here an important definition occurs, because lean principles are often interpreted as “common sense” and can easily be interpreted as something that is already a part of the working practice.

The line between what is and what is not a part of the technical-organizational learning environment is not easy to define and should therefore be explicitly stated as an important part of the business framework to remove doubt. Our observations indicate that leaders get results when they ask for answers from principles but if they don`t ask, the frequency of initiatives drops very fast (Skaar 2019). These observations are made on project level in an organization, where the project as an organization is not familiar with extensive use of principle based leadership. In these contexts, defined and written principles have been used in order to legitimize and make them a part of a periodic routine to trigger the use of them (Bøe and Meland 2019). Some of the master and bachelor thesis connected to this research also use a “lean house” as a place or symbol in order to build a common understanding of the meaning of purpose and the principles that support it (Grøtvedt and Haddeland 2020). The research indicates that the principle centred framework must be an undisputed part of the projects and/or organization's structure in order to take out a higher potential at least in the implementation phase of the framework. A clear purpose behind the principles will give an aligned understanding towards a “true north” (Covey 2001).

THE SOCIO-CULTURAL LEARNING ENVIRONMENT

“Culture eats strategy for breakfast” is a phrase attributed to Peter Drucker (Ellender 2016) that becomes a metaphor for how important culture is for strategic deployment and improvements programs in an organization. Illeris also emphasizes the socio-cultural aspect of learning. Even though the construction business can be interpreted as a cultural community, every project can also be interpreted as its own standalone community. To answer the overall challenge to make lean construction a consistent way of working the improvement and learning must be brought from one project to the next. A continuous improvement culture is necessary for making this happen. The construction industry is project based so investments done cross projects in the construction business is relatively low. Every project is therefore expected to deliver, and interviews indicate that the project management fear a potential “loss project” more than they feel motivated to increase margins in the project, this might reduce effort to innovate in the culture. To create a culture that foster improvement rather than fear of losing is important for a principle based framework.

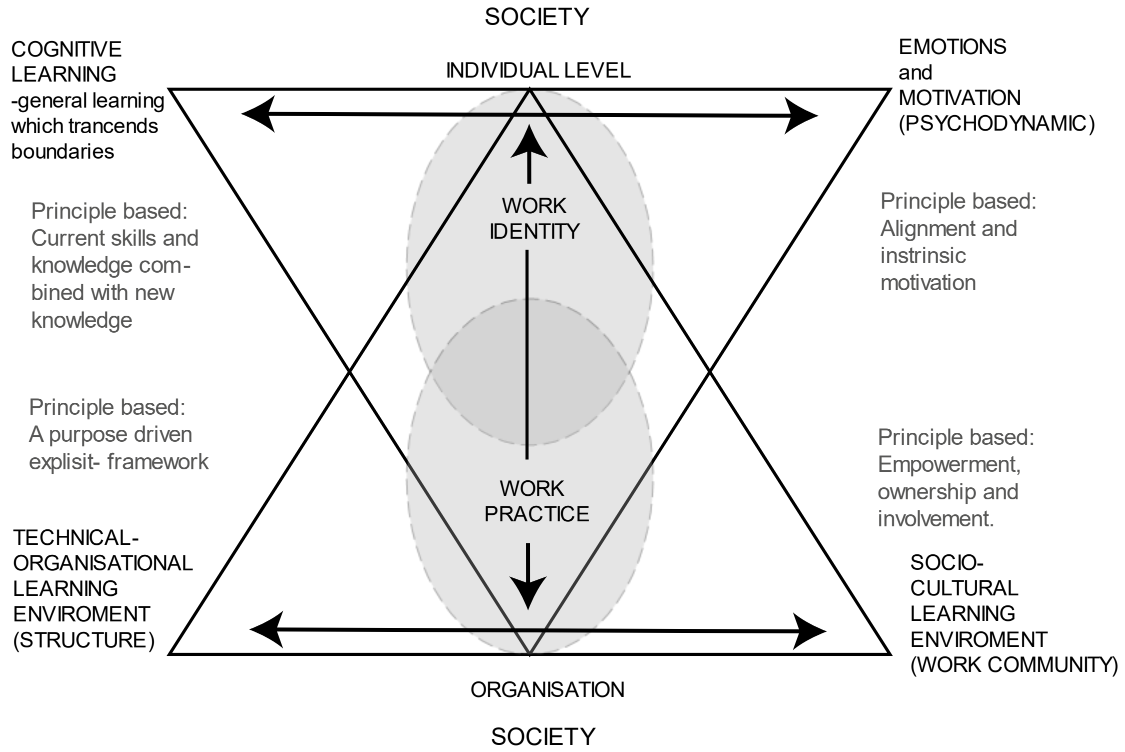

Figure 1: Workplace learning (Adapted and translated from Illeris (2009)). The grey text is added to the original model as contributions towards a principle - based leadership framework.

REFLECTIONS ON PRACTICAL APPLICATIONS

START WITH WHY

By working with all conditions in the Illeris model, the purpose, leadership ownership, employee's motivation and skills gets attention. But how can this be translated and affect the project level? In a project you have stakeholders with a variety of motivation, the owner, contractor, subcontractors, architect, and consultants all have their own opinion and motivation. Using the principle “Start with the end in mind” (Macomber and Davey 2018) the common purpose might be considered as the first piece of the puzzle. Start with “Why” (Sinek 2014) is a way to find a common purpose, “Why do we build this project? Every construction and gathering of people in a project team can be challenged to find a deeper meaning that can motivate the entire group across companies. Building the “best” product of its kind or creating the “best” team environment can be stretch goals for most situations. Finding principles that support these goals put are recommended (Structure). Ex. If the goal is the best team, "Build relations with everybody” can be an example of a principle the project can strive to master (Work community). The leaders must then own the principle and ask for answers (Work community), all employees can be challenged to learn colleagues across companies (Cognitive learning) and find their own ways to interact (Psychodynamics).

INTEGRATION OF INTERESTS IN THE CONSTRUCTION VALUE CHAIN

The project can be conceived as the organization and each project will develop/emerge its specific technical organizational learning environment and socio cultural the like.

Projects with relational contract are likely to have an advantage to achieve a fruitful socio-cultural learning environment due to the impact from involvement in planning and control. On the technical organizational part relational contracts may be based on sharing risk and gain which is likely to increase trust and motivation to the best for the project. In other words, less incentives for suboptimization.

To support a holistic learning environment the project management would organize learning sessions for project staff who is new to the actual way of working (cognitive learning - Figure 1)). Learning on project level will also be stimulated by taking the time to mutual reflections and application techniques like Plan-Do-Check-Act or Kolb's learning circle.

Negative feelings by individuals in the project teams affects the learning potential (Psychodynamics - Figure 1), hench it is important for the management to have a style of leadership which apply the possessed power to correct unwanted/negative behaviour to build or to prevent trust to deteriorate (Sørhaug 1996). A successful project will moreover make effort to pick its people to have individual match between work identity and the work practice we want to establish or have.

CONCLUSIONS

The illeris model is a challenging model that contributes to a good depth in discussing the prerequisites for learning. The model challenges the different aspects of learning and thereby becomes a good model that a leadership framework can test its capabilities against. Key takeaways are the emphasis needed on alignment to purpose, training of knowledge, making the framework explicit so it can support a culture of empowerment and involvement. Most of all the Illeris model learns that all of these learning points are dependent on each other, so in order to implement a principle centered leadership framework all aspects of the model have to be taken into account.

REFERENCES

Arbulu, Roberto, and Todd Zabelle. (2006). "Implementing Lean in Construction: How to Succeed." In 14th Annual Conference of the International Group for Lean Construction, 553–65. Santiago, Chile.

Argyris, Chris. 1996. "Actionable Knowledge: Design Causality in the Service of Consequential Theory." The Journal of Applied Behavioral Science.

Ballard, Glenn, and Greg Howell. (1998). What Kind of Production Is Construction?

Bøe, Marie, and Lene Meland. (2019). "Aktiv implementering av operasjonelle Lean prinsipper blant prosjektdeltakere på byggeplass: En kvalitativ casestudie." Universitetet i Agder ; University of Agder.

Covey, Stephen R. (2001). Principle Centered Leadership. Provo, UT: Covey Leadership Center.

Covey, Stephen R. (2009). Principle-Centered Leadership. Rosetta Books.

Dave, Bhargav, Stefan Boddy, and Lauri Koskela. (2013). "Challenges and Opportunities in Implementing Lean and BIM on a Infrastructure Project." In 21th Annual Conference of the International Group for Lean Construction, edited by Carlos Torres Formoso and Patricia Tzortzopoulos, 741–50. Fortaleza, Brazil.

Drake, Andrea R., Jeffrey Wong, and Stephen B. Salter. (2007). “Empowerment, Motivation, and Performance: Examining the Impact of Feedback and Incentives on Nonmanagement Employees.” Behavioral Research in Accounting 19 (1): 71–89.

Ellender, Peter. (2016). “Culture-the Ultimate Differentiator... and Path to Delivering Strategic Outcomes.” Proctor, The 36 (1): 58–60.

Grøtvedt, Anders, and Silje Haddeland. (2020). “Representere Lean Tenkning Gjennom Bruken Av Prinsipper: En Aksjonsstudie Av Lean Prinsipper På Avdelingsnivå I Veidekke.” University of Agder.

Illeris, Knud. (2004b). “A Model for Learning in Working Life.” Journal of Workplace Learning. 16 (8): 431–41.

Illeris, Knud. (2009). Læring i arbeidslivet. Denmark: Learning Lab Denmark, Roskilde Universitetsforlag.

Johnson, Russell E., Chu-Hsiang (daisy) Chang, and Liu-Qin Yang. (2010). “Commitment and Motivation at Work: The Relevance of Employee Identity and Regulatory Focus.” AMRO 35 (2): 226–45.

Kalsaas, Bo Terje (2012). The Last Planner System Style of Planning: Its Basis in Learning Theory, Journal of Engineering, Project, and Production Management, 2012, 2(2), 88-100.

Kalsaas, Bo Terje, John Skaar, and Rein Terje Thorstensen. (2009). “Implementation of Last Planner in a Medium-Sized Construction Site.” In 17th Annual Conference of the International Group for Lean Construction, edited by Ype Cuperus and Ercilia Hitomi Hirota, 15–30. Taipei, Taiwan.

Lehtovaara, Joonas, Iina Mustonen, Petteri Peuronen, Olli Seppänen, and Antti Peltokorpi. (2019). “Implementing Takt Planning and Takt Control Into Residential Construction.” In Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC), 417–28. Dublin, Ireland.

Liker, Jeffrey K. (2003). The Toyota Way: 14 Management Principles From the World’s Greatest Manufacturer. McGraw Hill Professional.

Lim, Wen Shien, and Rashad Yazdanifard. (2014). “A Multidimensional Review on Organizational Change’s Perspectives, Theories, Models, and Types of Change: Factors Leading to Success or Failure Organizational Change.” Global Perspective on Engineering Management 3 (2): 27–33.

Mackey, John, and Rajendra Sisodia. (2014). Conscious Capitalism, With a New Preface by the Authors: Liberating the Heroic Spirit of Business. Harvard Business Review Press.

Macomber, H. and D., Calayde (2017). The Pocket Sensei: Mastering Lean Leadership. United States, Pemi River Media.

Macomber, Hal, and Calayde Davey. (2018). Mastering Lean Leadership: Lean Construction Institute Canada - Special Edition. CreateSpace Independent Publishing Platform.

Mota, Bruno Pontes, Ricardo Rola Mota, and Thais da C. L. Alves. (2008). “Implementing Lean Construction Concepts in a Residential Project.” In 16th Annual Conference of the International Group for Lean Construction, edited by Patricia Tzortzopoulos and Mike Kagioglou, 251–57. Manchester, UK.

Mukherjee, Sanjoy. (1995). “Book Reviews: Stephen R. Covey, Principle-Centred Leader Ship. London: Simon and Schuster Ltd., 1992, Pp. 326, £8.99.” Journal of Human Values.

Musa, Muktari M., Christine Pasquire, and Alan Hurst. (2016). “Where Lean Construction and Value Management Meet.” In 24th Annual Conference of the International Group for Lean Construction. Boston, USA. http://www.iglc.net/papers/details/1361.
Nonaka, Ikujiro, and Hirotaka Takeuchi. (2019). The Wise Company: How Companies Create Continuous Innovation. Oxford University Press.
Roberts, R. (2018). “Twelve Principles of Modern Military Leadership.” NCO Journal, 1–8.
Rodrigues, Carl A. (2001). “Fayol’s 14 Principles of Management Then and Now: A Framework for Managing Today’s Organizations Effectively.” Management Decision.
Sinek, Simon. (2014). Leaders Eat Last: Why Some Teams Pull Together and Others Don’t. Penguin.
Skaar, John. (2019). “The Power of Lean Principles.” In Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC), 393–404. Dublin, Ireland.
Skaar, J., Bølviken, T., Koskela, L., & Kalsaas, B. T. (2020, July). Principles as a bridge between theory and practice. In 28th Annual Conference of the International Group for Lean Construction. The International Group for Lean Construction.
Sørhaug, Tian. 1996. Om Ledelse: Makt Og Tillit I Moderne Organisering. Universitetsforlaget Oslo.
Szypszak, Charles. (2016). Military Leadership Lessons for Public Service. McFarland.
Tsoukas, Haridimos, and Christian Knudsen. (2005). The Oxford Handbook of Organization Theory. Oxford University Press.
Wallace, C. Richard, and Jr. (1996). From Vision to Practice: The Art of Educational Leadership. Corwin Press, Inc., 2455 Teller Road, Thousand Oaks, CA 91320.
Zanone, P. G., and J. A. S. Kelso. (1992). “Learning and Transfer as Dynamical Paradigms for Behavioral Change.” Tutorials in Motor Behavior, 2. 2: 563–82.

Erazo-Rondinel, A. A. and Huaman-Orosco C. (2021). "Exploratory Study of the Main Lean Tools in Construction Projects in Peru" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 542–551, doi.org/10.24928/2021/0213, online at iglc.net.

EXPLORATORY STUDY OF THE MAIN LEAN TOOLS IN CONSTRUCTION PROJECTS IN PERU

Andrews A. Erazo-Rondinel [1] and Cristian Huaman-Orosco [2]

ABSTRACT

Lean Construction (LC) has been applied in various construction projects in Peru for over 20 years in different projects: buildings, roads, sanitary works, mining, sports infrastructure, energy, oil, and industrial plants; as well as a series of tools such as Last Planner® System (LPS), takt time, visual management, among others. However, in Peru, practitioners are focused on LPS, leaving aside other lean tools that can help manage construction projects. The research aims to identify the main lean tools applied in Peru's construction projects and classify them according to the project type. First, a literature review of lean tools applied in Peru is conducted; second, expert judgments are interviewed to validate the tools, and fourteen main LC implementation tools are identified. Then, one hundred and twenty-four engineers answered the survey from various types of projects and classified the primary tools that have been implemented in their respective projects. The data is analysed by linear correlation and reliability. It was found that the primary tools used in Peru are: LPS, Visual Management (VM), Continuous Improvement, Feedback, Big Room, and Value Stream Mapping (VSM). The study found that professionals do not know the benefits of each tool or when to apply it. Also, the professionals implement few tools in the design stage of the projects.

KEYWORDS

Lean construction, tools, benefits, Perú, Latin America.

INTRODUCTION

Implementing lean tools has had key benefits in the construction industry for better cost and time control, greater safety, and other benefits (Arbulú and Zabelle, 2006). Thus, in Peru, they have been implemented since 1997 (Ghio 1997), achieving the following benefits: generating and adding value for the client (Orihuela et al. 2019; Erazo et al. 2020), increasing productivity, and reducing waste (Yoza 2011; Román and Juárez 2014), delivering the project to the client on time (Flores and Orello 2013; Murguia et al. 2016), and improving communication, and collaboration (Gómez et al. 2018). Ghio (2001) identifies the factors that generate low productivity in Peruvian construction and proposes three lean tools: LPS, work sampling method, and takt time. LPS is the tool most used by professionals in Peru (Murguia 2019). The benefits of LPS are to generate a more

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predictable workflow and speed in scheduling, design, and construction of projects (Ballard et al., 2007). These benefits served to motivate professionals to put in place Lean in various projects in Peru. Likewise, the need to complement them and improve their potential led them to put them on par with other tools such as balance charts, feedback, and visual management (Gómez et al., 2018).

Tools such as Value Stream Mapping (VSM), Target Value Delivery (TVD), and Integrated Project Delivery (IPD) have been inserted as pilot plans as part of testing and learning (Medina 2014). VSM has had a better application in linear projects to standardize processes in different work fronts and map processes (Róman and Juárez 2014). TVD has been incorporated only as a pilot plan and occasionally (Gutiérrez 2020). IPD has taken relevance since 2018 to involve project stakeholders and reach the project scope with defined timelines (Erazo et al. 2020; Gómez et al. 2018). Also, the increased adoption of Building Information Modeling (BIM) has motivated professionals to use Big Room, LPS, Virtual Design Construction (VDC), tack time, and Choosing By Advantages (CBA). BIM-enabled pre-conceptualization of the project, allowing for better decision making, more accurate and collaborative planning, safer work fronts, and strategies for a continuous workflow (Gómez et al. 2018; Gutiérrez 2020; Suarez et al. 2020).

In addition, Peruvian public projects present different problems. In 2018, the number of public projects paralyzed was 867 (Auditor-General of Peru, 2019. The main reasons for these were technical deficiencies and contractual non-compliance (39%), exceeding the cost (28%) and time of that formulated in their technical file (15%). These problems mentioned above are frequently in Peru's projects. LC is a good solution to the previous problem, but it is necessary to show the Lean tools that are used and their respective benefits. Through this study, the professionals will know recent results (most used tools and their benefits) of Lean implementation (the last study was in 2001).

LITERATURE REVIEW

For this stage, a literature review of IGLC articles from 1997 to 2020 is carried out. The articles are filtered by the word Peru, and the publications were also reviewed year by year. As a result, 26 articles evaluating Peruvian construction projects are identified. These are classified according to the tools applied and the benefits of each type of project. Table N°1 shows this analysis according to the type of tool and its respective implementation project.

Table 1. Use of lean tools by project type in Peru.

Lean tool	Source	Projects Implemented
LPS	(Arbulu y Soto 2006; Brioso 2011; Flores y Ollero 2013; Ghio 1997; Murguia 2019; Murguía et al. 2016; Orihuela et al. 2019; Román y Juárez 2014; Suarez et al. 2020; Yoza 2011)	Buildings, Highway Infrastructure, Energy and Oil, Mining, Sanitary and sewerage infrastructure
VSM	(Murguía et al. 2016; Román y Juárez 2014)	Highway Infrastructure, Buildings
IPD	(Gomez et al. 2018; Medina 2014)	Highway Infrastructure, Buildings
Lean in design	(Arbulu y Soto 2006; Brioso 2011; Orihuela et al. 2019)	Highway Infrastructure, Buildings
Big Room	(Gomez et al. 2018; Gutiérrez 2020)	Highway Infrastructure and Buildings
Visual Management	(Guzman y Ulloa 2020; Orihuela et al. 2019)	Buildings and sports infrastructure
LBMS	(Murguía et al. 2016; Murguia y Urbina 2018; Suarez et al. 2020; Yoza 2011)	Buildings, Sanitary and sewerage infrastructure
Takt Time	(Murguia y Urbina 2018)	Mining and Buildings
Continuous Improvement	(Murguia et al. 2020)	Buildings
Feedback	(Izquierdo et al. 2011)	Buildings
Continuous Flow	(Villagarcia 2011)	Buildings and Highway Infrastructure
Information management	(Gutiérrez 2020; Villagarcia 2011)	Buildings and Highway Infrastructure
LPDS	(Brioso 2011; Medina 2014)	Buildings
Standardization	(Flores y Ollero 2013)	Sanitary and sewerage infrastructure
Target Cost	(Gutiérrez 2020; Medina 2014)	Buildings
CBA	(Gomez et al. 2018; Suarez et al. 2020)	Buildings and Highway Infrastructure
A3 Report	(Gomez et al. 2018)	Buildings and Highway Infrastructure

RESEARCH METHOD

To better understand the study phenomenon, the authors followed the method used in Figure N°1. The study had a mixed approach, as it considered a qualitative and quantitative approach to take a better "snapshot" of the study phenomenon at a given time (Cresswell, 2014). Quantitative questions were asked through closed-ended questions to tools and benefits. The qualitative questions served to corroborate the data and give space to relate experiences of particularities of the interviewees (these accounts revealed particular benefits of LC).

Figure N° 1. Diagram of the method Proposed.

SELECTION OF LEAN EXPERTS

Table N°2 shows the profile of the six selected experts. Nine experts were selected, but only six met the requirements according to the objectives of the study: Civil Engineer with more than 10 years of experience implementing lean in the sector of study and professionals with teaching experience, published articles and at least a master's degree.

Table 2. Characteristics of lean experts

Expert	Experience	Description
Building	15 years	Civil Engineer, consultant, and Lean Implementer in mega-projects of real estate, educational centers, hospitals, and shopping centers. Advanced Instructor of the Peruvian chapter of Lean Construction.
Infrastructure	12 years	Civil Engineer, consultant, and Lean implementer in highway and railroad infrastructure megaprojects.
Mining	13 years	Civil Engineer, consultant, and Lean implementer in the largest Peruvian mining companies.
Industrial Plants	10 years	Industrial Engineer and Lean implementer, production and planning engineer in major industrial plants in Peru. Advanced Instructor of the Peruvian chapter of Lean Construction.
Energy and Oil	13 years	Civil Engineer, manager of energy, oil, and gas projects. Advanced Instructor of the Peruvian chapter of Lean Construction.
Sports infrastructure and roads	12 years	Civil engineer and lean implementer in sports megaprojects. Senior lecturer at Peruvian universities.

EXPLORATORY INTERVIEWS AND VALIDATION WITH EXPERTS

The interviews with the experts are semi-structured: This starts with selecting experts according to the type of project. The next step is knowing the professional profile of the expert and his experience in the various projects where they have taken part and implemented LC. Later, the research team collected the tools they used in their project and the benefits they got. Finally, the expert reviews the survey and give the feedback according to their expertise. All interviews are archived and stored; based on the feedback from the experts in the interviews, the research team adjusted the surveys.

QUESTIONNAIRE DESIGN AND DATA COLLECTION

The survey was structured as follows: (1) General data; (02) Professional data: this section collects information on company size, years of experience of the participants, (03) Lean tools: knowledge and application of the tools in their projects. (04) Lean Benefits: The professionals' perceptions got by using the Lean tools in their projects are evaluated. (05) Final aspects: Information and data care is collected from the participants in this section.

The final questionnaire is answered by one hundred and twenty-four professionals and is conducted virtually. The tools were evaluated with the Likert scale from 1 to 5 points, asking the respondents to evaluate the tools they most frequently used in their project as "Never=1, Rarely=2, Occasionally=3, Frequently=4 and Very frequently=5". The benefits they got after using the Lean tools were evaluated with the Likert scale from 1 to 5 points, asking the respondents to evaluate which were the benefits they perceived the most in their project as "Strongly disagree=1, Somewhat disagree=2, Neither agree nor disagree=3, Somewhat agree=4 and Strongly agree=5".

RESULTS AND DISCUSSION

The questionnaire was validated by experts and the consistency of the results by Cronbach's Alpha (α) with a consistency of 0.92 or an 8% error. Table 3 shows the relevant results of the 124 respondents.

Table 3. Bibliographic characteristics of the survey respondents.

Demographic Characteristics	Frequency	Percentage
Experience		
1-5 years	82	66.39%
6-10 years	24	19.33%
11-15 years	10	7.56%
16-20 years	6	5.04%
More than 20 years	2	1.68%
Experience working with lean.		
1-2 years	51	41.13%
3-5 years	38	30.65%
6-8 years	21	16.94%
9- 10 years	12	9.68%
More than 10 years	2	1.61%
Size of organization		
micro (1 to 10 people)	27	22%
small (10 to 50 people)	32	26%
medium (50 to 250 people)	30	24%
Large (more than 250 people)	35	28%

The figures below show the most used tools according to the type of project. The code "{n=x}" represents the tool "n" used by "X" professionals. Where the value of "x" is the number of professionals who use the tools only "frequently" and "very frequently."

Table 4 shows the ranking of the tools most used by professionals in Peru and their comparison with other countries. The percentages are calculated based on the total number of respondents. The results show remarkable growth in applying LTs in Peru compared to other countries around the world and other Latin American countries. Most of the LTs used are related to their diffusion, popularity, and benefits. However, the A3 report shows a growth of more than 20% compared to other countries. Its use would be related to the ease of transmitting ideas quickly and effectively. They are avoiding extensive reporting and accumulation of non-relevant information in project control. SBD has a remarkable increase in creating many designs for the client based on recent technologies, such as sustainable buildings, smart buildings, new technological materials, or creating customized departments for each client. But none of the most used LT are related to design or integration between all stages of the project. The lack of knowledge of the other tools could be the cause of the problems in Peruvian construction.

Table 4. Comparison of lean tools

Description	Peru (2021)	Chile(Salvatierra et al. 2015)	Colombia(Castiblanco et al. 2019)	Global(McGraw Hill 2013)
Number of respondents	124	25	254	193
LPS	62.9%{n=78}	100% {n=25}	18.11%{n=46}	30%{n=58}
VM	50% {n=62}	45%{n=11}	10.24%{n=26}	---
Continuous Improvement	41.9%{n=52}	55%{n=14}	---	---
Kanban	33.9%{n=42}	1%{n=1}	4.72%{n=12}	---
Big Room	31.5%{n=39}	---		20%{n=39}
A3 Report	25.8%{n=32}	9%{n=3}	3.15%{n=8}	---
Gemba	25.8%{n=32}	100%{n=25}	1.97%{n=5}	---
VSM	19.4%{n=24}	18%{n=5}	6.69%{n=17}	21%{n=41}
CBA	18.5%{n=23}	---	5.12%{n=13}	15%{n=29}
TVD	12.9%{n=16}	---	6.3%{n=16}	24%{n=47}
SBD	9.7%{n=12}	---	1.97%{n=5}	----

Figure 2 shows the ten most used tools in building projects (shopping centers, hospitals, real estate, educational centers, and others), in infrastructure projects (roads, sanitation works, trains, and other linear works), and energy, gas, oil, and industrial plant projects. In building projects, LPS and VM are the most frequently used tools to improve collaboration and planning between specialties. Big Room allows project stakeholders to make decisions, work collaboratively and engage through LPS. The integration of these three LTs allows engineers to perform segmentation, continuous flow, and design understanding. Compared to similar studies in Peru, building projects have matured to a greater degree LC. Professionals integrate design and construction. However, client value mapping is still minimal. Also, decision-making and cost control are still not perceived in building projects. In infrastructure projects most of the tools are focused on the construction stage. Projects of this type of longitudinal need a great effort to control different work fronts. A3 reporting is an excellent alternative to a large amount of information reported on many work fronts. This allows interpreting the information quickly and efficiently. It can be identified that the tools are more focused on the division of labor, such as LPS and process tracking (Kanban). Continuous Improvement and Work Sampling are focused on waste identification. These tools are due to the extensive earthworks and the focus on machinery to optimize and save time.

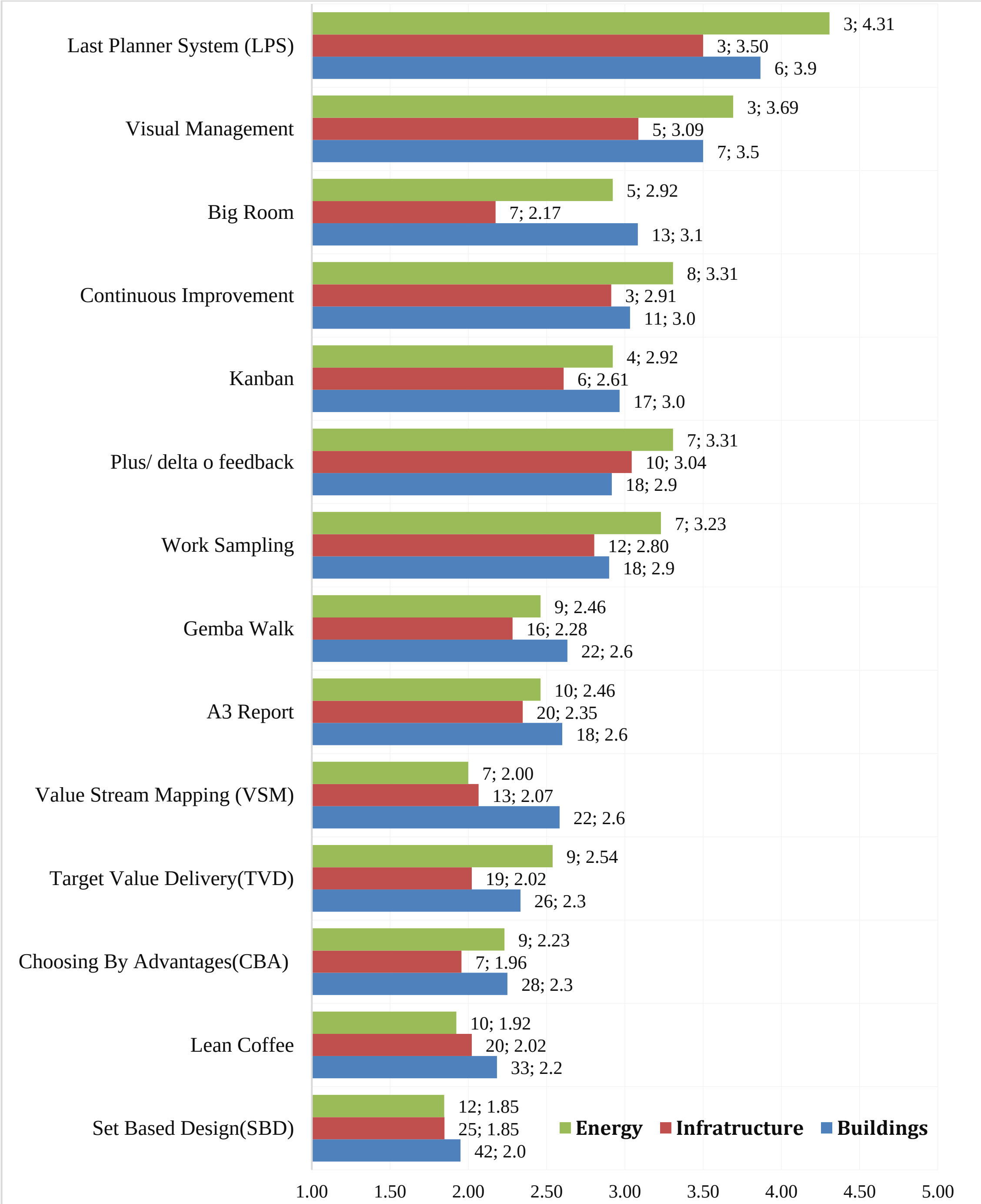

Figure 2. Most used tools in construction projects in Peru

Finally, Figure 3 shows the ten main tools used in the project design and formulation stage. Professionals in this field are unaware of any other tools besides the known ones. TVD and SBD have a notable use by professionals to generate better designs to the client's scope. The tools allow the integration of the clients and the designer. However, they still do not develop tools that allow the integration of stakeholders in the construction stage. This could be the main factor that causes deficiencies in the technical file and contractual problems. There are still very few practitioners of these tools frequently (three to five practitioners).

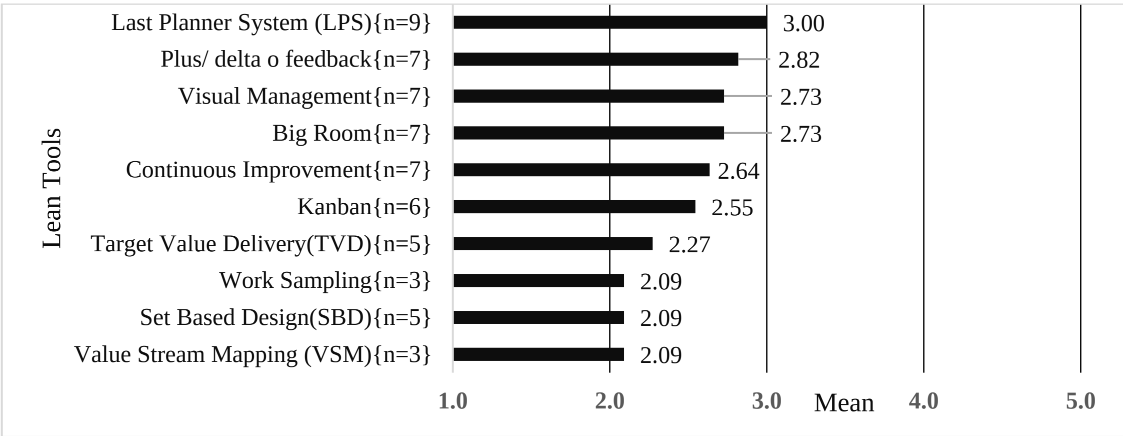

Figure 3. Lean tools most used in the design and formulation of projects.

Figure 4 shows the benefits obtained by lean practitioners. The benefits are correlated to the most used tools. The benefits of lean compared to McGraw Hill Construction (2013) do not differ much. For example, according to the study, the improvement of planning is 79% compared to 80% of the mentioned literature. So, we can say that the benefits of lean tools in Peru are quite correlated to the global literature.

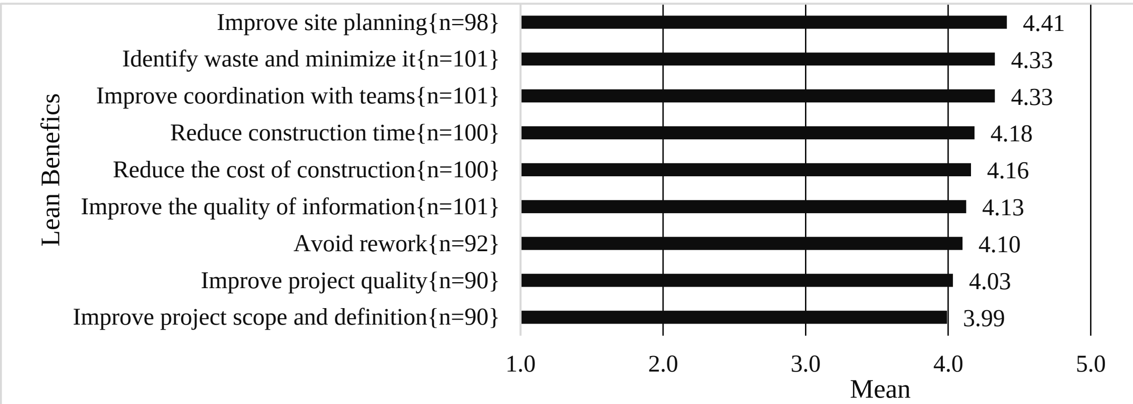

Figure 4. Lean benefits

Looking at the results of the application of the LTs in each type of project, it is evident that there is no correlation of data between the construction and design stages. So, it is necessary to carry out studies to show why professionals do not use lean in the design stages. Generating designs without observing the entire project is also a way to generate problems and waste in the construction stage (Huthwaite 2012). LT has been applied to a greater extent in building and infrastructure projects. The results of its application are notorious in the benefit charts. However, it is necessary to identify the benefits of each tool in energy, oil, and industrial plant projects, to encourage professionals to become Lean practitioners.

CONCLUSIONS

The exploratory results show that the most used tool in Peru is LPS in projects of buildings, road infrastructure, sanitation, trains, energy, oil, and industrial plants. The analysis shows that professionals and companies are more focused on the construction stage, leaving aside the design and integration stages of the project stakeholders. Even the construction industry in Peru is still working in silos, focusing objectively only on the project stage they oversee. Also, there is little motivation in professionals to use design tools such as TVD and Big Room. Big Room has been the tool that is taking more relevance at this stage, generating good design strategies, and making it even more powerful with BIM use. Finally, there is still a long process to include IPD in Peruvian companies to integrate all stages and stakeholders of the project. However, using Lean tools in the diversity of projects generates a promising long-term Lean maturity in the companies. The benefits obtained so far in the study show a correlation close to the global literature references. It is expected that the results shown will motivate Peruvian professionals to become Lean practitioners. The authors recommend developing a study about the drivers and barriers that motivated the use of LC in the design process. Also, it is essential to develop exploratory studies of SBD, TVD, and other tools to know the maturity of these tools in Peruvian projects.

REFERENCES

Arbulu, R., y Soto, J. (2006). "A Design Case Study: Integrated Product and Process Management". *Proc. 14th Annual Conference of the International Group for Lean Construction*, Santiago, Chile.

Arbulu, R. & Zabelle, T. 2006, 'Implementing Lean in Construction: How to Succeed' *Proc. 14th Annual Conference of the International Group for Lean Construction.* Santiago, Chile.

Ballard, G., Howell, G., Tommelein, I., y Zabelle, T. (2007). "The Last Planner Production System Workbook". *Lean Construction Institute, San Francisco, California, USA, 81pp*, 82.

Brioso, X. (2011). "Applying lean construction to loss control". *Proc. 19th Annual Conference of the International Group for Lean Construction*, Lima, Peru.

Castiblanco, F. M., Castiblanco, I. A., y Cruz, J. P. (2019). "Qualitative Analysis of Lean Tools in the Construction Sector in Colombia". *Proc. 27th Annual Conference of the International Group for Lean Construction, Dublin, Ireland.*

Cresswell, J.W., (2014). Research Design. Qualitative, Quantitative and Mixed methods approach 4th ed., London: Sage.

Erazo, A., Guzman, G., y Espinoza, S. (2020). "Applying BIM Tools in IPD Project in Perú". *Proc. 28th Annual Conference of the International Group for Lean Construction*, Berkeley, California.

Flores, G., y Ollero, C. (2013). "Productivity Improvement Applying Production Management in Projects with Repetitive Activities". *Proc. 21st Annual Conference of the International Group for Lean Construction*, Fortaleza, Brazil.

Ghio, V. A. (1997). "Development of Construction Work Methods and Detailed Production Planing for on-Site Productivity Improvement". *Proc. 5th Annual Conference of the International Group for Lean Construction*, Gold Coast, Australia.

Ghio, V. (2001). *Construction Site Productivity*. Pontificia Universidad Católica del Perú, Lima.

Gomez, S., Ballard, G., Naderpajouh, N., y Ruiz, S. (2018). "Integrated Project Delivery for Infraestructure Projects in Perú". *Proc. 26th Annual Conference of the International Group for Lean Construction*, Chennai, India.

Gutiérrez, F. M. (2020). "Influence of Integrated Teams and Co-Location to Achieve the Target Cost in Building Projects". *Proc. 28th Annual Conference of the International Group for Lean Construction,* Berkeley, California.

Guzman, G., y Ulloa, W. (2020). “Bim Application in the Operation and Maintenance Management of a Sports Infrastructure”. *Proc. 28th Annual Conference of the International Group for Lean Construction*, California, USA, 949–960.

Huthwaite, B. (2012). *The Lean Design Solution. A practical guide to streamlining product design and development.* Mackinac Island, Michigan: Institute for Lean Innovation.

Izquierdo, J. L., Cerf, M., y Gómez, S. A. (2011). “Lean Construction Education: Basic Management Functions Workshop”. *Proc. 19th Annual Conference of the International Group for Lean Construction*, Lima, Peru.

Medina, A. (2014). “Learning Through Failure: The Challenge of Lean Project Delivery from the Contractor’s Perspective in Perú”. *22nd Annual Conference of the International Group for Lean Construction, IGLC 2014*, Oslo, Norway.

McGraw Hill Construction Research y Analytics. (2013). *Lean Construction Leveraging Collaboration and Advanced Practices to Increase Project Efficiency*. *SmartMarketReport*, (M. Hill, ed.), Bedford.

Murguia, D. (2019). “Factors Influencing the Use of Last Planner System Methods: An Empirical Study in Peru”. *Proc. 27th Annual Conference of the International Group for Lean Construction*, Dublin, Ireland.

Murguía, D., Brioso, X., y Pimentel, A. (2016). “Applying Lean Techniques to Improve Performance in the Finishing Phase of a Residential Building”. *Proc. 24th Annual Conference of the International Group for Lean Construction*, Massachusetts, USA.

Murguia, D., Felix, K. M., y Guerra, M. A. (2020). “An Approach to Capture Design and Construction Lessons Learned From Facility Managers”. *Proc. 28th Annual Conference of the International Group for Lean Construction*, California, USA.

Murguia, D., y Urbina, A. (2018). “Complex Production Systems: Non-Linear and Non-Repetitive Projects”. *Proc. 26th Annual Conference of the International Group for Lean Construction*, Chennai, India.

Orihuela, P., Noel, M., Pacheco, S., Orihuela, J., Yaya, C., y Aguilar, R. (2019). “Application of virtual and augmented reality techniques during design and construction process of building projects”. *Proc. 27th Annual Conference of the International Group for Lean Construction*, Dublin, Ireland.

Román, B., y Juárez, G. (2014). “A Lean-Triz Approach for Improving the Perfomance of Construction Projects”. *Proc. 22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway.

Salvatierra, J. L., López, A., Alarcon, L. F., y Velásquez, X. (2015). “Lean Diagnosis for Chilean Construction Industry: Towards More Sustainable Lean Practices and Tools”. *Proc. 23rd Annual Conference of the Internatioanl Group for Lean Construction, Perth, Australia.*

Suarez, J. C., Zapata, J., y Brioso, X. (2020). “Using 5D Models and CBA for Planning the Foundations and Concrete Structure Stages of a Complex Office Building”. *Proc. 28th Annual Conference of the International Group for Lean Construction*, California, USA.

The Auditor General of the Republic of Peru (2019). *Stalled Works Report 2019*. Lima, Peru.

Villagarcia, S. (2011). “Formalization as a Way of Coordination and Control in a Construction Firm”. *Proc. 19th Annual Conference of the International Group for Lean Construction 2011, IGLC 2011*, Lima, Peru.

Yoza, A. (2011). “Impact of ‘The last planner’ Method on Sanitation works”. *Proc. 19th Annual Conference of the International Group for Lean Construction*, Lima, Peru.

Garcia, A. and Murguia, D. (2021). "A scenario-based model for the study of collaboration in construction." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 552–561, doi.org/10.24928/2021/0216, online at iglc.net.

A SCENARIO-BASED MODEL FOR THE STUDY OF COLLABORATION IN CONSTRUCTION

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ABSTRACT

The construction sector has been widely criticized for its low productivity, fragmented structure, and adversarial relationships. To address these problems, some industry actors are adopting innovations such as lean construction, digital technologies, and collaborative contracts. However, these transformative innovations are underpinned by inter-organizational collaboration within complex supply chain networks. Understanding collaboration in theory and practice is a difficult task. Therefore, this study aims to investigate factors influencing collaboration and develop a model for inter-organizational collaboration. To achieve this aim, first, a literature review on collaboration in construction was conducted. Second, qualitative data were collected via semi-structured interviews using the critical incident technique. Third, data were deductively and inductively analyzed using thematic nodes. Data showed that collaboration can be classified into four dimensions: trust, project uncertainty management, client's operational capability, and business relationships. Finally, an empirical framework was constructed using the scenario technique. Client attributes and Supply Chain Capabilities were found to be the most influential and uncertain factors. Based on these, four collaboration scenarios were developed and assessed with illustrative implications derived from the empirical data. The scenario-based model would provide a further understanding of inter-organizational collaboration within supply chains and would aid Lean Construction practitioners to develop collaborative relationships.

KEYWORDS

Collaboration, supply chain management, lean construction, relationships, scenarios.

INTRODUCTION

Over the last few years, the construction industry has experienced very rapid technological growth. However, despite major transformation efforts to meet global challenges, the industry is still known as the least efficient compared to the manufacturing sector or the total economy. On the other hand, isolated pockets of innovation will not deliver the expected transformational results (Ozorhon and Oral 2017). Practitioners require to exchange information and knowledge with other partners to achieve the benefits of innovations (Xue et al. 2018). However, little emphasis has been placed on

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the collaborative practices to ensure this exchange and on the collaborative environments where efficacy and efficiency flourish. As such, previous studies suggest that effective collaboration between the project owner and the contractor is essential for project success. Karlsson and Kindbom (2018) claimed that parties involved should strategically work to gather timely feedback before the project is launched.

Previous research has acknowledged that collaboration is a complex concept. Moreover, there are divergent perspectives of collaboration in construction (Hughes et al. 2012). Xue et al. (2018) identified several types of collaborative working such as teamwork, partnership, project alliance, joint venture, strategic alliance, coalition, and supply chain management. Moreover, actors from various disciplines make sense of collaboration depending on their previous experience and current values. Thus, divergent interpretations of the constituents of collaboration become evident in the decision-making process, where stakeholders vary their intent and degree of involvement. Willis and Alves (2019) argued that collaboration keywords in contracts would promote collaborative behaviors in practice. They showed that Design-Build (DB) and Integrated Project Delivery (IPD) contracts have far more collaborative language than traditional Design-Bid-Build (DBB) contracts. This suggests that owners who choose the project delivery method should carefully decide on the language to be used in contracts. However, this research argues that industry actors poorly understand both the concept of collaboration and collaborative practices. Therefore, it is necessary to broaden the understanding of collaboration to have a clearer picture of inter-organizational collaboration. For this reason, the main objective of this study was to develop a model for inter-organizational collaboration that can be used to foster collaborative behaviors among project participants.

LITERATURE REVIEW

DEFINITIONS

Previous studies highlighted the difference between coordination, cooperation, and collaboration. Roberts and Bradley (1991) conceptualized collaboration as *"an interactive process that has a shared transmutational purpose with the characteristics of having an explicit voluntary affiliation, joint decision-making, a need for agreed norms, and that has a temporal structure toward the same end"*. On the other hand, coordination is defined as the planning or arranging of different activities involving two or more parties, and cooperation explains how an inter-organizational relationship occurs between project participants who are not commonly related by vision or mission, resulting in the creation of separate projects with independent structures (Schöttle et al. 2014). However, Haghsheno et al. (2020) recently argued again that *“collaboration goes beyond as it describes the common vision to create a common project organisation with a jointly defined structure and to create a project culture based on trust, and transparency”*. Therefore, in this research, collaboration is defined as a process of inter-organizational interaction that involves the effective and transparent transfer of information and knowledge so that working together will increase value for each independent unit.

FACTORS INFLUENCING COLLABORATION

Collaboration is difficult to achieve in the construction industry due to low margins and a lack of trust between stakeholders. Previous studies have catalogued the most important factor influencing collaboration. For example, Deep et al. (2019) claimed that collaboration was strongly associated with trust, commitment of the organization to a contract, and reliability of the supplier. Moreover, Haaskjold et al. (2019) found that quality of communication, project uncertainty, client's operational capability, change orders and trust represent the most influential factors in collaboration. Similarly, Eskerod et al. (2010) argued that the most representative collaboration antecedents in the field of project management were clear roles and processes, trust, physical and cultural proximity, alignment of incentives, commitment to the project, goal congruence, conflict resolution, and expectations fulfillment. Likewise, Schöttle and Gehbauer (2012) found that uncertainty had to be counteracted by an incentive system to develop a collaborative project environment. Knapp et al. (2014) proposed that the owner's representative plays a critical role in the active promotion of harmony, collaboration, and cooperation among all entities performing on the project. To support a collaborative approach, Schöttle and Tillmann (2018) collected findings from two case studies in which an explicit process for goal setting and tracking was used. These previous studies suggest that collaboration factors are linked to social and managerial dimensions as detailed in Table 1.

Table 1: Factors Influencing Collaboration

Factor	Description	Author(s)
Quality of communication	Allows all parties to share and spread the objectives of project organization, responsibilities, and roles.	(Aasrum et al. 2016)
Project uncertainty	Failing to fully understand the scope of work packages, therefore, losing project control status.	(Riley and Horman 2001)
Client's operational capability	Business competencies affiliated with active participation and the right mandate on decision-making.	(Knapp et al. 2014)
Change orders	Work that is added to or removed from the original scope of work, as defined in the original contract.	(Matthews et al. 2018)
Trust	Facilitator of mutual openness in terms of behavior and cohesion.	(Bond-Barnard et al. 2018)
Clear roles and processes	Roles, standardized processes, value mapping and learning to establish an integrated coalition.	(Erdogan et al. 2008)
Physical and cultural proximity	Physical and geographical co-location of members recognizing inherent personality differences to achieve a close exchange of information.	(Koolwijk et al. 2018)
Alignment of incentives	Mechanisms of positive stimulation to improve performance to be the same win-win community.	(Schöttle and Gehbauer 2012)
Commitment to project	Attitudes of mutual support to increase genuine interest and set stakeholder priorities.	(Tillmann et al. 2012)
Goal congruence	Identification of clear objectives to achieve relational efficiency in obtaining results.	(Schöttle and Tillmann 2018)
Conflict resolution	Competencies for the business continuity of a challenging relationship with disputes at the front-end.	(Vaaland 2004)
Expectations fulfillment	Perception of service based on expected return management.	(Tillmann et al. 2011)

RESEARCH METHOD

Collaboration and collaborative practices are produced by actors' experiences and social interactions with other actors. Therefore, an abductive and qualitative research approach was selected for this research. Semi-structured interviews using the critical incident technique (CIT) were selected as the data collection method. By incident is meant any observable human activity that allows inferences to be made. To be critical, the incident must have significance and depict the phenomenon being investigated (Flanagan 1954). CIT was employed to seek expert knowledge and experience of the constituents of collaboration. CIT enables the possibility to gather critical incidents from interviewees' narratives. Therefore, the interviews were designed to reveal memorable incidents regarding collaboration, or lack of collaboration, illustrated by empirical explanations. Interviewees were selected based on their proven experience in design and construction, and a seniority level ranging from middle management to decision-makers. Data were later analyzed using a mixture of deductive and inductive coding. Therefore, the most important factors of collaboration were compared with factors found in the literature.

Finally, the scenario-axis technique was deployed to construct scenarios for collaboration. This technique is recommended to systematically construct images of the future. The method aims to identify the most uncertain and impactful driving forces that could have a decisive output in the dependent variable under study (van't Klooster and van Asselt 2006). If two influential forces were identified, it was possible to use the technique to map collaborative environments within a construction project. The result is a 2x2 matrix that forms four quadrants which are the basis of four possible outcomes. These quadrants are then developed into scenario narratives, reflecting the influence of the previously identified critical incidents. Finally, the scenarios were discussed through implications to demonstrate their impact on collaborative lean management practice.

DATA ANALYSIS AND RESULTS

EMPIRICAL VALIDATION

Thirteen participants from the Peruvian construction industry were recruited and a total of 11 hours of recorded interviews were obtained. The interviewees' professional experience ranged from 7 to 25 years, and 30% of them had extensive lean construction practice. They had roles such as project managers, project engineers, chief executive officers, site engineers, and others. Data were carefully transcribed, resulting in 105 pages of content. The interviews were anonymized and stored in a data management system. Data were analyzed using MAXQDA 2020. Transcripts were loaded onto the system to start the coding process. Nodes were created based on the theoretical themes as described in Table 1. Transcripts were analyzed by assigning texts to nodes. However, during the data analysis process, up to eighteen nodes inductively emerged. Therefore, a factor reduction procedure was performed. The nodes with the highest number of evidence from data were retained for the analysis and a subnode level was created according to sample correlation. Moreover, the terminology was revised, the node-subnode association was revisited and grouped where appropriate. Table 2 shows the results of the data analysis, including a quote sample from the data.

Table 2: Empirical results for collaboration factors

Node	No.	Subnode	Quote Sample
Trust	1	Achievement capacity	"An achievement translates into greater belief to perform the work assigned for you, for the company and your customers"
	2	Physical and cultural proximity	"Rapid interaction of a formal and informal nature between team members is made possible for the value realization"
	3	Quality of communication	"Having transparent and open discussions from the beginning enables more power to understand the situation and expose your problems freely"
Project uncertainty management	4	Goal congruence	"Need to generate a common understanding of the value generated throughout the supply chain"
	5	Change orders	"Mandatory to manage change orders under a triangle of compromise, technical flexibility and negotiation"
	6	Conflict resolution	"Knowing from the start what will happen in a dispute preserves peace of mind and reduces future controversies"
Client's operational capability	7	Clear roles and processes	"Creates boundaries between functions and procedures that condition the development of value engineering"
	8	Alignment of incentives	"Increase performance by enhancing the value people place on goals, causing them to engage more strongly with those goals and achieve them"
	9	Team empowerment	"Grows reciprocal respect between people's opinions because it provides autonomy and responsibility to acquire the required skills"
Business relationships	10	Intra-organizational support	"Initial and ongoing senior management support and secondly in terms of gaining the support of other parts of the organization/peers"
	11	Expectations fulfillment	"Keep all parties informed of the overall service to be provided to avoid disappointment"

A SCENARIO-BASED MODEL

The next step is to conflate the emerging nodes from Table 2 into two complementary and independent intersecting axes. Briscoe et al. (2004) argued that clients are key drivers of performance improvement and innovation. Therefore, they are the most significant actor in achieving integration in the supply chain. However, these ideas have been debated and currently, researchers are investigating whether innovations should be client-led or supply-led (Lindblad and Guerrero 2020). Therefore, the emerging nodes were subsequently divided into two key uncertainties 'client attributes' and 'supply chain capabilities' as depicted in Figure 1. The inclusion of the nodes into two groups was based on the interview data which suggested an asymmetry between supply and demand maturity/capability. Moreover, to determine the appropriate axes, the approach was to uncover the relationship between the connection of the emerging themes and the axes.

For example, an interviewee highlighted an experience where physical proximity was crucial to reduce the latency in a major mechanical, electrical, and plumbing (MEP) clash in the field. The client went to the construction site and provided feedback to resolve the issue which was approved within a few minutes, compared to the traditional 4 days. However, this is still a rare practice as most contractors send requests for information (RFIs) to clients through the supervision/project management teams. The lack of clear communication between contractors and clients is also depicted as follows. A contractor sent several RFIs requesting clarification on how trucks will access a showroom in a retail project. However, the client's project manager responded that such requested change was not part of the scope. However, upon completion, the client noticed the problem and blamed the contractor for the error. Therefore, this situation shows a lack of project understanding and miscommunication between actors as the main barriers to effective collaboration. Moreover, most interviewees described that clients do not have clear design criteria and make constant changes even during construction. Thus, in practice, projects resemble the fast-track delivery method. This problem escalates when clients are unwilling to pay for the additional costs for design and construction changes. An architect said, *"I know the client will change the layout 6 or 7 times; thus, I charge these costs in advance"*. From the narratives above, actors are focused on action and deliverables rather than on collaborative decision-making. For this reason, tensions emerge between the appointing party (client) and the appointed party (architects, engineers, contractors, and subcontractors).

The analysis then involved compiling names for each of the quadrants depicted in Figure 1. Following a logic of internal consistency together with a logic of cause and effect, scenarios were described using elements from the interviews (van't Klooster and van Asselt 2006). Below, we discuss these plausible events that were constructed from the data.

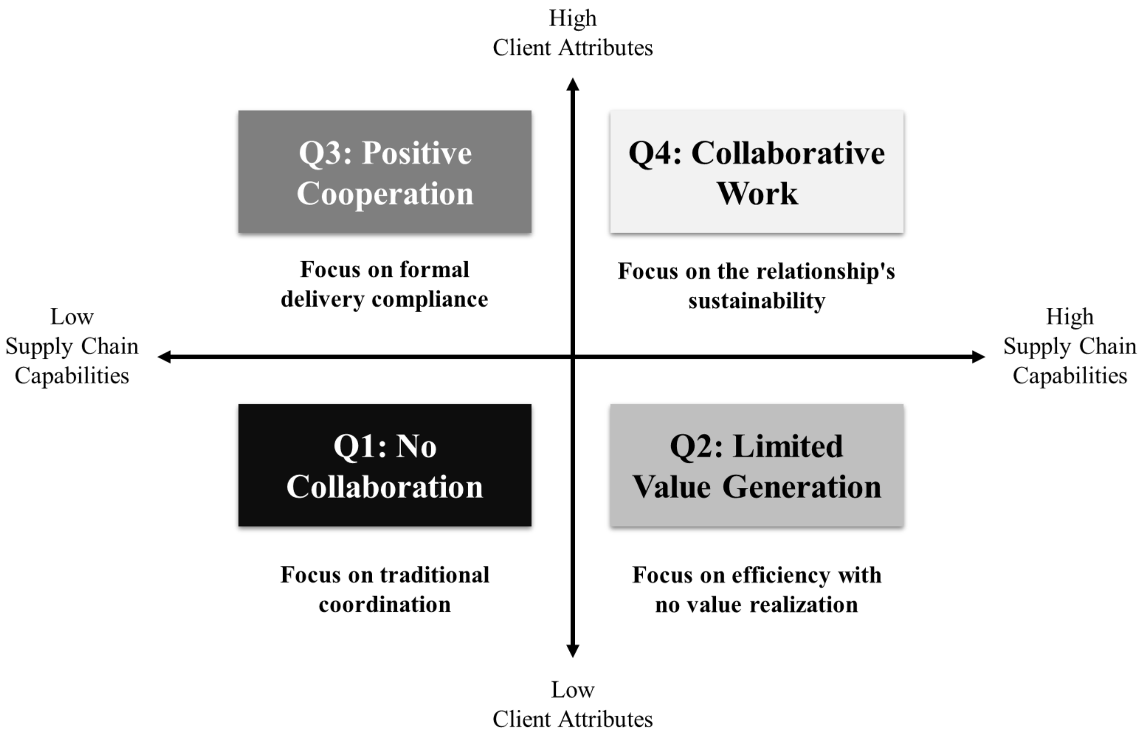

Figure 1: A scenario-based model for collaboration in construction

Collaborative Work (High Client Attributes/High Supply Chain Capabilities)

Collaboration is underpinned by value-based relationships with symmetric power and profuse information and knowledge exchange throughout the project lifecycle. The intersection between client/project objectives and operational processes have been well defined. There is a high degree of shared expertise at all organizational levels with clear corporate commitment and leadership cascading throughout project activities. The task of creating an integrated culture is based on organizational-driven policies. This scenario depicts IPD projects with a focus on long-term project outcomes.

Limited Value Generation (Low Client Attributes/High Supply Chain Capabilities)

This scenario is defined by a focus on efficiency with unknown value realization to the client. The supply chain demonstrates competencies in the use of cutting-edge platforms and digital engineering tools, as well as building information modeling and integrated concurrent engineering. The client, on the other hand, requests a project to be built on budget and on time. Small subcontractors might not be ready to collaborate, but they are integrated into the network by big players such as a DB contractor.

Positive Cooperation (High Client Attributes/Low Supply Chain Capabilities)

This scenario focuses on processes that deal with unbalanced interaction between teams and deliverables, whilst striving to maintain project compliance. This scenario depicts the digital divide between small and large firms. Designers and contractors do not possess the same maturity to deliver information and exchange knowledge. Thus, collaboration is limited by their capabilities. Normally, the most powerful firm acts as a system integrator.

No Collaboration (Low Client Attributes/Low Supply Chain Capabilities)

This scenario is cost- and time-driven, dominated by the traditional status-quo. Information is subject to basic coordination and knowledge exchange is minimal to non-existent. It also features a top-down relationship based on DBB contracts and lump sum subcontracting. There is unknown value generation, opportunistic behaviour, and relationships are based on tough contracts that protect the most powerful actor.

DISCUSSION

To map the existing collaborative environments within construction projects, we aimed to develop a scenario-based model for inter-organizational collaboration. Based on the scenario narratives, this section discusses demand and supply relationships, lean construction tools and techniques, and opportunities in each scenario. First, in Q1 we might observe real estate developers with a focal interest in the business' return on investment. Therefore, there is a structural fragmentation between design and construction, and a disparity between the client's objectives (if any) and the contractor's operation (Schöttle and Gehbauer 2012). In Q2 we might see a DB contractor leading lean and digital implementation, and a client unaware or unwilling to be part of collaborative practices. Therefore, the DB contractor retains the benefits. In Q3, we might see a forward-looking client, but noticeable disparities within the supply chain. For example, in Peru, some clients are being aware of implementing Lean Construction, Building Information Modeling (BIM) and Virtual Design and Construction (VDC). However, there is a substantial gap between designers' and contractors' capabilities, with most major contractors being the leaders in implementing collaborative practices. Q4 is still an ideal scenario with very few examples in practice. However, Q4 is driven by pre-existing trust between the client, designer, and contractors with a focus on long-term relationships (Tillmann et al. 2012).

The scenarios could also help establish roadmaps for Lean, BIM, and VDC implementation. Some tools and techniques outlined here can be applied in one or even all the quadrants. Given the limited possibility to collaborate at the project level, contractors might implement the Last Planner System (LPS) in Q1 to achieve better collaboration with subcontractors at the operational level (Schöttle and Tillmann 2018). Moreover, contractors can create BIM models to detect clashes and for quantity take-off which is sometimes considered as the first step into BIM implementation. In Q2, contractors can implement Target Costing in the early project stages. In that sense, this would reduce risks and ensure profitability for the contractor, but little value is passed on to the client. Additionally, this is a rich environment for lean design management with BIM (Aasrum et al. 2016) for both synchronous (integrated concurrent engineering) and asynchronous collaboration (common data environments). Moreover, DB contractors are engaged early in the project and off-site solutions are used in the design. In Q3, there is an opportunity to include client decisions using Target Value Design (TVD) to manage product profitability during product development and to reduce uncertainty and risk (Riley and Horman 2001). Also, Choosing by Advantages (CBA) would be used to bring actors with lower capabilities towards a more collaborative environment. From there, it drives the pathway towards Q4 that leverages previous tools within financial incentives and moves from project outputs to social, environmental, and economic outcomes.

Finally, some practical implications were identified for each scenario. In Q1, there is a potential for lean design management with BIM by convincing the client of the need for more collaborative approaches. This would move clients and contractors towards Q2 and Q3. In Q2, there is a potential to engage the client in lean and BIM applications in the operation and maintenance stage, and collecting lessons learned from facility managers from previous projects (Murguia et al. 2020). By doing so, the client's attributes would improve, and supply chains would move towards Q4. Supply chains within Q3 would benefit if the focus changes from cost and time to end-user satisfaction. Finally, Q4 supply chains have the imperative to transform the industry by developing new business models from one-off transactions to long-term partnerships. The scenarios would also be used as a training tool to raise awareness on collaboration in construction.

CONCLUSIONS

This study aimed to develop a model for inter-organizational collaboration. In practice, the common belief of collaboration is referred to perform outstanding coordination to achieve a common goal. It implies that parties should be willing to share information and knowledge for the greater project good. However, adversarial relationships and opportunistic behaviors stand in sharp contrast to delivering value and establishing a long-term business relationship. Primary data showed that collaboration can be established by improving the client's operational capacity, reinforcing strategies to reduce project uncertainty, promoting trust, and developing partnerships over time. Moreover, inductive analysis of interview data suggested that collaboration practice is a tension between client's and supply chains' technological, operational, and contractual capabilities. As such, four scenarios were developed based on low/high capabilities of clients and supply chains, namely 'Collaborative Work', 'Limited Value Generation', 'Positive Cooperation' and 'No Collaboration'. The knowledge of these collaboration factors and four scenarios would provide valuable insights for practitioners. For example, clients would understand their current position and formulate strategies to improve their technological, operational, and contractual capabilities to form more collaborative relationships with supply chains. Likewise, contractors and designers would deliver more value by strategically implementing Lean, BIM, and VDC methods, educating clients and developing business models that support collaboration. Future research would scrutinize case studies in each scenario to provide richer insights into how collaborative practices evolve.

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REFERENCES

Aasrum, J., Lædre, O., Svalestuen, F., Lohne, J., and Plaum, S. (2016). "Communication in building design management: A comparative study of Norway and Germany." *In: Proc. 24th Annual Conference of the International Group for Lean Construction*, Boston, MA, USA, 43–52.

Bond-Barnard, T. J., Fletcher, L., and Steyn, H. (2018). "Linking trust and collaboration in project teams to project management success." *International Journal of Managing Projects in Business*, 11(2), 432–457.

Briscoe, G. H., Dainty, A. R. J., Millett, S. J., and Neale, R. H. (2004). "Client-led strategies for construction supply chain improvement." *Construction Management and Economics*, 22(2), 193–201.

Deep, S., Gajendran, T., and Jefferies, M. (2019). "A systematic review of 'enablers of collaboration' among the participants in construction projects." *International Journal of Construction Management*, 1–13.

Erdogan, B., Anumba, C. J., Bouchlaghem, D., and Nielsen, Y. (2008). "Collaboration Environments for Construction: Implementation Case Studies." *Journal of Management in Engineering*, 24(4), 234–244.

Eskerod, P., Denmark, S., Dalcher, D., and Sandhawalia, B. (2010). "The role of project collaboration quality and knowledge integration capability in multi-partner projects." *Paper presented at PMI® Research Conference: Defining the Future of Project Management*, Project Management Institute, Washington, DC, 1–18.

Flanagan, J. C. (1954). "The critical incident technique." *Psychological Bulletin*, 51(4), 327–358.

Haaskjold, H., Andersen, B., Lædre, O., and Aarseth, W. (2019). "Factors affecting transaction costs and collaboration in projects." *International Journal of Managing Projects in Business*, 13(1), 197–230.

Haghsheno, S., Budau, M. R.-D., and Russmann, E. (2020). "Collaboration Barometer – Development of a Tool for Measuring Collaboration During Design and Construction." *In: Proc. 28th Annual Conference of the International Group for Lean Construction*, Berkeley, California, USA, 323–336.

Hughes, D., Williams, T., and Ren, Z. (2012). "Differing perspectives on collaboration in construction." *Construction Innovation*, 12(3), 355–368.

Karlsson, A., and Kindbom, I. (2018). "Collaboration between project owners and contractors during the tender process in the construction industry (Master Thesis)." Jonkoping University International Business School.

Knapp, S., Long, D., and Howell, G. (2014). "The role of the Owner's Representative on IPD projects." *In: Proc. 22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway, 1369–1377.

Koolwijk, J. S. J., van Oel, C. J., Wamelink, J. W. F., and Vrijhoef, R. (2018). "Collaboration and Integration in Project-Based Supply Chains in the Construction Industry." *Journal of Management in Engineering*, 34(3).

Lindblad, H., and Guerrero, J. R. (2020). "Client's role in promoting BIM implementation and innovation in construction." *Construction Management and Economics*, Routledge, 38(5), 468–482.

Matthews, J., Love, P. E. D., Mewburn, J., Stobaus, C., and Ramanayaka, C. (2018). "Building information modelling in construction: insights from collaboration and change management perspectives." *Production Planning and Control*, 29(3), 202–216.

Murguia, D., Felix, K. M., and Guerra, M. A. (2020). "An approach to capture design and construction lessons learned from facility managers." *In: Proc. 28th Annual Conference of the International Group for Lean Construction 2020*, 997–1008.

Ozorhon, B., and Oral, K. (2017). "Drivers of Innovation in Construction Projects." *Journal of Construction Engineering and Management*, 143(4), 04016118.

Riley, D., and Horman, M. (2001). "The effects of design coordination on project uncertainty." *In: Proc. 9th Annual Conference of the International Group for Lean Construction*, Singapore, Singapore, 1–8.

Roberts, N. C., and Bradley, R. T. (1991). "Stakeholder Collaboration and Innovation: A Study of Public Policy Initiation at the State Level." *The Journal of Applied Behavioral Science*, 27(2), 209–227.

Schöttle, A., and Gehbauer, F. (2012). "Incentive systems to support collaboration in construction projects." *In: Proc. 20th Conference of the International Group for Lean Construction*, San Diego, California, USA.

Schöttle, A., Haghsheno, S., and Gehbauer, F. (2014). "Defining cooperation and collaboration in the context of lean construction." *In: Proc. 22nd Annual Conference of the International Group for Lean Construction*, Oslo, Norway, 1269–1280.

Schöttle, A., and Tillmann, P. A. (2018). "Explaning the benefits of team-goals to support collaboration." *In: Proc. 26th Annual Conference of the International. Group for Lean Construction*, Chennai, India, 432–441.

Tillmann, P. A., Tzortzopoulos, P., Miron, L. I. G., and Formoso, C. T. (2011). "The challenges of managing stakeholder requirements in a urban regeneration project." *In: Proc. 19th Annual Conference of the International Group for Lean Construction*, Lima, Peru, 362–371.

Tillmann, P., Ballard, G., Tzortzopolous, P., and Formoso, C. (2012). "How integrated governance contributes to value generation - Insights from an IPD case study." *In: Proc. 20th Conference of the International Group for Lean Construction*.

Vaaland, T. I. (2004). "Improving project collaboration: start with the conflicts." *International Journal of Project Management*, 22(6), 447–454.

van't Klooster, S. A., and van Asselt, M. B. A. (2006). "Practising the scenario-axes technique." *Futures*, 38(1), 15–30.

Willis, D., and Alves, T. da C. L. (2019). "Contracting for collaboration in construction." *In: Proc. 27th Annual Conference of the International Group for Lean Construction*, Dublin, Ireland, 809–818.

Xue, X., Zhang, R., Wang, L., Fan, H., Yang, R. J., and Dai, J. (2018). "Collaborative Innovation in Construction Project: A Social Network Perspective." *KSCE Journal of Civil Engineering*, 22(2), 417–427.

Paucar-Espinoza, A. F., Erazo-Rondinel, A. A. and Yong-Zamora, S. (2021). "Choosing by Advantages for the selection of a new member of the project team" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.)*,* Lima, Peru, pp. 562–571, doi.org/10.24928/2021/0219, online at iglc.net.

CHOOSING BY ADVANTAGES FOR THE SELECTION OF A NEW MEMBER OF THE PROJECT TEAM

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ABSTRACT

The construction industry works through projects; each project needs people who make its realization possible, and these people relate to each other, forming work teams. Thus, there is an important relationship between the projects and the team members of a construction project, who must be selected based on competencies that allow them to satisfactorily perform their role in the project and thus contribute to the project's success. This research aims to provide a systematic approach while also providing decision-makers with best practices by demonstrating the application of the Choosing By Advantages (CBA) system tabular method in selecting a member of the project team. To this end, the research begins with a bibliographic compilation to consolidate the main factors that allow us to choose a new member of the project team. Later, the team is trained in the CBA system. The choice is determined by applying the Tabular CBA method to support a collaborative virtual platform and a remote communication program. Finally, the team decided and chose the new member to be part of the project team in the Project Control area.

KEYWORDS

Choosing by Advantages, project team, multi-criteria decision analysis, CBA tabular method, project controls.

INTRODUCTION

The construction industry works through projects (Campero & Alarcon, 2003); each project needs people to make it possible, and these people interact with each other forming work teams (Fong and Lung, 2007). Thus, work teams are part of organizations that allow individuals to satisfy different needs: emotional, spiritual, intellectual, economic. Ultimately, organizations exist to achieve goals that isolated individuals cannot achieve due to their limitations. Across organizations, the last limitation to achieve many human goals is working efficiently as a team (Chiavenato, 2009). Therefore, there is an important relationship between the organization and the human resource. Therefore, it is necessary to have a more prepared staff, who adapt more quickly to modern technology, proactive,

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and know-how to interpret what changes are generating (García and Tantalean, 2012). That is why the selection of project team participants is an important decision. Usually, intuitive decision-making is carried out, that is to say, to perform a rapid recognition of patterns and select an alternative based on the stored memories (Wilson, 2003). Alternatively, consider cost as the predominant factor in decision-making processes, or even little or no other stakeholders' participation (Ding and Parrish, 2019). In this way, CBA could help discern the relative value between applicants better and know the skills gap to develop to occupy a specific role in construction projects.

Thus, the following research aims to develop the CBA application to select a project control team member. For this, the investigation begins with a literary review of the selection process that construction companies follow, how the project control areas, and the lean profile for construction projects are composed. With this information, the tabular CBA method's application is carried out, and one of the three candidates is selected for the project control position.

RESEARCH METHOD

The following research is part of a case study and details the application of CBA in selecting a member for the team of a Hospital project in Peru (Figure 1). For this, a literary review of the recruitment and selection process of team members, roles of the Project Control area, and the competencies required for a lean professional to perform construction projects are initiated. The factors are selected, taking into account the lean competence developed by Pavez & Alarcon (2007). With the factors already defined, the project team is trained in the CBA system, the CBA Tabular method, and the steps of its application. Finally, the Tabular CBA method's application is illustrated in the selection of a new member of the Project Control area team in a hospital building project in Peru.

Figure 1: Stages of research

THEORETICAL OVERVIEW

In an engineering and construction company, the key processes are based on obtaining and executing projects, while the other areas support them. Recruitment and selection are within the functional area of Human Resources in the company's central office; its objective is to satisfy the demand for personnel from the different areas that make up the company and the projects, according to specific profiles requested (Castellano, 2013). According to Castellano (2013) the recruitment and selection process in a company whose projects are developed in the Construction and Engineering sector has the following steps (Figure 2):

1. Launch of the admission requirement: The search begins once the request has been made by the client, this requirement is originated from 3 sources, the Staffing Plan (Project Personnel Plan), Individual Requirements and Proposed Candidates.

2. Internal Search: Then, the requested requirements are searched in the internal database, the search is made based on the defined profiles and the candidates are filtered towards the one that suits the requested position. In this database, personnel information is stored soon to leave a project, those that have been saved by previous applications and proposals. If there is no candidate that meets the requested requirement, a search is carried out in external sources.

3. External Search: The process, therefore, continues with the definition of the profile of the requested requirement and the profile survey, managing to have the information of the personnel that is required in detail (what is defined in step 1 is made explicit but this time in greater detail for an optimal external search). Subsequently, the requirement is published in external sources (via the web, publications in specialized magazines, other external sources). In this way, the Curriculum Vitae of the candidates who apply are filtered. This is how the approval of the candidates sent is expected to cite them to Evaluations or continue with the search in external sources. Once this process is finished, the second phase of the process, that of Selection, continues.

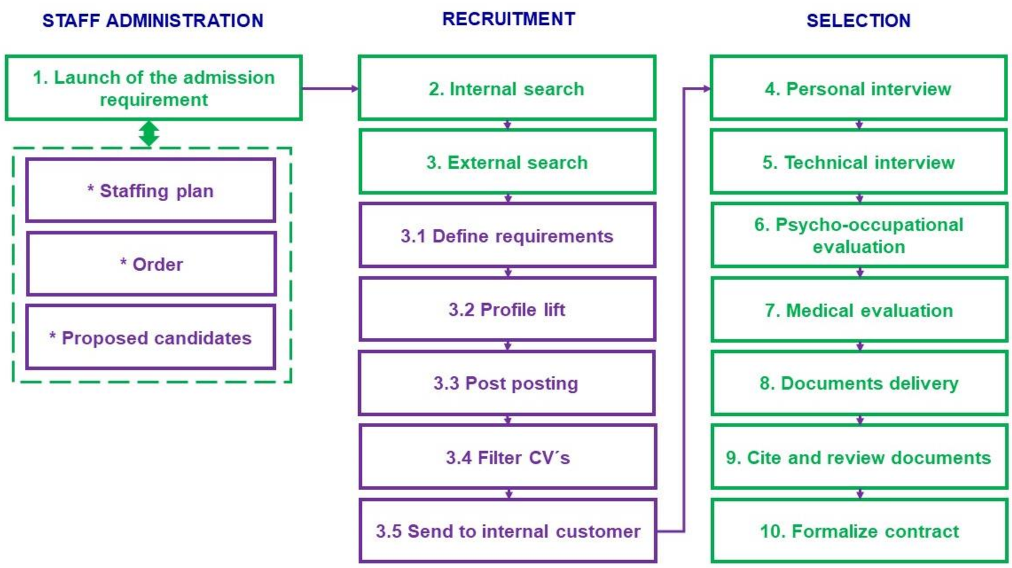

Figure 2: Selection Process in Construction Projects. Adapted from Castellano (2013).

The construction project's work is based on the processes to be executed by the Project Team, which are organized by Project Areas from the beginning to the end of the project (Figure 3).

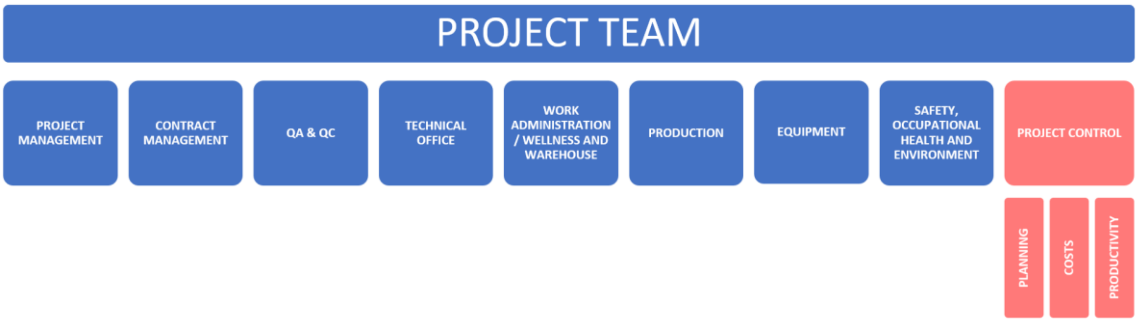

Figure 3: Structure of the work team. Adapted from COSAPI SA (2012)

Construction Project Control Area

Three areas that are part of the Project Controls (COSAPI SA, 2012):

Planning and Scheduling

Its objective integrates, represents, and controls the project's construction planning in direct coordination with the production area and according to its requirements. The Production Area directs construction planning, while the Planning Area provides support through the development and monitoring of the General Schedule, Intermediate, and Weekly Plans, among others. Also, it is in charge of generating indicators to analyze the performance of the project deadlines.

Cost Area

Its main objective is to quantify and report project costs and margin periodically to detect deviations in the financial result concerning the updated baseline, analyze their causes and provide alerts on time for the project team to take relevant actions. The main functions of the cost area are the following: (1) Prepare the Project Phases Plan (In Cosapi, the grouping of items or related activities for their monitoring, control, and reporting is called Phase), (2) quantify costs incurred in the project, (3) prepare the projection of costs until the end of the project, in coordination with the areas of production, planning and project management and (4) integrate reports that include the sale, cost, and margin of the project to the project and the Headquarters.

Productivity Area

Its objectives are: (1) Measure the actual performance of the main construction processes of the project to their performance goals, (2) identify and propose actions to improve the performance of the main construction processes of the project and (3) document the actual performance of the construction processes considered critical by the organization and the project team, to improve feedback of the projects to the rest of the organization.

THE LEAN CONSTRUCTION PROFESSIONAL PROFILE (LCPP)

The consolidation of lean construction requires the active participation of people capable of implementing this management philosophy. For this reason, the pioneering research by Pavez and Alarcon (2007) defines a Lean Construction Professional Profile (LCPP), which identifies three areas of competence that must be developed simultaneously: Business vision, technical competence, and social competence. This research revealed the coherence of the model in terms of what construction companies expect from their project staff and how, through the identification of specific competencies, it is possible to address the three elements of lean management:

- Business purpose (business vision): It is related to understanding the strategic problems of the business and customer needs, sharing values and organizational objectives and needs of the organization.

- Processes (technical competence): It is related to construction techniques, project management, lean tools.

- People (social competence): Self-control, social skills.

For the case study of the present investigation, factors related to the LCPP are identified to select the new member for the Project Control area, as will be seen later in the application.

Choosing by Advantages (CBA)

CBA is a complete system for consistent decision-making, including principles and definitions, models and methods, tools, and techniques. The methods it includes can be used for practically all types of decisions, both monetary and non-monetary, from simple to complex decisions (Bettler, 2010). For the present research, we used the Tabular CBA method, ideal for decisions with moderate complexity. This method can be summarized in the following seven steps (Figure 4):

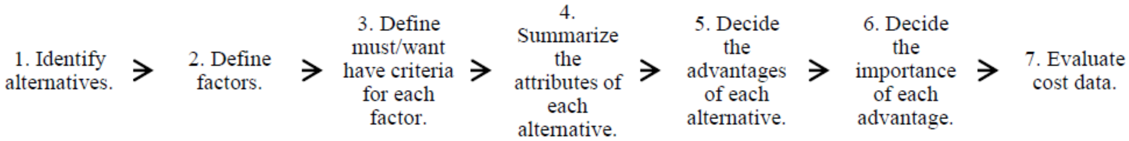

Figure 4: Steps of the CBA Tabular Method (Schöttle et al., 2015)

CASE STUDY BACKGROUND

Implementing CBA training is necessary (Schöttle & Arroyo, 2016). Considering this critical requirement, before the application, the team proceeded to theoretical training sessions plus a practical workshop of the Tabular CBA method in person with the project team (keeping distance and using protective equipment in the current context of the pandemic). This training with members from different areas allowed us to brainstorm potential future applications in decision-making to continue consolidating the culture of making decisions using this consistent method.

In the project, the need arose to add one more member to the Project Control area team. Therefore, the new staff's required profile to join the area is generated, and a request is sent to the Human Resources area of the Central Office.

Due to fluctuations in physical permanence in work due to both the work regime and the promptness of following the recruitment and selection processes to select the new member of the area, the CBA Tabular method's application was carried out remotely. Supporting us with a collaborative virtual tool, so we proceeded to design the necessary interface and template. In this way, counting on the previous training of the Tabular CBA method's concepts and using the virtual tool containing the prepared template and the high predisposition, we proceeded to the application.

Application of the Tabular CBA Method

Step 1. Identify alternatives: A list of personnel available in the company that meets the team's indicated requirements is proposed. It is facilitated for us also to add referrals to the list. A list is made with all the identified alternatives, from which a single person will be chosen to fill the vacant position.

Step 2. Define the factors: We asked ourselves the need for the project that our Project Control area could efficiently cover with the incorporation of a person. Measurements in the field were not taking place continuously due to two relevant root causes: 1. the work regime, which is 21x7, which left field measurements with an empty week, 2. the saturation of the workweek between the requirement for deliverables from the Central Office and the requirement for deliverables requested by the Client, allowing only one productivity measurement per week to be obtained. Also, the objective was to become a high-performance team in the shortest possible time to overcome the challenges that are approaching in the coming months when addressing the monitoring and control of Architecture and Installations activities that will be executed at home.

After brainstorming in the team, the following factors were defined to evaluate the applicants:

- **Factor 1. General previous experience.** It is important to know the experience and knowledge of the company's management system that will help accelerate the learning curve in the team.

- **Factor 2. Previous experience in the Project Control area.** How related are Project Control's specific issues (Costs, Planning, and Productivity)? Having worked directly or indirectly with the aforementioned topics will significantly benefit the team's work and help accelerate their learning curve. Knowledge (minimally basic) of the Lean Construction philosophy, project management standards such as that provided by the Project Management Institute, Earned Value methodology, among other specifics, is essential.

- **Factor 3. Inclination or affinity towards the Project Control area**. It is important to know the applicant's expectations concerning the area of Project Control. The specialization in this area is aligned with the company's vision, allowing it to improve the processes according to the organization's needs. Also, suppose the professional projection is in accordance with the topics of the area. In that case, the applicant will have a greater focus and motivation to learn, develop knowledge, and seek improvements and implement them.

- **Factor 4. Attitude or predisposition towards work.** It will allow being up to date with the challenges to comply with the monitoring and control of the project's work.

- **Factor 5. Create a good work environment.** Spending 3/4 of a month living at work implies that a requirement is to facilitate a good or excellent work environment in the area. Informal conversation topics, hobbies, professional/personal goals, or other related will allow the creation of this space that allows developing a degree of affinity and trust among the team members to face the project's challenges.

- **Factor 6. Software domain.** Due to the processing of a massive amount of information and the creation of databases to manage them efficiently, the domain of Excel and dynamic tables are necessary for an adequate performance of Project Control and the management of Autocad for consultation metering of plans. Optional knowledge and management of other tools that allow the monitoring and updating the 3D and 4D models currently used in the project.

- **Factor 7. Home location.** This factor was determined due to the specific geographic context of the project. It is located approximately 10 hours from Peru's capital, with a single route and limited companies that provide transportation services and the established work regime. The applicant's location should allow an accessible movement, which does not generate inconveniences than the stipulated work hours, in addition to reducing the risk of potential contagion (in the current context of the pandemic) caused by exposure in long trips to and from the construction site.

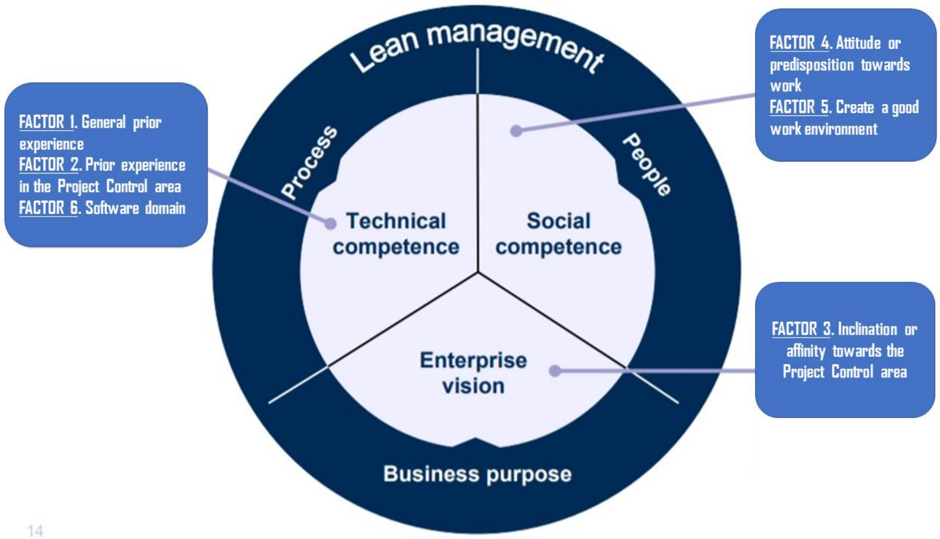

Figure 5: Factors used related to LCPP. Adapted from Pavez & Alarcon (2007)

Step 3. Define the criteria: The guidelines that will allow routing the advantages between the alternatives' attributes are determined associated with each factor.

Step 4. Summarize each alternative's attributes: The information indicated in each of the applicants' CVs and information obtained directly from a personalized interview carried out with each of them was used as sources of the attributes. For this step, it is necessary to detail that the interview aimed to obtain the attributes according to the factors and their respective criteria identified in the previous steps. This information was fed directly to the template generated in the virtual tool after each interview was carried out.

Step 5. Decide the advantages for each alternative: After completing the interviews and completing all the alternative attributes. The team proceeded to obtain the advantages of each of them, anchoring the difference against the "worst attribute" obtained, depending on each factor's criteria. From this step forward, work was done directly on the virtual platform template collaborative and real-time.

Step 6. Decide the importance of each advantage: We find in this particular step the great support of working in a collaborative virtual platform, due to the ease of emulating reality when working with post-its, ease of moving figures, writing in time real and shared, in addition to that the video call program allows argumentation and the exchange of ideas, both tools being of great help when generating consensus.

According to Suhr (1999), there is no totally objective decision, all decisions are loaded with values and therefore it is finally necessary to decide or weigh intensities of preferences. In our application, the subjectivity regarding the importance of the advantages in our factor "Affinity for the area of Project Control" lies in our perception of the applicant based on their training information (certificate at a basic level in project control, the number of courses, seminars and workshops related to Project Control that each one attended) and the answer to questions related to Project Control. What marked the differential of advantage among the applicants in this last interview, was the responses of one of them, which showed that his desired career line was aimed at becoming a Project Control Manager. Finally, being considered by us, this advantage as the most important in our selection, it was labeled as the paramount advantage.

In this way, we determine the paramount advantage, to which we assign the maximum score of 100 (great Affinity for Project Control), and then from this, we give a score to each of the other advantages (in decimal scale). Finally, we add the total advantage importance score for each of the alternatives.

Step 7. Evaluate the cost information: This step was not relevant for our analysis because the applicants were in a company's salary band. In our country, for junior engineers, the salary band used in the construction market varies in an interval between approximately 10% and 15%, this difference was within the limits of the project budget for the requested position. For this reason, for practical purposes, step 7 of the CBA selection was skipped. The decision was ultimately made based on the highest total advantage importance score.

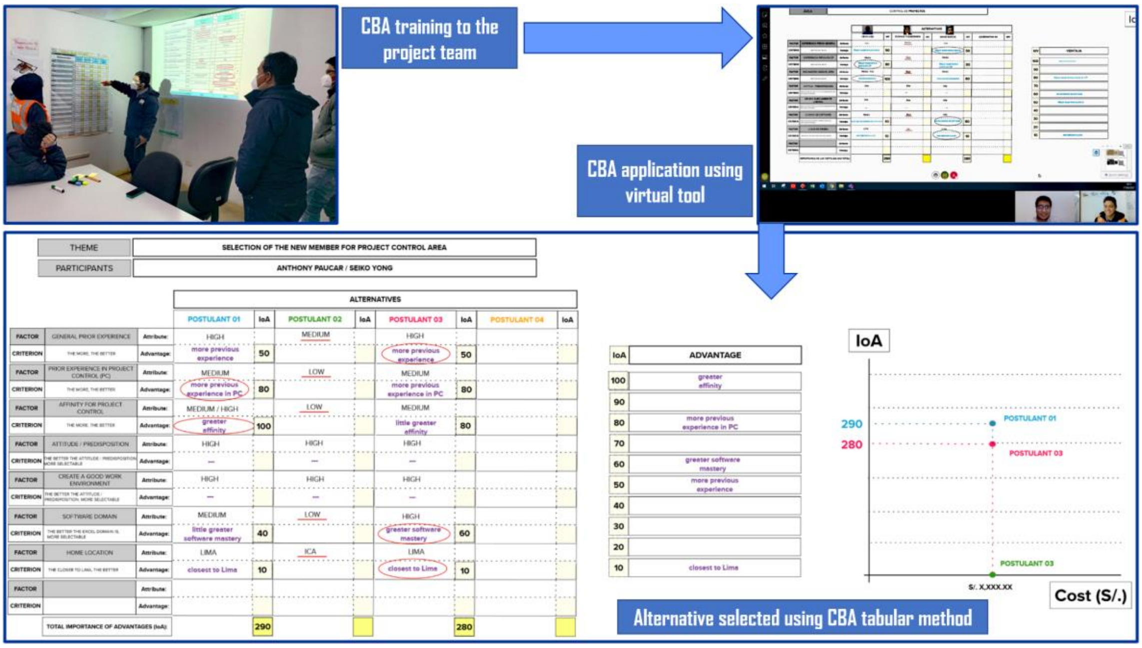

Figure 6: CBA application to select a new member of the project team.

DISCUSSION

The following table shows the matrix resulting from the application of the CBA Tabular method for our case. It is observed that applicant 02 does not have advantages over the other alternatives in any factor, obtaining a null score of the importance of advantages.

Among the factors related to technical competencies, the importance score of the advantages of the 'Software domain' factor differs due to the management of information in databases among the applicants.

The factor related to the business purpose differs in the importance score of the advantages of 'Affinity for Project Control,' which also contains the paramount advantage of the evaluation. The team's priority is that the selected applicant is found aligned to the vision of the company by belonging to the Project Control area, focusing on the search and implementation of improvements in the project.

Among the factors related to social competencies, there is no difference in the importance score of the advantages of any factor, showing that all the applicants interviewed had similar high attributes that did not generate an advantage over the other.

The 'Home location' factor contains the minor advantages scored on the importance scale with the same score for applicants 01 and 03.

Finally, the decision is made to select a new member of the Project Control area, applicant 01, with the highest total IoA score (290).

	Factor (Criterion)		Alternative 1: Postulant 01			Alternative 2: Postulant 02			Alternative 3: Postulant 03		
Process Technical competence	General Prior Experience	Att.:	High			Medium			High		
	(The more general prior experience, the better.)	Adv.:	More previous experience	Imp.:	50		Imp.:		More previous experience	Imp.:	50
	Prior experience in Project Control (PC)	Att.:	Medium			Low			Medium		
	(The more general prior experience in PC, the better.)	Adv.:	More previous experiencein PC	Imp.:	80		Imp.:		More previous experience in PC	Imp.:	80
	Software domain	Att.:	Medium			Low			High		
	(The better software domain, more selectable.)	Adv.:	Little greater software mastery	Imp.:	50		Imp.:		Greater software mastery	Imp.:	60
Business Purpose Enterprise vision	Affinity for Project Control	Att.:	Medium / high			Low			Medium		
	(The more affinity for PC, the better.)	Adv.:	Greater affinity	Imp.:	100		Imp.:		Little greater affinity	Imp.:	80
People Social competence	Attitude / predisposition towards work	Att.:	High			High			High		
	(The better attitude/predisposition, more selectable.)	Adv.:	-	Imp.:		-	Imp.:		-	Imp.:	
	Create a good work environment	Att.:	High			High			High		
	(The better potential for create a good work environment, more selectable.)	Adv.:	-	Imp.:		-	Imp.:		-	Imp.:	
	Home location	Att.:	Lima			Ica			Lima		
	(The closer to Lima, the better.)	Adv.:	Closest to Lima	Imp.:	10		Imp.:		Closest to Lima	Imp.:	10
	Total of IoA				**290**			**0**			**280**

Figure 7: Constructed Case - Evaluation using CBA Tabular method.

CONCLUSIONS

Construction is a project-based industry. Each project needs work teams made up of people who will contribute with their professionalism, knowledge, and experience to guide it to its successful completion, meeting the established objectives.

This research was carried out in the context of incorporating a new member of the project team, supported by factors related to the profile of a lean professional, to perform functions in the Project Control area of a hospital building project. Taking seriously the task of finding the right person who would add to the efforts to achieve the area's objectives and the project, the CBA tabular method was applied.

We recommend designing and carrying out the previous training of the CBA system, and that it includes both developed and application examples, ranging from simple to complex decisions. This good practice allowed, in our case, to fix the concepts of the system in each of the participants, arouse interest in applying the Tabular CBA method in various selection problems. Create a predisposition to participate in collaborative decisions, and document decision-making as a knowledge asset that can be consulted later in the face of future similar selection problems in the organization.

In this study case, we indicate the support provided by technology by using a virtual collaborative platform plus a video call platform, which allowed the development of personalized interviews with each of the applicants. It permits the application of the CBA tabular method to make the selection decision (we use the collaborative platform 'Mural' and the video call platform 'Microsoft Teams'). Future research may delve into the use of digital platforms to efficiently develop a CBA method's training and application with the team. Finally, this work details the CBA application until the selection of the new member. In future research we will delve into an application that allows us to go to reconsideration, where new alternatives or the impact of cost on the advantages after its implementation can be analyzed.

REFERENCES

Bettler, L. (2010). "Choosing By Advantages: A very brief introduction," Accessed March 20, 2021. Slide 1 (leanconstruction.org).

Campero & Alarcón (2003). *Administración de proyectos civiles (Segunda Ed.)*. Ediciones Universidad Católica de Chile.

Castellano, F. (2013). *Propuesta de mejora del proceso de reclutamiento y selección en una empresa de construcción e ingeniería [Proposal to improve the recruitment and selection process in a construction and engineering company]*. BSc. Peruvian Universiy of Applied Science [In Spanish].

Ding, X. & Parish, K. (2019).'A Proposed Lean Decision-Making Process for Building Energy Retrofits' In:, *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC).* Dublin, Ireland, 3-5 Jul 2019. pp 1357-1366.

Fong, P. S. W. & Lung, B. W. C. (2007). Interorganizational teamwork in the construction industry. *Journal of Construction Engineering and Management*, 133(2), 157-168.

COSAPI S.A. (2019). Manual de Gestión de Proyectos. Gerencia de Gestión de Operaciones, Lima, Perú.

García, T. D., & Tantalean, I. (2012). "Selección y control del factor humano en empresas de construcción civil". *[Selection and control of the human factor in civil construction companies]* [In Spanish] *Industrial Data*, *15*(2), 063–072.

Lean Construction Enterprise (2011). “Equipos de Trabajo en Proyectos de Construcción.” Accessed April 15, 2021. https://sites.google.com/a/leanconstructionenterprise.com/lean-construction-enterprise/documentacion/equipos-de-trabajo-en-proyectos-de-construccion.

Pavez, I. & Alarcon, L. F. (2007). 'Lean Construction Professional's Profile (LCPP): Understanding the Competences of a Lean Construction Professional' In: Pasquire, C.L, C. L. & Tzortzopoulos, P., *15th Annual Conference of the International Group for Lean Construction.* East Lansing, Michigan, USA, 18-20 Jul 2007. pp 453-464.

Schöttle, A., Arroyo, P. & Bade, M. (2015). 'Comparing Three Methods in the Tendering Procedure to Select the Project Team' In: Seppänen, O., González, V. A. & Arroyo, P., *23rd Annual Conference of the International Group for Lean Construction.* Perth, Australia, 29-31 Jul 2015. pp 267-276.

Schöttle, A. & Arroyo, P. (2016). 'The Impact of the Decision-Making Method in the Tendering Procedure to Select the Project Team' In: *24th Annual Conference of the International Group for Lean Construction.* Boston, Massachusetts, USA, 20-22 Jul 2016.

Suhr, J. (1999). The Choosing By Advantages Decision Making System. Quorum, Westport, CT.

Wilson, M. A. (2003). Collaborative decision making: building consensus group decisions for project success. Paper presented at PMI® Global Congress 2003—North America, Baltimore, MD. Newtown Square, PA: Project Management Institute.

Reed, D., Powell, W., and Berg, P. (2021). “Competitive Capability-Building for Integrated Design Scheduling and Management.” *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 572–581, doi.org/10.24928/2021/0221, online at iglc.net.

COMPETITIVE CAPABILITY-BUILDING FOR INTEGRATED DESIGN SCHEDULING AND MANAGEMENT

Dean Reed[1], Will Powell[2], and Peter Berg[3]

ABSTRACT

This paper explores the relevance of Takahiro Fujimoto’s theory of the role capability-building played in the emergence of the Toyota Production System to design and construction. It is the third in a series on this topic. The research question is whether Fujimoto’s explanation of how capability was built within Toyota can help project teams build better capability leading to system-level improvement. In this new paper the authors connect Fujimoto’s evolutionary perspective with the possibility that complex systems theory is a useful starting point for understanding design and construction. The authors explain Fujimoto’s theory and how they used it to evaluate building-capability for Integrated Design Scheduling and Management on several projects they reviewed retrospectively. Key findings are: 1, effective use of routines is important and a prerequisite for effectiveness; 2, routinized capability (regular patterns of doing essential things) is essential to affect change at system level; 3, entrepreneurial leadership is necessary for effective capability-building, and 4, system emergence, where there is no relationship between the content and pattern of system changes, together with routinized capability is possible although rare; 5; this is also possible, but even more rare with a second, systems level of problem solving.

KEYWORDS

Theory, capability, complexity, emergence, evolutionary.

INTRODUCTION

A survey of IGLC papers indicates a gap in literature using Takahiro Fujimoto’s theory of emergent development of the Toyota Production System to understand building of competitive capability-building. A search of all previous papers on the IGLC.net website with these keywords: capability, capability-building, emergence, evolutionary, Fujimoto and Pucchi found 5 papers referencing Fujimoto. Two were authored by the first and third authors of this paper, two by Flávio Picchi , and one by others. Only the authors’ previous 2 papers

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used Fujimoto's theory to examine design and construction operations capability-building. The first paper focused on developing capability on 6 different projects to prefabricate exterior wall panels on construction sites and install them (Berg and Reed 2019). The second used Fujimoto's theory to explain capability-building for "Programmatic Spatial Cost Modeling" on a series of 7 building projects (Berg et al 2020). This paper is a retrospective study to understand how competitive capability for Integrated Design Scheduling and Management (IDSM) has been built and extended within projects. As with the 2 previous papers, the limitation of this paper is that it relies on assessments by a single subject matter expert (SME) because none of the capability-building was designed and carried-out with Fujimoto's theory in mind. In this case the research assessments were made retrospectively by the second author, who was the capability SME.

Fujimoto explains the development and functioning of the Toyota Production System (TPS) from an evolutionary perspective (Takahiro Fujimoto 1999), which he does not associate with complex systems theory. The authors do connect the two perspectives. This is because complexity theory sees human actions and behaviors as a response to intersections of factors in dynamic complex systems which are so specific to local conditions that they can never be completely designed or described entirely by humans or even computers. The evolutionary and complex system perspectives are synergistic because they both look up and across organizations rather than down and into them to explain the why and how of innovations and accidents, successes, and failures in project delivery. Neither focuses on the behaviors of exceptional leadership nor the dedication and discipline of individual performers. Systems thinkers argue that behavior and outcomes emerge from local intersections of interests and actions by well-intended people.

The authors agree with Bertelsen that a systems approach will enable better performance outcomes for lean thinkers in the Construction industry (Bertelsen 2003). Sidney Dekker and others who've studied adaptive complex systems offer an alternative to the dominant deterministic worldview that causes can be identified to explain breakdowns. The authors suspect that constructors will appreciate Dekker, a leading safety researcher and thinker, because he uses complex systems theory to explain why well intended efforts focused on controlling behaviors fail to prevent serious accidents, which continue to occur all too often in the Construction industry (Dekker 2011)

THE PROBLEM AND A METHOD TO SOLVE IT

Toyota and every other automaker develop the products they make. This is often not the case for construction projects. Regardless of whether this work is done inside or outside of building companies, design work must be done well within an allotted time. Safe, high quality and efficient construction depends on the quality and timeliness of the design work product. In the authors' experience, designs are either often completed during construction, and / or the process of design is not adequately aligned with construction and procurement deadlines, leading to knock-on effect delays and the potential for costly rework. That's why the capability to design buildings that meet customer needs and expectations in a way that supports procurement, fabrication and final assembly is a competitive advantage.

Design Structure Matrix (DSM) is an analysis model for identifying information dependency, which Tuholski and Tommelein explained well in a previous IGLC paper (Tuholski and Tommelein 2008). Founders of Adept Management Limited (AML), participated as industry practitioners in research on its application to AEC in the 1990s, and began consulting with teams to use DSM on large, complex projects in 2001. They applied the Analytical Design Planning Technique (ADePT), which they had helped invent (Austin et al. 2002).

The second author, the expert who worked with every one of the teams on all the projects studied here, spent 18 years as a deployment specialist for AML helping project teams implement a highly structured, repeatable process in which progress towards well defined deliverables could be measured. AML's practice was to bring their SMEs together regularly to report on and discuss their work. He joined a large U.S. based General Contractor (GC) in 2020. In all, he taught the ADePT method and use of the routines identified in this paper to teams on over 40 projects. He selected 11 diverse projects for this study, the earliest beginning in 2010 and the latest ongoing, representing a range of responses to the challenge of scheduling and managing design in an integrated way for this study.

THE THEORY OF CAPABILITY-BUILDING COMPETITION

EVOLUTIONARY PERSPECTIVE

The Toyota Production System (TPS) is a complex web of capabilities invented and refined to solve specific problems throughout this particular automaker. There was no grand design; TPS evolved over time (Shimokawa and Takahiro Fujimoto 2009). Its logic can only be seen in hindsight looking backward. Ways of functioning and the outcomes they produce, or influence emerge in complex systems that are dynamic by nature. Fujimoto argues that this provides the best framework for explaining Toyota and other Japanese automakers he studied (Fujimoto 1999).

Fujimoto defines organizational capability as the power or ability of an organized group to do something using effective routines. The word "routine" derives from the French word for path and encompasses the concept of patterns. Charles Duhigg explains how capability is built and exercised by people creating and following routines (Duhigg 2012). Capability can be exceptional and episodic or consistent and a matter of course.

Fujimoto closely links capability with problem-solving. Solutions must be made real and tangible, i.e., converted, through capabilities. What he calls "Dual-Layer Problem-Solving" is a capability to combine solutions to solve seemingly unrelated or new problems. This requires leaders with authority to be intentional in doing this work.

INFORMATION AND MANUFACTURING CAPABILITY

Fujimoto believes that the capability to make things depends on capabilities to create, transform, and transfer information to make products. Toyota has focused on capabilities to make information, material and components flow exactly when they are needed (just-in-time). He argues that the problem-solving cycle of goal setting and problem recognition, searching for feasible alternatives, evaluating alternatives, and selection used in product development is a rich source of information and knowledge. Fujimoto believes that information for making the product connects the routines for product development, suppliers, and fabrication and assembly with the next and ultimate customer. He argues that the flow of information is actually the only way to understand TPS.

Rather than speeding-up individual operations, Toyota follows a dense information strategy in which only the right information is transmitted repeatedly until received at the right time by the right production resources (people and machines). Fujimoto explains that the imperative for eliminating the 7 wastes identified by Taiichi Ohno (Ohno 1988) is that they prevent these resources from receiving the information they need.

MULTIPLE PATHS FOR DEVELOPING SOLUTIONS

Takahiro Fujimoto identifies 5 paths for generating solutions to problems. Organizational, as opposed to individual, capabilities are a sequence of steps a group routinely follow in a specific way to solve a problem or implement a solution. These are the 5 paths:

1. Rational Calculation. For Fujimoto this is the complete problem-solving cycle for product development of goal setting and problem recognition, searching for feasible alternatives, evaluating alternatives and selection. Previously, the authors misinterpreted this as careful planning.
2. Environmental Constraints. This is finding and deciding between feasible alternatives constrained by external factors.
3. Entrepreneurial Vision. This is pursuing solutions advocated by leaders. While these leaders are often in positions of formal authority, they need not be.
4. Knowledge Transfer. This means following the advice of experts from outside the project. Often these experts are professional trainers and coaches.
5. Random Trails. This is trying different solutions advocated by leaders.

These paths are not mutually exclusive; one or more can influence problem-solving work.

THREE LEVELS OF MANUFACTURING CAPABILITY

As noted in *This Is Lean* (Modig and Åhlström 2012) and by Flávio Pucchi (2001), Fujimoto identifies 3 levels of manufacturing, as follows.

- Routinized Production Capability. The basic nature of routinized production capability is static and regular; variability is low. Its influence is competitive performance in a stable environment where necessary prerequisites flow and the product can be made predictably. Its primary characteristics are a firm or project-specific pattern of steady-state and efficient transfer of accurate information.
- Routinized Learning Capability. The basic nature of routinized learning is dynamic and routine so that people have regular ways for dealing with variability. Its influence is changes or recoveries of competitive performance in a dynamic environment. Its primary characteristics are a firm or project-specific ability of handling repetitive problem-solving cycles or an expected pattern of system changes.
- Evolutionary Learning Capability. The basic nature of evolutionary learning is dynamic and not regular. Its influence is changes in patterns of routines that contribute to capability. Its primary characteristic is a firm or project-specific ability of handling system emergence, i.e., dealing with non-routine patterns of system changes to form new routine capabilities (Takahiro Fujimoto 1999).

MULTI-PATH SYSTEM EMERGENCE

Fujimoto asserts that 2 conditions must be present for the 5 paths for developing solutions to influence changes in systems, which he calls “Multi-Path System Emergence.”

- There are a variety of patterns in changes to the larger system, in this case project design and engineering. This is indicated by consistent changes in the arrangement and timing of the functioning of the system.
- There is no relation between the pattern of changes and content, meaning the changes aren’t limited to certain ways of working or work products in the larger system.

EVOLUTIONARY LEARNING CAPABILITY

Fujimoto defines a third condition, which is firm specific patterns of routine capabilities for production and learning. This is when capabilities become consistent, i.e., people are regularly following the routines. This combined with Multi-Path System Emergence indicate evolutionary learning capability. This is the capability to build new capability, which Fujimoto points to as the key to Toyota’s success.

DUAL-LAYER / LEVEL PROBLEM SOLVING

Fujimoto argues that a two-level capability for problem-solving emerged within Toyota and that this enabled leaders to continually improve competitiveness throughout the organization. He attributes this to 3 factors, which are preconditions, lower-level paths for solution generation, and higher-level conversion of solutions to competitive capabilities. Preconditions are historical imperatives, visions and strategies and evolutionary capabilities. Lower-level paths are the 5 leading to solutions and system changes. The higher-level is problem-solving for competitive capabilities, which is the essence of deep competition in the auto industry. This involves problem recognition, modification of solutions for competitiveness and selection of partial solutions for the problem. Fujimoto asserts that this leads to retention of solutions and renewed capabilities (Takahiro Fujimoto 1999). Intentional selection and modification of capabilities to produce new ones to solve other problems indicates dual-layer problem-solving for projects with multi-path system emergence and evolutionary learning capability.

CASE STUDY ANALYSIS

DATA COLLECTION & EVALUATION

All data was provided by the second author, who served as the subject matter expert (SME)

Competitiveness

First, the expert identified 4 criteria for competitive success, each worth 25%, were as follows:

- No unplanned negative iteration in the design process
- All team members are working on same thing at the same time / coordination amongst the disciplines
- Delivering design packages reliably: on time and meeting agreed quality criteria

- Team participation: everyone together and on the same page; and committed to follow the process for design scheduling and management

Second, the expert chose 11 projects with diverse scopes to study, as follows:

- New Commercial
- New Hotel / Residential
- New Higher Education Research Lab
- New Corporate Campus
- New Higher Education Research & Simulation Labs / Conference Center / Classrooms
- New Airport Terminal
- New Hotel & Entertainment
- New K-12 School
- New Airport Inter-Terminal Transportation
- New Hospital
- New Biotechnology Research Lab

Third, the expert described the routines required for competitive organizational capability, listed in Table 1. Fourth, the expert scored the effective use of each routine for every project using a 0 to 5 scale. It is important to note that while many of the routines are specific to the construction of an integrated design schedule, several go beyond into the ongoing management and leadership required in a continually evolving process. Fifth, the expert rated the capability's contribution to success for each criteria using a 0 to 5 scale.

Multi-Path Development and System Emergence

Next, the expert answered true / false for whether each of the 5 solution paths contributed to the capability as a whole for each project, which was totaled. The next question was also true / false for whether the expert noticed changes within the larger design and engineering system. If false, meaning no changes, there was no possibility and need to investigate multi-path system emergence, evolutionary learning, and dual-layer problem-solving. That was the case with 8 out of the 11 projects. The next questions were also true / false. The first question was whether the expert saw a variety of patterns (sequence and arrangement) in system changes. The second question was whether the expert saw a clear relationship between the pattern and content of system changes. Multi-path system emergence occurred on only 2 projects precisely because there was no discernible relationship between the pattern and content of system changes, meaning they weren't anticipated or planned. Because both of these projects had routinized capability for design scheduling and management along with multi-path system emergence, they also manifested evolutionary learning capability.

Dual-Layer Problem-Solving

The last question for the expert, true / false, was whether there was intentional selection and modification of capability solutions to create new capability to solve other problems on the 2 projects that displayed evolutionary learning capability. Only one exhibited this.

FINDINGS

Table 1 shows the data that supports the findings listed below it.

Table 1: Competitiveness, Multi-Path System Emergence & Evolutionary Learning

ID	Routines Effective Use % by Project	1	2	3	4	5	6	7	8	9	10	11
1	Continuous advocacy and engagement by leaders	3	3	5	2	3	5	1	2	1	5	0
2	Team understanding and commitment to the process	3	4	4	5	2	5	1	2	1	4	0
3	Tasks defined by design team	4	4	4	2	3	4	3	2	3	5	3
4	Durations applied to tasks by design team	3	3	4	2	2	4	1	2	2	5	3
5	Logic applied to tasks by the design team	3	3	3	2	1	4	0	1	1	4	3
6	Milestones or constraints (Defined Information Requirements) identified and applied to talks by GC and trade contractors	4	4	3	2	2	3	2	2	2	2	2
7	Iterative loops identified, analyzed and broken-down if necessary	4	4	5	2	3	5	1	3	1	3	2
8	Schedule aligned with milestone / constraints	5	5	5	0	5	5	5	5	5	5	5
9	Continuous process improvement PDCA cycle to identify, root-cause and remove constraints	4	4	5	0	2	5	1	2	2	2	0
	Effective Use Percentage	73	76	84	38	51	89	33	47	40	78	40
	Routinized Capability Achieved	No	No	Yes	No	No	Yes	No	No	No	No	No
	Competitiveness / Improvement Percentage	75	80	95	40	45	90	30	60	35	90	20
	Entrepreneurial Vision Path	No	Yes	Yes	No	No	Yes	No	Yes	No	Yes	No
	Rational Calculation Path (Generic Product Development Problem-Solving)	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes	No
	Design & Engineering System Changes	No	No	Yes	No	No	Yes	No	No	No	Yes	No
	Mult-Path System Emergence	No	No	Yes	No	No	Yes	No	No	No	No	No
	Evolutionary Learning Capability	No	No	Yes	No	No	Yes	No	No	No	No	No
	Dual-Layer Problem-Solving	No	No	Yes	No	No	No	No	No	No	No	No

- Effective Use of Routines. The 5 projects with the highest percentage of effective use routines achieved the greatest improvement in competitiveness.
- Routinized Capability. Only 2 of the 11 projects met or exceeded 80% effective use for the 9 routines, achieving routinized capability.
- Multi-Path Development: Knowledge Transfer contributed to capability on all projects. The 5 projects with no Rational Calculation had the lowest effective use scores, and the 5 with Entrepreneurial Vision had the highest effective use scores.
- Key Routines for Success / Competitiveness. These 2 projects had the highest scores for both of the first 2 routines (Driving Leadership and Team Buy-in to the Process).
- Competitiveness. These 2 projects were also the ones that had over 80% improvement in competitiveness measured against the 4 success criteria.
- Percentage of Routines Used. The 5 projects having the highest percentage of routines effectively used achieved the highest competitiveness. They also scored higher for effective use of the first 2 routines.
- System Changes. The Integrated Design Scheduling and Management capability in the 2 projects with routinized capability and another that came close led to changes in the larger design and engineering system.
- Multi-Path System Emergence. Only 2 of the projects with system changes did not show a clear relationship between the pattern and content of system change, which characterizes multi-path system emergence.
- Evolutionary Learning Capability. Because Integrated Design Scheduling and Management was routinized, it could be said that these 2 project team displayed evolutionary learning capability.
- Dual-Layer Problem-Solving. This was not visible to the SME on either of the 2 projects which reached that level. However, the third author, who was responsible for outcomes and provided entrepreneurial vision for project 3, did see this and, in fact, consciously leveraged Integrated Design Scheduling and Management capability to create new capabilities. This may also have occurred on the other project. By the time the construction documents are completed, the SME is working with the team remotely and has little or no visibility into how the team has leveraged their new capability. In this study the SME could only report that he could not see dual-layer problem-solving. This question should be put to top-level project leaders. Unfortunately, those people were not available for the other qualifying project.

CONCLUSION

NEW INSIGHTS

The authors now believe that stopping to identify constituent routines is necessary for understanding capability, regardless of whether it's individual or organizational. Fujimoto is right in directing attention there. Getting people to agree to work in a sequence of steps in a regular manner and actually doing that are two different things. So, asking an expert in the particular capability whether agreement has led to effective action is essential. Knowing what success means is also essential. That begs the question of how often people are carrying out tasks without a clear idea of what the outcome should be. These are just the beginning of understanding how to create organizational capability that improves system performance relative to competitors.

Investigating system emergence using Fujimoto's framework provides the opportunity for much deeper understanding of how people do their work and create capability. Without it, the authors would have focused on tasks executed and behaviors manifested, and attributed success or failure to how individual attitudes and abilities influenced their willingness to learn and implement something new. Nor would the authors have thought about competitive success, nor paid much attention to routines, much less their effective use. It's also likely that there would have been no insights into why or how some project teams succeeded in scheduling and managing design while others did not.

INTUITIONS AND QUESTIONS

Entrepreneurial Vision (EV) is as important for Integrated Design Scheduling and Management, as it proved to be for Programmatic Spatial Cost Modeling (Berg et al 2020). While the importance of leadership is widely recognized in the Construction industry, it's not generally associated with building capability, which is seen as a matter of training. This begs the question of how it can be included in projects. Bill Seed has described a new integrated project leader that, in our opinion, could drive the development of capabilities (Seed 2014).

Toyota created a new position, the Chief Engineer (Sobek et al. 1998), to drive problem-solving in product development. It seems that a such a person with visibility across so much of this work could promote evolutionary learning and the intentional development of new capabilities during the design of construction projects. Is this required in lieu of or in addition to Seed's new integrated project leader?

Integrated Project Delivery agreements specify the formation of a Project Management Team (PMT) to steer project management (Allison et al. 2018). Ideally, this small team of leaders would include people who individually or in aggregate can assume the responsibilities Seed described. Should this team include or function as the Chief Engineer? Or should they be capable as individuals of leading capability-building to the level of evolutionary learning and dual-layer problem-solving?

FURTHER STUDIES

The authors' hope for the opportunity to do action research where project leaders and the team or people tasked with executing one or more capabilities can design their work based on the insights gained from this and the two previous studies. The aim would be for those doing this work to evaluate competitiveness and impact on whatever the larger system is during execution. This research will be necessary to understand the limits of competitive capability building for: temporary project organizations versus ones like Toyota organized for continuous production; separate and often fragmented design and construction versus integrated product development; long-term investment timeframes versus short-term; continuous improvement versus quick fixes organizational culture; and stable vs highly variable production.

REFERENCES

Allison, M., Ashcraft, H., Cheng, R., Klawens, S., and Pease, J. (2018). "Integrated project delivery: an action guide for leaders." Charles Pankow Foundation, Integrated Project Delivery Alliance (IPDA), Center for Innovation in the Design and Construction Industry (CIDCI).

Austin, S. A., Baldwin, A. N., and Steele, J. L. (2002). "Improving building design through integrated planning and control." Engineering, Construction and Architectural Management, MCB UP Ltd.

Berg, P. and Reed, D. (2019). "Capability-Building Competition in Construction: Case Study Reinterpretation." *Proc. 27th Annual Conference of the International Group for Lean Construction*, Dublin, Ireland, 265–274.

Berg, P., Reed, D., and Sriram, S. (2020). "Capability-Building Competition in Design: Case Study." Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC), Berkeley, California, USA, 121–131.

Bertelsen, S. (2003). "Complexity - A New Way of Understanding Construction." 11th Annual Conference of the International Group for Lean Construction, Virginia, USA.

Dekker, S. (2011). *Drift into failure: from hunting broken components to understanding complex systems*. Ashgate Pub, Farnham ; Burlington, VT.

Duhigg, C. (2012). *The power of habit: why we do what we do in life and business.* Random House, New York.

Fujimoto, T. (1999). *The Evolution of a Manufacturing System at Toyota.* Oxford University Press, Inc., New York, New York.

Modig, N., and Åhlström, P. (2012). This is lean: resolving the efficiency paradox. Rheologica Publishing, Stockholm.

Ohno, T. (1988). Toyota production system: beyond large-scale production. Productivity Press, Cambridge, Mass.

Picchi, F. A. (2001). "System View of Lean Construction Application Opportunities." 9th Annual Conference of the International Group for Lean Construction, G. Ballard and D. Chua, eds., Singapore, Singapore.

Seed, W. R. (2014). "Integrated Project Delivery Requires a New Project Manager." 22nd Annual Conference of the International Group for Lean Construction, B. T. Kalsaas, L. Koskela, and T. A. Saurin, eds., Oslo, Norway, 1447–1459.

Shimokawa, K. and Fujimoto, T. (Eds.). (2009). *The Birth of Lean: Conversations with Taiichi Ohno, Eiji Toyoda, and other figures who shaped Toyota management.* The Lean Enterprise Institute, Cambridge, Massachusetts.

Sobek, D. K., Liker, J. K., and Ward, A. C. (1998). "Another Look at How Toyota Integrates Product Development." Harvard Business Review, (July–August 1998 Issue), 12.

Tuholski, S. J., and Tommelein, I. D. (2008). "Design Structure Matrix (DSM) Implementation on a Seismic Retrofit." 16th Annual Conference of the International Group for Lean Construction, P. Tzortzopoulos and M. Kagioglou, eds., Manchester, UK, 471–484.

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PRODUCT DEVELOPMENT AND DESIGN MANAGEMENT

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Chuquín, F., Chuquín, C., and Saire, R. (2021). "Lean Design in Hydraulic Infrastructura – River Defenses and Dikes – A Case Study from Peru." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 585–584, doi.org/10.24928/2021/0130, online at iglc.net.

LEAN DESIGN IN HYDRAULIC INFRASTRUCTURE – RIVER DEFENSES AND DIKES - A CASE STUDY FROM PERU

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ABSTRACT

The construction sector has been changed in different aspects since the implementation of best practices of lean construction and others. It is crucial to remark that those new methodologies have been trying to address construction issues related to the execution part but with little attention to the design stage.

In Peru, the use of lean construction started as part of an initiative from the private sector and specifically in the execution part. In that sense, lean design was introduced later and always by the private sector. Little by little the public sector started to get used to lean construction. Nevertheless, in hydraulic infrastructure such as river defenses and dikes the progress of introduction lean design has been insignificant in the country. This paper describes step by step the implementation of lean design in capital projects related to hydraulic infrastructure in Peru specifically for river defenses and dikes.It is the objective of this paper to address the difficulties founded in the implementation and what strategies have been deployed in order to overcome those barriers. Two tools of lean design that were used are: set based design and value stream mapping along with concepts of change management.

KEYWORDS

Change management, lean design, set based design, value stream,. hydraulic infrastructure.

INTRODUCTION

The construction of public infrastructure in Peru is characterized by a lack of certainty about when the project is going to finish and at what the total budget will be at the end of the execution part, this is also closely related to corruption. As a result, society suffers from not having the necessary infrastructure such as hospitals, roads, schools, bridges, and hydraulic infrastructure. In 2017 the coast of Peru suffered intense damage due to heavy rains and enormous areas were flooded, the total damage was estimated at 384 millions dollars only in hydraulic infrastructure. A governmental institution was created

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in order to be responsible for protecting people from floods. Then, in 2020 the deployment of resources in order to start the design and construction of river defenses and dikes started in a fast track manner.

According to Forbes and Ahmed (2011) poor design and documentation quality have been identified as a major factor in reducing the overall performance and efficiency of construction projects. Moreover, Hill et al. (2017) report that the design stage can have more opportunities to reach better engineering solutions.Then, design can have a bigger impact in the cost and time of a project as well as the opportunity of the changes which are aligned with the MacLeamy curve. It was important to include methodologies or best practices that can ensure that those objectives (cost and time) will be reached.

Ballard and Howell (2003) pointed out that lean project delivery system (LPDS) provides a means of improving the entire design and construction process. As it is known, LPDS consists of five phases: project definition, lean design, lean supply, lean assembly and use. The lean design phase comprises three processes: design concept, process design and product design. As it is stated by Seed (2018) lean/Integrated Project Delivery is a response to the dissatisfaction of what we have in the construction industry. Therefore, the lean project delivery system was chosen as a framework for developing the lean design management. In particular two tools were included as part of the design stage: value stream mapping and set based design. Moreover, Mota et al. (2019) pointed out that there are limitations in major infrastructure projects when implementing lean design management such as: lack of collaboration, insufficient knowledge and rigidity of the organization.

Firstly, Kanai and Fontanini (2020) mentioned three positive factors of the value stream mapping: it helps to visualize the whole process, it is a manner to identify waste. The map is a first step for an implementation. Then, the description of the entire design process is not included in traditional design offices. Even, the most experienced organizations in Peru do not use a value stream mapping. Therefore, this tool was introduced to the technical team in order to generate this flow process with the input of each discipline. This tool is aligned with the process design part of lean design.

Secondly, Sacks et al. (2010) explain it is essential to invest time in the concept design phase and not to rush into the design detail. Besides, Forbes and Ahmed (2011) reported that a technique suggested for lean design is to pursue a set based design strategy. Then, the optimal solution is the result of different alternatives of design and the fact that creating different scenarios and the analysis of them can take us to a better solution. Therefore, this search of the optimal solution is included through the concept of set based design which played a pivotal role in finding this best alternative. This tool is aligned with the product design part of lean design.

Apart from those tools mentioned in the paragraphs above and its importance as a medium to implement lean design from the technical point of view. This case study explores the managerial aspect of this endeavor. In that regard, Wandahl (2014) pointed out that although several companies are introducing new management concepts, most of them fail in implementing them due to their internal culture. Therefore, this paper explains the barriers found in the implementation of lean design from the perspective of change management. It was notorious the natural resistance from people who were used to work in a traditional framework which means without tools from lean design.

In this regard, Kotter (1997) explains how to sustain in the long term any change in a company through the implementation of the methodology named the eight steps of Kotter. Moreover, Fischer et al. (2017) state it is necessary to repeat the strategic steps periodically, because executive managers need to remember lessons learned. In that context, the authors recognized that in order to reach the implementation inside an organization it is necessary to address a change management strategy.

KEY CONCEPTS

CHANGE MANAGEMENT

As part of social studies this concept gives us insights about how to defeat barriers when we try to apply new ideas, concepts and methodologies inside an organization. According to Zimmermann (2000) any important change will have resistances or difficulties to overcome. It is crucial to keep in mind that it is necessary to include leadership in all the processes of change. This model of implementation or transformation requires sacrifice, dedication and creativity. None of those elements are close friends with coercion. It will be important to keep in mind those eight steps mentioned by John Kotter in his book "Leading change" (1997) in order to really create an environment in which change is possible, and it will keep going in the long run. Those steps are the following: create a sense of urgency, create a guiding coalition, create a vision, communicate vision, remove barriers, generate quick wins, sustain the pace and make it stick. This is aligned to Schein (2009) who pointed out that change leadership must comprise: credibility, clarity of vision, ability to articulate the vision, understanding of cultural dynamics and process skills.

LEAN PROJECT DELIVERY SYSTEM (LPDS)

It comprises five phases that juxtaposes them and those phases influence each other which creates a necessary integration between different stakeholders (Forbes and Ahmed, 2011). The lean design phase comprises: conceptual design , process design and product design.

SET BASED DESIGN (SBD)

It is a design method in which sets of alternative solutions are evaluated until the last responsible moment (Hill et al., 2017). This last responsible moment should not impact in a negative manner the duration of the design process. Ballard (2000) precises the definition of this last responsible moment as the "point at which failing to make the decision eliminates an alternative". Moreover, Parrish et al. (2007) consider this tool improves the stakeholders engagement in order to increase the value generated by eliminating rework.

VALUE STREAM MAPPING (VSM)

As stated by Orihuela et al. (2015) VSM is a visual tool which permits teams to correctly identify how the flow processes are executing. Additionally, Kanai and Fontanini (2020) pointed out VSM helps to comprehend the flow of material and information. It is a tool that permits to know step by step the entire process of a work. It permits mapping the flow of value. Through this tool anyone in a team (i.e. a designer) can understand when and how his contribution helps to reach the goal of having the design done. By knowing how each process interacts with others and translating this idea on how different specialists, designers or stakeholders are able to have a holistic point of view of the design process and even they could make suggestions of improving the entire process through innovation and creativity. This tool permits global optimization and not only local ones because it is easier to notice the presence of waste in the whole process. This is supported by Orihuela et al (2015) by stating that VSM will reduce waste at the design phase by preventing negative iterations and rework.In that sense, the use of a value stream mapping leads to a continuous improvement.

HYPOTHESIS

The implementation of a structured strategy of change management in a governmental institution in Peru (that is in charge of the design and construction of hydraulic infrastructure) will permit to develop new methodologies such as lean design management and tools such as value stream mapping and set based design as manner to reach effectiveness and efficiency in the delivery of hydraulic infrastructure projects such as river defenses and dikes.

For this case study, the research questions are the following: how feasible is the implementation of lean design in hydraulic public projects? and how to overcome the technical and managerial barriers?

METHODOLOGY OF IMPLEMENTATION

There were different meetings with the directives of the governmental institution, designers and project managers and specialists in order to explain the necessity to incorporate a lean design methodology, as a manner to assure that the engineering solution reached was the most suitable and optimal, considering a multi-criteria analysis and a cost-benefit analysis. In order to reach the necessary support for this initiative we followed the eight steps (figure 1) described in Kotter (2012) including the following considerations:

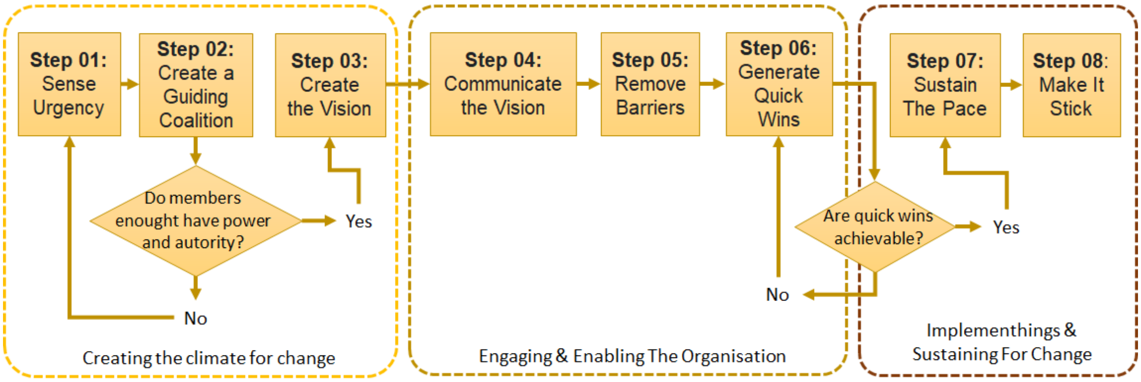

Figure 1: Steps of the methodology (adapted from Kotter 2012)

First, sense of urgency: In 2017, the northern part of Peru suffered flood damage and still in 2020 there was no definitive infrastructure designed to protect people and agricultural areas. Then, to convey the sense of urgency, senior management was sensitized by watching videos of the damage that occurred and the impact on the population. This message immediately reached directors, executives, project managers, designers and specialists who work in this institution and who are responsible for the design and construction of protective hydraulic infrastructure such as river defenses and dikes.

Second, create a guiding coalition: The power of position is crucial for the success of the endeavor of using new methodologies as lean design, set based design and value stream mapping. In this sense, it is essential to get the support of the organization's executives. Moreover, to strengthen this coalition, workshops must be offered to the members of the coalition to be trained in the use of lean design management.

Parallel that, not only bringing in people who have some experience in similar systems and have worked in academia enhances this guiding coalition, but also part of this coalition is the academy and it is important to prioritize an alliance between academia and the industry (institution).

Third, create a vision : This has to show a clear direction to all stakeholders because it increases motivation and makes changes in the design process much easier. Then, keeping in mind the urgency of protecting people from the effects of natural disasters, some informal meetings and two formal meetings were held with coalition members to create the vision. Consequently, this resulted in a clear, communicable and achievable vision that emphasizing how essential it was to quickly complete the design and construction of the hydraulic infrastructure to high standards with all talented individuals considered.

Fourth, to communicate vision: it is crucial that not only the coalition team knows the vision, but also most of the people involved in the change**.** Then, in each of the weekly meetings with those involved, structured speech emphasized the importance of combining the use of a lean approach to design. Workshops were given to explain the tools (SBD and VSM). Technical guides were also written in order to explain more about the tools to be used.

Fifth, remove barriers: Management change includes barriers that must be removed. For this, it is necessary to show the need of urgency to the actors to sensitize them and commit them to the cause. Likewise, optimal solutions must be offered. In this case study, the problem was the deficiencies generated by using the traditional work methodology. That is why it was necessary to explain and demonstrate the benefits of using the new methodology to gain more allies in the process.

Sixth, generate quick wins: in order to generate trust in the environment and help to consolidate the process, it is necessary to plan quick wins. In this particular case study the first quick win was to gain the support of the organization's executives. A second win was when we had onboarding members to the coalition team such as the design manager and construction manager. Then, the first draft of the value stream mapping was a quick win because it demonstrated how helpful and important it was to have the opportunity to see in detail the entire process. The next win was when some specialists such as the archaeologist and the landscaping architect started spreading the work with other stakeholders. These quick wins demonstrated the positive effects of the new methodology and not only increased the momentum of the people involved in the change, but also they were recognized by people who were against the changes and consequently, they changed their attitude.

Seventh, sustain the pace: Once those quick wins were reached the coalition team was more sure that people were compromised with a further analysis of flow processes by categorizing in three different components: customer value-added, business value-added and non value-added. Also, in order to sustain the pace of the implementation, designers and specialists created a more collaborative environment in which the goal was to deliver a leaner design process. At this point, the coalition team found more advocates between the participants which facilitated the implementation process.

Eighth, make it stick: The ultimate goal of an implementation is to change the culture in terms of norms of behavior and shared values of the organization. This involves a long-term commitment. So, we need to assure quick or early wins in order to inspire people to continue with their effort. In this sense, communication is critical because people need to be reinforced about the objectives of the changes. In this case study the long-term commitment will be visible when this new manner to work in the design process will be used in each project in charge of the hydraulic infrastructure.

RESULTS

As a result of the implementation, the strategy focuses on change management and the collaboration of the coalition team and advocates. In the following, it summarizes different aspects of the implementation processes such as: strategies for implementing lean design management (SBD and VSM), facilitating elements for implementation, difficulties and barriers found and strategies for overcoming difficulties. Then, each step of the framework is evaluated from those four dimensions.

1.SENSE OF URGENCY

Strategies for implementing lean design management: People were told about the delay in these projects. The flood damages occurred in 2017 and still in 2020 we have not had a final solution for protecting people and infrastructure in urban cities and agricultural areas.

Facilitating elements for implementation: Directives, executives, project managers, designers and specialists were aware and conscious about the necessity of these projects.

Difficulties and barriers found: It was difficult to transform this sense of urgency in activities and measurable tasks that permits a call to action.

Strategies for overcoming difficulties: In formal meetings a topic of discussion was to define milestones of the design and the time frame.

2.CREATE A GUIDING COALITION

Strategies for implementing lean design management: To get people involved with authority and power inside the organization.

Facilitating elements for implementation: Two of the executives: the construction manager and the design manager on board of this implementation helped to propel it.

Difficulties and barriers found: To convince the executive director, construction manager and design manager that it is worth implementing

Strategies for overcoming difficulties: To explain best international practice of implementing new methodologies such as lean design management.

3.CREATE A VISION

Strategies for implementing lean design management: To create a message about the importance of finishing as soon as possible and at the same time with high standards the design and construction of hydraulic infrastructure that can protect people from death and poverty.

Facilitating elements for implementation: The vision created was communicable, clear and most importantly feasible considering all the talented people involved in this endeavor.

Difficulties and barriers found: Multidisciplinary projects like this one need to address many concerns coming from each discipline. There were eleven disciplines.

Strategies for overcoming difficulties: Through one to one meetings with each specialist we sought to understand the concerns and to figure out how to include them in the vision.

4.TO COMMUNICATE THE VISION

Strategies for implementing lean design management: There were three key elements that helped to communicate the vision: multiple forums, repetition and bilateral communication. As part of the strategy there were seven workshops delivered to stakeholders (executives, directors, project managers, designers, specialists) in which the methodology of lean design. in particular value stream mapping and set based design were explained.

Facilitating elements for implementation: In informal meetings the coalition team delivered the message, the repetition of the message was important. Also, it was convenient to be open to feedback and to stimulate this bilateral communication between people involved and the coalition team. Also, the vision was repeated at the beginning of each weekly meeting.

Difficulties and barriers found: The problem was to recognize at what level people were understanding the vision (message).

Strategies for overcoming difficulties: Surveys were implemented in order to measure at what extent people were engaged to the vision.

5. REMOVE BARRIERS

Strategies for implementing lean design management: It was a priority to identify barriers, so through surveys we collected data about the level of knowledge and the flexibility of implementing new tools by the stakeholders. Then, a schedule of training was developed. The selected topics were change resistance and technical tools such as set based design and value stream mapping.

Facilitating elements for implementation: The support of the guiding coalition was fundamental for implementing the strategy in this step. Also, the specialized knowledge of the consultants from academia was important.

Difficulties and barriers found: There were two types of barriers such as: structural impediments and skills-knowledge obstacles. Those structural barriers were related to the traditional design process in which there is no room for evaluation of different design alternatives and it is not appreciated to develop and share the mapping of the value creation. Also, not knowing what lean design is about or its tools is the second type of barrier categorized as insufficient skill and knowledge.

Strategies for overcoming difficulties: Through extensive workshops, technical notes and a clear communication, the knowledge gap was fullfill and the structural barrier was overcome.

6. GENERATE QUICK WINS

Strategies for implementing lean design management: To set clear goals which comply with the following characteristics: measurable, achievable and quantifiable. Therefore, planning how to achieve those goals was important and to get into details such as: resources, time and constraints. It was established goals of first level and goals of second level of detail. Those of the first level were each step of Kotter framework. Second level goals were related to the internal process with all the stakeholders.

Facilitating elements for implementation: The framework designed by Kotter gave a clear path of how to establish those goals. Those eight steps were taken initially as measurable goals.

Difficulties and barriers found: The elaboration itself of the value stream mapping was difficult because of the number of participants. Each specialist from his/her point of view weighted differently the time, importance and precedence of each activity. Also, meetings with all people involved were relevant, but initially those meetings took more working hours than expected.

Strategies for overcoming difficulties: One to one meetings were established. Those helped to understand the point of view of each specialist. From this, a first draft of the value stream was proposed. This was a manner to decrease the duration of meetings with all people involved.

7. SUSTAIN THE PACE

Strategies for implementing lean design management: Weekly meetings were established between members of the guide coalition and specialists. In each meeting a general perspective was given about where we are in the roadmap (quick wins). Then, a gap analysis between actual progress and planned progress. Also, discussion about constraints and an analysis of foreseen activities.

Facilitating elements for implementation: Those initial advocates helped to increase confidence in other participants.

Difficulties and barriers found: Attendance at those weekly meetings was a big issue at the beginning of implementation.

Strategies for overcoming difficulties: To those people who were absent at that weekly meeting, it was necessary to schedule a one to one meeting in order to increase awareness and commitment.

8. MAKE IT STICK

Strategies for implementing lean design management: The strategy was to implement this new methodology in each project in charge of the institution. The portfolio consists of nine projects such as: Cañete river, Huaura river, Matagente river, La Leche river, Motupe river, Tumbes river, Casma river, Huarmey river and Mala river. Therefore, through repetition we expected to improve the design management and make it repeatable in each project.

Facilitating elements for implementation: By having a portfolio of nine projects , this gives us the opportunity to use lessons learned from previous projects. This is because each project has a differentiated start.

Difficulties and barriers found: Since each project had its own personnel who did not make the effort of implementation from the beginning this makes it difficult at the outset. Also, people from each region were far away from the central office. Then, virtual meeting were commonly used.

Strategies for overcoming difficulties: Training and workshops were given for people in each region. Apart from virtual meetings, a physical one was established once a month.

DISCUSSION

The feasibility of implementation is analyzed in two levels at the global and local one. At the global level the most important barriers were: the decision at the executive level of implementing a lean design management approach, the conformation of the coalition team, the planning of the workshop-training to specialists and to plan which those quick wins will be. Nevertheless, the governmental institution took more time than expected just to consider the implementation or not of lean design management. It was expected that in 2 weeks the decision would be made, but it took 6 weeks just to start. The importance of having an alliance between the governmental institution with academia in this endeavor played a pivotal role. This is because the guidance from scholars helped the path of the coalition team.

At the local level, two elements were closely related: communications and the restrictions for pandemic in the country. This virtualizes the work because the restriction of having a limited number of professionals at the office propelled the use of virtual teams. The use of technology eases the implementation because people could join training sessions and workshops from their home. Also, the level of commitment increased when people started seeing the results of applying lean design. At the end of the design process of one of the projects, a survey was applied and it was found that 72% believed the quality of their work increased and the rework decreased.

There were eleven different types of specialists for each project: topography, geology, archeology, environmental, geomorphology, geotechnics, hydrology, hydraulic, social, landscaping and civil works. What those specialists expressed in the survey at the end of the design process was the importance of knowing when to start interacting with other specialists and what they expected from the previous process is what they highlighted as valuable in the implementation of lean design.

Considering there is a portfolio of nine projects, this gives the opportunity to learn from repetition and from the lessons learned of previous projects.

CONCLUSIONS

Those difficulties that we encountered were mainly related to the structure of the organization. It was a governmental institution which was in charge of the design and construction of hydraulic infrastructure. Then, the feasibility of the implementation had an important barrier to overcome which is related to how executives and directors used to work in a traditional framework and it took a long time to make a decision to implement it. Also, the organizational structure did not allow to allocate new staff with experience in lean design. Then, the alliance with academia was important for a successful implementation.

Despite those challenges, directors, executives and specialists were convinced that knowing the entire process using a tool named value stream mapping and being aware of each interaction between different disciplines will bring more chances to obtain an optimal engineering solution from a cost benefit analysis that guarantees a better value for money.

The use of a structured framework such as the eight steps of change management helped to overcome the technical and managerial barriers. It was found that each of the steps are important in order to protect the implementation from detractors and create the environment for those who advocate for this new methodology of lean design. The framework was used as a guide of each step in the entire process of implementation. Two of the most relevant steps that were highlighted by stakeholders in a survey were the coalition team and the establishment of quick wins. Both were crucial for the implementation and for keeping the interest of all designers, specialists, executives, directors, project managers and design managers.

It will be important for future research to analyze at the end of the construction stage how the decision made in the design influences the result of the execution part.

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REFERENCES

Ballard, G. (2000). “Positive vs Negative Iteration in Design”. Proc. 8th Ann. Conf. of the Int´l Group for Lean Construction (IGLC-8), Univ. of Sussex, Brighton. UK. 44-55.

Ballard, G. and Howell, G. (2003). Lean Project Management. Building Research & Information. 31(2) 119-133.

Fischer M., Ashcraft H., Reed, D. and Khanzode, A.(2017). “Integrating project delivery”, John Willey and Sonc Inc, New Jersey, USA.

Forbes, L.H. and Ahmed, S.M. (2011). “Modern Construction: lean project delivery and integrated practices”, Taylor and Francis Group Inc., Florida, USA.

Hill, K., Copeland, K., Pikel, C. (2017). “Target Value Delivering: Practioner guidebook to implementation”, Lean Construction Institute, Virginia, USA.

Kanai, J. and Fontanini, P.S.P. 2020. “Value Stream Map and Visilean for Prefabricated Concrete Panels

Kotter J. (1997). “El lider del cambio”, McGraw-Hill Interamericana Editores. México.

Management.” Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC). Berkeley, California, USA, pp 673-674".

Mota, B., Biotto, C., Choudhury, A., Abley, S. and Kagioglou, M. (2019). “Lean Design Management in a Major Infrastructure Project in UK”. Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC). Dublin, Ireland, 3-5 Jul 2019. pp 37-48.

Orihuela, P., Orihuela, J. and Pacheco, S. (2015). “Communication protocol for implementation of Target Value Design (TVD) in building projects”. Procedia Engineering, Creative Construction Conference 123, 361-369.

Parrish K., Wong, J., Tommelein, I., and Stojadinovic, B. (2007). “Exploration of Set-Based Design for Reinforced Concrete Structures”, In Proc. 15th Ann. Conf. of the Int´l Group for Lean Construction (IGLC-15), Michigan, USA. 213-222.

Sacks R.; Koskela L.; Dave B.; and Owen R. (2010) “Interaction of Lean and Building Information Modeling in Construction” Journal of Construction Engineering and Management, Vol. 136, No. 9, September 1, 2010.

Schein, E. (2009). “The corporate culture survival guide”. John Wiley & Sons, San Francisco, USA.

Seed, W.B. et al (2018). “Transforming Design and Construction: A Framework for Change”, Lean Construction Institute, Virginia, USA.

Wandhal, S. (2014). “Lean Construction with or without Lean–Challenges of implementing” Lean Construction. In Proceedings of the 22nd Annual Conference of the International Group for Lean Construction, Oslo, Norway, 97-108.

Zimmermann (2000) “Gestión del Cambio Organizacional”. Ediciones ABYA-YALA, Quito, Ecuador.

Gravina da Rocha, C., Kemmer, S. (2021). "Product Variety in Construction: A Critical Review and Way Forward" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 595–604, doi.org/10.24928/2021/0133, online at iglc.net.

PRODUCT VARIETY IN CONSTRUCTION: A CRITICAL REVIEW AND WAY FORWARD

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ABSTRACT

This paper presents a critical analysis of current construction literature on product variety. In particular, two theoretical bases, namely, (i) hierarchical product breakdown and (ii) generic supply chain types, that address such conceptualization are reviewed. Three limitations were encountered, which hinder their application in measuring levels of product variety and associated disruptions in the production flow of building projects. Hierarchical product breakdowns (i) do not reflect the production sequence employed for erecting a building and (ii) do not enable spatial and layout changes (a key aspect of variety in building projects) to be appropriately framed. Supply chain types, in turn, provide only a high-level understanding of the effect of product variety (or customisation) on the production flow, and thus do not allow product variety to be assessed and compared at a project level. The paper concludes by discussing a number of conceptualizations (Work structure & Work Packages, Product Variants, Decoupling Point, Modules, and Design Structure Matrix) that can advance in the understanding of product variety in construction.

KEYWORDS

Customization, process, flow, work packages, modularity.

INTRODUCTION

The Transformation-Flow-Value theory (TFV) emphasizes that construction should be viewed as (i) transformation of inputs into outputs, (ii) flow comprised of value-adding activities and non-value-adding activities (waste), and (iii) value generation (Koskela 2000). The flow view is relevant as it shines a spotlight on waste (Sacks 2016; Sacks et al. 2017): products wait for crews and crews wait for materials, information, equipment, space, to complete a task. Waste exists in construction due to inherent variability of processes (Hopp and Spearman 2001) and also due to specificities of this sector (e.g., Tommelein et al. 1999, Vrijhoef and Koskela 2000). Yet, it is aggravated when customization (or product variety) is offered.

Customization requires clients to provide an input, which usually consists of design drawings with changes in terms of layout and/or material specifications, for units forming a building (offices or apartments in a building, stores in a mall, etc.). Customization contributes to the value element of TFV by fulfilling clients' specific requirements. Yet, it introduces an additional source of variability in the production flow. Indeed,

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customization creates different types of waste as exemplified in the project examined by Sacks and Goldin (2007) and Sacks et al. (2007), detailed as follows. Delays in receiving clients input lead to waiting for such input or to rework (in case a standard unit is already built). Such waiting is often fought back by working in several (or all) units, which creates inventory and excessive movement of crews and/or materials. Lastly, unnecessary activities such as cleaning and repairing are also required since units stay as work-in-progress for long periods.

Besides the variability in client input, customization also creates variability (or variety) of the product itself (da Rocha et al. 2016): namely, rather than having a single standard product for the units forming a building, each of these becomes a product variant. While the former source of variability and its effect on the production flow has been examined, the latter has not received the same attention. It is acknowledged that product variety negatively affects production. Increasing the number of product variants creates (Fisher and Ittner 1999): (i) less accurate demand forecasts, (ii) high levels of inventories and materials transportation, (ii) additional setups, (iii) a complex scheduling, (iv) increased supervision requirements, and (v) risk of workers selecting the wrong parts.

Yet, it is unclear how to measure product variety levels (or customisation levels) in construction as well as the extent of disruptions in the production flow yield by such different levels. Upon reviewing two theoretical bases for understanding such concept in this sector (i.e. hierarchical product breakdown and supply chain types), three limitations were encountered and are discussed here. In order to address such limitations, a number of conceptualizations from construction and manufacturing (Work structure & Work Packages, Product Variants, Decoupling Point, Modules, and Design Structure Matrix) that can advance in the understanding of product variety in construction are reviewed.

PRODUCT VARIETY IN CONSTRUCTION

HIERARCHICAL PRODUCT BREAKDOWN

Open Building (Habraken 1972) introduced the notion of buildings being composed by two levels (infill and support). Yet, a detailed breakdown of buildings and their constitutive physical parts was only later proposed by Schoenwitz et al. (2012). Such a breakdown suggests that buildings can be organized in three hierarchical levels (Schoenwitz et al. 2012, 2017): categories, components, and sub-components (Figure 1). The criteria for such a breakdown are not clearly presented in the above-mentioned studies, but the results suggest they involve (i) the physical decomposition of a building (ii) from the highest to the lowest level (i.e. the entire building to individual components such as tiles or bricks).

The categories level seems to address a building systems as suggested by the terms “sanitary” and “heating” presented in Schoenwitz et al. (2012). Systems (structural, enclosure, electrical, heating, etc.) can indeed be decomposed into components and sub-components. However, it is not clear what “construction design” and “internal design” (in Schoenwitz et al. 2012, 2017) might be in terms of systems. Particularly, it is puzzling to have “house” as a component of the “construction design” category in Schoenwitz et al. (2012). Similarly, “roof” (under “construction design”) is formed by “tiles”, “dormer”, “windows” but also by “type” and “conversion” which do not seem to be sub-components.

Despite these problems, hierarchical product breakdown is in line with product architecture (e.g., Ulrich 1995, Fixson 2005) and the notion that a product can be subsequently decomposed or partitioned (both in terms of components and functions).

Nonetheless, such partitioning, particularly in terms of components, should reflect the product assembly or manufacturing. For example, small components (metal plates, bolts, axis, etc.) are grouped into particular modules (box, hitch, fairing, bed, springs, and wheels) in the cargo trailer examined in Ulrich (1995) and Fixson (2005) because these are the chunks used for assembly. Likewise, a cockpit is defined as a module (from the car manufacturer perspective) since it is the chunk added in the car assembly line (Baldwin and Clark 2003).

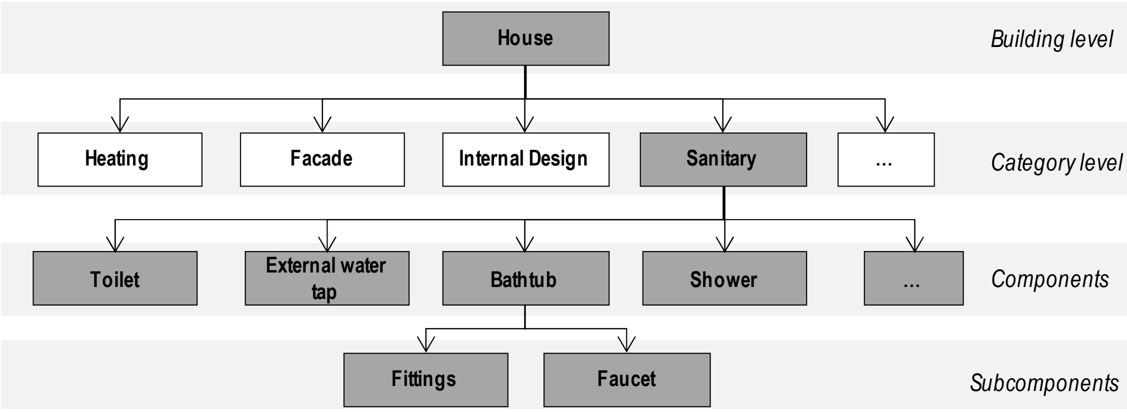

Figure 1 – Example of a hierarchical product breakdown (based on Schoenwitz et al. 2012, 2017)

SUPPLY CHAIN TYPES

Hoekstra et al. (1992) suggest that customization and its impacts on operations can be determined by the Decoupling Point (DP). The DP is the first point in which a client order enters the supply chain, thus separating forecast and demand driven tasks (Naylor et al. 1999, Olhager 2003, Yang and Burns 2003, Yang et al. 2004). Five supply chain types emerge by varying the DP position (Hoekstra et al. 1992): make and ship to stock, make to stock, assemble to order, make to order, and purchase and make to order. These were later re-named and detailed (Naylor et al. 1999) as shown in the first and second columns of Table 1: buy to order (unique products), make to order (bespoke products made from the same materials), assemble to order (products made from a pre-defined mix of parts), make to stock (standard products delivered to varied locations), and ship to stock (standard products delivered to fixed locations).

Barlow et al. (2003) propose a one-to-one correspondence between the five supply chain types and customization strategies (Lampel and Mintzberg 1996): pure standardization, segmented standardization, customized standardization, tailored customization, and pure customization (a product designed according to clients order). They also convert the four generic production stages (Table 1) in a combination of (i) production stages (e.g., design, distribution, assembly) and (ii) physical parts (e.g., components, sub-assemblies) to adapt the supply chain types (Hoekstra et al. 1992, Naylor et al. 1999) to house building. More recently, Schoenwitz et al. (2017) used these supply chain types (Barlow et al. 2003) and the hierarchical product breakdown (Schoenwitz et al. 2012) to analyse the Decoupling Points (DPs) in building products.

Table 1: Relationships: DP location, supply chain type, and customization strategy

Generic production stage	Supply chain type	Customization strategy
DP in design	Buy to order	Pure customization
DP in fabrication	Make to order	Tailored customization
DP in assembly	Assemble to order	Customized standardization
DP in distribution	Make to stock	Segmented standardization
--	Ship to stock	Pure standardization

LIMITATIONS OF CURRENT UNDERSTANDINGS

Two limitations arise when using a hierarchical product breakdown as in Schoenwitz et al. (2012, 2017) for assessing variety in construction. First, such breakdown does not reflect how buildings are erected. Buildings are often produced by adding component and sub-components from different systems throughout the construction process rather than assembling only components and sub-components from a specific system and finally adding all systems together. Furthermore, the construction processes can vary from traditional construction (bricks and cast in place concrete) to full off-site construction (volumetric pods only assembled on-site). This differs from manufacturing in which a single set of modules and a unique process are used to deliver a large number of products.

The second limitation refers to spatial (or layout) changes such as integrating a bedroom space (by removing walls) to create a large living room. Such changes are a fundamental element of variety in buildings that cannot be appropriately framed in hierarchical product breakdowns. This is because such breakdowns are organized in terms of systems (and their constitutive physical parts such as components and sub-components) instead of spaces such as living room, kitchen, bedroom, etc. (and the physical parts enclosing such spaces that pertain to distinct systems). Yet, the latter (spaces) instead of the former (physical parts) is the appropriate unit for framing spatial (or layout) changes.

Lastly, the positioning of the DP in generic stages (or supply chain types) such as in Barlow et al. (2003) and Schoenwitz et al. (2017) allows only a generic understanding of customization (or product variety) and its implications in production. Indeed, it can be used to position and characterize construction in comparison to other sectors: construction is often labelled as engineer to order (e.g., Pero et al. 2015). However, this definition does not assist practitioners in defining customization strategies for the project at hand. This is because the operational impact of distinct variety levels embedded in such strategies (namely, attributes and options) is not clear.

RELEVANT NOTIONS FOR UNDERSTANDING PRODUCT VARIETY IN CONSTRUCTION

WORK STRUCTURE & WORK PACKAGES

Work structure refers to the packaging of tasks and related resources (crews, materials, design information, equipment) needed to erect a building into chunks or work packages (Ballard 1999; Tsao, 2005; Tsao et al., 2004). Managing such chunks (instead of individual tasks) reduces the number of hand-offs, thus simplifying production. Differently from manufacturing in which a single process (workstations in a factory) delivers a large number of products, each building is erected via a unique work structure (or process) (da Rocha and Kemmer 2018). Such one-off nature arises from specific characteristics that define construction: (i) temporary supply chains often put together to deliver only one project (Vrijhoef and Koskela 2000) and (ii) varied construction methods ranging from traditional bricks and blocks to volumetric pods fully produced off-site.

Work packages are considered here to be the output of work structuring (as defined by Ballard 1999), namely, the “chunks” in terms of production that need to be carried out to complete a building. A number of studies (e.g., Spitler and Wood 2016; Tsao et al. 2004) have detailed the elements comprising a work package. Here a work package is considered to involve (da Rocha and Kemmer 2018): (i) the resources to complete the construction tasks, (ii) the crew, and (iii) the construction tasks carried out. Such resources are understood here as the pre-requisite conditions for task completion defined by Koskela (2000): construction design; components, and materials; workers; equipment; space, connecting works; and external conditions.

PRODUCT VARIANTS

Product variety arises from a set of attributes for which different options (or levels) are offered. Each attribute can be specified at distinct options, yet only one option is activated at each product variant (Raman 1995). Thus, the amount of product variants is a function of the number of customizable attributes and options. In case all attributes are independent and all options can be combined, the amount of product variants is straightforward: the product (multiplication) of all options offered. Scavarda et al. (2010) propose a similar formula for cars involving the amount of (i) car models, (ii) body style, (iii) powertrain, (iv) paint and trim combination, and (iv) factory fitted options (e.g., sunroofs, radio). Yet, some options are not available for all models (e.g., a sunroof for a convertible) and option bundling might also apply (e.g., fog lamps only on the winter package) (Scavarda et al. 2010; Pil and Holweg 2004), and thus need to excluded from the total amount of product variants (e.g., Stäblein et al. 2011; Scavarda et al. 2010). The amount of product variants might appeal as a/the measure of product variety due to its simplicity but it is not sufficient (e.g., Martin and Ishii 1996, Stäblein et al. 2011). Ten fundamentally different options (e.g., platforms) do not create the same variety level as ten similar options (e.g., colours) (Stäblein et al. 2011).

DECOUPLING POINT & POSTPONEMENT

The Decoupling Point (DP) is the point in which client order enter the production or the supply chain. Its positioning in distinct generic stages such as fabrication, assembly, distribution, etc. has led to traditional supply chain types such as assemble-to-order, make-to-order and engineer-to-order (e.g., Hoekstra et al. 1992; Naylor et al. 1999) that illustrate the trade-off production efficiency and customisation. Indeed, as the DP moves upstream the product variety (or customisation) levels increases so does the operational impact, resulting in high costs and delivery time (Olhager 2003). Barlow et al. (2003) adapted such generic supply chain to the construction context and more recently Rocha and Kemmer (2013) proposed the use of DP in the context of work packages and line of balance. That is, the DP would be located in the first work package for which client input is needed to perform the construction tasks.

Postponement is closely related to the Decoupling Point (DP) and the ensuing supply chain types. Such concept seeks to minimize the uncertainty and variability of the logistics and manufacturing operations affected by client input (or customisation requirements) by postponing such activities as much as possible (Pagh and Cooper 1998). Similar to the supply chain types, different postponement strategies can be applied such as (i) labelling postponement, (ii) packaging postponement, (iii) assembly postponement, (iv) manufacturing postponement, and (v) time postponement (Zinn and Bowersox 1998). This same rationale has been explored in construction by Rocha and Kemmer (2013), which proposed and simulated the implementation of Delayed Production Differentiation (a synonymous for postponement) for an apartment building project.

MODULES

Previous studies (Gosling et al. 2016; da Rocha and Kemmer 2018) have shown that modules can assume distinct forms in construction projects ranging from simple and small components (e.g., brick, rebars, pipe) to large and complex sub-assembly (e.g., prefabricated pods). In addition, they can be understood from a spatial or component-oriented perspective (Rocha et al. 2015) both of which involve the definition of functional elements, physical components, and interfaces as discussed by Ulrich (1995). The former focuses on the activities performed by people in the spatial voids such as working, cooking, reading, sleeping. The latter focuses on the functions (e.g., thermal insulation, load bearing, etc.) performed by the physical mass forming a building such as beams, walls, ceiling, etc. (Rocha et al. 2015, Rocha and Koskela 2020). Clearly, adopting a spatial perspective requires the components to be considered since spaces only exist in juxtaposition to physical mass. However, adopting a component-perspective creates the modularization of only a particular system (e.g., MEP system) rather than the building as whole, thus limiting the benefits created (Rocha and Koskela 2020).

DESIGN STRUCTURE MATRIX (DSM)

Design Structure Matrix (DSM) is a tool used to model systems, in particular their decomposition into parts (or subsystems) and their integration (Tuholski and Tommelein 2008). It enables the relationship between such subsystems as well as internal and external inputs and their impact on the system to be noted (Browning 2001). DMS modelling entail three basis steps (Tuholski and Tommelein 2008): (1) decomposition of a system or process into discrete parts, identifying inputs, outputs and information dependencies; (2) organization of such parts in a matrix with identical rows and columns and marking of connections between rows and columns; and (3) triangulation, entailing the identification of dependencies among parts (such as parallel, sequential, or coupled). Browning (2001) classifies DSMs in two major groups: (i) static, which represents parts coexisting at the same moment in time such as components of a product architecture or members in an organization and (ii) time-based, which models events over time such as activities that are carried out to complete a project.

In construction, many studies appear to fall on the second group as they map the relationships among the activities involved in projects design or construction (e.g., Khalife et al. 2018; Rosas 2013; Tuholski and Tommelein 2008). Differently, the theme of product variety appears to bridge the static and the time-based domains. The former is related to the modelling of modules and platforms and the connections among them (similar to Veenstra et al. 2006). DSM could be applied to identify such parts (based on step 1) and the relationships among them (based on step 2 and 3), defining more or less coupled interfaces. The latter is related to the construction activities required to complete a project and the relationships among them, thus similar to previous studies on DSM in construction. The final step would require these two matrices (static modelling of product architecture and time-based modelling of work packages) to be integrated: by identifying when the modules and platform are assembled or erected within the work packages as well as the critical points in construction (interfaces between such parts identified in the first matrix).

DISCUSSION

Work Structure & Work packages and Design Structure Matrix (DSM) seem to provide suitable theoretical basis to model the product and process perspectives required to understand product variety in construction. Both appear to be sufficiently generic and flexible to accommodate distinct production sequences and construction methods used. The other conceptualizations account for the effect of distinct product variety levels in the production. Overall, disruptions in flow arising from product variety augments as (i) the number of product variants increases, (ii) the number of work packages delivering product variants rather than a single standard product increases, (iii) the DP moves to an upstream position, and (iv) the number of modules in work packages increases. This last notion exacerbates the ‘matching problem’ (Tommelein 2006), which shows that as the number of different units (e.g., pipe spools) increases, the time needed for matching each of them to their correct position/locations augments substantially. The reasoning behind all these trends (except for the DP) is based on the notion that complexity increases as the number of parts increases (Baccarini 1996) or conversely that simplification is achieved by reducing the number of parts (Koskela 2000).

This seems particularly appropriate considering the labour-intensive nature of construction and that having more parts or elements to cope with increases the cognitive burden and consequently the potential for errors and reworks, which directly affect flow. Furthermore, construction is most often characterized by a sequential configuration also known as the Parade of Trades (Tommelein et al. 1999). Thus, any disruptions in early work packages affect not only affect such work package but potentially all subsequent ones. As a result, the potential for disruptions in the production flow reduces, as the delivery of product variants (marked by the work package in which the DP is located) is postponed. Finally, although work packages, which map the construction activities, provide the focal point here for analysing disruptions in flow yield by product variety, such impact are determined to a large extent by design decisions. For example, layout options might be devised in a way to minimize changes in walls that have MEP embedded (or alternatively to have such systems embedded in other walls) to reduce the number of work packages impacted by customisation.

CONCLUSIONS

This paper performed a critical analysis of two main conceptual frameworks (hierarchical product breakdowns and supply chain types) addressing product variety (or customisation) in construction. Three limitations were encountered mainly related to specificities of construction not being appropriately framed or considered in such frameworks (e.g., spatial or layout aspects of product variety and the varied production sequences and methods employed for erecting buildings). This in turn hinders their usage to assess the product variety at a project level and precludes a detailed assessment of the disruptions in the production flow created by distinct product variety levels. It also suggests that new conceptual frameworks that allow the granularity and data at a project level are needed.

Seeking to address this problem, a number of conceptualizations from construction and manufacturing domains were reviewed: Work Structure & Work Packages, Product Variants, Decoupling Point (DP), Modules, and Design Structure Matrix (DSM). In this sense, Work Structure & Work Packages and Design Structure Matrix (DSM) emerge as a promising theoretical bases for understanding product variety and applying conceptualizations such as Product Variants, Decoupling Point (DP), and Modules to assess the extent of disruptions in flow crated by distinct levels of product variety. Clearly, this study and propositions have an exploratory nature and should be integrated in a cohesive framework to be applied in real world projects.

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REFERENCES

Baccarini, D. (1996). "The concept of project complexity—a review." *International Journal of Project Management*, 14(4), 201–204.

Baldwin, C. Y., and Clark, K. B. (2003). "Managing in an age of modularity." *Managing in the modular age: Architectures, networks, and organizations*, 149, 84–93.

Ballard, G. (1999). "Work structuring." *White Paper*, 5.

Barlow, J., Childerhouse, P., Gann, D., Hong-Minh, S., Naim, M., and Ozaki, R. (2003). "Choice and delivery in housebuilding: lessons from Japan for UK housebuilders." *Building Research & Information*, 31(2), 134–145.

Browning, T. R. (2001). "Applying the design structure matrix to system decomposition and integration problems: a review and new directions." *IEEE Transactions on Engineering Management*, 48(3), 292–306.

Fisher, M. L., and Ittner, C. D. (1999). "The Impact of Product Variety on Automobile Assembly Operations: Empirical Evidence and Simulation Analysis." *Management Science*, 45(6), 771–786.

Fixson, S. K. (2005). "Product architecture assessment: a tool to link product, process, and supply chain design decisions." *Journal of Operations Management*, 23(3–4), 345–369.

Gosling, J., Pero, M., Schoenwitz, M., Towill, D., and Cigolini, R. (2016). "Defining and Categorizing Modules in Building Projects: An International Perspective." *Journal of Construction Engineering and Management*, 142(11), 04016062.

Habraken, N. J. (1972). *Supports: an alternative to mass housing*. Architectural Pr, London.

Hoekstra, S., Romme, J., and Argelo, S. M. (Eds.). (1992). *Integral logistic structures: developing customer-oriented goods flow*. Industrial Press, New York.

Hopp, W. J., and Spearman, M. L. (2001). *Factory physics: foundations of manufacturing management*. Irwin/McGraw-Hill, Boston.

Khalife, S., Mneymneh, B. E., Tawbe, A., Chatila, M. H., and Hamzeh, F. (2018). "Employing Simulation to Study the Role of Design Structure Matrix in Reducing Waste in Design." *26th Annual Conference of the International Group for Lean Construction*, Chennai, India, 879–889.

Koskela, L. (2000). *An exploration towards a production theory and its application to construction*. VTT Technical Research Centre of Finland.

Lampel, J., and Mintzberg, H. (1996). "Customizing customization." *Sloan management review*, 38(1), 21.

Martin, M. V., and Ishii, K. (1996). "Design for variety: a methodology for understanding the costs of product proliferation." *Proceedings of The 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, California*.
Naylor, J. B., Naim, M. M., and Berry, D. (1999). "Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain." *International Journal of Production Economics*, 62(1–2), 107–118.
Olhager, J. (2003). "Strategic positioning of the order penetration point." *International Journal of Production Economics*, 85(3), 319–329.
Pagh, J. D., and Cooper, M. C. (1998). "Supply chain postponement and speculation strategies: How to choose the right strategy." *Journal of business logistics*, Blackwell Publishing Ltd, Hoboken, 19(2), 13.
Pero, M., Stößlein, M., and Cigolini, R. (2015). "Linking product modularity to supply chain integration in the construction and shipbuilding industries." *International Journal of Production Economics*, 170, 602–615.
Pil, F. K., and Holweg, M. (2004). "Linking Product Variety to Order-Fulfillment Strategies." *Interfaces*, 34(5), 394–403.
Raman, N. (1995). "Simultaneous determination of product attributes and prices, and production processes in product-line design." *Journal of Operations Management*, 12(3–4), 187–204.
da Rocha, C. G., and Kemmer, S. (2018). "Integrating product and process design in construction." *Construction Management and Economics*, 36(9), 535–543.
da Rocha, C. G., Kemmer, S. L., and Meneses, L. (2016). "Managing Customization Strategies to Reduce Workflow Variations in House Building Projects." *Journal of Construction Engineering and Management*, 142(8), 05016005.
Rocha, C. G. da, and Koskela, L. (2020). "Why Is Product Modularity Underdeveloped in Construction?" *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC)*, Berkeley, California, USA, 697–708.
Rosas, E. (2013). "Integrating the Design Structure Matrix and the Last Planner System Into Building Design." *21th Annual Conference of the International Group for Lean Construction*, C. T. Formoso and P. Tzortzopoulos, eds., Fortaleza, Brazil, 389–398.
Sacks, R. (2016). "What constitutes good production flow in construction?" *Construction Management and Economics*, 34(9), 641–656.
Sacks, R., Esquenazi, A., and Goldin, M. (2007). "LEAPCON: Simulation of Lean Construction of High-Rise Apartment Buildings." *Journal of Construction Engineering and Management*, 133(7), 529–539.
Sacks, R., and Goldin, M. (2007). "Lean Management Model for Construction of High-Rise Apartment Buildings." *Journal of Construction Engineering and Management*, 133(5), 374–384.
Sacks, R., Seppänen, O., Priven, V., and Savosnick, J. (2017). "Construction flow index: a metric of production flow quality in construction." *Construction Management and Economics*, 35(1–2), 45–63.
Scavarda, L. F., Reichhart, A., Hamacher, S., and Holweg, M. (2010). "Managing product variety in emerging markets." *International Journal of Operations & Production Management*, 30(2), 205–224.
Schoenwitz, M., Naim, M., and Potter, A. (2012). "The nature of choice in mass customized house building." *Construction Management and Economics*, 30(3), 203–219.

Spitler, L., and Wood, N. (2016). "Work Structuring at the Boundary of Realization: A Case Study Analysis." *24th Annual Conference of the International Group for Lean Construction*, Boston, USA.

Stäblein, T., Holweg, M., and Miemczyk, J. (2011). "Theoretical versus actual product variety: how much customisation do customers really demand?" *International Journal of Operations & Production Management*, (P. Jonsson, ed.), 31(3), 350–370.

Tommelein, I. D. (2006). "Process Benefits From Use of Standard Products – Simulation Experiments Using the Pipe Spool Model." *14th Annual Conference of the International Group for Lean Construction*, Santiago, Chile, 177–188.

Tommelein, I. D., Riley, D. R., and Howell, G. A. (1999). "Parade Game: Impact of Work Flow Variability on Trade Performance." *Journal of Construction Engineering and Management*, 125(5), 304–310.

Tsao, C. C. Y. (2005). "Use of Work Structuring to Increase Performance of Project-Based Production Systems." University of California Berkeley, Berkeley.

Tsao, C. C. Y., Tommelein, I. D., Swanlund, E. S., and Howell, G. A. (2004). "Work Structuring to Achieve Integrated Product–Process Design." *Journal of Construction Engineering and Management*, 130(6), 780–789.

Tuholski, S. J., and Tommelein, I. D. (2008). "Design Structure Matrix (DSM) Implementation on a Seismic Retrofit." *16th Annual Conference of the International Group for Lean Construction*, P. Tzortzopoulos and M. Kagioglou, eds., Manchester, UK, 471–484.

Ulrich, K. (1995). "The role of product architecture in the manufacturing firm." *Research Policy*, 24(3), 419–440.

Veenstra, V. S., Halman, J. I. M., and Voordijk, J. T. (2006). "A methodology for developing product platforms in the specific setting of the housebuilding industry." *Research in Engineering Design*, 17(3), 157–173.

Vrijhoef, R., and Koskela, L. (2000a). "The four roles of supply chain management in construction." *European Journal of Purchasing & Supply Management*, 6(3–4), 169–178.

Vrijhoef, R., and Koskela, L. (2000b). "The four roles of supply chain management in construction." *European Journal of Purchasing & Supply Management*, 6(3–4), 169–178.

Yang, B., and Burns, N. (2003). "Implications of postponement for the supply chain." *International Journal of Production Research*, 41(9), 2075–2090.

Yang, B., Burns, N. D., and Backhouse, C. J. (2004). "Postponement: a review and an integrated framework." *International Journal of Operations & Production Management*, 24(5), 468–487.

Zinn, W., and Bowersox, D. J. (1998). "Planning Physical Distribution with the Principle of Postponement." *Journal of Business Logistics*, 9(2), 117–136.

Lappalainen, E., Uusitalo, P., Seppänen, O., and Peltokorpi, A. (2021). "Design process stability – observations of batch size, throughput time and reliability in design." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 605–612, doi.org/10.24928/2021/0144, online at iglc.net.

DESIGN PROCESS STABILITY: OBSERVATIONS OF BATCH SIZE, THROUGHPUT TIME AND RELIABILITY IN DESIGN

Eelon Lappalainen[1], Petteri Uusitalo[2], Olli Seppänen[3], and Antti Peltokorpi[4]

ABSTRACT

Despite recent developments in construction design management, too much variability still occurs in design processes. Batch size (BS) and throughput time (TT) reduction are recurring concepts in the lean construction literature related to the Last Planner© System (LPS). These three parameters are often used to reduce variability and improve flow and reliability in work processes. Some have attempted to reduce design variability through lean design management (LDM) and agile methods, but very few studies have analysed the interaction of these parameters in the design process. The purpose of this study is to investigate these variables and their interactions. Design process stability and reliability were measured over nearly two years in this study by using three parameters. According to the results, design teams with smaller BS's of design tasks and higher percentages of planned tasks completed also had shorter design task TT's. Designers may use these findings to improve their workflow monitoring and as a novel addition to LDM and coordination metrics.

KEYWORDS

Lean construction, Last Planner® System, agile, design.

INTRODUCTION

Because poor management and design process inefficiency often lead to construction project delays and cost overruns, design process management is a key factor in successful project delivery (Tilley, P. 2005a). Low reliability levels and high levels of variability in TT's cause problems for design stability and negatively affect the construction process (Khan and Tzortzopoulos 2014). Design could be said to be a bottleneck in the construction process (Tribelsky & Sacks 2011). Bottlenecked processes with low reliability levels and high variability in delivery times inevitably mean that contractors must prepare contingency plans and demand earlier delivery times from designers. Such

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situations then reduce the time reserved for design work and ultimately lead to a vicious cycle in which even earlier design delivery and larger BS's in designs are required (Ballard & Howell 1995). These scheduling buffers between stakeholders can protect contractors from the effects of delay but are often costly due to the extended construction times involved (Kenley & Seppänen 2010).

A growing body of literature recognises the need to improve the flow of design processes (Ballard 2001; Sacks & Goldin 2007; Hamzeh et al. 2009; Uusitalo et al. 2017). Many scholars have provided concepts for adapting agile methods, from software development to the design phase of construction projects (Koskela & Howell 2002; Owen et al. 2006). Some engineering companies have implemented these methods as part of their processes (Streule et al. 2016; Føreland & Halvorsen 2018; Uusitalo et al. 2017). The focus of several lean design methods and tools is to improve information flow among the design team, with the hope of lower design process variability (Uusitalo et al. 2019; Tribelsky & Sacks 2011).

Although production is often controlled by adjusting BS and measuring the TT of process phases and process reliability (Hopp & Spearman 2011), the concepts of BS, lead time and design process stability and reliability are typically limited in traditional construction design and design management. Instead, designers focus on implementing traditional project management methods, optimising sub-processes and cutting costs (Tilley 2005b). According to lean principles, process flow is a prerequisite for value creation (Bertelsen & Koskela 2004) and the utilisation of indicators that will affect process flow and stability in design control and management. The goal is to achieve a more reliable design process.

Previous studies (Alarcón et al. 2008; Baladrón & Alarcón 2017) have examined the relationship between process stability and PPC. The authors observed a relationship between high PPC and the stability of construction and mining processes. As PPC increased, the process was noted to stabilise accordingly. In these studies, the coefficient of variation (CV) was used as a measure of process stability, calculated by dividing the standard deviation (SD) by the mean. Hopp and Spearman (2011) divided process variability into three categories: (1) low variability ($CV < 0.75$; process times without outages), (2) moderate variability ($0.75 < CV < 1.33$; process times with short adjustments) and (3) high variability ($CV > 1.33$; process times with long outages). Alarcón et al. (2008) showed that with the increase of PPC, the production process was stabilised by up to 30–40% as measured by CV.

Clearly, the pre-production process (i.e. design) must also be stable and predictable. Although several design-related studies of PPC have been published, very few are related to BS and TT in design. Similarly, very few studies have measured the stability of the design process using CV. The purpose of this empirical study was to examine connections between BS, TT and PPC in design process by using a single case study consisting of seven construction sites in Finland.

RESEARCH DATA AND METHODS

The research data used in this paper was gathered from a single case study consisting of seven construction sites. The sites are located in Finland and pertain to a client-driven subway project consisting of five stations, one depot and a railway line connecting them, with its own design teams consisting of different design disciplines. Six of the construction sites used agile methods and the Last Planner® System (LPS) among the structural design teams, while the one remaining site was managed with traditional methods, and thus research data was not available for that site. The agile method known as “Scrum” was introduced for the first time in this project and involved 156 structural engineers from several structural engineering companies that operate in the Nordic countries. The structural engineers worked on the project as teams of 15 to 25 people. After a short orientation period, the structural engineering work was broken down to a workable backlog of design tasks, for which task-specific responsible persons were appointed. These tasks were pulled from the backlog into the two-week design periods called “sprints.” The progress of the work was monitored over a two-year period using Jira software, where design tasks were managed based on Scrum principles. The software provided a chart of work progress as well as progress projections of the design work. After the orientation phase, which was done in physical space, latter bi-weekly meetings were held in virtual space, with teleconference tools. Structural designers worked with other disciplines, such as architects and MEP designers, in coordination meetings.

All sites had their own design managers (DM), but structural design was centrally coordinated by one DM, who was responsible for structural design coordination, created biweekly status reports of the design progress. These reports included design progress, projections and possible problems or resource shortfalls that could lead to the client’s control actions, if necessary. The information also provided data on the development of TT and PPC for design tasks, which were addressed in retrospectives with design teams. For this study, the data we collected was exported to Microsoft Excel and statistical analysis program Minitab 19.0, which we used to sort and analyse the data with functions as well as to generate tables and graphs.

The main data used in this study contains the designers’ workload estimates for design tasks, PPC values (measured biweekly during the design phase) and measured TT’s for design tasks. Workload estimate data was stored during the project on the task cards included in the programme. The programme calculations were based on workload estimates, such as forecasts for the completion of the remaining work. For the purpose of this study, these task-specific workload estimates were then exported from the software to an Excel spreadsheet. PPC values were calculated using sprint reports generated by the programme by calculating completed and non-completed tasks during the sprint and dividing their ratio by the PPC percentage. TT’s were calculated to the accuracy of one sprint (i.e. whether the design task was completed during one or more two-week sprints). This data was then transferred to an Excel spreadsheet, in chronological order. Workload estimates were measured in hours per task, PPC values were measured as percentages and design task TT’s were measured as two-week work periods (sprints nr 1, nr 2, nr 3, etc.). Minitab was utilised to perform an analysis of variance (ANOVA) for TT’s, using one-way ANOVA as the statistical method.

RESULTS

The results are presented in three sections according to the collected data: observations of (1) BS, (2) TT and (3) PPC values. We will first focus on the BS results. The data analysis showed that the use of the agile method, with a sprint length of two weeks and a maximum workload estimate of one week, guided the division of design tasks towards the desired BS, which in this context was a maximum of one work week (40 hours). Figure 1 shows the average BS’s of the design tasks for the two-year follow-up period; the upper limit of the target BS is shown. As the figure makes apparent, only one site exceeded the target-specific maximum number of hours per task in the first year; in the second year, all sites fell below the target, and half the sites remained at less than 20 hours per planning task.

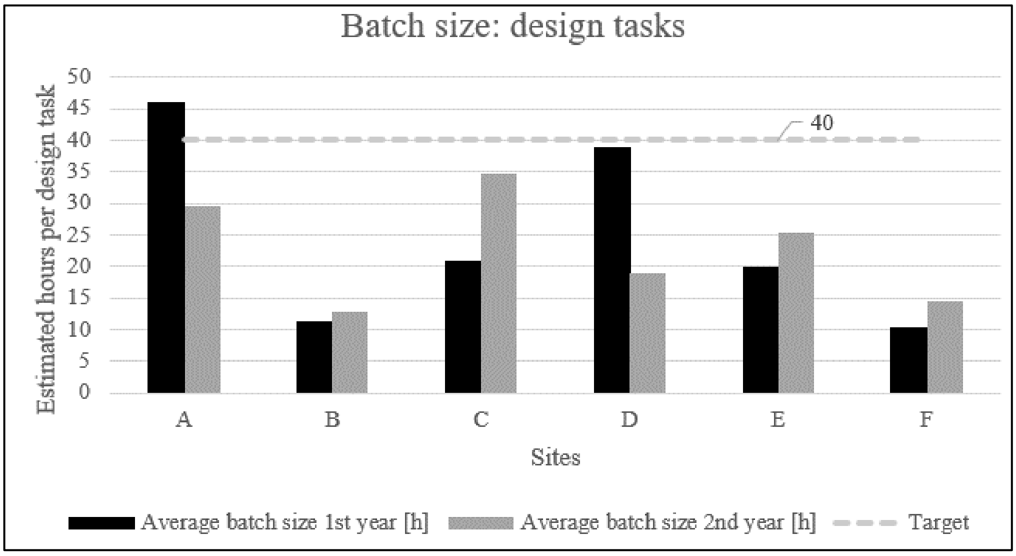

Figure 1: Estimated BS's of design tasks

Because the results are workload estimates, we also examined the relationship between the estimated working hours and the actual, invoiced working hours during the monitoring period. The estimated workload estimates of the design tasks varied from 1.5 to 3 times higher during the measurement period, meaning the working hour estimates in relation to the actual hours were overestimated. In discussions with designers, some of them noted experiencing challenges in providing workload estimates; the results suggest that task-specific workloads include significant capacity buffers.

Another part of the results included observations of TT's. As Figure 2 shows, sites E and F clearly differed from the other sites by having faster task TT's. Sites C and D had the longest TT's while sites A and B and were located between the two groups.

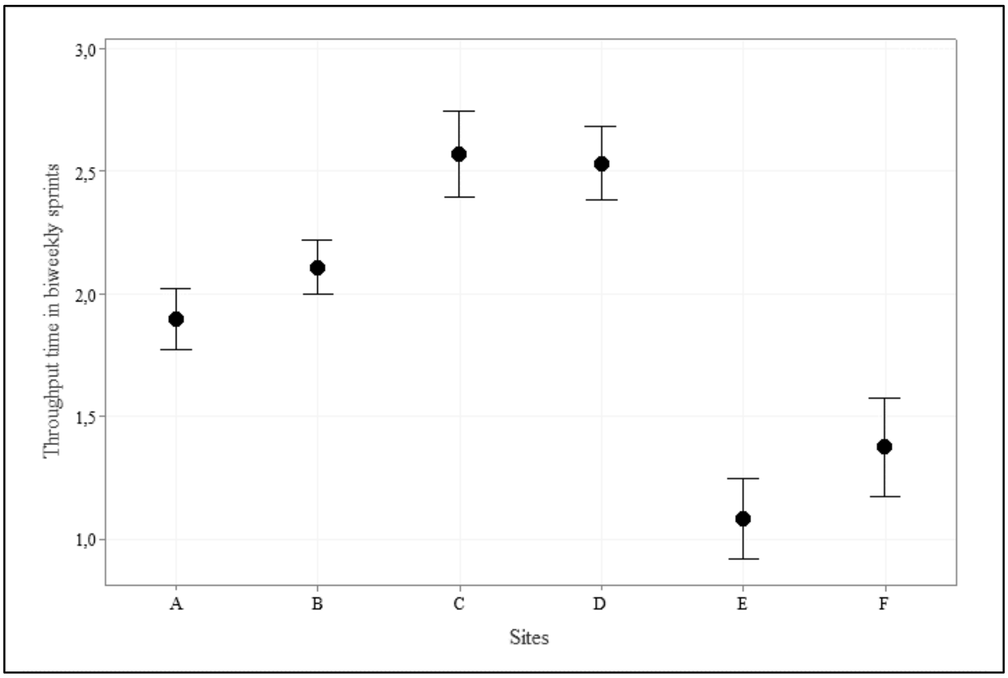

Figure 2: Analysis of variance, interval plot of TT in years 1 and 2.

For the TT, we noted a statistically significant difference in the results of sites E and F (group 1), sites A and B (group 2) and sites C and D (group 3). This difference also appeared in an interesting way in the analysis of PPC values, as discussed below.

Table 1 is grouped into three segments: (1) plan reliability, which is described by data related to PPC values; (2) BS; and (3) the stability of the design process, which is described by the CV value of the design process. As shown in Table 1, all sites improved PPC levels during the follow-up period, but for PPC variability, only half the sites saw reduced PPC variability during the follow-up period. For BS, only two sites saw BS reduction during the follow-up period. Four sites managed to improve their CV during the follow-up period.

Table 1: Summary table of key metrics. PPC = planned percentage completed, SD = standard deviation, CV = coefficient of variance, LV = low variability, MV = moderate variability and HV = high variability

	Reliability				BS's in design tasks				Stability of design process	
Site	PPC ave. of 1st year	PPC ave. of 2nd year	SD of PPC 1st year	SD of PPC 2nd year	Ave. BS 1st year [h]	Ave. BS 2nd year [h]	SD in BS 1st year	SD in BS 2nd year	CV 1st year	CV 2nd year
A	38.2	56.1	37.2	23.3	45.9	29.4	88.8	46.2	1.93 (HV)	1.57 (HV)
B	26.5	58.9	26.2	24.6	11.2	12.9	12.4	8.2	1.11 (MV)	0.64 (LV)
C	13.3	52.2	14.8	22.3	20.8	34.6	13.8	32.4	0.66 (LV)	0.94 (MV)
D	24.0	51.9	26.4	24.1	38.8	19.0	59.7	26.8	1.54 (MV)	1.41 (HV)
E	37.7	71.2	36.1	14.2	19.7	25.4	13.4	27.2	0.68 (LV)	1.07 (MV)
F	35.3	71.3	32.4	19.0	10.3	14.4	94.8	11.7	9.20 (HV)	0.81 (MV)

All sites met their BS targets during the second year, and three sites halved their BS targets. CV also fell, except at two sites (C and E), although CV was at a moderate level in these two sites. In site F, the high HV was due to difficulties in using the new method at the beginning of the first monitoring year and the use of very low task-specific workload estimates, which led to a large variance from the workload forecasts for the rest of the year. This data has not been removed or modified, however, because it contributes to an understanding of the challenges of implementing agile methods in design.

In summary, these results show that sites E and F differed from other sites with higher PPC numbers and clearly different faster TT's. Correspondingly, sites C and D, where PPC was lowest, also had the highest TT's. In workload estimates (i.e. BS), differences between the sites were not so clear. Sites B and F were clearly lower than the other sites in both years, while for C and E BS increased in the second year. Sites A and D managed to improve BS in their second year. However, sites E and F were evidently in low level in BS and TT as well in high level in PPC.

DISCUSSION

In this study, we set out to assess the importance of design process stability and reliability by comparing three key parameters: (1) BS, (2) TT and (3) PPC level. A comparison of the findings with those of previous studies confirmed the positive effect of PPC on process stability in design processes (Alarcón et al. 2008; Baladrón & Alarcón 2017). These results also corroborate the findings of previous work by El-Samad et al. (2017), who suggested that new metrics should be developed for LPS. However, research on these metrics has been limited so far because teams often do not adequately document their results, making the results unverifiable. Fortunately, in this study, the design teams documentation was comprehensive due to the agile task management system (TMS) they used, which allowed data to be analysed with different metrics. The results are also consistent with those of Tribelsky and Sacks (2011), who showed how BS's, bottlenecks and other obstacles of flow in the design process can be measured from a project's data management system (DMS). Based on our results and those of previous studies, we encourage further research to focus on combining data from LPS, DMS and task management tools such as Jira and to use the data to create a holistic view of the stability of the design process.

Despite the small number of sites we examined for this study, the findings are encouraging. Connections could indeed exist between BS, TT and PPC level. Despite these findings relate to each other, PPC levels were low in these sites, and these results therefore must be interpreted with caution. One factor that may have contributed to the low PPC values was the lack of daily management. For comparison, Streule et al. (2016) presented how the performance of the design team examined in their study improved within 27 days through day-to-day management. We have noted similar preliminary findings in our current research, in which daily management quickly and permanently raises PPC levels in design.

The amount of work in progress (WIP) was not limited during the design work in the case study. The impact of this situation was especially evident during the first year, when the designers became accustomed to using the Scrum method. The lack of WIP limits may also have limited the increase of PPC to a higher level than was currently the case. We will continue to explore this relationship as the study progresses.

Discussions with the designers revealed that despite the challenges they reported in evaluating workload estimates, the task-specific workload forecasts were significantly buffered. We checked this claim by comparing the ratio of workload forecasts to actual invoiced hours worked. Researchers have made similar observations on the production side (e.g. Kala et al. 2012), and design and production actors seem to have similar ways of building a safety buffer for their planned tasks. This finding raises the question of whether bottlenecks in design tasks could be identified by combining DMS data and TMS data (Tribelsky & Sacks 2011). According to the general concept of bottlenecks, a buffer accumulates in front of the process bottleneck (Goldratt, 1990). For future research, we propose to identify tasks or task groups where the planned and actual workloads differ significantly as the design progresses and to focus on broadening factors of these bottlenecks, for example through root cause analysis.

In design, as in other processes, the different steps of the process follow each other, partly iteratively. Uusitalo et al. (2019) have presented the significance of BS and the related results, for example regarding the inspection of design documents, which is the end point of the design process. Our observation of decreased BS's in relation to increased design reliability and reduced throughput raises intriguing questions for the developers of design management processes. When interpreting the results, readers should keep in mind that the relationships we observed do not explain how the factors interact with each other, and we cannot say with certainty whether, for example, a small BS leads to a short TT and thus higher PPC. Or compliance to planned TT leads more likely to a higher PPC. Evidence of a causal relationship will require future research using different methods.

CONCLUSIONS

This paper contributes to previous research by presenting the interrelations between design process stability and reliability through a case study and by using three parameters, BS, TT and PPC.. Based on this study's results, this interrelation seems to exist in design work. This observation opens several new questions for future research. For example, regarding BS, the key question is to discover the optimal BS for different design phases and disciplines. Similarly, further research is needed on different types of projects: for example, whether the connection we found in this case study would be similar, regardless of the design target. By combining PPC, task TT's and BS tracking of design tasks, researchers can potentially create new perspectives on more reliable and stabile design processes. Perhaps the most topical question for further research is how a production method based on small BS, such as takt production, affects design BS's and TT's. Unfortunately, our study did not include other design disciplines or other design phases, where interrelations may not be similar, which would require more research data. The findings of this study have raised a number of practical implications in construction design management. First, this study's findings suggest that, in addition to PPC monitoring alone, taking advantage of the TT's and BS measurements provided by task management tools to monitor the design process can provide a new perspective on the design process and the flow of design work. Second, this study demonstrates how differences between design teams can be measured by relatively simple methods and with existing digital tools and how digitally collected information can be used to solve the problem of design inefficiency.

REFERENCES

Alarcón, L.F., Diethelm, S., Rojo, O. and Calderón, R. (2008). "Assessing the Impacts of Implementing Lean Construction." *Revista Ingeniería de Construcción*, 23(1), 26-33.

Baladrón, C. and Alarcón, L.F. (2017). "Assessing the Impact of Lean Methods in Mining Development Projects." In *Proc., 25th Ann. Conf. IGLC* (pp. 137-144). Budapest, Hungary: IGLC.

Ballard, G. (2001, August). "Cycle Time Reduction in Home Building." In *Proc., 9th Ann. Conf. IGLC* (pp. 06-08). Singapore: IGLC.

Ballard, G., & Howell, G. (1995). Toward construction JIT. Lean construction, 291, 300.

Bertelsen, S. and Koskela, L. (2004, August). "Construction beyond Lean: A New Understanding of Construction Management." In *Proc., 12th Ann. Conf. IGLC* (pp. 02-05). Helsingor, Denmark: IGLC.

El-Samad, G., Hamzeh, F. and Emdanat, S. (2017, July). "Last Planner System: The Need for New Metrics." In *Proc., 25th Ann. Conf. IGLC* (pp. 637-644). Budapest, Hungary: IGLC.

Føreland, J.A. and Halvorsen, A.B. (2018). *Managing Change When Implementing a New Project Management Methodology: A Constructive Approach to Change Management*. Master's Thesis, University of Agder.

Goldratt, E.M. (1990). *Theory of Constraints* (pp. 1-159). North River, Croton-on-Hudson, N.Y.

Hamzeh, F.R., Ballard, G. and Tommelein, I.D. (2009, July). “Is the Last Planner System Applicable to Design? A Case Study.” In *Proc., 17th Ann. Conf. IGLC* (vol. 17, pp. 13-19). IGLC: Taipei, Taiwan.

Hopp, W.J. and Spearman, M.L. (2011). *Factory Physics*. Waveland Press, Long Grove, IL (pp. 268-271).

Kala, T., Mouflard, C., & Seppänen, O. (2012, December). Production control using location-based management system on a hospital construction project. In 20th Annual Conference of the International Group for Lean Construction, San Diego, California, USA (p. 039).

Kenley, R. & Seppänen, O. (2010). Location-Based Management for Construction. CRC Press. Kindle Edition. p. 4764.

Khan, S., & Tzortzopoulos, P. (2014, June). Effects of the interactions between LPS and BIM on workflow in two building design projects. In 22nd Annual Conference of the International Group for Lean Construction. Oslo, Norway, 25-27 Jun 2014. (Vol. 2, pp. 933-944). IGLC and Akademika forlag.

Koskela, L. and Howell, G. (2002, August). “The Theory of Project Management: Explanation to Novel Methods.” In *Proc., 10th Ann. Conf. IGLC.* (vol. 10, no. 1, pp. 1-11). Gramado, Brazil: IGLC.

Owen, R., Koskela, L., Henrich, G. and Codinhoto, R. (2006). “Is Agile Project Management Applicable to Construction?” *Proc., 14th Ann. Conf. IGLC.* Santiago, Chile: IGLC.

Sacks, R. and Goldin, M. (2007). “Lean Management Model for Construction of High-Rise Apartment Buildings.” *J. Const. Eng. Man.*, 133(5), 374-384.

Streule, T., Miserini, N., Bartlomé, O., Klippel, M. and De Soto, B.G. (2016). “Implementation of Scrum in the Construction Industry.” *Proc. Eng.*, 164, 269-276.

Tilley, P. A. (2005a March). Design and Documentation Quality Problems—A Lean Thinking Opportunity. *In Proceedings of the International SCRI Symposium*, Salford, UK (pp. 12-13).

Tilley, P.A. (2005b July). “Lean Design Management: A New Paradigm for Managing the Design and Documentation Process to Improve Quality?” *Proc., 13th Ann. Conf. IGLC* (p. 283). Sydney, Australia: IGLC.

Tribelsky, E. and Sacks, R. (2011). “An Empirical Study of Information Flows in Multidisciplinary Civil Engineering Design Teams Using Lean Measures.” *Arch. Eng. Des. Man.*, 7(2), 85-101.

Uusitalo, P., Olivieri, H., Seppänen, O., Pikas, E. and Peltokorpi, A. (2017, July). “Review of Lean Design Management: Processes, Methods and Technologies.” In *Proc., 25th Ann. Conf. IGLC* (pp. 571-578). Heraklion, Greece: IGLC.

Uusitalo, P., Seppänen, O., Lappalainen, E., Peltokorpi, A. and Olivieri, H. (2019). “Applying Level of Detail in a BIM-Based Project: An Overall Process for Lean Design Management.” *Buildings*, 9(5), 109.

Ransolin et al. (2021). "The built environment´s influence on resilience of healthcare services: lessons learnt from the COVID-19 pandemic." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 613–622, doi.org/10.24928/2021/0172, online at iglc.net.

THE BUILT ENVIRONMENT´S INFLUENCE ON RESILIENCE OF HEALTHCARE SERVICES: LESSONS LEARNT FROM THE COVID-19 PANDEMIC

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ABSTRACT

The COVID-19 pandemic has posed unprecedented challenges for healthcare services, which have been forced to upscale their capacity to cope with successive surges in demand. The adjustments to match capacity to demand and deal with a new disease have involved creativity and solutions that were not part of the pre-pandemic standardized operating procedures. Those changes are considered manifestations of resilience. This paper focuses on the role played by the built environment of healthcare services during the pandemic, in terms of how it is integral to resilient performance. As such, we investigated the experience of a leading private hospital in Brazil, documenting the main changes related to the built environment and how they influenced resilience. Data collection involved eight interviews with hospital staff. A content analysis allowed the development of a generic functional model of the patient journey and the identification of ten resilience practices. Based on this, six lessons learnt were devised. These lessons are expected to be useful for the design and use of the built environment, supporting the resilience of services.

KEYWORDS

Healthcare services, complexity, resilience, COVID-19, built environment.

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INTRODUCTION

The COVID-19 pandemic has posed unprecedented challenges for healthcare services, such as coping with a very high and volatile demand in face of scarce human and material resources. The built environment plays a key role in this context as a much larger number of patients, staff, and supplies needs to be accommodated in the existing facilities, although expansions and construction of temporary facilities have also been common. A few studies have discussed the role of the built environment of healthcare facilities during the pandemic, although not based on primary data (Capolongo et al., 2020; Keenan, 2020). Furthermore, little empirical evidence has been gathered and analysed based on explicit theoretical frameworks.

This paper uses the lens of resilience engineering (RE), which is concerned with the development of "theories, methods, and tools to deliberately manage the adaptive ability of organizations in order to function effectively and safely" (Hollnagel, 2017). In light of RE, resilient healthcare is the "ability of the healthcare system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required performance under both expected and unexpected conditions" (Hollnagel et al., 2013, p. xxv). RE is a useful perspective as the pandemic has forced healthcare services to build adaptive capacity on the fly, which includes adapting the built environment. The literature linking resilient healthcare and the built environment is scarce, mostly focused on how healthcare facilities and services cope with demand from acute natural disasters such as floods, earthquakes, and short-lived demand spikes (Bosher et al., 2007; Achour and Price, 2010).In addition to these studies, Ransolin et al. (2020b) investigated the implications of the built environment for the resilience of healthcare services during everyday work, in the context of intensive care units (ICUs).

Thus, there is a need for studies on resilience and built environment in the context of chronic and prolonged disasters such as the COVID-19 pandemic. The far reaching impacts of the pandemic across several hospital units and infrastructures (e.g., wards, emergency services, intensive care units, utilities, etc.) have made it clear that the scope of earlier studies on the built environment and resilient healthcare was limited. This gap is explored in this paper through a case study of how a leading private hospital in Brazil has adapted its facilities to cope with the pandemic through the viewpoint of key informants. Lessons learnt from this case study are expected to be useful to other hospitals facing a similar challenge as well as for the design of future facilities. This investigation is relevant to the lean construction community at least for two reasons: (i)design management, which is a traditional lean construction topic, can benefit from the lessons learnt from the pandemic and put more emphasis on the development of theories and practices for the design of more resilient healthcare services; and (ii) the collapse of healthcare services, which has occurred in many places, implies wastes to society at large, including the construction industry – e.g., absenteeism, closures of construction sites.

HEALTHCARE SERVICES AS COMPLEX SOCIO-TECHNICAL SYSTEMS

Complex Socio-technical Systems (CSSs) have properties such as uncertainty, technical, social and organizational diversity, as well as a large number of elements in dynamic interactions (Cilliers, 1998). These elements involve several stakeholders, technologies, and regulations working collaboratively towards common goals (Hollnagel et al., 2013). Regarding the built environment, healthcare facilities encompass technical aspects such as layout of workspaces, equipment, furniture, and utilities that are constantly changing as a result of their interactions with the environment (Ransolin et al., 2020a).

Due to complexity, there is a gap between what people actually do (Work-as-Done - WAD) and what they should do according to policies and standard operating procedures (Work-as-Imagined - WAI) (Hollnagel, 2012). The gap between WAI and WAD is also a relevant analytical approach to the built environment, which in practice differs from what is prescribed in regulations and building design. Ransolin et al., (2020a) refer to this as the gap between Built environment-as-Done (BEAD) and Built environment-as-Imagined (BEAI).

BEAD stems from the resilient performance (e.g., changes in layout, furniture, etc.) of the users of the built environment, either in order to fill out gaps in design or to cope with the variability of everyday work (Ransolin et al., 2020a). Resilient performance is characterized by four interrelated abilities, namely Respond (know what to do), Monitor (know what to look for), Learn (from positive and negative events), and Anticipate (know what to expect) (Hollnagel, 2017). The Functional Resonance Analysis Method (FRAM) is an effective approach to model the interactions between the functions that make up healthcare services, whether or not these functions are directly associated with the four resilience abilities (Clay-Williams et al., 2015). In FRAM, a function corresponds to the activities required to produce a certain outcome. FRAM also allows for the identification of variabilities in individual functions and the understanding of how they propagate across the whole system, producing non-linear effects (Hollnagel, 2012). For these reasons, FRAM is aligned with the nature of healthcare services and has been used for studying that context (Clay-Williams et al., 2015; Ransolin et al., 2020a/b).

RESEARCH METHOD

DESCRIPTION OF THE STUDIED HEALTHCARE FACILITIES

The hospital investigated is located in Southern Brazil and was chosen based on convenience, as one of the authors works as the infrastructure manager. It is a private institution known as a reference centre for high-complexity and critical cases, which took a leading role in coping with COVID-19 (Polanczyk et al, 2020). The hospital counts on nearly 3,390 physicians and 2,980 allied health professionals. There are also about 1,020 administrative employees. The main building dates from 1921 and has been expanded and renewed multiple times. Nowadays, the facilities spread over 97,912m² of built area. There are adult and paediatric emergency departments, two surgical centres, a maternity unit, five adult ICUs (55 beds), a paediatric ICU (10 beds), a neonatal ICU (28 beds), and 15 patient wards (379 inpatient beds).

DATA COLLECTION AND ANALYSIS

Case study (Yin, 2014) was the research strategy adopted. This choice was due to the exploratory nature of this study, which was interested in investigating new phenomena in a real-world context. Data collection was based on eight semi-structured interviews and a walkthrough (1 hospital visit) in the main patient flows. The study was approved by the hospital's ethics committee. Interviews occurred in December 2020, a period in-between pandemic waves of COVID infections in Southern Brazil. The interviewees were: (i) six nurses, of which two had managerial positions and the other four were at the front-line of patient care; (ii) one doctor with a managerial position; and (ii) one infrastructure manager. The interview script encompassed questions related to the functions performed by the interviewee and the changes in the built environment and services as a result of the pandemic. Each interview lasted on average 1 hour and they were audio-recorded and then fully transcribed.

Content analysis (White & Marsh, 2006) was used for data extraction from interviews. There were two main data analysis themes defined upfront. The first theme referred to the necessary information for the development of a FRAM model (i.e., functions and their description) that encompassed both the care of COVID and non-COVID patients. Daily activities described by the interviewees were interpreted as their WAD and considered as FRAM functions, which are described according to six aspects as follows: input (I), output (O), resources (R), preconditions (P), control (C), and time (T) (Hollnagel, 2012). Functions are coupled to each other when the output of an upstream function provides one or more of the other aspects to a downstream function. A general FRAM function referred to as <Cope with the pandemic> was created in order to encompass the decisions undertaken by the hospital management in charge of the major decisions related to the pandemic. This function encapsulates the organization resilient performance during the pandemic, and its outputs were linked to the other functions through their precondition aspects. According to Hollnagel (2012), a precondition in FRAM corresponds to conditions that must be ready for a function to start.

The second theme referred to the resilience practices to cope with the pandemic. These practices were modelled as the output of <Cope with the pandemic>. Two of the authors independently read the transcripts of the interviews and coded them according to the two aforementioned themes. Then, they met to compare their codifications and reached an agreement on the findings. A third author also thoroughly reviewed these codifications and some additional adjustments were made.

The lessons learnt from the pandemic from a built environment perspective were devised based on the FRAM model. These lessons were mostly implicit in the resilience practices that were outputs of <Cope with the pandemic> and they were also related to the four abilities of resilient systems. The lessons learnt were stated in a manner that they could be of interest to other healthcare organizations and not only to the specific studied hospital.

RESULTS

FRAM MODEL

The FRAM model is presented in Figure 1. It has 23 functions and encompasses the flow of both COVID and non-COVID patients.

The couplings between the functions, except for <cope with the pandemic>, are not shown in order not to clutter the visual representation of the model. The outputs of this function are described in the next section.

Twelve functions are applicable to both types of patients, even though they are carried out by different people, while not necessarily in different areas. For this reason these functions are represented twice at the model. They are: <Seek for Emergency Care>; <Admission, dressing, and snack rooms>; <Triage>; <Wait for Medical Consultation>; <Medical Evaluation>; <Tomography Exams>; <Provide Emergency Care>; <Transport Patients>; <Carry out surgery>; <Provide Ward Care>; <Provide ICU Care>; and <Patient Discharge>. The physical space where each function is carried out is represented in Figure 1 by the coloured rectangles on the background. In fact, two functions, namely<Transport Patients> and <Wait for Medical Consultation> occur in shared spaces such as certain corridors, elevators, and rooms in the emergency department. Some functions were new and specifically created to face the pandemic. These functions are: <donning and doffing PPE>; <lab tests>; <provide COVID-19 care – emergency>; <collect samples for exams (COVID-19)>; <provide COVID-19 care – ICU>; <Provide COVID-19 care ward>.

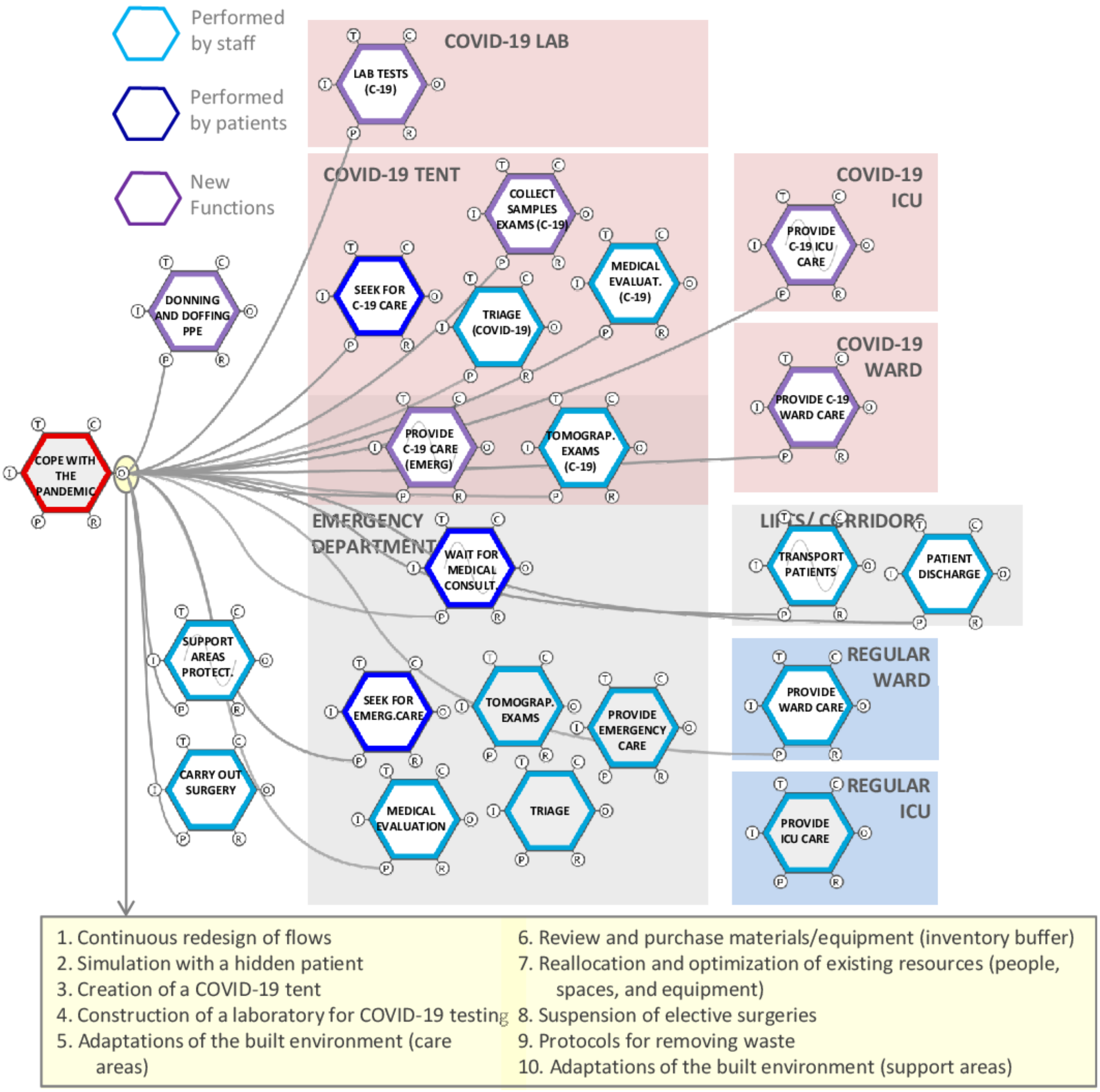

Figure 1 - FRAM model highlighting the outputs of the function <Cope with the pandemic> performed by the COVID-19 Committee.

The sequencing of the functions varies according to the circumstances. For instance, depending on the patient's condition, they may need to undertake a tomography exam, a surgery, and then be transferred to the ICU. Others will be discharged after receiving treatment at the emergency department. Thus, the journey of both COVID and non-COVID patients can involve, broadly speaking, a mix of emergency, ward, and ICU care. Furthermore, patients can change from COVID to non-COVID (and vice versa) after being hospitalized.

RESILIENCE PRACTICES TO COPE WITH THE PANDEMIC

The hospital adopted measures to cope with the pandemic even before the first infected patient was admitted in March 2020. Since then and up to the time of writing this article, a multidisciplinary committee for combating coronavirus, hereafter named COVID-19 committee has been in charge of assessing the threats imposed by the pandemic and developing plans for the provision of the necessary resources (e.g., staff, materials, and space). It is a multidisciplinary team composed mainly of hospital units´ managers (e.g., emergency, ward, ICU, infection control service, risk management). This team meets on a daily basis. The committee and the hospital have a strong culture of involving professionals before making important decisions. Thus, whenever needed, they consult workers from care units (e.g., nurses and physicians) and administrative positions, such as infrastructure managers.

One of the regular activities of this committee has been the continuous redesign of flows **(output 1)** of patients and resources. Indeed, since March 2020 the staff was aware of the need for the design of dedicated clinical (e.g. triage) and non-clinical (e.g., waste disposal) pathways to COVID-19. An important event that took place at the hospital two months before the first case of a COVID-19 patient in Brazil was the simulation with a hidden patient **(output 2)** hypothetically infected with the new coronavirus. In fact, this activity was mandatory as the hospital is accredited by the Joint Commission International (JCI) and, for that reason, it is required to carry out an annual verification of preparedness for emerging global diseases. A managerial team was formed to draw the simulation flow. The hidden patient started their journey at the emergency department in which staff members were supposed to identify whether or not the patient was infected with COVID-19. Thus, on each step passed by the patient, the managerial team gave feedback to frontline healthcare workers on how to properly respond. All interviewees agreed that this simulation allowed for the identification of vulnerabilities and opportunities to adjust hospital flows. Another action taken by the COVID-19 committee was the creation of a COVID-19 tent **(output 3)** outside of the main hospital building and nearby the entrance to the emergency department in order to triage suspected cases. Furthermore, the managerial team realized that the outsourced laboratory was not providing timely results of COVID-19 tests (function <Lab Tests> **(output 4)**. Then, resources were set up for the construction of the hospital's own COVID-19 test laboratory in order to reduce the processing lead time of tests from 4 days to no more than 24 hours (Polanczyk et al., 2020).

A crucial resource available to respond to COVID-19 patient flows was the area previously occupied by the paediatric emergency department, which had recently moved to another building inside the same hospital site. This change occurred before the onset of the pandemic and luckily allowed for the just-on-time expansion of the existing adult emergency department **(output 1)**. As part of these changes, an exam room dedicated to the testing of COVID-19 suspected patients was set up within the emergency department **(output 5)**. However, some of the spaces could not be totally separated between COVID and non-COVID patients, which was the case of the room where the function <Wait for Medical Consultation> occurred. This situation posed variability as non-infected patients could be infected while waiting for the consultation; there was only a curtain separating beds.

Although the separation of COVID and non-COVID patient flows was imagined in design, it was challenging to be maintained that way all the time. A core function that addressed breaches in that design was <Donning and Doffing PPE>, which should be carried out by all employees immediately after entering and leaving the hospital building. Safeguards for coping with the impossibility of fully separate flows were also adopted for the function <Transport patient> when it occurred in the elevator. The initial plan was to designate a dedicated elevator for COVID-19 patients, but as they would move across public areas of the hospital and as flows were constantly changing, the decision was made to allow the circulation in the same elevators, although not at the same time. Elevators were frequently cleaned and people inside were wearing personal protective equipment (PPE).

Regarding the function <Provide COVID-19 ICU Care> **(output 5),** the committee firstly decided to transfer the Bone Marrow Transplant (BMT) Unit to another location in order to use that space to create 22 ICU beds to COVID-19 patients. This area was selected due to its physical attributes, such as the high quality of the Heating, Ventilation, and Air Conditioning (HVAC) system. However, the airflow required for the treatment of patients subject to BMT was the opposite to that required by COVID patients – i.e., the former needs to block airflow from the outside air, while the latter needs to block airflow to the outside air – this latter is referred to as negative air pressure areas. In common, both situations demand equipment to provide air renovation to match their specific needs. Thus, it was easier for the infrastructure team to change the air direction in that area than in other units with no existing similar air renovation facilities. In addition, High-Efficiency Particulate Air (HEPA) filters were installed as a barrier to the coronavirus spread in those units. Initially, the idea was to place COVID-19 patients in isolated rooms with negative air pressure, divided by medical specialty. However, this would imply in maintaining COVID-19 patients dispersed in several units, which would also increase infection opportunities during inter-unit flows. As a result, the committee created a few hubs of infected patients, all of them with the proper HVAC system's adaptation.

The BMT unit occupation was particularly useful during the early stages of the pandemic as it provided a window of time for the committee to plan other changes in the hospital flows and physical areas. Even though that unit played a key role, the lack of visibility among rooms had a negative impact on staff performance. The area was not originally designed to support ICU functions and interviewees reported that the rooms did not have the necessary visibility to allow staff to communicate and work collaboratively. This hindered the abilities of monitoring the processes and anticipating events. Thus, as time passed, that unit was found not appropriate for COVID patients, which were then transferred to other areas.

Since the hospital's physical structure cannot further expand, the management of buffers of materials and equipment as well as the reallocation and optimization of existing resources (people, spaces, and equipment) **(outputs 6 and 7)** have been vital. For instance, the committee decided to suspend the elective surgeries early in the outbreak to increase the availability of beds for COVID-19 patients, readmitting the most acute patients gradually **(output 8)**. Additionally, individual rooms were transformed into shared rooms. Extra equipment and materials have been acquired to the possible extent, especially PPE, medications, and mechanical ventilators. These measures have been stopped and reinstated cyclically as the pandemic evolves in order to free up resources during the most critical periods.

Regarding the protocols for removing waste **(output 9)**, they addressed the activities of the cleaning staff, more specifically when they picked up the bags of dirty clothing, threw them into trolleys and then moved them to the laundry. These activities pose a risk of environmental contamination, as throwing the bags can produce aerosol. The committee established measures to monitor these activities and the cleaning staff is now required to perform a different procedure. They collect the dirty clothes from COVID-19 units at the end of their shift, wearing a specific apron and label the plastic bags to make it clear that it stems from a COVID-19 unit. Some built environment adaptations in the administrative and support areas **(output 10)** were a precondition to the function <Support areas protection>. For example, glasses were installed in all hospital reception desks to protect workers and patients. Other measures involved the separation of the dressing room for COVID and regular staff and changes in the layout of the staff room to ensure social distancing and prevent gatherings.

DISCUSSION

Six main lessons can be learnt from the outputs of the FRAM function <Cope with the pandemic> (Figure 1). The lessons are described according to the design and operation phase of the building. Thus, lessons to the design phase are primarily targeted at the BEAI, while lessons to the operation phase are applicable to the BEAD. The lessons are logically related to the four resilience abilities.

LESSONS TO THE DESIGN PHASE (BEAI)

The lessons learnt for the building design phase are mostly related to the resilience abilities of **anticipating and responding**. Indeed, the life cycle of buildings extends for decades or centuries. Although anticipation is challenging at the long-term, major threats such as pandemics are expected and therefore the building design must support prepared responses. The main lessons learnt are presented below and they resulted from both insights from the literature and difficulties experienced by the studied hospital – i.e., the proposals embedded in the lessons learnt were not fully accounted for in the design phase of the hospital building.

- To design flexible workspaces that can accommodate functions other than the primary functions (Capolongo et al., 2020; Saurin, 2021). For instance, wards are used primarily for the hospitalization of regular in-patients. However, the case study indicated that designers could anticipate the need for attending patients with breathing difficulties that need extra oxygen supply in the ward (output 5). In this case, the built environment should allow for the quick expansion of the HVAC systems, the adjustment of air direction, and the easy flow of the medical gases throughout the building structure (Gordon et al., 2020; Capolongo et al., 2020). These infrastructures need walls on which they can be inserted or attached, which are not easily available in all areas. In other hospitals in Brazil and elsewhere, the lack of walls nearby the beds has implied the need for using oxygen tanks; and
- To design the main hospital entrance, emergency department, and a portion of the intensive care units, preferably on the same floor, in order to shorten the flow of infected patients and therefore reducing the possibility of contagion (Capolongo et al., 2020). For buildings with multiple floors, an alternative solution might be the design of dedicated elevators for patients with highly contagious diseases, which was a measure considered but not implemented in the case study.

LESSONS TO THE OPERATION PHASE (BEAD)

The lessons for the operation phase of the building are mostly related to the resilience abilities of **monitoring** and **responding**. Monitoring might point out gaps between the BEAI and the BEAD, triggering responses to threats unanticipated in the design phase. Four main lessons can be mentioned in this regard. Differently from the lessons related to the design phase, those for the operation phase reflect strategies that were in place at the studied hospital.

- To save financial resources for acquiring scarce supplies in a competitive market as well as to maintain a multi-skilled workforce to cope with demand surges. Purchasing drugs, equipment, construction of new spaces (e.g., laboratory and COVID-19 tent), refurbishment or adaptation of existing facilities (outputs 4, 5, and 6) are costly measures that might be necessary to cope with unexpected events (Achour and Price, 2010; Polanczyk et al., 2020; Capolongo et al., 2020);
- To develop internal capabilities for the best use of available resources, which includes their quick reallocation when necessary (output 7) as well as combining short-term and long-term thinking. In the studied hospital those capabilities were mainly represented by the committee formed in the early stages of the pandemic. An example of reallocation of resources refers to the suspension of elective surgeries (output 8), allowing for the reallocation of beds and staff to other hospital units. Similarly, the telemedicine resources that have been used by family members to virtually interact with ICU patients will be used after the pandemic for the same purpose;
- To use visual management strategies to quickly and publicly announce changes in the built environment, avoiding misunderstandings that may put workers and patients at risk of contamination. This practice, which reinforces the importance of redundant information, was suggested by one of the nurses interviewed who had witnessed a co-worker inadvertently entering a COVID area without being aware of that. To respond to this situation, investments in wayfinding in hospital flows are necessary when changing routes and units functioning (Capolongo et al., 2020); and
- To strengthen a collaborative organizational culture by encouraging multidisciplinary committees in charge of monitoring processes and deploying quick responses to unexpected events (e.g., COVID-19 Committee).

CONCLUSIONS

This paper offers an exploratory report of how the COVID-19 pandemic has demanded resilience from healthcare services, emphasizing built environment implications. Lessons learnt were identified for the design and operation phase of healthcare facilities. These lessons are likely to be of interest not only to the studied hospital but also for others facing similar challenges around the world. The lessons were related to the resilience abilities of anticipating, monitoring, and responding. In fact, it is worth noting that these lessons were compiled by the researchers and therefore we are not certain of the extent to which they have been actually learnt by the studied healthcare organization and will be used in the development of new procedures of care and building designs.

All of the lessons learnt were underpinned by the problem of matching capacity to demand. Therefore, the design of flexible workspaces (e.g., possibility of installing ICU equipment in regular patient wards) stands out as a major theme. Further work will focus on updating the lessons learnt as the pandemic evolves and retrospective in-depth studies after it subsides.

REFERENCES

Achour, N., Price, A.D.F., (2010). "Resilience strategies of healthcare facilities: present and future."*Int. J. Disaster Resilience Built. Environ.* 1 (3), 264–276.

Bosher, L., Carrillo, P., Dainty, A., Glass, J., Price, A., (2007). "Realising a resilient and sustainable built environment: towards a strategic agenda for the United Kingdom."*Disasters* 31 (3), 236–255.

Capolongo, S.; Gola, M.; Brambilla, A.;Morganti, A.; Mosca, E. I.; Barach, P. (2020). "COVID-19 and Healthcare Facilities: a Decalogue of Design Strategies for Resilient Hospitals". *ActaBiomed.*, Vol. 91, Supplement 9: 50-60. doi.org/10.23750/abm.v91i9-s.10117.

Clay-Williams. R.; Hounsgaard, J.; Hollnagel, E. (2015). "Where the rubber meets the road: using FRAM to align work-as-imagined with work-as-done when implementing clinical guidelines."*Implementation Science*, 10(1), 125.

Cilliers, P. I. (1998). *Complexity and postmodernism: understanding complex systems.*, London: Routledge.

Gordon, D.; Ward, J.; Yao, C. J.;Lee, J. (2020). "Built Environment Airborne Infection Control Strategies in Pandemic Alternative Care Sites." *HERD: Health Environments Research & Design Journal*, 1937586720979832.

Hollnagel, E. (2012). FRAM: The Functional Ressonance Analysis Method – modelling complex socio-technical systems. Burlington: Ashgate.

Hollnagel, E., Braithwaite, J., Wears, R., (2013). *Resilient Health Care*. Ashgate, Burlington.

Hollnagel, E. (2017). *Safety-II in practice: developing the resilience potentials*. Routledge.

Keenan, J. M. (2020). "COVID, resilience, and the built environment."*Environment Systems and Decisions*, v. 40, p. 216-221.

Polanczyk, Carisi A. et al.(2020). "Getting Ready for the Covid-19 Pandemic: Experience of a Brazilian Hospital."*NEJM Catalyst Innovations in Care Delivery*, v. 1, n. 5.

Ransolin, N.; Saurin, T. A.; Formoso, C. T. (2020)a. "Integrated modelling of built environment and functional requirements: Implications for resilience." *Applied Ergonomics*, 88, 103154.

Ransolin, N., Saurin, T.A.;Formoso, C.T. (2020)b."Influence of the Built Environment on Patient Safety and Well-being: a Functional Perspective." In: Tommelein, I.D. and Daniel, E. (eds.). *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC28),* Berkeley, California, USA.

Yin, R. (2014). *Case Study Research: Design and Methods* (5 th ed.). Los Angeles, CA: SAGE.

White, M. D., & Marsh, E. E. (2006). *Content analysis: A flexible methodology*. Library trends, 55(1), 22-45.

Nguyen Q. A., Koskela L., Potter D., Tezel A., Pedo B. and Tzortzopoulos P. (2021). "Application of Ji Koutei Kanketsu in highways design process improvement." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 623–633, doi.org/10.24928/2021/0186, online at iglc.net.

APPLICATION OF JI KOUTEI KANKETSU IN HIGHWAYS DESIGN PROCESS IMPROVEMENT

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ABSTRACT

This paper provides an introduction to '*Ji Koutei Kanketsu*' (JKK) as a recently developed Lean method and illustrates its potential to support the improvement of BIM-based highways design work processes. JKK is developed based on the concept of *jidoka* to enhance the autonomation in non-physical work processes. This method provides the employees the confidence to complete their own processes without defects, while requiring a strong collaboration between the managers and their teams. The paper is based on an action research study for trialing the use of JKK in a large engineering company. It is concluded that JKK, when its prescription is compared to the current state, focuses attention to the following issues: defining individual work activities, their support factors, their pre-conditions, the judgment criteria of their outputs, and continuous improvement. JKK is also evaluated by comparing it to other, overlapping methods.

KEYWORDS

Lean, BIM, jidoka, ji koutei kanketsu.

INTRODUCTION

Ji Koutei Kanketsu (JKK) is a Japanese term which refers to a practice in White Collar departments at Toyota (Manabe 2014). JKK means 'completing your own process' which relates to the philosophy of '*jidoka*' – expanding the autonomation in each employee's work. This method requires strong collaboration between the personnel, and a deep understanding of their own working process and that of others'. It also looks deeply into business for its process, purposes/targets, work elements, work condition, and judgement criteria (Manabe 2014). JKK implementation is evaluated as a success at Toyota; however, there has not been many studies about its implementation in other types of industry or in

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countries other than Japan. Because of its novelty, there is a lack of academic research into JKK in general, and especially of its implementation in the construction industry. The study of Manabe (2014)[7] is the only **English** academic source which provides a comprehensive description of JKK. This paper is a part of an action research which aims to test the application of JKK in a real context of highway projects in terms of process improvement. Hence, its main aim is to present the JKK method and initially evaluate it regarding its suitability for construction contexts. This is done, firstly, by introducing the concept of JKK and comparing it to the other methods and tools that have aligned elements. The comparison is to support the understanding of how JKK stands out from other existing methods. Secondly, the prescriptions of JKK are compared to the current state of a selected (partial) process of a highways design project in a global engineering company that has a branch in the UK.

RESEARCH METHOD

The underlying research is being carried out as action research. This paper partly describes the first two phases of the action research, covering an introduction of JKK as a new method, and its initial application as an evaluation tool in a selected specific process. The introduction of JKK is carried out through literature review, which also includes the comparison JKK to other relevant methods to define the overlaps and differences. Then, JKK as an evaluation tool is used to analyse the process performance in a particular project. The data on process performance is collected via open and semi-structured interview methods.

JI KOUTEI KANKETSU

According to Liker (2004), '*jidoka',* known as built-in quality, also refers to '*autonomation*' which allows the production line to be halted with human intelligence when a problem arises. In other words, *jidoka* gives the employees the power to stop the production line when they detect an issue. The importance of *jidoka* is related to its support to the *just-in-time* (JIT) system in terms of reducing variability. Remarkably, in *jidoka*, quality is treated as a factor inside production instead of an outcome of production (Koskela et al. 2019).

Since the 1960s, the concepts of JIT and *jidoka* have been applied widely in physical production; however, in 2007 Toyota decided to apply *jidoka* to all departments (Manabe 2014). Due to the different characteristic of the work between the physical production department and other departments, Toyota's attempt did not fulfil its expectations (Manabe 2014). Unable to apply the original *jidoka* concept, Toyota developed a new concept, known as *Ji Koutei Kanketsu* or JKK, which enhances the autonomation with a different approach. The concept of JKK is briefly introduced in Masai (2017) and Heller and Fujimoto (2017) as a built-in quality with ownership. The main goal of JKK is to ensure the clarity on work inputs and outputs, and the understanding of how one's personal work suits into the whole processes in which such work is placed (Heller and

[7] The study of Manabe (2014) - "Applying the Autonomation Concept to White-Colla Departments at Toyota Motors: The Basics of JKK (Ji Koutei Kanketsu)" was firstly presented at the 22nd International Colloquium of GERPISA conference by Seiji Manabe. Since then, it has been updated as a working paper series with the involvement of Daniel Heller. The latest version of this study (version 5) can be found at https://www.researchgate.net/publication/340827257_Applying_the_Autonomation_Concept_to_White_Collar_Departments_at_Toyota_Motors_The_Basics_of_JKK_Ji_Koutei_Kanketsu

Fujimoto 2017). The study of Manabe (2014, cited in Heller and Fujimoto 2017, p.107) shows that JKK is also about getting the employees to understand their co-workers' work and to treat them as customers.

The JKK implementation route is a six-step procedure (Figure 1), which primarily focuses on improvement of individual activities (the mentioned authors do not distinguish between activities and processes consisting of activities; for clarity we use the activity when dealing with the smallest elements) to ensure that each individual activity is executed accurately (Manabe 2014). Accordingly, the entie process should run smoothly with zero defects.

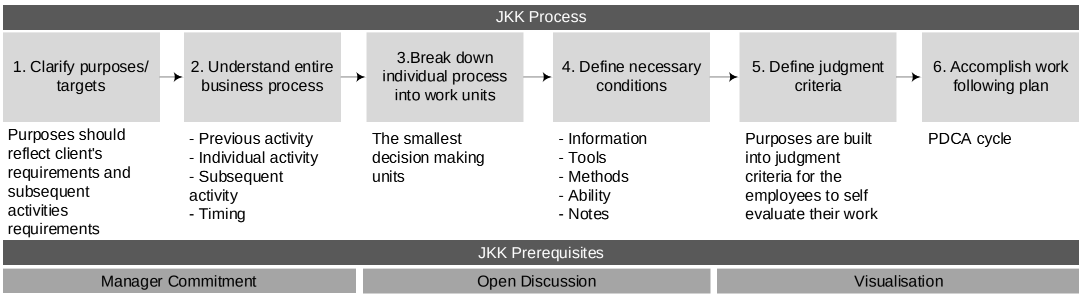


Figure 1: JKK implementation procedure and prerequisites.

Drawn based on (Manabe 2014)

The first step of JKK is to clarify the work purposes/targets. At this step, the purposes and performance targets, indeed all the requirements from the client and the subsequent activities, should be identified (Manabe 2014). Beside defining the purposes/targets of the whole business process, the purposes of individual activities also need to be pinpointed as it effects on the successful of JKK implementation (Manabe 2014). The second step is to understand the business processes as chunks which encompass the previous activity, individual activity, and the subsequent activity. The previous activity in the process provides the information for the individual activity, which receives the transferred information, processes it and then delivers to the subsequent activity. Both content and transfer time of information are important at this step. After clearly understanding the activities as well as work purposes/targets, the next step is to break down the individual activity into work units, which indicate the 'smallest decision-making units' where the person in charge can make his/her own decision and which does not require the involvement of the superior. In order to do so, the organisation must have a clear standard for the crucial conditions and judgment criteria, from which the employee can make his/her own decision with the confidence of not passing the defects into subsequent activity (Manabe 2014).

The definition of the necessary conditions of work is in step 4 in the JKK procedure. Work in the individual activity can only begin if the essential conditions for producing the output are met. The essential conditions include information, tools, methods, ability to carry out the work, and notes, which are past experience from previous works. The person in charge can start the work if he/she gets adequate input information, software, devices, guidance, and training. After all essential conditions are at hand, the work can be carried out. The fifth step in the JKK framework refers to the identification of the judgement criteria, which form the basis to assess if the work meets the requirements. In other words, how the person in charge will know if the quality of his/her work meets the standards and requirements before passing it to the subsequent activity. The judgment criteria should be built based on the purposes/targets which are already defined in the first step of JKK. The final step is to regularly accomplish the Plan-Do-Check-Act (PDCA) cycle in management. Applying the PDCA cycle into the JKK framework is presented in Figure 2.

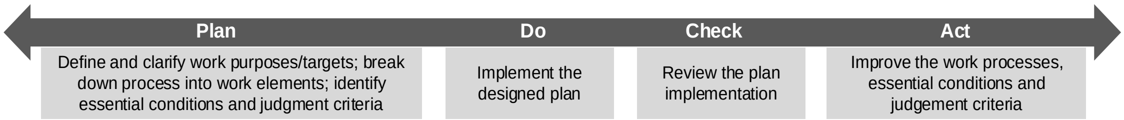


Figure 2: The PDCA cycle in the JKK implementation.

Drawn based on (Manabe 2014).

JKK implementation cannot be achieved without three crucial prerequisites: visualisation, open discussion, and manager commitment (which refers to the roles and duties of the managers) (Manabe 2014). The manager needs to comprehensively prepare their employees to commence JKK and to closely engage in the employees' work. Five main duties of the managers as part of manager commitment include: (1) to raise awareness of employees, (2) to operate a JKK working environment, (3) to encourage applying the PDCA in daily management, (4) to clearly understand which work cannot be performed in compliance with JKK, to promote its improvement, and (5) to develop the organisational area of JKK.

The purpose of visualisation in JKK is to ensure the visibility of information so that it can be shared to solve the issues (Manabe 2014). The manager is responsible for maintaining such information visualisation. Besides, the manager also must create an environment for open discussion in which the employees can freely share their problems and search for diverse solutions. The open discussion feature in JKK enhances the principle of *jidoka* in terms of giving employees the chance to address problems as soon as they emerge. Indeed, this feature fits into one of the purposes of *jidoka* – "decouple the quality and the process from direct supervision" provided by Kitazuka and Moretti (2012). In physical production, this purpose of *jidoka* is often obtained by using *poka yoke* technique to detach the quality and the process from direct management by halting the operation as a problem occurs, and to require assistance to fix the process (Kitazuka and Moretti 2012). Alongside the manager responsibilities in JKK implementation, the employees are expected to continuously gain knowledge and skills, and to take responsibility for their own work, and to cooperate with others.

Sörkvist (2016) expresses the idea of JKK application based on his meeting with Mr. Sasaki – the JKK's originator, who worked in Toyota for nearly 50 years. JKK should be simple with the aim of everyone being able to understand and participate. In Toyota, JKK is applied at three levels, from top managers level, middle managers level to worker level.

JKK is recognised to provide up to eight benefits: improved quality of work, increased customer satisfaction, improved efficiency, active communication between departments, organisational memory for standards and knowhow, improved employee abilities, smooth job rotation, and enhanced employee motivation (Manabe 2014).

COMPARISON OF JKK TO OTHER METHODS

Similarly to prior methods, the main aim of JKK is to improve work quality; however, Toyota had to create a new one – JKK – to address intellectual work. Because of its novelty, and as its differences to prior methods are subtle, a comparison between JKK and aligned prior methods is made.

PROCESS MODELLING

Process modelling not only brings benefits for the organisation, but it also improves the processes and the outputs for the client, according to the literature synthesis provided by Tzortzopoulos et al. (2005). Similarly, JKK offers benefits to the whole business process, activities and client through improving quality of work and increasing client satisfaction (Manabe 2014). In the JKK framework, understanding the business process is an obligatory activity. At this point, the similarity between JKK and process modelling is the necessity to comprehend the whole process. However, according to Tzortzopoulos et al. (2005), process modelling requires two model types (as-is and to-be) for understanding and improving the process, while in the JKK framework, it seems like it requires only the ‘as-is’ model for current practice, and then proceeds to expanding understanding of the individual process activities at a deeper level.

Another important factor that distinguishes JKK and process modelling is their focus. Understanding the process in terms of workflow is an important activity in both process modelling and JKK. However, in JKK, focusing on preparing for the outside factors of the activities, which are addressed in two steps in the framework (step 4 – define necessary conditions, step 5 – define judgement criteria), is as important as understanding the activities themselves, accordingly to Manabe (2014).

TARGET VALUE DESIGN

Target Value Design (TVD), is a version of target costing adapted to the construction industry (Zimina et al. 2012). It applies different methods to develop the design in accordance with a constraint such as cost (Miron et al. 2015). The core concept of TVD is to make the client’s values a “driver of design”, to meet the client’s expectations as well as to reduce waste (Zimina et al. 2012). Thus, both TVD and JKK start from a definition of customer requirements. However, the focus in TVD is cost reduction, whereas in JKK, the central objective is how to achieve individual work performance with zero defects. Moreover, in JKK, internal customers are meticulously addressed, besides the external customer. In TVD, the emphasis is on achieving the constraints posed by the external customer.

LAST PLANNER SYSTEM

The Last Planner System (LPS) is a key method in lean construction (Ballard and Tommelein 2021). The main functions of the LPS include setting up tasks and milestones, planning/replanning to complete the tasks, achieving reliable promises, measuring the production system performance, and learning from the failures.

At the outset, it has to be stated that the Last Planner System and JKK are different regarding their purpose. The LPS is a method for production management in a project context, with emphasis on the short term. In turn, JKK is a method for ensuring the quality in intellectual work. JKK focuses more on giving the employee confidence to perform zero-defect work rather than making them to promise to complete a task according to agreed schedule.

However, there are interesting similarities. Removing constraints in the LPS and defining necessary work conditions in JKK share the same purpose in terms of preparation for a work operation. In turn, the term Conditions of Satisfaction (Ballard and Tommelein 2021) seems to be similar to judgment criteria of JKK. Furthermore, both methods rely on the PDCA cycle for realizing continuous improvement.

Because the LPS, as such, is based on intellectual work, the prospect of considering the use of JKK as a support method to the LPS arises. However, this idea cannot be pursued further in this presentation.

STANDARDISATION

Among the lean production principles, standardisation is the baseline for continuous improvement and a key factor for building in quality (Liker 2004). When evaluating JKK from the standardisation viewpoint, it seems that the main aim of JKK is to set out a standard for product quality, working procedure, methodology, and techniques. Therefore, JKK can be considered as part of standardisation. The application of standardisation, as introduced by Liker (2004), is quite broad. Since JKK is part of standardisation, it provides a more specific direction for building standards in work processes and products, along with the implementation of continuous improvement.

ANALYSIS OF THE CURRENT STATE THROUGH JKK

THE PROCESS OF DESIGN RISK MANAGEMENT

The ongoing action research comprises of understanding and improving the BIM-based highway design sub-processes in a large engineering design company in the UK. These sub-processes play a vital role in providing information for the whole design process. Among the studied sub-processes, the Design Risk Management Process (DRMP) has been selected for this paper as its improvement is urgently needed. At the moment, the process is quite fragmented and it has not been standardised. The company is targeting to standardise and improve the DRMP so that it could be used in all types of highway projects, with some adjustment depending on each project's characteristics. The original name of DRMP is Hazard Elimination Schedule (HES), however, the company has changed the name to DRMP as part of their efforts in process improvement. DRMP complies with the Construction Design and Management (CDM) Regulations (2015), which is a legislatory document developed by the UK government to improve the handling of Health and Safety (H&S) issues in all stages of the asset lifecycle and particularly during the pre-construction stage of a construction project (Zhou et al. 2012).

The main aim of the CDM regulations is to support designers in the planning, managing, and mitigating of design risks throughout the construction process, ensuring that stakeholders are involved in all aspects of health and safety during the design and construction process (Zhou et al. 2012). DRMP is a chain of activities to capture and eliminate all possible risks in design, construction, and maintenance stages by complying with the Principles of Prevention, which are addressed in The Management of Health and Safety at Work Regulation (1999). The process requires the involvement of the client, principal designer, designers, principal contractor, and subcontractors (Zhou et al. 2012).

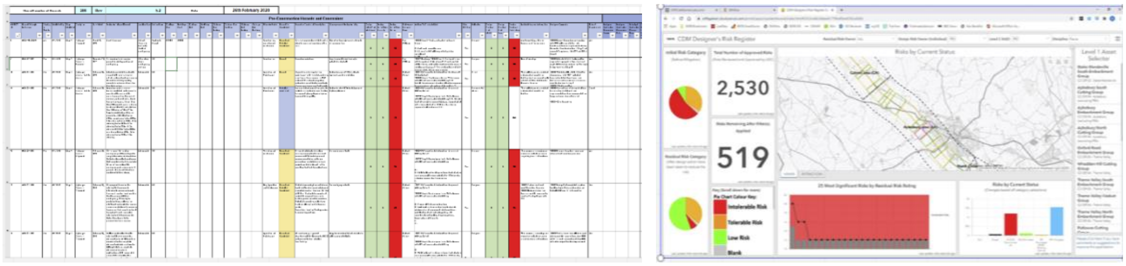
The understanding of DRMP in the chosen company has been captured through a process mapping exercise. During design development, the designers use a design checklist to classify and assess each risk with regard to its severity and likelihood and then look to develop mitigation actions for it. In this phase, the risks are identified as initial risks. The designers' optimal mitigation solution is to eliminate as many risks as possible. After applying mitigation actions, such risks that cannot be eliminated, should be reduced to be as low as practicable prior to their transfer to the principal contractor during the construction phase.

These risks are now known as residual risks. At the handover point, from design into the construction stage, all risks should be transferred from the design team to new (risk) owners, including the client, the principal contractor, and the maintainer as the designers should have completed their duties under the legislation by evidencing they have followed the DRMP.

The Principal Designer and Design Managers have the responsibility of reviewing and confirming their sub-ordinates' risk assessment and mitigation actions. In the construction stage, the principal contractor is responsible for developing any further mitigation actions for the residual risks. On completion of construction activities, any remaining risks will be passed to the client.

The term 'initial risk' and 'residual risk' are used to classify the current risk status, while the term 'generic risk' and 'specific risk' are used to classify them regarding risk location factor. Generic risks are those risks that are common and easy to manage and may be widespread across the construction site. Specific risks are those risks that are unusual and difficult to manage and are always defined by their specific location, being normally attached to a new or existing asset on the scheme.

The risks in a project are also classified into disciplinary categories which include Environment, Health and Safety, Geotechnical, Highway, Structure, Land, and Stakeholders. The number of risks defined in the scheme depends on scheme's scope and the risk impact related to disciplinary categories described above. It also depends on the location classification. For instance, a generic risk which impacts across a large number of assets will be converted into multiple specific risks by attaching it to all relevant assets. This can lead to a considerable increase in the number of risks within the project. In the project selected for this paper, the number of risks has increased from 3,000 risks to approximately 40,000 risks after attaching generic risks to all relevant assets. For H&S purposes it is important that the Principal Contractor is aware of all risks, but it is the difficulty to identify and manage the risks that they need to pay particular attention to.



(a) (b)

Figure 3: The Company's Design Risk Management Schedule in Excel spreadsheet (a) and in GIS platform (b)

The company has been using an electronic spreadsheet (Excel file) for risk management (Figure 3a); however, it has gradually replaced this traditional spreadsheet with an online platform (Geographic Information System – GIS) as a single source of information (Figure 3b). Instead of populating risk information into the spreadsheet, the designers can do the same activity in the GIS system, which provides the same information fields as the spreadsheet. The risk information in GIS is always up to date; therefore, the probability of missing information is low. The layout of the GIS platform is different in each project as it depends on the preference of the project. However, either the spreadsheet or GIS platform, risk information fields must always replicate the DRMP sequence and activities. The adoption of the GIS platform has not yet been widely applied due to project budget limitations. The use of the GIS platform also supports the integration of DRMP and BIM as the risks captured during the design stage can now be linked into the BIM model to assist locating risks and related design decision making. The risks are extracted from GIS layers in 2D drawings, then linked into the BIM model. Nevertheless, the integration of GIS and BIM is limited as currently data can only be updated within GIS and not from within the BIM software.

ANALYSING OF DESIGN RISK MANAGEMENT PROCESS THROUGH JKK IN THE SELECTED PROJECT

The DRMP varies across different projects due to differing requirements across various clients. Nevertheless, its main aim is the same in every project, namely capturing and, where possible, eliminating risks. JKK has not been applied in the DRMP in any project, thus it is only used here as an evaluation tool to assess the performance of the DRMP in a selected particular project. At the moment, the DRMP in this project has proceeded into the risk handover procedure; however, there are many issues which have emerged during the process. The evaluation is based on the result of an initial assessment of DRMP through nine interviews with the Principal Designer (PD) and Design Managers. The assessment provided evidence on wastes such as rework, inefficiency in information management and control, and lack of defined plan/process for transferring information. In order to understand the root causes of these wastes, a deeper assessment of every aspect inside the process is necessary. To identify the root causes of the wastes in the DRMP, the assessment elements for this action are built based on the JKK implementation procedure (Table 1) and its prerequisite factors.

In respect to manager commitment, one of the JKK prerequisites, the Principal Designer (PD) of this process has carried out a training workshop at the beginning of the process to ensure that all designers understand their responsibilities and the work procedure. However, the PD has assumed that the designers have achieved full understanding of the process without a firm validation that this is the case. Due to an incomplete process model, the PD also does not have a thorough view of how this process interacts with other processes. There is a lack of regular review workshops, which has led to delays in problem detection and solution. Indeed, the workshops were only organised after the PD received an audit from a third party. In addition, the work outputs are only reviewed near the end of each phase; this causes a heavy workload for both the PD and the designers.

Regarding the another prerequisite of JKK - open discussion and visualisation perspectives, there is also a lack of a collaborative platform and atmosphere, in which the designers can openly share their problems. For instance, when having technical problems, instead of discussing with the technology team and the PD, the designers try to solve the problems themselves. The GIS platform can be considered as a key part of the visualisation. It is used ideally as a repository for all risk information, as a single source of the truth, so that all designers can access and share the information. However, to access and use this platform, a license, under the control of another department, is needed. At the beginning of the process, the PD did not have a clear vision of who would need this license; therefore, the PD has had to request further access rights during the process progression. The request process is a time-consuming activity that leads to delays in the risk population activity. Moreover, the information fields in the GIS platform are not yet sufficiently reflecting the whole of the DRMP. For example, handover points, date system integration, risk approval processes, etc., are not captured in the current GIS platform.

Table 1: JKK as an evaluation tool for Design Risk Management Process

Assessment elements	JKK requirements as interpreted in the context of DRMP	Aspects of DRMP in compliance to JKK criteria	Aspects of DRMP not in compliance to JKK criteria
1. Purposes built based on client's requirements	The purposes of the whole process and individual activities includes capturing and eliminating all possible risks in design, and transferring a detailed information set of risks to the client and the contractor.	The main purpose of the process is defined at the early stage of the project.	Detailed client's requirements are not specified, so have not been explicitly converted into process purposes/targets.
2. Understanding the process	Understanding the whole DRMP along with individual activities inside the process, also the interaction with other activities and processes such as Pre-Construction Information (PCI) process.	Understanding the work process has been realised via training and process management plan, which presents the process model in written format and through a high-level work diagram.	The process is not clear and has not been completed as it is being updated during the project's progression. The handover procedure from the design stage to the construction stage has not been well defined. There is a lack of connection between the DRMP and other processes such as PCI process in terms of providing information.
3. Breakdown individual activities into work units	Understanding work units in which the individual decision making can be done without approval from managerial level.		There has not been any exercise to define work units.
4. Necessary conditions (Input, Tool, Methods, Ability, Notes/ Past experience)	Necessary conditions for DRMP comprise of input from PCI process, technical tool for populating risk information (Excel spreadsheet or GIS platform depending on each project's budget), method for capturing risks, ability to capture risks and to propose elimination solutions, lessons learned from previous projects.	The existing conditions to carry out the work include input information provided by the client; site surveys; a DRMP management plan; a technical tool for risk management (GIS platform) and a general user guide.	There is a lack of clear instructions & guidance for the employees to carry out the work; likewise, there is a lack of the past experience from previous projects as there has not been the opportunity to capture and disseminate information. The general user guidance of the technical tool and process instructions may not be sufficient as there is evidence that the designers have failed to populate information correctly. The lesson learned activity has not been organised to capture current experience related to the employees and the process for future projects.
5. Judgment criteria	Judgement criteria are a guide for designers and design manager to evaluate the quality of risk information before transferring to the client and contractor.		There is a lack of a set of judgment criteria for the employees to carry out a self-assessment of their work quality before transferring the output to other stakeholders.
6. PDCA cycle	Regular reviewing of DRMP and risk management during the whole process.	Few risk management reviews are planned during the process progress.	There is a lack of regular reviews of risk management and the whole DRMP before each stage gateway, which causes a heavy workload for both the PD and the designers when the stage gateway review is near.

DISCUSSION

The comparison between JKK and other aligned methods has brought an overview regarding the difference and novelty it offers. The analysis shows that JKK is a part of standardisation, it also covers related aspects of continuous improvement implementation. The analysis also shows that there are subtle differences between JKK and other methods.

It can possibly be used to support other methods' accomplishment. JKK and the other selected methods require the understanding of the whole process, planning the workflow, and removing constraints in process. However, JKK focuses more on the individual performance, which is normally left unmanaged. Also, in JKK, both the client's requirements and the subsequent activities' requirements are treated equally to make sure that the output is passed in perfect quality. For example, in DRMP, the designers should treat the PD, the contractor, and the project's client as customers to provide a detailed and accurate risk management schedule. Consequently, the PD's workload on approval is reduced. The contractor and the client are able to access to a proper information so that they can continue on progressing construction and maintenance stages.

The analysis of the current state of DRMP through JKK exposes the inadequate performance as it does not totally fulfill the JKK criteria. While some activities in DRMP in the chosen project to some extent cover the four criteria of JKK, none has been conducted in compliance with 'breaking down the individual activities into work units' and 'judgement criteria' features. Regarding the three prerequisites of JKK implementation, DRMP in the selected project is not sufficient. Both the PD and the designers lack a thorough understanding of the process. Also, the current state falls short regarding the open discussion and visualisation features of JKK.

CONCLUSIONS

JKK is a newly developed tool in Lean production. When applied in the construction industry, the concept of JKK has similarities with other aligned Lean construction methods in term of process improvement. However, JKK provides a unique contribution to process improvement by addressing individual intellectual work, which often remains poorly managed, at greater depth.

Up to now, JKK has been applied for an evaluation in DRMP, as a preparation step for the next phases of the action research – thorough implementation of JKK in DRMP in new projects. The results presented in this step can contribute to the 'past experience' feature of DRMP in new projects, as it provides a comprehensive overview of process problems and a direction for improvement.

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REFERENCES

Ballard, G., & Tommelein, I. (2021). *2020 Current Process Benchmark for the Last Planner(R) System of Project Planning and Control*. UC Berkeley. https://escholarship.org/uc/item/5t90q8q9.

Health and Safety (1999). "The Management of Health and Safety at Work Regulation 1999." *1999 No. 3242*. Accessed March 29, 2021. https://www.legislation.gov.uk/uksi/1999/3242.

Health and Safety Executive (2015). “Construction Design and Maintenance Regulation”. Accessed March 1, 2021. https://www.hse.gov.uk/pubns/priced/l153.pdf.

Heller, D. A., and Fujimoto, T. (2017). Monozukuri management In: T. Nakano (Ed.) (2017) *Japanese Management in Evolution: New Directions, Breaks, and Emerging Practices*, pp. 114-119. Routledge.

Kitazuka, R. E., & Moretti, C. (2012). Jidoka. In S. Obara, & D. Wilburn (Eds.) (2012). *Toyota by Toyota: Reflections from the Inside Leaders on the Techniques That Revolutionized the Industry* pp. 43-54.. CRC Press.

Koskela, L., Tezel, A., and Patel, V. (2019). “Theory of Quality Management: its Origins and History”. *Proc. 27 th Annual Conference of the International. Group for Lean Construction (IGLC)*, Pasquire C. and Hamzeh F.R. (ed.), Dublin, Ireland, pp. 1381-1390.

Liker, J.K. (2004). *The Toyota Way*. London; McGraw-Hill.

Manabe, S. (2014). “Applying the autonomation concept to white-collar departments at Toyota Motors: The basics of JKK (Ji Koutei Kanketsu)”. In *22nd International Colloquium of GERPISA*. Kyoto, Japan, June 2014.

Masai, P. (2017). *Modeling the lean organization as a complex system* (Doctoral dissertation, Université de Strasbourg).

Miron, L.I.G., Kaushik, A. and Koskela, L., (2015). “Target Value Design: The Challenge of Value Generation”. In: *Proc. 23rd Ann. Conf. of the Int’l. Group for Lean Construction* pp. 815-825. Perth, Australia, July 29-31.

Tsao, C. C., Tommelein, I. D., Swanlund, E. S., and Howell, G. A. (2004). “Work structuring to achieve integrated product–process design”. *Journal of Construction Engineering and Management*, *130*(6), 780-789.

Perez, A. M., and Ghosh, S. (2018). “Barriers faced by new-adopter of Last Planner System®: A case study”. *Engineering, Construction, and Architectural Management, 25*(9), 1110-1126.

Sörkvist L. (2016). “Ji koutei kanketsu (JKK) är Toyotas sätt att bygga in kvalitet genom ägarskap och ansvar” [Ji koutei kanketsu (JKK) is Toyota's way of building quality through ownership and responsibility]”. (In Swedish) https://www.larssorqvist.com/2016/05/16/ji-koutei-kanketsu-(jkk)-är-toyotas-sätt-att-bygga-in-kvalitet-genom-ägarskap-och-ansvar%C2%A0-32061367.

Tzortzopoulos, P., Sexton, M., and Cooper, R. (2005). “Process models implementation in the construction industry: A literature synthesis”. *Eng. Constr. Archit. Manag.*, 12(5), 470-486.

Zimina, D., Ballard, G., & Pasquire, C. (2012). “Target value design: Using collaboration and a lean approach to reduce construction cost”. *Construction Management and Economics, 30*(5), 383-398.

Zhou, W., Whyte, J., and Sacks, R. (2012). “Construction safety and digital design: A review”. *Automation in Construction*, 22, 102-111.

Oliva, C. A., Granja, A. D., Bridi, M. E., Soliman-Junior, J., Ayo-Adejuyigbe, M., and Tzortzopoulos, P. (2021). "Strengthening Target Value Design Benefits in the Real Estate Market through Living Labs." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Oliva; C. A; Granja; A. D.; Bridi, M. E.; Soliman-Junior, J.; Ayo-Adejuyigbe; M.; Tzortzopoulos; P. Lima, Peru, pp. 634–643, doi.org/10.24928/2021/0202, online at iglc.net.

STRENGTHENING TARGET VALUE DESIGN BENEFITS IN REAL ESTATE MARKET THROUGH LIVING LABS

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ABSTRACT

The Target Value Design (TVD) is a collaborative process where value drives the design process to achieve the client's expectations while maintaining the costs and schedule under control. Its application has been successful ing several construction projects, especially in the healthcare context. Applying TVD to the real estate context, however, can be challenging. This paper aims to identify links between TDV and the Living Lab (LL) concept which may potentially help overcome these challenges. LLs are user-centred initiatives that focus on developing innovative solutions through cocreation and collaboration among stakeholders in a real-life context. A review on existing literature was performed to identify how a LL approach can strength TVD in a real state context. The results present opportunities to synergize TVD and LL for a beneficial result.

KEYWORDS

Target Value Design, living labs, innovation, real estate.

INTRODUCTION

Target Value Design (TVD) is an adaption of Target Costing (TC) for the delivery of projects in the construction industry (Ballard, 2011; Macomber et al, 2007; Zimina et al. 2012) and emerged from Toyota's TC system to manage the organization's profit margins (Kato, 1993; Ansari et al., 1997; Cooper and Slagmulder, 1997). It is a proactive cost management approach, encouraging collaboration among stakeholders and positioning costs and users´ added value as a trigger to the design process (Ballard and Reiser, 2004; Macomber and Barberio, 2007; Ballard, 2011). The design teams must develop de product collaboratively, to achieve (or exceed) the client´s expectations but keeping the

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project under the agreed budget (Zimina et al. 2012). Furthermore, it is strategically applied for innovation through cost reduction, involving the suppliers with the design team in order to seek for new design solutions while maintaining quality and other value generation features (Miron et al. 2015).

Evidence shows that TVD has been successfully applied, specially to healthcare projects (Ballard and Reiser 2004; Macomber and Barberio 2007; Rybkowski et al. 2011; Denerolle 2013; Do et al. 2014). Some examples in other contexts are reported in the literature. Russel-Smith et al. (2014) discussed the possibility of a Sustainable Target Value Design, aiming to reduce the life cycle impacts, setting targets for environmental indicators tools to evaluate the results and use TVD in green buildings design Additional research on TVD included classroom's layout improvements, using TVD to facilitate the decision-making process (Sahadevan and Varghese, 2019), and simulation games to engage stakeholders in Nigeria's real estate context (Musa et al. 2019).

However, to date, TVD application to the real estate context has been insufficiently explored, and there are limited practical applications in this environment (Oliva, 2014, Oliva and Granja 2015; Neto et al. 2016; Oliva et al. 2016; Neto et al. 2018). The real estate context poses some challenges for collaborative approaches such as TVD (Oliva, 2019). The real estate sector usually applies highly fragmented design processes (Melo and Granja, 2017; Oliva, 2019). Also, adversarial and opportunistic relationships between stakeholders exist, where individual (hidden) agendas overlap the collective interests. Successful reported TVD cases in such competitive and hostile environments in construction are still lacking, such as in real estate markets and the opportunity for strengthening TVD for adoption in this context was already previously discussed (Oliva et al; 2016). Furthermore, some of the key challenges for applying TVD in real estate in Brazil were identified: (a) fierce competition through similar products offers; (b) "long time to market", which means loss of business opportunities; (c) difficulties in capturing values attributes of potential customers and (d) product price is externally defined (Oliva and Granja (2019).

To overcome those contextual challenges, it is necessary to find innovative approaches and tools to strengthen and intensify communication, collaboration (Oliva, 2019), and shared understanding (Koskela et al., 2016) between the stakeholders. In this sense, TVD could potentially benefit from Living Labs (LL), which seeks innovative solutions produced in a real-life context, collaboratively and in co-creation with users. LLs are defined as *"user-centric innovation milieu built on every-day practice and research, with an approach that facilitates user influence in open and distributed innovation processes engaging all relevant partners in real-life contexts, aiming to create sustainable values*" (Bergvall- Kareborn et al. 2009, p. 3).

The conceptual roots of TVD assume collaborative relationships between stakeholders (i.e., architects, engineers, contractors, designers, suppliers, customers). The approaches related to TVD, such as Integrated Project Delivery (IPD) and Building Information Modelling (BIM), are relevant and can work as catalysts to promote collaboration. The authors put forward the proposition that higher levels of stakeholder engagement and shared understanding could be achieved by the joint application of TVD and LLs. Hence, the paper focuses on identifying possible synergies of innovative approaches such as the LL with TVD. Therefore, the paper discusses the potential of using LLs as an innovative approach to strengthen the TVD benefits achieved in e.g., healthcare projects, in TVD adoption in the real estate market context.

LIVING LABS

The LLs are an innovation methodology that allows collaborative learning between users, researchers and producers in real-life experimentation. Users' needs are at the core of the LL process. It emerged in the early 1990s, exploring city neighbourhoods as a potential learning environment for students to engage in real-world problem solving (Geenhuizen, 2018). Nowadays, LLs initiatives can be either real-life experiments or arenas where participants collaborate to develop and test innovative solutions applying multiple approaches (ENOLL, 2021).

Through LLs, project participants engage collaboratively and share knowledge towards an innovation (Eriksson et al., 2005). The significant role of LL is to involve the key players in the development of an innovation, involving stakeholders and users required to coordinate the product and services under development (Almirall and Wareham, 2011). LL seeks to understand the techniques leading to ongoing changes through product innovation to support users' needs (Liedtke et al., 2012).

The creative process of involving humans in innovation is essential (Eriksson et al., 2005). To do so, LLs adopt a co-design and collaborative system that engages users and professionals to work together for a unique product by learning and creating a product in which users are key participants on the co-creation process (Almirall and Wareham, 2012; Eriksson et al., 2005; Leminen, 2015; Liedtke et al., 2012; Skiba et al., 2015).

Early users´ involvement and understanding their requirements is a vital feature in LLs. The co-creation aspect is another pivotal learning aspect of the LLs approach. It should embrace problem-definition and problem-solving through improvisation and experimentation, testing solutions more dynamically. The co-creation aspect's learning process takes multiple approaches, such as seeking a product's improvement, defining future needs and observing behaviours (Geenhuizen, 2018).

This process requires developing tools for proper feedback collection, balancing different players` goals during the process, bridging gaps between users' needs and product functionalities, solving conflicts and dealing with a diverse teamwork, and at same time recognizing shared goals and values (Skiba et al., 2015; Geenhuizen, 2018).

LLs consider value from all stakeholders, under a user-driven approach and projecting the user as co-designer and producer (Leminen et al., 2012). The above briefly exposes that the core idea behind LLs initiatives is to include the users in a value-creation process (Angelini et al, 2016). This places LL as closely aligned with TVD, as they are both targeting to fulfil users' expectations by developing shared understanding between stakeholders (Koskela et al., 2016).

RESEARCH METHOD

This paper used the Literature Review as a methodological approach. Literature reviews can identify gaps in a particular theme, discuss a defined agenda or develop new theory, provide a theoretical basis to achieve new conceptual models, or map the literature on specific pieces over time (Snyder 2019).

There are different literature review approaches, according to Snyder (2019), such as a systematic review, integrative review and semi-systematic review. In this paper, the integrative review was the method adopted. This study seeks to access and synthesize literature to enable new theory or frameworks to emerge. This method is suitable to the I research aim, as it proposes new approaches to strengthen TVD in the real estate context.

Review papers examine a particular research question by describing and synthesizing the appropriate literature using a theoretical method to provide readers with an understanding of recent research areas (Palmatier et al., 2018).

In the present research, three major themes were explored: (i)Target Value Design – origins and context applications – in order to establish the main concepts of TVD and its state of art so far, successful applications contexts (19 articles); (ii) Target Value Design in Real Estate context – research and challenges for adoption – with the objective to explore the context of interest, this stage searched the literature for previous papers that explored TVD and real estate – which has proven to be scarce (6 articles); (iii) Living Labs – to extend the knowledge about its concepts and potentialities to strengthening TVD for a real estate adoption, and address its main challenges for adoption (22 articles).

RESULTS AND DISCUSSION

THE LL APPROACH TO STRENGTHENING THE TVD

When focusing attention on the real estate market, some challenges exist for a full-fledge TVD implementation, especially those concerning some externalities that are inherent of this context (Oliva et al., 2019; Oliva 2019). Our research suggests some LL concepts can be seen to help address some of the TVD issues observed in the real estate context, especially those related to collaboration, shared understanding and value alignment, as shown in Table 1.

Table 1: Real estate key challenges and LLs propositions (The authors)

Real estate key challenges (Oliva et al., 2019; Oliva 2019):	LL propositions that can strengthen TVD adoption in the real estate context
Fierce competition through similar products offers In the real estate market, various similar products are offered by several construction companies, so a potential customer must choose between all those products, the one that can deliver more value for the same price, in his perspective.	Improving shared motivation for collaboration through LLs is essential and can help stakeholders overcome fierce competition when LL resources are made available to them (Veeckman et al., 2013). With improved co-creation innovations through LL, there is a tendency to have risk lowered, thereby increasing customer satisfaction and providing a competitive solution (Defillippi & Roser, 2014). Therefore, LL plays a mediating and facilitating role that allows for a participatory governance through shared value that ultimately integrates the interest of key participants to enhance a citizen-centered solution rather than a perceived competitor, making competition fierce (Angelini et al. 2016). Research and development can help efficiently, competitively, and socially drive products and services to an acceptable level that significantly reduces resources consumption. (Geibler et al., 2014).
“Long time to market”, which means loss of business opportunities” (“Time to Market”) - the product development process is too long. It is a fragmented process with low collaboration and a waste of time with a redesign and reworks. It can result in a loss of business opportunities, as a competitor launches a similar product first.	LL can help in both practical and organizational implementation of innovations that can help manage the adoption of new ways of doing business by implementing innovation models that can foster time management (Schuurman & Tõnurist, 2015). LL intervention can leverage the differences between research and market delivery in a fundamental and complicated structure (Claude et al., 2017). Customers' involvement in the whole innovation process improves marketing strategy, thereby allowing for a trial period to customers before purchasing, which convinces them of product usefulness. There is a further development stage to commercialization with customer engagement (Zimmerling et al., 2017). The collaboration with users at the early innovation stage serves as a risk management helpful tool to obligatory companies in overcoming future obstacles.
Difficulties in capturing values attributes of potential customers The companies often achieve obstacles in understanding and sharing the future user's value perspective with the design teams and incorporate it into product development. Usually, only post-occupancy evaluations are performed and not always provides feedback.	Adopting a mixed set of LL tools to discover new opportunities will help overcome the difficulty in capturing futuristic customers (Veeckman et al., 2013). Collaborative engagement of key participants in the natural environment is essential for developing attributes necessary for value capturing through the adoption of LL (Hossain et al., 2019). Exploring future needs and validating internal views is required at the initial stages with user’s collaboration. And at a later stage, market success is increased through users' collaborative effort (Zimmerling et al., 2017).
Product price is externally defined In the TVD original context, the client establishes the team's target budgeting. In the real estate, the external market will determine the average price. The profit margins are defined, so the left value is the cost target. This practice often results in confiscated value from the final user.	From the previous perspectives, where we address the user-centered process of the LLs and with users and stakeholders working collaboratively, this may suggest opportunity to maintain the value perspective as a trigger to the design process, managing external influences, but this point still needs further exploration.
Fierce competition through similar products offers In the real estate market, various similar products are offered by several construction companies, so a potential customer must choose between all those products, the one that can deliver more value for the same price, in his perspective.	Improving shared motivation for collaboration through LLs is essential and can help stakeholders overcome fierce competition when LL resources are made available to them (Veeckman et al., 2013). With improved co-creation innovations through LL, there is a tendency to have risk lowered, thereby increasing customer satisfaction and providing a competitive solution (Defillippi & Roser, 2014). Therefore, LL plays a mediating and facilitating role that allows for a participatory governance through shared value that ultimately integrates the interest of key participants to enhance a citizen-centered solution rather than a perceived competitor, making competition fierce (Angelini et al. 2016). Research and development can help efficiently, competitively, and socially drive products and services to an acceptable level that reduces resources consumption (Geibler et al., 2014).

Considering the synergies identified in Table 1, LLs appear to be a promising way of strengthen TVD adoption in the real estate context, while overlapping some of the main challenges found in such context. Also, because of the commonalities between LL and TVD, it was possible to identify some synergies between the approaches, as highlighted in Table 2:

Table 2: Similarities between LLs and TVD (The authors)

TVD features (Macomber & Barberio, 2007; Zimina et al., 2012)	LL features (Eriksson et al., 2005; Liedtke et al., 2012; Skiba et al., 2015)
Collaborative decision-making by all project participants.	LL allows for collaborative learning between all stakeholders (Van Geenhuizen, 2019). There are also participatory processes enhanced by social innovation (Keyson et al., 2017)
Engagement with the client for establishing target value and throughout the design process for the continuous revealing of clients' needs	Continuous coincides with a process of demand creation situated in use contexts or potential markets that confront real adoption barriers.
Several representatives' input to include relevant specialists and stakeholders committed to communicating and sharing design ideas.	Partners bringing their knowledge and know-how into the design team.
Paying attention to the value established by the customer	Users as co-creators of value and innovations

Although the LL approach can enhance some principles from TVD (Table 1), its potential focuses on a catalyst more than a tool, whereas this approach may help to overcome some key challenges for the adoption of TVD in the context of the real estate market with units for sale. The LL focuses on user-centred value, collaboration, vital stakeholder's engagement (and is a broader approach), TVD is a more direct and specific approach, and the challenges inherit from the real estate market context could benefit from its adoption. It is also possible to assume that TVD can be suitable to support further systematic and value-oriented process on LLs, since value generation is not always explicit in LLs, but further research is needed to deepen those synergies.

In Table 2, we highlight some synergies between LLs and TVD, specially concerning the user involvement, value generation and collaboration between stakeholders. As the TVD basis is to put user value as a trigger to the product development process, under continuous collaboration among stakeholders, the LL approach has a similar proposal, whereas users´ values and needs are un the cente, also seeking early involvement.

CONCLUSIONS

The TVD application in the real estate context can represent some obstacles. It encounters a very adversarial relationship between stakeholders, individual agendas, and very different levels of interest and influence in a determined product that can overlap the project's value perspective. Considering the LL as a broader user-centred approach towards co-creation, a TVD adoption within a LL perspective could facilitate overcome the obstacles presented in Table 1, with the early user and stakeholders´ involvement in the process, shortening and adding value to solution, therefore strengthening TVD in this particular environment. It features collaboration, shared understanding, stakeholder's engagement and co-creation, especially in the highlighted TVD concepts related to collaboration, value perspective, co-location and communication. Also, artefacts can help operationalize the so-called boundary objects to enable and improve the so-called boundary objects, to enable and improve the relations between the actors involved in the product development process.

Future research could address a pilot testing a TVD adoption within a LL as an innovative approach to achieve and improve shared understanding, stakeholder's engagement and communication, overlap obstacles to a TVD adoption, and could validate and base further development of the conceptual analysis of this paper. Even though a full-fledge implementation can be challenging, a partial adoption could benefit the market's product offer, raising the value perspective for stakeholders overall.

REFERENCES

Almirall, E., and Wareham, J. (2011). "Living Labs: Arbiters of midand ground-level innovation". Technology Analysis and Strategic Management, 23(1), 87–102. https://doi.org/10.1080/09537325.2011.537110.

Alves, T. C. L., Lichtig, W., and Rybkowski, Z. K. (2017). "Implementing Target Value Design: Tools and Techniques to Manage the Process." 10(3), 18–29. doi.org/10.1177/1937586717690865.

Ansari, S., Bell, J., the CAM-I Target Costing Group, 1997, Target costing – the next frontier in strategic cost management, Chicago, Irwin.

Angelini, L., Carrino, S., Khaled, O. A., Riva-mossman, S., & Mugellini, E. (2016). *Senior Living Lab : An Ecological Approach to Foster Social Innovation in an Ageing Society*. 1–19. doi.org/10.3390/fi8040050.

Ballard, G. (2011). "Target Value Design: Current Benchmark". Lean Construction Journal, 79-84.

Ballard, G., and Reiser, P. (2004). "The St. Olaf College Fieldhouse project: a case study in designing to target cost". Proceedings, International Group for Lean Construction. Dinamarca: [s.n.].

Bresnen, M. (2010). "Keeping it real? Constituting partnering through boundary objects". Construction Management and Economics, 28:6, 615-628, doi.org/10.1080/01446191003587711.

Claude, S., Ginestet, S., Bonhomme, M., Moulène, N., & Escadeillas, G. (2017). The Living Lab methodology for complex environments: Insights from the thermal refurbishment of a historical district in the city of Cahors, France. Energy Research & Social Science, 32, 121–130. doi.org/10.1016/j.erss.2017.01.018.

Cooper, R. and Slagmulder, R., 1997. Target costing and value engineering, Portland, Productivity Press.Defillippi, R., & Roser, T. (2014). Aligning the co-creation project portfolio with company strategy. 42(1), 30–36. doi.org/10.1108/SL-10-2013-0075.

Denerolle, S. (2013). "The application of Target Value Design to the design phase of 3 hospital projects". Project Production Systems Laboratory - University of California. Berkeley.

Do, D., Chen, C., Ballard, G., and Tommelein, I. (2014). "Target Value Design as a Method for Controlling Project Cost Overruns". Proceedings IGLC-22, June 2014. Oslo, Noruega: [s.n.]. p. 171-181.

Eriksson, M., Niitamo, V. P., and Kulkki, S. (2005). "State-of-the-art in utilizing Living Labs approach to user-centric ICT innovation-a European approach". Lulea: Center for Distance-spanning Technology. Lulea University of Technology Sweden: Lulea.

Lulea: Center for Distance-Spanning Technology., 1(13), 1–13. doi.org/10.1145/2072069.2072092.

Geibler, J. Von, Erdmann, L., Liedtke, C., Rohn, H., Stabe, M., Berner, S., Leismann, K., Schnalzer, K., & Kennedy, K. (2014). *Exploring the Potential of a German Living Lab Research Infrastructure for the Development of Low Resource Products and Services*. 575–598. doi.org/10.3390/resources3030575.

Hossain, M., Leminen, S., & Westerlund, M. (2019). A systematic review of living lab literature. *Journal of Cleaner Production*, *213*, 976–988. doi.org/10.1016/j.jclepro.2018.12.257.

Kato, Y., 1993, 'Target costing support systems: lessons from leading Japanese companies', Management Accounting Research 4, 33-47.

Keyson, D. V., Guerra-Santin, O., and Lockton, D. (Eds.) (2017). "Living labs: design and assessment of sustainable living." Springer. doi.org/10.1007/978-3-319-33527-8.

Koskela, L., Pikas, E., Gomes, D., Biotto, C., Talebi, S., Rahim, N., and Tzortzopoulos, P. (2016). "Towards shared understanding on common ground, boundary objects and other related concepts." In: *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, Boston, MA, USA, sect.1 pp. 63–72.

Lee, H. W., Ballard, G., and Tommelein, I. "Developing a Target Value Design Protocol for Commercial Energy Retrofits - Part 1". Construction Research Congress ASCE. West Lafayette, Indiana: [s.n.]. 2012. p. 1710-1719.

Leminen, S. (2015). "What Are Living Labs?" Technology Innovation Management Review, 5(9), 29–35. doi.org/10.22215/timreview928.

Leminen, S., Westerlund, M., and Nyström, A. G. (2012). Living Labs as Open-Innovation Networks. Technology Innovation Management Review, 2(9), 6–11. doi.org/10.22215/timreview602.

Liedtke, C., Jolanta Welfens, M., Rohn, H., and Nordmann, J. (2012). "LIVING LAB: User-driven innovation for sustainability". International Journal of Sustainability in Higher Education, 13(2), 106–118. doi.org/10.1108/14676371211211809.

Newcombe, R. (2003). "From client to project stakeholders: a stakeholder mapping approach". Construction Management and Economics (December 2003) 21, 841–848.

Macomber, H., and Barberio, J. (2007). "Target-Value Design: Nine Foundational Practices for Delivering Surprising Client Value". TVD Foundational Practices. 2–4.

Melo, R. S. S., Do, D., Tillman, P., Ballard, G., and Granja, A.D. (2015). "Target value design in the public sector: evidence from a hospital project in San Francisco, CA". Architectural, Engineering and Design Management, Nov 2015. 1-14.

Miron, L.I.G., Kaushik, A., and Koskela, L. (2015). "Target Value Design: The Challenge of Value Generation". In: Proc. 23rd Ann. Conf. of the Int'l. Group for Lean Construction. Perth, Australia, July 29-31, pp. 815-825.

Musa, M., Pasquire, C., and Hurst, A. (2019). "Using TVD Simulation to Improve Collaboration". Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC). Dublin, Ireland: [s.n.]. 2019. p. 503-514.

Neto, H. M., Costa, D. B., and Thomas, L. (2016). "Target value design approach for real estate development". In: Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction, Boston, MA, USA, sect.3 pp. 63–72.

Neto, H. M., Costa, D. B., and Ravazzano, T. C. (2018). "Recommendations for Target Value Design implementation for real estate development in Brazil". 2007. doi.org/10.1080/17452007.2018.1509054.

Oliva, C. (2014). "Proposal for Target Value Design integration into Design Process Management in Civil Construction Projects" (translated). Master's Thesis. The School of Civil Engineering, Architecture and Urban Design – UNICAMP - the State University of Campinas, Brazil.

Oliva, C., and Granja, A. D. (2015). "Proposal for target value design adoption in the design management in real estate projects" (translated). Ambiente Construído. Porto Alegre, 15(4), 131–147.

Oliva, C., Granja, A. D., Ballard, G., and Melo, R. (2016). "Assessing suitability of target value design adoption for real estate developers in Brazil". In 24th Annual Conference of the International Group for Lean Construction. Boston, USA, 2016.

Oliva, C. (2019). "Target Value Design in the Real Estate Market with Units for Selling: Model and Guidelines for Implementation" (translated). PhD Thesis (in Portuguese). he School of Civil Engineering, Architecture and Urban Design – UNICAMP - the State University of Campinas, Brazil.

Onwuegbuzie, A. J., and Frels, R. (2016). "Methodology of the Literature Review. In: Seven Steps to a Comprehensive Literature Review: A Multimodal and Cultural Approach". Sage Publications, UK.

Palmatier, R. W., Houston, M. B., and Hulland, J. (2018). "Review articles: purpose, process, and structure". Journal of the Academy of Marketing Science (2018) 46:1–5. doi.org/10.1007/s11747-017-0563-4.

Russell-Smith, S. V., Lepech, M. D., Fruchter, R., and Littman, A. (2014). "Impact of progressive sustainable target value assessment on building". Building and Environment, November 2014. 52-60.

Rybkowski, Z. K., Munankami, M. B., Gottipati, U., and Lavy, S. (2011). "Towards an Understanding of Cost and Aesthetics: Impact of Cost Constraints on Aesthetic Ranking Following Target Value Design Exercises". 21st Annual Conference of the International Group for Lean Construction, 1–10.

Sahadevan, V., and Varghese, K. (2019). "AHP and CBA Application to Layout Design: A Case of Classroom Layout Assessment" In: Proc. 27th Annual Conference of the International. Group for Lean Construction (IGLC), Pasquire, C and Hamzeh FR (Ed). Dublin, Ireland, pp. 1333-1344. doi.org/10.24928/2019/0256.

Schuurman, D., & Tõnurist, P. (2015). *Innovation in the Public Sector: Exploring the Characteristics and Potential of Living Labs and Innovation Labs.*

Silveira, S., and Alves, T. (2018). "Target Value Design Inspired Practices to Deliver Sustainable Buildings" (2018). Buildings ,8, 116. doi.org/10.3390/buildings8090116.

Skiba, N., Morel, L., Guidat, C., and Camargo, M. (2015). "How to emphasize the "living" part of Living Lab projects?" 2013 International Conference on Engineering, Technology and Innovation, ICE 2013 and IEEE International Technology Management Conference, ITMC 2013, 1–12. doi.org/10.1109/ITMC.2013.7352701.

Snyder, H. (2019). "Literature review as a research methodology: An overview and guidelines". Journal of Business Research, 104 (March), 333–339. doi.org/10.1016/j.jbusres.2019.07.039.

Van Geenhuizen, M. (2018). "A framework for the evaluation of living labs as boundary spanners in innovation". Environment and Planning C: Politics and Space, 36(7), 1280–1298. doi.org/10.1177/2399654417753623.

Van Geenhuizen, M. (2019). Applying an RRI filter in key learning on urban living labs' performance. Sustainability (Switzerland), 11(14). doi.org/10.3390/su11143833.

Van Der Walt, J. S.,. Buitendag, A. A. K, Zaaiman, J. J., and Van Vuuren, J. J. C. (2009). "Community Living Lab as a Collaborative Innovation Environment". Issues in Informing Science and Information Technology, 6 (January), 421–436. doi.org/10.28945/1070.

Veeckman, C., Schuurman, D., Leminen, S., & Westerlund, M. (2013). *Linking Living Lab Characteristics and Their Outcomes : Towards a Conceptual Framework*. *December*, 6–15.

Zimina, D., Ballard, G., and Pasquire, C. (2012). "Target value design: using collaboration and a lean approach to reduce construction cost Target value design". Construction Management and Economics, 30(5), 383–398. doi.org/10.1080/01446193.2012.676658.

Zimmerling, E., Purtik, H., & Welpe, I. M. (2017). End-users as co-developers for novel green products and services e an exploratory case study analysis of the innovation process in incumbent firms. Journal of Cleaner Production, 162, S51–S58. doi.org/10.1016/j.jclepro.2016.05.160.

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Neve, H.H., Lerche, J., and Wandahl, S. (2021). “Combining lean methods to improve construction labour efficiency in renovation projects” *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 647–656, doi.org/10.24928/2021/0107, online at iglc.net.

COMBINING LEAN METHODS TO IMPROVE CONSTRUCTION LABOUR EFFICIENCY IN RENOVATION PROJECTS

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ABSTRACT

The construction industry has experienced stagnation and perhaps even a decline in construction labor productivity for decades. This is problematic as labour costs in construction constitute up to 60% of the total project costs.

This research aimed to investigate further how much complimentary lean construction tools could impact Construction Labor Efficiency (CLE). CLE is a key element in the denominator when calculating Construction Labor Productivity (CLP) because CLP focuses on maximizing value-adding-work time (numerator) and minimizing nonvalue-adding-work time (denominator).

A case study research approach with four renovation projects was used to collect Lean Implementation Degree (LID) and CLE data. The research findings showed a strong positive correlation between LID and CLE in the four renovation projects.

The findings have implications for both academia and industry professionals. Academia now has initial results on which future research can be built. Industry professionals now have a better understanding of how lean improves efficiency and hereby better arguments for why lean construction methods must be implemented in future renovation projects.

The research was limited by a small sample size of only four renovation projects. Thus, further research is needed to validate the effects in renovation projects and other types of construction projects as well.

KEYWORDS

Performance, productivity, work sampling, efficiency, implementation, lean.

INTRODUCTION

Construction Labor Productivity (CLP) is calculated by dividing craftsmen's output (monetary value of the constructed) with craftsmen's input (number of working hours). CLP has a significant impact on construction projects because construction labour costs constitute 40-60% of the total project costs (Buchan et al. 2006; Kazaz et al. 2008; Smith 2013). Thus, having a high CLP is crucial for the construction project's cost, among others. Despite CLP’s importance for construction projects, research has shown that CLP has

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continually declined for four decades (1972-2010) in North America (Neve et al. 2020a), with similar trends in most EU countries (Farmer 2016). One approach to change the problematic development in CLP is improving Construction Labour Efficiency (CLE), which is known to be a key factor in increasing CLP (Neve et al. 2020a). CLE refers to the optimal use of labor time (denominator of CLP). That is when labor work is done with a maximum amount of time spent on value-adding work (better known as Direct Work (DW)) and a minimum of time spent on Non-Value Adding Work (NVAW).

Despite the importance of improving CLE, only a little knowledge exists on how to manage and improve DW and NVAW time in construction projects. Thus, this research aims to explore how significant impact lean construction methods have on CLE. The aim is to provide initial findings to academia and industry on the effects lean construction methods have on CLE. Improving CLE will additionally improve CLP and thus mitigate the main challenge of declining productivity.

BACKGROUND: LABOUR EFFICIENCY AND LEAN IN CONSTRUCTION

Data on CLE and hereby on how construction laborers use their time can be collected with the Work Sampling (WS) method. The WS method has been used since the 1970s in construction (Gong et al. 2011) and quantifies labor time usage by categorizing direct observations of construction labor work.

The WS method has proven itself to be able to create valuable insights on DW and NVAW time in the flow view (Neve et al. 2020b) of the Transformation-Flow-Value theory by Koskela (2000) in which, the production resource is time (Bølviken et al. 2014). The use of lean methods in construction initiates with the seminal work of Koskela (1992), who suggested that the use of lean in construction can have a significant effect on NVAW time. DW are activities like processing of materials, assembling of elements, etc.

One of the first lean construction tools was the Last Planner System™ (LPS) (Ballard 2000) which has proven its ability to improve planning effectiveness, e.g., Alarcón et al. (2005); AlSehaimi et al. (2009); Ballard (2000); Lerche et al. (2020a). Later, the lean construction tool Location-Based Scheduling (LBS) emerged (Kenley and Seppänen 2010) and proved its ability to compress construction schedules (Evinger et al. 2013; Lerche et al. 2019a; Lerche et al. 2019b; Seppänen et al. 2014). Takt Time Planning (TTP), which is similar to LBS (Seppänen 2014), has also shown its ability to compress schedules (Heinonen and Seppänen 2016; Lerche et al. 2020b). Only a few research have, though, investigated how DW can be increased. Examples are the Activity Analysis (AA) method (CII 2010) which has proven itself to be able to continuously improve the time construction laborers spend on DW (Gouett et al. 2011; Hwang et al. 2018).

As the latter outline, only a little knowledge exists on how DW time can be improved in construction. Thus, this research investigates if the combined use of lean tools can improve DW by reducing NVAW in construction projects. The complementary tools could be LPS and LBS, which work nicely together (Seppänen et al. 2010).

That limited knowledge exists on how the use of combined lean methods in construction affects CLE in construction and, hereby, the presence of NVAW time, is a gap in the current body of knowledge. This research, therefore, sets out to close this gap by providing an initial answer to the question: "What impact does the use of lean construction have on construction labour efficiency?".

METHOD

This research is an explorative case study based on Yin's third case study research design which uses multiple cases and a single unit of analysis. The research design was chosen because it enabled this research to explore if the use of lean methods influenced CLE. The unit of analysis studied was the correlation between the use of lean methods and CLE. The 4 cases are in the following firstly presented. Secondly, the work sampling method used to collect CLE data is outlined, and finally, the data analyses are described.

CASES

The cases were all renovation projects located in Denmark. Renovation projects have specific characteristics and peculiarities, which are not elaborated in this paper (e.g., Neve et al. 2020b; Kemmer 2018). The cases were similar in building structure consisting of multiple similar apartments in 1, 2, or 3 story buildings. The cases were all planned to go through deep renovation, including interior, installations, and building envelope. The cases are presented in table 1.

Table 1: Data collection from the three cases.

	Case 1*	**Case 2****	**Case 3*****	**Case 4******
Contract type	General	Turnkey	General	Turnkey
Duration	5 years	4 years	4 years	3 years
Apartments	291	297	601	470
m^2	22,800	23,700	46,500	41,000
Stories	Basement to 2	Basement to 2	Basement to 3	Ground to 1
Originally built	The 1950s	The 1960s	The 1950s	The 1970s

*WS data previously used in Neve et al. (2020b); Neve et al. (2020d); Teizer et al. (2020)

**WS data previously used in Neve et al. (2020b); Neve and Wandahl (2018); Teizer et al. (2020)

***WS data previously used in Neve et al. (2020b); Teizer et al. (2020)

**** WS data not previously published.

WORK SAMPLING

The work sampling method was used to collect CLE data from the four cases. The WS data was in this research collected using 7 categories to describe the work. The only one of interest for this research is the category of DW, which directly depicts CLE by quantifying the time construction laborers spent on value-adding work. Value-adding work is the work a given trade spent on doing work that directly adds value to the building, e.g., painting, nailing roof formwork, laying down tiles, etc.

This research followed Thompson's (1987) and Thompson's (1992) recommendation to ensure validity in the collected data. Thus, a minimum of 510 observations was collected for each WS data set to obtain 95% confidence. The same was also used by Gouett et al. (2011); Hwang et al. (2018).

The data was collected by inexperienced research assistants on cases 1,2, and 3 and by highly experienced management consultants on case 4. The research assistants were at all-time supervised to secure validity in the data.

The data was on cases 1,2 and 3 collected by observing the majority of trades individually, and case 4 was observed as a whole. The result is for both approaches a valid data set representing each of the cases. For each case, WS data was collected during 5-10 days of observation. The criterion was that data collection take place during ‘normal’ production conditions. Thus not during startup, during delivery problems, not during weather issues, etc.

LEAN IMPLEMENTATION DEGREE

A systematic concept was developed to evaluate the overall Lean Implementation Degree (LID) on each case. The concept consists of several main and subcategories based on a literature review of previous studies related to lean implementation and discussions with peers and industry consultants with expertise in lean. Wandahl’s (2014) industry survey of lean in the Danish construction industry provided great inspiration for the six main categories presented in table 2’s first row. The subcategories of A, B, and C were defined according to discussions with academic peers and industry consultants. The remaining subcategories were primarily based on the following literature and supplemented with input from discussions: D) comes from Kragh-Schmidt and Johansen (2000), E) is from Lindhard and Wandahl (2014), and F) is from Kenley and Seppänen (2010). When evaluating the different subcategories, a scale from 0 to 5 was chosen, with 0 being total absents of, e.g., knowledge or training and 5 being the full implementation of, e.g., JIT or 5S. The authors and industry consultants evaluated the LID for each case because it was assessed that the project team in each case did not have the necessary knowledge to do this. The LID was subjectively evaluated by authors/consultants through observation during WS data collection and by conservations with the whole project team.

F: Location Based Scheduling (LBS)	E: Last Planner System (LPS)	D: Just-in-Time (JIT)	C: Holistic use of lean	B: General knowledge level	A: Training provided by company
6f-Process planning/ Pull planning/ Takt time	8e-Learning Process/ 5xWhy	10d-JIT-A3	3c-Degree of a lean/Kaizen culture	4b-Location Based Planning	4a-Location Based Planning
5f-Lookahead planning phase	7e-Workable backlog	9d-JIT-5S	2c-Empowering employees to create continues	3b-Last Planner System	3a-Last Planner System
4f-Control Action	6e-lookahead Plan is formalized	8d-JIT-kaizen	1c-Is TFV theory as a common understanding of	2b-Just-in-time	2a-Just-in-time
3f-Forecasting	5e-Causes for non-compliance based on PPC	7d-JIT-TQM-TQC		1b-General Lean	1a-General Lean
2f-Progress tracking	4e-PPC measured on a weekly basis	6d-JIT-SCM (Material Delivery)			
1f-Overall sequencing/Master plan	3e-Process planning/ Pull Planning/ Takt time	5d-JIT-Production Layout			
	2e-Weekly workplan formalized into a plan	4d-JIT-TPM			
	1e-Weekly meetings with foremen	3d-JIT-SMED			
		2d-JIT-Small batches			
		1d-JIT-Kanban			

Figure 1: Lean implementation degree evaluation form.

Calculating the LID average was done by weighing averages from the main six categories equally. This was done to avoid making the implementation of, e.g., JIT being more important than, e.g., LBS given its lower number of subcategories.

ANALYSIS OF DW AND LID DATA

The analysis of DW and LID data was done using linear regression analyses. The regression model was evaluated through a t-Test determining the model's 95% coefficient intervals, analysis of regression coefficients to determine the Effect size, R2 to investigate the predictive capabilities, and finally, an ANOVA analysis to determine the statistical confidence level (p-Value). The Effect size (R) was compared to Cohen's (1988) and Cohen's (1992) work categorizing Effect sizes. The p-Value was used as a foundation to determine how statistically valid the identified relationship is. No lower limit for neither the R-value nor p-Value was set since the research was explorative and set out to explore a potential relationship on a small data sample.

RESULTS

Results from the 4 cases will initially be presented, followed by a statistical analysis testing the relationship between DW and LID. The WS study result is outlined in Table 2. The first row lists the four cases, the second row presents the measured DW levels, and the third row gives the total number of data points from the WS study. The table shows that DW levels are lowest in case 1 and increases steadily going towards case 4.

Table 2: DW levels from the four studies.

	Case 1*	Case 2**	Case 3***	Case 4****
DW	26.0%	33.0%	36.0%l	40.7%
N	29,884	3,927	13,682	861

The LID in the four cases is presented in Table 3. The table's first row starts by showing the main categories of the LID evaluation form ending with the average LID. The following rows outline the results of the LID from the four cases. The LID is evaluated on a scale from 0 to 5. The table outlines a LID being lowest in case 1, increasing steadily going towards case 4.

Table 3: Lean Implementation Degree for the four cases. LID is weight average.

	Case 1	Case 2	Case 3	Case 4
A: Training	0.5	0.75	1.12.	1.75
B: Knowledge	0.5	0.75	1.5	2.25
C: Use	0	0	0	1
D: JIT	0.1	0.1	0.2	0.4
E: LPS	1	0.5	1.25	3.38
F: LBS	0.00	0.67	1.17	3.17
LID	0.35	0.46	0.86	1.99

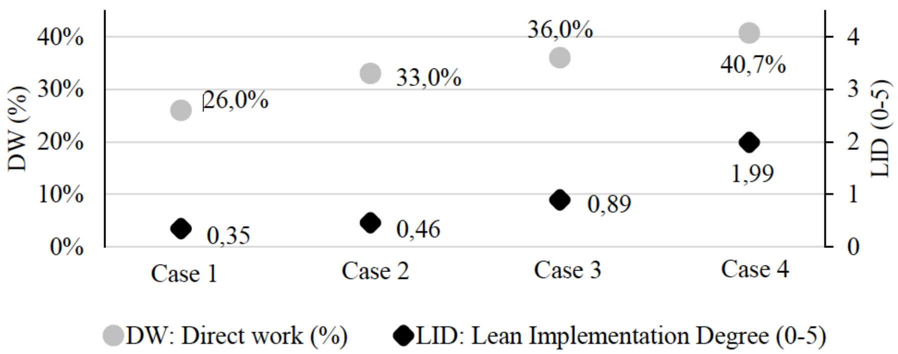

Figure 2: DW and LID plotted together for the four cases.

Figure 2 plots the DW levels and LID from the four cases together using two different y-axes, with the left being in % reflecting the DW level and the right going from 0-5 reflecting the LID score. The plot reveals an apparent linear relationship.

To test the apparent relationship shown in figure 1, linear regression analysis is used. LID acts as the independent (predictor) variable and DW as the dependent (response) variable in the analysis.

Table 4 present the result of the linear regression with the final model, the number of data points (N), t-Test outlining the 95% confidence intervals for the predictor coefficient (a) and constant coefficient (b), Effect Size (correlation coefficient (R)) predictive capabilities (R2) and the ANOVA analyses giving the statistical significance level.

Table 4: Result of linear regression analysis.

Model Y=ax+b	N	a	b	R	R^2	ANOVA p-value
y=7.21x+27.27	4	(-4.84;19.26)	(13.68;40,87)	.876	.768	.124

y=ax+b means that, x=LID, b=constant and y= predicted DW level

The linear regression analysis is also plotted in Figure 3 with DW and LID data from the four cases to validate the regression model visually. Figure 2 confirms both the linear tendency and the results of the linear regression analysis in Table 4.

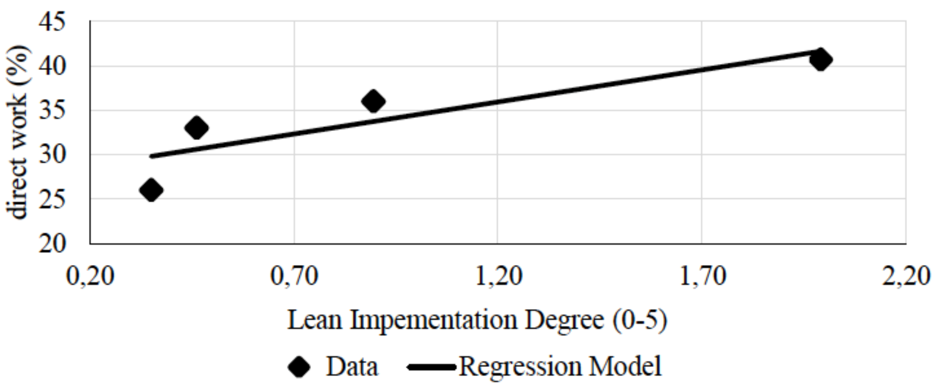

Figure 3: Direct work and lean implementation degree data from the four cases together with the regression model.

With the above result, the RQ: "*What impact does the use of lean construction have on construction labour efficiency*" can now be answered.

Firstly, the regression analysis reveals an effect size (R) of .876, which far exceeds Cohen's (1988) and (1992) lower limit at, 5 defining a large effect size. The predictive capabilities (R2) match well with the coefficient's confidence intervals looking at Figure 2. This shows that the Lean Implementation Degree has a significant effect on CLE.

Secondly, looking at the statistical significance level at 87.6% (p=.124), this means that in 1 out of 8.1 cases, the changes in DW are not explained by LID. This is lower than the 95% (p=.05) statistical confidence level, which is typically regarded as the lower limit where the risk of a false result is 1 out of 20. This means that the result is relevant and shows a clear trend, but it includes some uncertainty. The low p level is often seen when few cases constitute the sample size and were from the beginning seen as a limitation in this research.

DISCUSSION AND LIMITATIONS

The model's range is defined by the data and shows a span between LID=.35 and LID=1.99, predicting DW at respectively 29.8% (±17.8%) and 41.6% (±37.6%), which fits well with the data on 26% and 40.7%. Looking beyond the model's range using LID=0 and LID=5, the model predicts DW, respectively, at 27.3% (±13.6) and 63.3% (±73.8). The predicted DW values at LID=0 are realistic, as the model is based on LID as low as 0.35. The predicted DW on 63.3% at LID=5 contains a considerable uncertainty which is natural knowing that LID=5 is far from the highest data point on LID=1.99 used to make the model. Despite the uncertainty, it is quite interesting to see that previous analysis of the same WS data (Neve et al. 2020b; Neve et al. 2020c) unveiled that the refurbishment systems have the capacity to perform in this range. Neve et al. (2020c) further did a literature review of previous DW values from the literature, also confirming that a DW level at 63.3% is realistic. However, a LID=5 is likely not needed to manage a 'lean project,' as not all tools in the lean toolbox are required to optimize the project.

Neve et al. (2020c) go further and argues that having specific and ambitious DW targets to reach is an important part of creating motivation to change and, hereby, increase DW levels through lean implementation. Neve et al. (2020c) further explain that a key to increasing DW is bringing down variability in the project production system. That variability negatively influences performance in construction projects is also shown in Tommelein et al. (1999) and Lindhard (2014). Lean construction tools as the last planner system (Ballard 2000) is known to decrease variability. Thus seeing that higher LID degrees correlate with higher DW levels seems natural.

Having change targets and the methods to achieve them is an important step towards change and improvements. Understanding how a project system behaves is another key element in changing it, and both the work of Tommelein et al. (1999) and Lindhard (2014) is a testimony to that. Neve et al. (2020b) investigate system behaviors in renovation projects focusing on how time is used and identifies five specific system behaviors. Specifically, the system behavior, which shows no connection between the type of work and DW level, is highly relevant when setting DW targets to motivate lean implementation. Understanding this system behavior in renovation projects enables one to set overall targets for projects and, hereby, motivate the implementation of, e.g., lean tools listed in the LID evaluation form in figure 1.

As the above shows, the model is limited by a small sample. All data further stems from renovation projects thus might not be applicable to other construction production systems. Further, other management initiatives and evaluation forms have proven their ability to predict project-based production performance (Ballard 2000; Caldas et al. 2015; Nasir et al. 2016) and increase DW levels (CII 2010; Gouett et al. 2011; Hwang et al. 2018). Thus there's a risk that the LID scheme applied needs alterations or additions to cover the management initiatives that can increase DW fully. Therefore, further research is needed to expand knowledge on topics outlined in this section.

Investing in lean implementation or/and research in related areas such as an automated collection of WS data requires companies and national entities to see the potential as, e.g., economic. The work of Neve et al. (2020a) reveals that the economic potential of increasing DW with just 1% in North America is 5.4 billion dollars annually. Looking towards other work focusing on DW, only a 1% increase seems very conservative (Gouett et al. 2011; Hwang et al. 2018; Neve et al. 2020c). The continuing challenge of using the WS method is the current manual process of collecting data. Work by Teizer et al. (2020) is a step towards automated WS, and the potential of further research in this area is clear.

Implementing lean tools or other process optimization tools is by the authors seen as an essential initial step towards changing the construction industry. The authors do, though, believe that a more holistic and integrated approach is needed to solve the industry's problems. A well-proven holistic approach is integrated project delivery (IPD) (Fischer et al. 2017). IPD can be described as consisting of five elements (Neve et al. 2017) that consider the fundamental elements of a project with contract, culture, organization, Lean Construction, and building information modeling and recognizes that all elements are interdependent. This means that one cannot just solely focus on making the perfect contract and expect a successful project without also considering the remaining elements. IPD has proven itself to support innovation (Neve et al. 2017) and delivers projects on time and budget (Cheng et al. 2016), thus well-paved road forward.

CONCLUSION

Stagnation and decline in CLP have been documented in the USA, Canada, and EU. The development seen in CLP has considerable negative implications for the construction industry because labor cost constitutes up to 60% of the overall construction costs. Thus, knowledge is needed on how to change the current development in CLP.

It was found that the use of lean construction methods can increase CLE and, hereby, CLP in renovation projects. A strong positive correlation between the degree to which lean construction methods were implemented and CLE levels was documented by analyzing four renovation projects.

The results have implications for both academia and industry professionals. Academia now has initial results on which future research can be built. Industry professionals now have a better understanding and hereby argument for why lean construction methods must be implemented in future renovation projects.

The research was limited by a small sample size of four renovation projects. Thus, further research is needed to confirm further the effects in renovation projects but also other type of construction projects.

REFERENCES

Alarcón, L. F., Diethelm, S., Rojo, O., and Calderon, R. (2005). "Assessing the Impacts of Implementing Lean Construction." *Proc. 13rd Ann. Conf. Int. Group for Lean Sydney, Australia.*

AlSehaimi, A., Tzortzopoulos, P., and Koskela, L. (2009). "Last Planner System: Experiences From Pilot Implementation in the Middle East." *Proc. 17th Ann. Conf. Int. Group for Lean Constr., Taipai, Taiwan.*

Ballard, G. (2000). "The Last Planner System of Production Control." PhD Dissertation, School of Civil Engineering, University of Birmingham.

Buchan, R., Fleming, F. E., and Grant, F. E. K. (2006). Estimating for builders and quantity surveyors. MA, USA: Elsevier Butterworth-Heinemann.

Bølviken, T., Rooke, J., & Koskela, L. "The Wastes in Construction - A TFV Based Taxonomy." *Proc. 22nd Ann. Conf. Int. Group for Lean Constr., Oslo, Norway.*

Caldas, C. H., Kim, J.-Y., Haas, C. T., Goodrum, P. M., and Zhang, D. (2015). "Method to Assess the Level of Implementation of Productivity Practices on Industrial Projects." J. Constr. Eng. Manage. 141 (1).

Cheng, R., Johnson, A. J., Allison, M., Monson, C., Staub-French, S., and Dossick, C. S. (2016). "MOTIVATION AND MEANS: How and Why IPD and Lean Lead to Success." IPDA: Integrated project Delivery Alliance & LCI

CII (2010). "Guide to activty analysis." Construction Industry Institute (CII)
Cohen, J. (1988). Statistical power analysis for the behavioral sciences. US: Lawrence Erlbaum Associates, Publishers.
Cohen, J. (1992). "A power primer." Psychological bulletin. 112 (1): 155-159.
Evinger, J., Mouflard, C., and Seppänen, O. (2013). "Productivity Effects of Starting as Early as Possible in Hospital Construction." *Proc. 21st Ann. Conf. Int. Group for Lean Constr., Fortaleza, Brazil.*
Farmer, M. (2016). "The Farmer Review of The Uk Construction Labour Model." Construction Leadership Council.
Fischer, M., Khanzode, A., Reed, D., and Ashcraft, H. W. (2017). Integrating project delivery. USA: John Wiley & Sons.
Gong, J., Borcherding, J. D., and Caldas, C. H. (2011). "Effectiveness of craft time utilization in construction projects." J. Constr. Manage. Econ. 29 (7): 737-751.
Gouett, M. C., Haas, C. T., Goodrum, P. M., and Caldas, C. H. (2011). "Activity Analysis for Direct-Work Rate Improvement in Construction." J. Constr. Eng. Manage. 137 (12): 1117-1124.
Heinonen, A., and Seppänen, O. "Takt Time Planning: Lessons for Construction Industry from a Cruise Ship Cabin Refurbishment Case Study." *Proc. 24th Ann. Conf. Int. Group for Lean Constr., Boston, USA.*
Hwang, B.-G., Krishnankutty, P., Zhu, L., Caldas, C. H., Shounak, A., and Mulva, S. (2018). "Improving Labour Productivity in Process Construction Maintenance and Shutdown/Turnaround Projects." Int. J. of Constr. Manage.: 1-15.
Kazaz, A., Manisali, E., & Ulubeyli, S. (2008). "Effect of basic motivational factors on construction workforce productivity" J. of Civ. Eng. & Mgmt. 14 (2): 95-106.
Kemmer, S. (2018). “Development of a Method for Construction Management in Refurbishment Projects.” Diss., The University of Huddersfield, Huddersfield, UK.
Kenley, R., and Seppänen, O. (2010). Location-Based Management for Construction - Planning, schedueling and control. UK: Spoon Press.
Koskela, L. (1992). "Application of the new production theory to construction."
Koskela, L. (2000). "An exploration towards a production theory and its application to construction." PhD, VTT Technical Research Centre of Finland.
Lerche, J., Neve, H., Pedersen, K. B., Wandahl, S., and Gross, A. (2019b). "Why Would Location-Based Scheduling Be Applicable for Offshore Oil and Gas Construction?" *Proc. 27th Ann. Conf. Int. Group for Lean Constr., Dublin, Ireland.*
Lerche, J., Neve, H., Wandah, S., and Gross, A. (2020b). "Continuous Improvements at Operator Level." Journal of Engineering , Project and Production Management. 10 (1): 64-70.
Lerche, J., Neve, H. H., Ballard, G., Teizer, J., Wandahl, S., and Gross, A. (2020a). "Application of Last Planner System to Modular Offshore Wind Construction." Journal of Construction Engineering and Management. 146 (11)
Lerche, J., Seppänen, O., Pedersen, K. B., Neve, H., Wandahl, S., and Gross, A. (2019a). "Why Would Location-Based Scheduling Be Applicable for Offshore Wind Turbine Construction?" *Proc. 27th Ann. Conf. Int. Group for Lean Constr., Dublin, Ireland.*
Lindhard, S. (2014). "Understanding the Effect of Variation in a Production System." J. Constr. Eng. Manage. 140 (11): 04014051.
Lindhard, S., and Wandahl, S. (2014). "Scheduling of large, complex, and constrained construction projects – an exploration of LPS application." International Journal of Project Organisation and Management. 6 (3): 237-253.

Nasir, H., Haas, C. T., Caldas, C. H., and Goodrum, P. M. (2016). "An Integrated Productivity-Practices Implementation Index for Planning the Execution of Infrastructure Projects." J. of Infrastructure Systems. 22 (2)

Neve, H., and Wandahl, S. (2018). "Towards identifying Making-Do as lead Waste in Refurbishment projects." *Proc. 26th Ann. Conf. Int. Group for Lean Constr., Chennai, India.*

Neve, H., Wandahl, S., and Lerche, J. (2020d). "Feedback Loop: The missing link in activity analysis." In Proc., 10th EPPM conference.

Neve, H., Wandahl, S., Lindhard, S., Teizer, J., and Lerche, J. (2020a). "Determining the relationship between direct work and construction labor productivity in North America: Four decades of insights." J. Constr. Eng. Manage. 146 (9)

Neve, H., Wandahl, S., lindhard, S., Teizer, J., and Lerche, J. (2020b). "Learning to see value-adding and nonvalue-adding work time in refurbishment production systems." In Journal of Construction Engineering and Management, 146(9).

Neve, H. H., Wandahl, S., Kaeseler, S. M., and Tandrup, A. (2017). "INTEGRATING IPD AND EXPLORING POTENTIALS." In Proc., 33rd ARCOM.

Seppänen, O. (2014)."A Comparison of Takt Time and LBMS Planning Methods." *Proc. 22nd Ann. Conf. Int. Group for Lean Constr., Oslo, Norway.*

Seppänen, O., Ballard, G., and Pesonen, S. (2010). "The combination of last planner system and locationbased management system." LCJ. 6 (1): 43-54.

Seppänen, O., Evinger, J., and Mouflard, C. (2014). "Effects of the location-based management system on production rates and productivity." Construction Management and Economics. 32 (6)

Smith, R. (2013). Estimating and tendering for Building work. NY, USA: Routledge.

Teizer, J., Neve, H., Li, H., Wandahl, S., Koenig, J., Ochner, B., König, M., and Lerche, J. (2020). "Construction Resource Efficiency Improvement by Long Range Wide Area Network Tracking and Monitoring." Automation in Construction.

Thompson, S. K. (1987). "Sample size for estimating multinomial proportions." The American Statistician. 41 (1): 42-46.

Thompson, S. K. (1992). Sampling. Hoboken, New Jersey, USA: Wiley.

Tommelein, I. D., Riley, D. R., and Howell, G. A. (1999). "Parade Game: Impact of Work Flow Variability on Trade Performance." J. Constr. Eng. Manage. 125 (5): 304-310.

Wandahl, S. (2014). "Lean Construction with or without Lean – Challenges of Implementing Lean Construction." *Proc. 22nd Ann. Conf. Int. Group for Lean Constr., Oslo, Norway.*

Cossio, N.A. and Salazar, L.A. (2021). "Implementing elements of Last Planner® System in the Orchestra Wheel method" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 657–666, doi.org/10.24928/2021/0108, online at iglc.net.

IMPLEMENTING ELEMENTS OF LAST PLANNER® SYSTEM IN THE ORCHESTRA WHEEL METHOD

Natalia A. Cossio[1] and Luis A. Salazar[2]

ABSTRACT

Due to the high costs and low level of productivity of high-rise building constructions, it is necessary to plan the Tower Crane's stay on site. In a first instance and to establish a baseline, a survey was conducted along with a Panel of Professional Experts to validate how the Tower Crane works and the performance indicators mostly used in Chile. The authors then developed a planning methodology, which has its origin in the "Orchestra Wheel" method but incorporates elements from the Last Planner® System. The primary aims were to achieve strategic planning and greater logistical detail to program the crane, generating greater control of the fulfillment of tasks, adding stages for better planning, and improving productivity. This new method was validated with an expert in the "Orchestra Wheel" methodology and with a Panel of academic experts and researchers who specialize in LPS—posing as future research, implementing this methodology in different high-rise building construction projects.

KEYWORDS

Planning system, orchestra wheel, Last Planner® System, high-rise building.

INTRODUCTION

CONTEXT

The construction industry is among the most relevant economic sectors worldwide, providing employment to 7% of the world´s working age population, generating expenditures in goods and services that reach 13% of the world's GDP (McKinsey 2017). However, this sector lags far behind other industries, as labor productivity growth in construction has only been 1% in the last 20 years (McKinsey 2017; The World Bank 2020). The above has led to rise in construction costs due to the low level of productivity because of the large number of activities that do not add value to the final product (Salazar et al. 2020).

Therefore, the construction industry, particularly regarding high-rise constructions, finds itself in the need and obligation to create new forms of planning, including performance measurement. Productivity must be measured to control and maximize the value of production by minimizing losses (Ballard and Tommelein 2016).

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NEED AND RELEVANCE OF THE RESEARCH

In the '80s, in France, a construction company noticed the problem of productivity in construction and created a planning methodology for high-rise buildings by optimizing the use of the Tower Crane. Hence, the main problem in the stage of thick and finished works is the low productivity of the lifting of materials due to the large number of stops and waits. This methodology, known as "Orchestra Wheel" (OW), consists of saturating the Tower Crane(s), scheduling their use and the rotation of materials, and thus guaranteeing compliance with simple and repetitive series of operations (daily production unit) under the same construction rhythm. Its name comes from the fact that the Tower Crane directs the work, giving it a continuous constructive rhythm throughout the team's stay, just like a conductor conducts a concert. In addition, it has a circular movement and it is based in its axis of rotation, just like a wheel. In this case, the idea is that the work revolves around the crane as the main axis (Muttoni 2015). Subsequently, another construction company in Colombia adopted this methodology, managing to improve its productivity by strengthening the planning and integration of the processes of all the areas that participate in the planning and construction of the work (Muttoni 2015).

On the other hand, in the '90s, Ballard and Greg Howell developed The Last Planner® System (LPS) to better integrate Lean principles in construction (Salazar et al. 2020). LPS is based on reducing workflow uncertainty and maximizing performance due to reliable planning (Ballard 2000), improving management of commitments in stabilizing the work flow, reducing variability and improving the operation of the processes (Álvarez Pérez et al. 2019). Therefore, the authors propose to integrate both planning systems since both are based on people, the trust of teamwork, and the efficiency of its elements, understanding that the fulfillment of processes in a timely and optimal way benefits both the work in which it is working as well as each collaborator who works in it (Álvarez Pérez et al. 2019; Muttoni 2015).

STATE OF THE ART AND PRACTICE

According to the IGLC state of the art, we found seven studies addressing high-rise building constructions, focusing mainly on productivity, planning, reduction of project duration and associated costs, how to deal with changes in client-initiated floor designs, environmental impacts, workflow monitoring, and advanced formwork systems (Bae and Kim 2008; Esquenazi and Sacks 2006; Ibrahim and Hamzeh 2015; Kemmer et al. 2008; Linnik and Berghede 2013; Maia et al. 2016; Priven et al. 2014). In addition, from these studies published in the IGLC, we found two studies that propose different planning methods and tools for high-rise construction, in both studies it is confirmed that the Critical Path Method (CPM) is the most currently used method (Aburto 2016; Toro 2017).

Moreover, we found studies in other countries where the planning, productivity, location, interference between towers, and operating costs of the Tower Crane are discussed (Al Hattab et al. 2014; Mena 2007). Still, none in conjunction with the OW or LPS method; Nevertheless, the research found helped us understand how it has worked in other countries and how to improve the Tower Crane's productivity in high-rise building constructions.

METHODOLOGY "ORCHESTRA WHEEL" (OW)

There is practically no literature apart from the publication of Muttoni (2015), so we decided to contact a collaborator of the Colombian construction company who had already implemented this methodology, and according to the above we could determine that the OW methodology is a strategic planning, with a scope of greater logistical detail, which rigorously schedules the use of the Tower Crane and the internal rotation of materials to guarantee compliance with the daily production unit. It is a method that requires measuring and collecting performance data, which allow obtaining the production capacity with a synchronization of all the variables. Additionally, OW is concerned with having an incentive plan for workers so that they have a better income and therefore, generate a better work environment and thus improve productivity.

PURPOSE OF THE INVESTIGATION AND WHY IT IS NEW KNOWLEDGE

Tower Cranes' implementation has transformed the perception of high-rise building constructions; the Tower Crane is no longer just load-lifting equipment but it is an essential instrument to give flow to construction processes, maximizing the use of time in productive tasks.

The main objective of this research is to develop a methodology for implementing elements of LPS in the OW method, to improve the planning of construction projects of high-rise buildings and thus increase productivity, since, as previously mentioned, the OW methodology is based on enhancing project productivity by saturating the Tower Crane (Muttoni 2015).

Although the OW methodology has worked well in France and Colombia (Muttoni 2015), it has deficiencies in achieving commitments in planning, given that it does not keep a record of planning and productivity indicators, identification record nor a release of restrictions record (as discussed with the Colombian collaborator), and therefore LPS provides those maneuvering tools that lead to an even more adequate level of control and detail (Ballard 2000; Álvarez Pérez et al. 2019).

As there is currently no research that relates LPS with OW Methodology, this study is a contribution to the planning and improvement of productivity of the Tower Crane.

RESEARCH METHOD

DESIGN SCIENCE RESEARCH

For the development of this research, the authors used Design Science Research (DSR), which is a methodological approach that tries to solve a problem in the real world, from the innovative creation of an "artifact" that has outstanding theoretical and practical contributions (Lukka 2003), given that the final purpose is to perform an Applied Science/Engineering (AS/E) to produce a methodology (artifact) (Briggs and Schwabe 2011).

Therefore, this research consists of five primary activities proposed by Salazar et al. (2020), based on: 1) Discovery of problems and opportunities through an exhaustive analysis of the context; 2) In-depth knowledge of the subject, state of the art and practice; 3) Design and construction of artifact; 4) Evaluation of the artifact to find a satisfactory solution; and 5) Validation of the artifact, through a survey, expert panels and analysis of results.

This artifact was developed through four cycles, based on the five activities described. The first cycle was set from the problem encountered, the low productivity in the construction area, where we looked for opportunities to solve the problem through strategic planning of the Tower Crane to improve construction projects' productivity in high-rise buildings. To find out which planning methods and productivity indicators are used and controlled in high-rise constructions in Chile, the authors created a survey for professionals with experience in the high-rise building sector; the survey was evaluated and validated by a panel of academic experts (Delphi Method), to be later applied and subsequently analyzed. This leads to cycle number two, where it is necessary to know if the Tower Crane is planned in the time of permanence at work, which was reflected in a process diagram and was later evaluated and validated by a panel of professional experts with extensive practical experience in high-rise building constructions and the use of the Crane-Tower (Delphi Method). After that comes the third cycle, where the authors realized that the current form of planning is not the optimal one to solve productivity problems, so we evaluated the state of practice, finding that there is a methodology that by saturating the Tower Crane it improved productivity, which is called "Orchestra Wheel" (Muttoni 2015). Therefore, we designed a process diagram with this methodology, validating it with the Colombian construction company's collaborator. To improve the OW methodology, the fourth cycle is complemented with LPS elements, which provide implementations and strategic planning controls (Ballard and Howell 2003). The LPS elements are entered into the Orchestra method's process diagram where a panel of academic experts and researchers (Delphi Method), who have worked and studied LPS in different investigations and practical implementations, evaluated and validated it.

DELPHI METHOD

The Delphi Method consists mainly of collecting expert judgments on a topic to evaluate and validate the process diagrams used during the investigation to determine each of the summoned experts' opinions in a collective and superior review (Caldera 2018). In the panel of professional experts, relevant information emerged to consider the solution to the productivity problem, thus adding essential aspects when planning the Tower Crane's use. To mention important considerations: assembly and disassembly, bracing, maintenance, security, among others.

SURVEY: CURRENT PRODUCTIVITY PLANNING AND CONTROL

To understand the real planning and productivity control problems of the Tower Crane, a survey containing closed questions (yes or no) was carried out, in Likert scale, and open-ended (justified). This survey took place online due to the pandemic.

The survey was conducted with various professionals in the area of high-rise construction: 6 Project Managers (PM), 7 Site Administrators (SA), 3 Field Managers (FM), 3 Technical Offices (TO), 3 Planners (P), and 3 others. Where more than 50% of the respondents have more than 10 years of experience in the sector. The main idea of the survey was to know how they currently work with the Tower Crane. Based on the answers obtained, 90% of the respondents agreed that it is essential to measure productivity and plan exclusively with the Tower Crane. However, only 36% currently measure productivity and plan for the Tower Crane.

CURRENT WORK PROCESS DIAGRAMS AND METHODOLOGY "ORCHESTRA WHEEL"

As previously described, during the investigation, the authors developed a process diagram which represents, in a preliminary way, how Chile is currently working in terms of planning and production control, specially the operation of the Tower Crane. The diagram was presented to a panel of professional experts to generate contributions, evaluate and later validate the proposed artefact.

After that, the authors created an activity diagram from Muttoni (2015) presentation, which they later validated thanks to the conversation with the Colombian construction company's collaborator. According to Muttoni (2015) and the expert in OW, the method is divided into 3 phases, which are explained below:

1. **Starting point:**

It begins at least three months before the start of the construction, with a transfer meeting, in which the most important background of the project must be obtained. Orchestra team members should provide planning and strategies for selecting the most productive methods.

Later, meetings are held (two weeks maximum), where the team studies all the antecedents before presenting themselves in the sessions, so that the meetings can hold question and answer sessions.Then the tasks and managers are defined, the suppliers are integrated in order to plan the supply and make strategic decisions, people who meet the profiles for the operational functions of the project are sought, and the 4M are defined: 1) Machinery: Crane -Tower, formwork and others; 2) Method: daily productive unit, sequence and rotation, Tower Crane saturation, logistics; 3) Labor: formation of crews, training; and 4) Materials: histograms, supply frequency, packaging units, negotiation with suppliers.

Finally, this phase is concluded by establishing the schedule, where the schedule and Gantt diagram are made with all the detailed activities. The Starting Point is defined with their respective time limits and budget, prioritizing the activities (20% of the actions represent 80% of the result).

2. **Programming studies:**

This second phase begins with the Work Quantities, where the following are defined: 1) the daily production unit; 2) the necessary resources for the execution of the project; and 3) quantity of material and packaging unit. Then, we proceed with the Definition of construction systems, where the best formwork systems, prefabricated, stairs, collective protections and packaging units are selected, in this way the most productive combination is chosen.

Afterwards, we continue with the Cadence Calculation, which is a tool that allows determining the daily workload of the Tower Crane with which the productive unit defined in this process is achieved. This begins two months after the “Transfer Meeting”. The capacity and dimensions of the Tower Crane are defined according to the selected construction systems. The number of cycles is calculated with the amount of material and weight to be transported, and depending on the results obtained, the number of Tower Cranes and their respective specifications are defined.

It continues with the Installation Plan (layout), which defines the location of the Crane (s), with the provisional facilities, loading and unloading areas, vehicle circulation routes within the project, materials storage areas, collection of waste, and finally, safety zones and routes. Then, we continue with the Planning of the schedule, where a detailed planning of each of the activities that will be carried out day by day is created. The respective schedules and execution times are designed in order to know how many hours a day are required to move each material, and thus continue with the next stage, having the necessary information.

Finally, this second phase is finished with the definition of daily material rotation. In this process, a list of materials is drawn up, which will be included in each daily production unit. These materials must be transported just in time to the work fronts, before the execution of each activity, by being unloaded directly from the truck to the site where they will be used.

3. **Application and safety history:**

At the same time, four very important concepts are being worked on, constantly on site: 1) Detailed rotation; 2) Safety; 3) Time Budget; and 4) Work sequence diagrams. Each team progresses in its activities at a work rate that allows the Tower Crane to be used in the assigned time and place. In order to comply with the hours of use of the Tower Crane, the exact hours in which the planned activities will be carried out are assigned and established to achieve the synchronization and the programmed work rhythm.

Similarly, regarding the management and productivity monitoring, the next follow-ups are carried out in parallel: 1) Planning and execution of material rotations; 2) Continuous improvement strategies; 3) Execution of the planning of the saturation of the Crane; 4) Performance of the workforce; and 5) Decisions on safety and quality.

At the end of the three phases, we have the “Return of the experience”, where the lessons learned are documented and consolidated. This is the most important step, it serves for all the company's processes, since it allows learning from experience and guarantees continuous improvement.

ORCHESTRA WHEEL METHODOLOGY PROPOSAL WITH LAST PLANNER® SYSTEM ELEMENTS

Starting from the original OW methodology, for each phase, we propose the integration of the following LPS elements: 1) Starting point, integrating the master planning and the main activities through Pull Planning; 2) Programming study, merge Lookahead, managing and controlling restrictions; and 3) Application and security history, combine Weekly Planning and Daily Planning, managing commitments and detecting deviations.

Therefore, we included the LPS elements mentioned within the process diagram of the Orchestra method, and we presented them to a panel of experts, academics and researchers, with a vast knowledge of LPS, in theory, and application, to contribute, evaluate and validate the proposed diagram (Figure 1).

Each phase of the OW + LPS diagram is detailed below:

1. **Master plan through Pull Planning:**

Like the original methodology, it must be started at least three months before the start of the construction. It begins with a transfer meeting to empower the Orchestra team with all the information of the under study project. The Orchestra team will arrive at the transfer meetings with all the background studies since, in 2 weeks, they must clear up doubts and propose solutions to possible problems.

Besides, according to the original methodology, the 4M must also be defined: 1) Machinery; 2) Method; 3) Labor; and 4) Materials.

Preliminarily, the team must create the Master Plan or Schedule through Pull Planning by dividing the plan into different proposed stages to develop more detailed work plans, clearly defining the objectives (Koskela et al. 2010). Two tools that contribute directly to the exhaustive list of tasks are the definition of duration and the crane’s movement times through the determination of: 1) The quantities of work; and 2) The construction systems.

When the Master Plan of the work is approved, the Tower Crane cadence must be calculated, defining its capacity and dimensions. This is how the Tower Crane's daily workload is determined to achieve the desired productive unit.

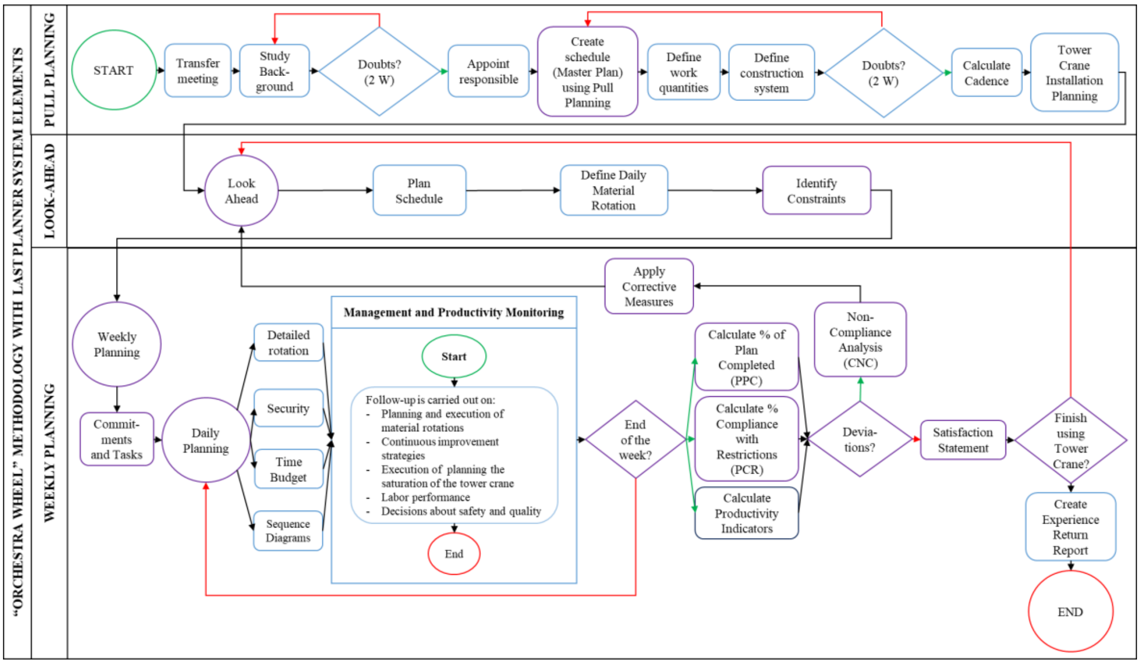

Figure 1: Diagram of the "Orchestra Wheel" methodology processes with LPS elements, validated by a panel of academic experts (Own elaboration).

Finally, the Installation Plan is carried out, defining the Tower Crane (s) location for its subsequent disposal on the ground.

2. **Identification of restrictions through Look-ahead:**

At this stage, the orchestra team must anticipate what will happen in the future, that is, generate an anticipated planning, and the activities to be studied in this way are: 1) Planning the schedule, defending it and also calculating execution times of each one of the tasks to be performed daily; and 2) The rotation of the material, detailing how, when and where the materials should be transferred before their use in each activity, always taking into account the daily production unit. Subsequently, the restrictions are identified, which will be modified according to the work's needs, calculating the percentage released (or compliance, PCR) in each one.

3. **Control of commitments and planning and productivity indicators through Weekly and Daily Planning:**

This phase begins with Weekly Planning and Daily Planning. The first thing is to commit to periodic weekly and daily meetings, so that through iterative control, all programmed processes are fulfilled (Koskela et al. 2010). In these meetings, commitments are established regarding safety, quality, resources, construction methods, and any problem in the project. The original methodology works in parallel: 1) Detailed rotation; 2) Security; 3) Time Budget; and 4) Work sequence diagrams.

In Management and Productivity Monitoring, deviations from scheduled tasks are also periodically measured and recorded to later review the Non-Compliance Analysis (NCA) (Sabbatino 2011). With this information, it is possible to analyze the improvement strategies to apply the corrective measures in the next iteration (weekly or daily according to the corresponding process). Also, the planning and correct execution of the tasks must be continuously monitored, mainly the Tower Crane, labor performance, and decisions on safety and quality, which are also included in the analysis of possible restrictions of the construction site (Ballard and Howell 2003; Koskela et al. 2010).

At the end of a work day on the site, it is consulted if it is the end of the week. If the week does not end, the cycle is returned to the Daily Planning; If the week ends, the planning and productivity indicators are calculated.

The planning indicators used will be the PPC and the PCR since they generate a release of restrictions in an appropriate time to have a good performance in the short term (Sabbatino 2011). For productivity indicators, according to Caldera (2018), The factors that cause productivity decreases must be taken into account: 1) Use of overtime; 2) Program compression; 3) Type of project; 4) Security; 5) Quality; 6) Management factors; 7) Manpower equipment; 8) Motivation; 9) Supervision; 10) Materials and tools; 11) Project management factors; 12) Natural factors; 13) Political factors. Therefore, the authors suggest that at least one performance indicator, which directly affects the construction site, must be measured in each area. On the other hand, it is also suggested, according to the results of the survey, that the work be controlled with Curve “S” or Curve of Progress, since a follow-up can be carried out that allows establishing if the project is ahead or behind according to what is expected. In addition, it is also possible to analyze project trends and help make preventive and/or corrective decisions.

According to the result of the indicators mentioned, it is later verified if there are deviations in these; if there are deviations, the non-compliance analysis is made, the respective corrective measures are developed and applied, and a return to the Lookahead planning is carried out so as to re-identify restrictions and go through the Weekly Planning and the Daily Planning again; If there are no deviations, the Declaration of Satisfaction of compliance with the schedule is made. It is then verified if the Tower Crane is still necessary; if required on-site, the cycle is returned to the Lookahead schedule, restarting the weekly and daily control cycle. When the Tower Crane is no longer required on-site, it is uninstalled. A report is created with all the information on the Tower Crane's operation, compiling all the documents and experiences learned, which helps future construction sites to understand and learn from the previous occasion. With this, continuous planning and productivity improvements of the project are guaranteed, thus, terminating the participation of the Tower Crane in the project.

DISCUSSION OF THE ARTIFACT

According to the results obtained from the surveys and the Panel of Professional Experts, we were able to determine the Tower Crane's planning system in high-rise building projects in Chile. Also, we managed to implement elements of the Last Planner® System in the “Orchestra Wheel” methodology, validating this proposal through a Panel of Academic Experts. Thus, creating an Orchestra Wheel Method 2.0, which achieves greater control and management of commitments in the construction process.

With the above mentioned, this method has great potential to be generalizable worldwide. It must still be applied in real projects since it was only validated by a panel of experts (Delphi Method) and could not be implemented in an actual project. Furthermore, the pandemic being experienced worldwide has caused quarantines and, therefore, it prevented the researchers from carrying out the practical implementation.

CONCLUSIONS

Due to the low productivity of construction, the authors proposed the integration of the unknown "Orchestra Wheel" method and the famous "The Last Planner® System, since both are concerned with improving project productivity and are based on people, the trust of the work team and the efficiency of its elements, understanding that the fulfillment of processes in a timely and optimal manner benefits both the work on which we are working and each collaborator who works on it. The authors, for this research, used two research methods: 1) DSR: a methodological approach that tries to solve a problem in the real world, based on the innovative creation of an "artifact" that has great theoretical and practical contributions, which is just what the authors had as their objective; and 2) The Delphi Method: consists mainly of collecting expert judgments on a topic, which contributed to the evaluation and validation of the process diagrams and the methodology proposed in this research. The main contribution was creating the methodological proposal for the implementation of the elements of LPS in the OW method to improve the planning of projects in high-rise buildings that use Tower Cranes. The main limitation of this research was that the system could not be implemented in a case study. Furthermore, this methodological proposal is limited to a single Tower Crane. However, although the proposed diagram could be adapted to two or more Cranes- Tower, it is not shown in the present investigation. Finally, as future research, we offer to implement this new methodology in different construction projects in high-rise buildings in other countries around the world.

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REFERENCES

Aburto, A. (2016). "Desarrollar un manual de procedimientos para la planificación de obras de construcción de edificios." Universidad de Chile.

Álvarez Pérez, M. Á., Soler Severino, M., and Pellicer Armiñana, E. (2019). "An improvement in construction planning: Last Planner System." *Building & Management*, 3(2), 60.

Bae, J.-W., and Kim, Y.-W. (2008). "Assessing the Environmental Impacts of Lean Supply System: A Case Study of High-Rise Condominium Construction in Seoul, Korea." *16th Annual Conference of the International Group for Lean Construction, IGLC 2008*, Manchester, UK, 735–742.

Ballard, G. (2000). "The Last Planner System of Production Control." The University of Birmingham.

Ballard, G., and Howell, G. A. (2003). "An Update on Last Planner." *11th Annual Conference of the International Group for Lean Construction*, Virginia, USA, 1–13.

Ballard, G., and Tommelein, I. (2016). "Current Process Benchmark for the Last Planner System." *Lean Construction Journal*, 13(1), 57–89.

Briggs, R. O., and Schwabe, G. (2011). "On Expanding the Scope of Design Science in IS Research." *Service-Oriented Perspectives in Design Science Research*, Berlin, Heidelberg, 92–106.

Caldera, F. (2018). “Propuesta y estudio de método de medición de productividad para obras civiles.” Universidad Técnica Federico Santa María.

Esquenazi, A., and Sacks, R. (2006). “Evaluation of Lean Improvements in Residential Construction Using Computer Simulation.” *14th Annual Conference of the International Group for Lean Construction*, Santiago, Chile, 137–149.

Al Hattab, M., Zankoul, E., and Hamzeh, F. (2014). “Optimizing joint operation of two tower cranes through look-ahead planning and process simulation.” *22nd Annual Conference of the International Group for Lean Construction, IGLC 2014*, Oslo, Norway, 535–546.

Ibrahim, H. A. A., and Hamzeh, F. R. (2015). “Expected Lean Effects of Advanced High-Rise Formwork Systems.” *23rd Annual Conference of the International Group for Lean Construction*, Perth, Australia, 83–92.

Kemmer, S. L., Heineck, L. F. M., and Alves, T. da C. L. (2008). “Using the Line of Balance for Production System Design.” *16th Annual Conference of the International Group for Lean Construction, IGLC 2008*, Manchester, UK, 299–308.

Koskela, L., Stratton, R., and Koskenvesa, A. (2010). “Last planner and critical chain in construction management: Comparative analysis.” *18th Annual Conference of the International Group for Lean Construction, IGLC*, Haifa, Israel, 538–547.

Linnik, M., and Berghede, K. (2013). “An Experiment in Takt Time Planning Applied to Non-Repetitive Work.” *21th Annual Conference of the International Group for Lean Construction, IGLC 2013*, Fortaleza, Brazil, 609–618.

Lukka, K. (2003). “The Constructive Research Approach.” *In: Case study research in logistics*, Series B(June), 83–101.

Maia, L. O. de M., Saggin, A. de B., Albuquerque, M. M. P., and Mourão, C. A. M. do A. (2016). “Analysing the Acceptance of Customizable Attributes: A Case Study of a Construction Company in Fortaleza, Brazil.” *24th Annual Conference of the International Group for Lean Construction*, Boston, Massachusetts, USA.

McKinsey. (2017). “Reinventing Construction: A Route To Higher Productivity.” *McKinsey & Company*, (February), 20.

Mena, J. (2007). “Estudio de productividad y rendimientos en procesos constructivos, mediante el uso de Grúa Torre.” Instituto Tecnologico de Costa Rica.

Muttoni, F. (2015). “Metodología de gestión ‘Rueda Orquesta’ y proceso de saturación de Torre-Grúa.” *IEEM Revista de Negocios*, 25.

Priven, V., Sacks, R., Seppänen, O., and Savosnick, J. (2014). “A Lean Workflow Index for Construction Projects.” *22nd Annual Conference of the International Group for Lean Construction, IGLC 2014*, Oslo, Norway, 715–726.

Sabbatino, D. (2011). “Directrices y recomendaciones para una buena implementación del Sistema Last Planner en proyectos de edificación en Chile.” Universidad de Chile.

Salazar, L. A., Arroyo, P., and Alarcón, L. F. (2020). “Key Indicators for Linguistic Action Perspective in the Last Planner® System.” *Sustainability*, 12(20), 8728.

The World Bank. (2020). “World Development Indicators | DataBank.” https://databank.worldbank.org/source/world-development-indicators (Oct. 25, 2020).

Toro, C. (2017). “Propuesta de mejoramiento para planificación, programación y control de obras de edificación en altura.” Andres Bello University.

Lerche, J., Neve, H., Gross, A., and Wandahl, S. (2021). "A Model to Link Takt Schedules and Operations in Construction" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 667–676, doi.org/10.24928/2021/0111, online at iglc.net.

A MODEL TO LINK TAKT SCHEDULES AND OPERATIONS IN CONSTRUCTION

Jon Lerche[1] Hasse Neve[2], Allan Gross[3], and Søren Wandahl[4]

ABSTRACT

This research paper presents a model for construction that can bridge the gap between the schedules (takt planning or location-based management) and the on-site operations using visual management (VM). The model was developed using design science. It was shaped in a modular construction environment and evaluated theoretically. The knowledge base consists of; takt planning, location-based scheduling (LBS), plan-do-check-act, and visual management. The evaluation of the model revealed that a generic model could accommodate both schedule methods and incorporate continuous learning. The discussion provided knowledge about the industrial implication and how managers could apply this in Takt or LBS planned and controlled projects. This research further contributes to the literature by extending the existing knowledge of scheduling and visual management.

KEYWORDS

Design science, location-based management (LBM), takt planning (TP), visual management, work structuring.

INTRODUCTION

Visual Management (VM) in construction has taken different forms through the years (Tezel et al. 2016), Leth et al. (2019) revealed how it is applicable on a strategic level when implementing "hoshin kanri" in mega projects. Different models of VM have been investigated in various case studies, revealing the industry implications and numerous visual expressions (Valente et al. 2016). Valente et al. (2017) found that VM systems tend to be static, lack process transparency, and fail to involve the workers performing the tasks. Finding less than 5% had created a link between the planning function and the visual expression. Reinbold et al. (2020) support this and expand how it affects decision-making among managers and workers—revealing a gap in understanding how to include VM with a planning function that engages and encourages learning among the actors. This research was further motivated by the stagnation of labor productivity within construction (Neve et al. 2020) and that Lerche et al. (2020) showed how VM led to increases in productivity.

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The literature review made it evident that multiple case studies present implementation of VM in numerous expressions and also in relation to different planning methods such as Takt at operators level in modular construction (Lerche et al. 2019; Lerche et al. 2020), Mariz et al. (2019) used VM to visualize Kanban for planning the construction of a dam. (Brandalise et al. 2018) used VM for Kanban combined with a performance board, where Farzad and Cameron (2019) used it for deliverable matrixes. Wesz et al. (2018) presented a complete project VM adaption of Last Planner System (LPS) (Ballard 2000), and Mota et al. (2019) instead defined the VM as part of the collaborative planning alone. Jabbari et al. (2020); Singh et al. (2020), on the other hand, presented digital solutions for organizing Takt zones according to work density without practical application. Despite Takt and Kanban being seen as part of VM models, limited knowledge exists of these combined as part of a VM model on project levels. These findings reveal a gap in the body of knowledge, where a model accommodating practical applications for takt planning or LBS at the project level could contribute.

The objectives of this research are to provide a production model which accommodates the following:

- facilitates interaction between managers and workers,
- practical application of takt planning or LBS at the project level,
- provides a clear overview of activities and labor resources.

As this research project is within the design science domain, the paper has the following structure to meet the objectives. First, the introduction frames the problem, the background the presents the literature review, and the method that describes the research framework. The results then present the model and its theoretical adoption, leading to the evaluation and discussion of its relevance to the literature, and finally, the conclusion reveals the potential implications.

BACKGROUND

The artifact is composed of the knowledge base, and it is meant to improve the application of Takt and LBS in a construction environment. Hence, the background displays Takt and LBS's topics as the planning methods, second the visual management, and third the learning culture. Together these topics form the knowledge base.

TAKT PLANNING AND LOCATION-BASED SCHEDULING

When graphically presented, Takt planning and location-based scheduling (LBS) both rely on tasks moving through locations or designated space (production areas), generating a continuous visual flow, strengthening the focus on the flow of operations and processes. Within each project, the location structures can be determined according to workload, which applies to both LBS (Lerche et al. 2019; Lerche et al. 2019) and Takt (Jabbari et al. 2020; Lehtovaara et al. 2019; Singh et al. 2020), in particular, the Takt time as described by Frandson and Tommelein (2016).

When Frandson et al. (2015) compared Takt and LBS, they found them to have similar capabilities;

- continuous flow production areas
- ability to trade scope

The two methods differentiate when it comes to buffering and controlling; first, we address the four buffer types listed here; 1. Time, 2. Capacity, 3. Space, and 4. plan buffers.

For buffering, LBS utilizes 1,3, and 4, whereas Takt utilizes 2,3, and 4. Takt further underload the activities, creating a capacity buffer. For controlling the takt and LBS, Frandson et al. (2015) argue LBS to have a more engineered approach and decentralized approach, where Takt relies on verifying the actual area completion.

VISUAL MANAGEMENT

Visual management on a construction site is not limited to visual boards, it also encompasses visual aids in the environment (Brady et al. 2012; Brandalise et al. 2018; Farzad and Cameron 2019; Reinbold et al. 2020; Tezel et al. 2016; Tezel et al. 2011; Valente et al. 2016; Wesz et al. 2018), our focus here is on VM production boards or models. According to Tezel et al. (2016), VM has nine functions in total, mentioned here below;

- “Discipline,”
- “On-the-job training (OJT),”
- “Job facilitation,”
- “Process transparency,”
- “Continuous improvement,”
- “Management-by-facts,”
- “Simplification,”
- “Creating a shared ownership and the desired image,” and
- “Unification and creating a boundaryless organization.”

1,2 and 3 are related to the behavior of the managers and workers, 4,5,6 and 7 are associated with the structure of the processes and plan, 8 and 9 are related to the organizational values. Fiallo C and Howell (2012) focused on 4, 6, and 7 when they presented project drawings as part of the Takt plan to better overview workers. Tezel et al. (2010) supports this and stretch the importance of making VM accessible in the proximity of the area needed, which further supports Tezel et al. (2013) finding that VM could increase project safety by tracking workers who are working in or around hazardous environments.

CONTINUOUS LEARNING AND IMPROVEMENT

Whether seen in production or construction, the Deming cycle of Plan-Do-Check-Act (PDCA) is a method to ensure management of quality through continuous improvements (Deming 2000; Koskela et al. 2019). The direct link to the plan is part of the iterative process, which keeps repeating while striving towards perfection. The PDCA model function in a corporation with a production planning or control method was seen with LPS (Ballard and Tommelein 2016), utilized to prevent deviations from occurring. Lerche et al. (2019) showed similar approach incorporation with Takt planning. Although the PDCA method has been available for almost a century, there is to our understanding still limited knowledge of how to combine it in a practical application with LBS.

METHOD

This research project follows the design science framework from Hevner et al. (2004), similar to what was utilized in Lerche et al. (2020). Both Baskerville (2008) and van Aken et al. (2016) approve this approach in an operations management setting. Figure 1 shows the framework used to develop the model. Based on the knowledge base on the left side, the model becomes an artifact (Simon 1996). For finalization and implementation, industry experts from a given project are to further shape is based on the right side of Figure 1 knowledge of the environment.

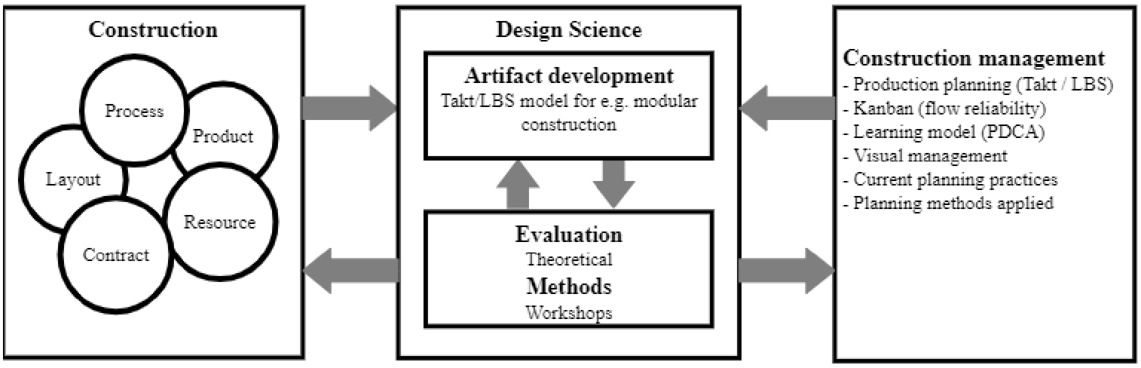

Figure 1. Framework for model development.

The research project had the following sequence, similar to what Rocha et al. (2012) presented;

1. frame the problem from the industry and literature,
2. the knowledge base was developed through a literature review, searching visual management, Takt, LBS, learning culture,
3. the model was developed based on the knowledge base and past planning applications
4. the model was adjusted and evaluated through three workshops held with part of a project team (a site manager, a supervisor, two foremen, and two technicians) from a modular construction site in the United Kingdom,
5. the model was theoretically evaluated based on its functions (Tezel et al. 2016) and ability to:
    a) facilitate learning and engagement of both managers and operators
    b) accommodate both LBS and Takt planning
    c) visualize the plan (processes) and labor resources effectively
    d) operate through a given set of rules

By following this approach, we differentiate from action research, as also argued by Järvinen (2007). We do not seek to develop or find a model which only applies in one given context but conceptualize it for a broader application purpose.

ARTEFACT FOR VISUAL TAKT AND LBS MODEL

INNER ENVIRONMENT

The key elements of the inner environment consist of the tasks, resources, an area for listing deviations and actions, and an area for the key safety and quality issues. The tasks are organized according to the Takt or LBS schedule. This also applies to the resources, for the resources picture cards or name signs are intended. When tasks and resources are organized, the operational rules are as follows. The resource marking under each task illustrates the required number of operators by a change in colors, white being the minimum, a grey color illustrating the potential for ramp-up, black representing the upper limit for resources.

The artifact works with a magnet representing the location or module is being moved across the board from left to right, starting by positioning a magnet with a location tag attached in a). When operations are started, the magnet is moved into b) while the work ongoing or determined Work in Progress (WIP). When the Takt or process has been completed, the location magnet is placed in c), when the succeeding task is ready for the location magnet, it is pulled into b) task 2 and so forth. Meaning that the location moves a) to task 1 b), when finished, it moves task 1 c). When task 2 is ready, it moves to task 2 b), when finished, it moves to c). These steps continue until the location magnet reaches d), which is an overview drawing of the final location as seen in, e.g. (Jabbari et al. 2020; Singh et al. 2020) or (Frandson and Tommelein 2016). This overview drawing should be detailed enough for workers to identify the zones. The magnet functions as a production card from Kanban (Hopp and Spearman 2004), representing the operation from Lehtovaara et al. (2020) moving through process steps. The magnet is not to be moved randomly but must follow the organized Takt as in a Kanban system.

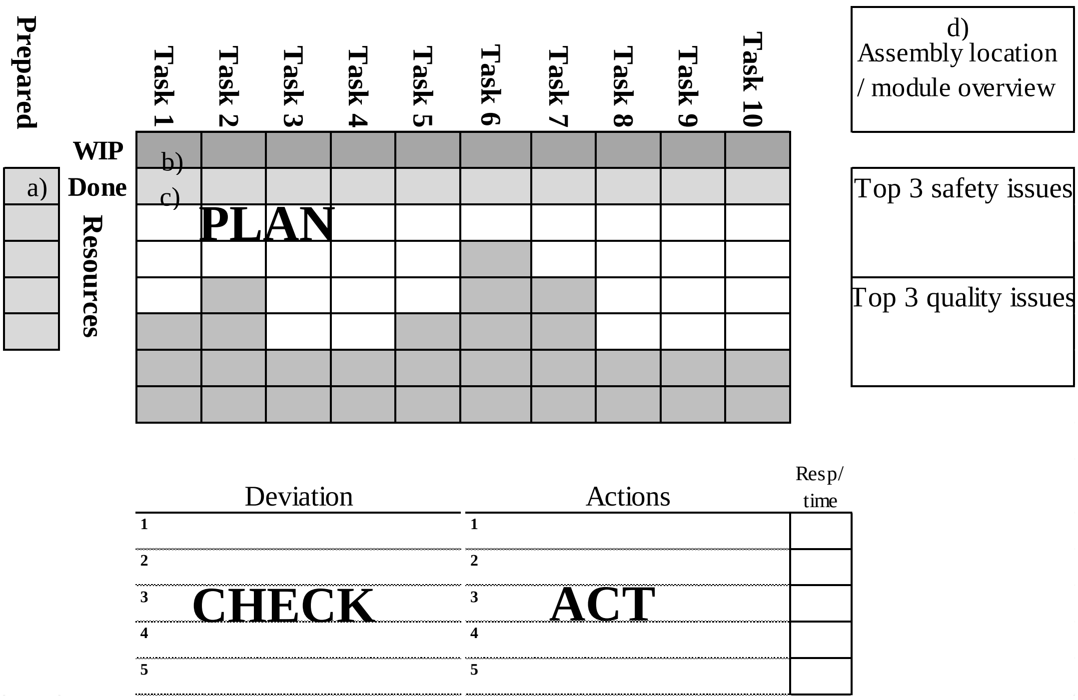

Figure 2: Key elements for artifact

Plan, Check, Act is another layer of key elements in this artifact. The list of deviations (check) shows the current daily issues, and the action list (act) reveals how workers and managers will solve these issues. Ballard and Tommelein (2016) described 5 Why's should be used to make use of the deviations and prevent reoccurrence of issues. Reoccurring issues are intended to be uplifted to either the top 3 safety or quality issues. This could be expanded with graphs showing preconditions that are not met (Lindhard and Wandahl 2012; Lindhard and Wandahl 2014).

INTERFACE TOWARDS THE OUTER ENVIRONMENT

The visual impression is interfacing towards the outer environment. It requires an understanding of organizing the tasks, the labor resources in accordance with the sequence from the designed plan. Figure 2 can be visualized as a whiteboard design. The additional board configurations for this application could have a lower quadrant prepared for off-shift workers and management picture cards. These picture cards of workers would further be used to show who is working and where. Between the area b) and the task could be where a time measure is placed for each task completion. If the process requires it, a buffer between tasks/ process steps could protect the flow. For modular wind construction, this was used to protect the crane activities to keep a continuous flow. As seen in Lerche et al. (2020), an implementation and communication plan would be required to enable the connection between the artifact and the outer environment. Tezel et al. (2016) support this, arguing that it is necessary to create organizational connections to the VM aid.

EVALUATION

Table 1 shows the evaluation of the model by using the functions from Tezel et al. (2016). It was not considered relevant to evaluate 8) and 9) as these were related to the organization and thereby the outer environment implementation.

Table 1: Evaluation of the model's visual management functions.

Functions	Evaluation
1. Discipline	The magnet route encourages discipline among managers and workers, as it will be visual to all if the sequence is neglected or ignored.
2. On-the-job training	This has not been evaluated, but the simplicity and overview could be considered enabling factors. The resource cards allow individuals to be easily identified in case help etc., is needed.
3. Job facilitation	The artifact allows through its usage of magnets to display where teams are located, not only for managers or other workers but also for visitors with limited knowledge of the progress.
4. Process transparency	Tasks and locations are visible to all actors involved, bottlenecks and queuing
5. Continuous improvement	The PDCA continuously allows managers and workers to engage in knowledge sharing, assess deviations and actions directly related to the production. Enabling this.
6. Management-by-facts	Both 5 and 7 contribute to this function, as everything is available for the decision-makers, top 3 functions further support this.
7. Simplification	The direct link between the plan, process, resources, and location

DISCUSSION

The artifact was developed in a modular construction environment accommodating both takt and LBM scheduling, created as a visual expression of the who, what, when, and where. Providing managers and workers with a visual overview of the plan (processes), resources, its deviations, and outstanding actions, Lerche et al. (2019); Lerche et al. (2020) showed how this approach allowed productivity improvements up to 50% on operators level, as the inputs remained consistent, but the throughput time was reduced. Lerche et al. (2019); Lerche et al. (2020) also revealed the combination of takt and PDCA at the operator level. Our findings here expand on this and extend the body of knowledge by creating a model for practical application of LBS and takt at the project level. Furthermore, this also reveals the model's potential usefulness.

TAKT AND LBS PRODUCTION IMPLICATIONS

Frandson et al. (2015) argued that, for controlling Takt and LPS to be different, the artifact presents a unified method for controlling tasks and resources independent of the planning method. The magnet rules and movement further provide the involved parties and external parties with a clear overview of process status and visualizes potential bottlenecks if such should occur. Frandson and Tommelein (2016) presented a field production board, which at first glance does not provide such a visual overview of the status or potential bottlenecks in the production.

VISUAL MANAGEMENT IMPLICATIONS

In terms of usefulness and relevance, this model and potential VM solution provide both managers and workers with a visual link between the plan, location, and resources. This is relevant for practical implementation and decision-making. But it also contributes to the discussion Koskela et al. (2018) started of why VM. Our artifact is grounded in the planning and control of the processes. The PDCA then continuously allows managers and workers to engage in knowledge sharing, assess deviations and actions directly related to the production. These insights can then be reused to nurture skill development (Yap et al. 2020), improve productivity (Neve et al. 2020) as waste and non-value-adding activities surface and become identifiable. From an operational safety perspective, Tezel et al. (2013) argued that VM increased safety among actors as; when, where, and who becomes visual for everyone. The Takt and LBS both present task collisions or limited time buffers, which visually allow the first assessment of variability, risks, and hazards. Future research would be required to verify this and the actual effect on safety measures.

CONCLUSION

The objectives of this research were met, as the artifact engages with both managers and workers through visual expression. Illustrating the Takt or LBM schedules in a simple overview of all tasks and resources required, with identifiable pictures. The adaptation of the artifact requires an understanding of the outer environment, requiring that planners, managers, and workers collaborate on organizing the locations, task sequence, and resources. A limitation to this research was the lack of practical implementation, which allows future research to continue with the model in either modular or regular construction context where Takt or LBS is applied. Further research would be required to understand the application of the model in other project types, e.g., high-rise buildings. Or if the model could be incorporated with, e.g., “hoshin kanri” or other managerial VM solutions.

REFERENCES

Ballard, G. (2000). "The last planner system of production control." University of Birmingham, Unpublished.

Ballard, G., and Tommelein, I. (2016). "Current process benchmark for the last planner system." *Lean Construction Journal*, 89, 57-89.

Baskerville, R. (2008). "What design science is not." *European Journal of Information Systems*, 17(5), 441-443.

Brady, D. A., Tzortopoulos, P., and Rooke, J. (2012). "Using Design Science To Further Develop Visual Management Application in Construction." *20th Annual Conference* *of the International Group for Lean Construction*, I. D. Tommelein, and C. L. Pasquire, eds.San Diego, California, USA.

Brandalise, F. M. P., Valente, C. P., Viana, D. D., and Formoso, C. T. (2018). "Understanding the Effectiveness of Visual Management Best Practices in Construction Sites." *26th Annual Conference of the International Group for Lean Construction*Chennai, India, 754-763.

Deming, W. E. (2000). *The new economics : for industry, government, education*, MIT Press, Cambridge, Mass.

Farzad, M. R., and Cameron, V. A. (2019). "Implementing Lean Visual Tools on the Closeout Phase of a Globalscale Industrial Project." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 675-686.

Fiallo C, M., and Howell, G. (2012). "Using Production System Design and Takt Time To Improve Project Performance." *20th Annual Conference of the International Group for Lean Construction*, I. D. Tommelein, and C. L. Pasquire, eds.San Diego, USA.

Frandson, A. G., Seppänen, O., and Tommelein, I. D. (2015). "Comparison Between Location Based Management and Takt Time Planning." *23rd Annual Conference of the International Group for Lean Construction*, O. Seppänen, V. A. González, and P. Arroyo, eds.Perth, Australia, 3-12.

Frandson, A. G., and Tommelein, I. D. (2016). "Takt Time Planning of Interiors on a Pre-Cast Hospital Project." *24th Annual Conference of the International Group for Lean Construction*Boston, USA.

Hevner, A. R., March, S. T., Park, J., and Ram, S. (2004). "DESIGN SCIENCE IN INFORMATION SYSTEMS RESEARCH." *MIS Quarterly*, 28(1), 75-105.

Hopp, W. J., and Spearman, M. L. (2004). "To pull or not to pull: what is the question?" *Manufacturing & service operations management*, 6(2), 133-148.

Jabbari, A., Tommelein, I. D., and Kaminsky, P. M. (2020). "Workload leveling based on work space zoning for takt planning." *Automation in Construction*, 118, 103223.

Järvinen, P. (2007). "Action Research is Similar to Design Science." *Quality & Quantity*, 41(1), 37-54.

Koskela, L., Tezel, A., and Patel, V. (2019). "Theory of Quality Management: Its Origins and History." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 1381-1390.

Koskela, L., Tezel, A., and Tzortzopoulos, P. (2018). "Why Visual Management?" *26th Annual Conference of the International Group for Lean Construction*Chennai, India, 250-260.

Lehtovaara, J., Mustonen, I., Peuronen, P., Seppänen, O., and Peltokorpi, A. (2019). "Implementing Takt Planning and Takt Control Into Residential Construction." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 417-428.

Lehtovaara, J., Seppänen, O., Peltokorpi, A., Kujansuu, P., and Grönvall, M. (2020). "How takt production contributes to construction production flow: a theoretical model." *Construction Management and Economics*, 1-23.

Lerche, J., Neve, H., Pedersen, K. B., Wandahl, S., and Gross, A. (2019). "Why Would Location-Based Scheduling Be Applicable for Offshore Oil and Gas Construction?" *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 1295-1306.

Lerche, J., Neve, H., Wandahl, S., and Gross, A. (2019). "Combining takt and Deming cycles at operator level – practical study." *10th International Conference on Engineering, Project, and Production Management (EPPM2019)*, Springer, Berlin, 9.

Lerche, J., Neve, H., Wandahl, S., and Gross, A. (2020). "Continuous Improvements at Operator Level." *Journal of Engineering, Project, and Production Management*.

Lerche, J., Neve, H. H., Ballard, G., Teizer, J., Wandahl, S., and Gross, A. (2020). "Application of Last Planner System to Modular Offshore Wind Construction." *Journal of Construction Engineering and Management*, 146(11), 05020015.

Lerche, J., Seppänen, O., Pedersen, K. B., Neve, H., Wandahl, S., and Gross, A. (2019). "Why Would Location-Based Scheduling Be Applicable for Offshore Wind Turbine Construction?" *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 1283-1294.

Leth, S., Lerche, J., Neve, H. H., and Wandahl, S. (2019). "Lessons for Construction: Delivering Mega Project on Time Through Culture and Hoshin Kanri." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 1011-1022.

Lindhard, S., and Wandahl, S. (2012). "Improving the Making Ready Process - Exploring the Preconditions To Work Tasks in Construction." *20th Annual Conference of the International Group for Lean Construction*, I. D. Tommelein, and C. L. Pasquire, eds.San Diego, USA.

Lindhard, S., and Wandahl, S. (2014). "Exploration of the reasons for delays in construction." *International Journal of Construction Management*, 14(1), 36-44.

Mariz, R. N., Galvao, E. L., Picchi, F. A., Melo, R. S. S., and Barcelos, M. C. B. (2019). "Daily Management Application in a Dam Construction Project." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 1425-1434.

Mota, B., Biotto, C., Choudhury, A., Abley, S., and Kagioglou, M. (2019). "Lean Design Management in a Major Infrastructure Project in UK." *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC)*Dublin, Ireland, 37-48.

Neve, H., Wandahl, S., Lindhard, S., Teizer, J., and Lerche, J. (2020). "Determining the Relationship between Direct Work and Construction Labor Productivity in North America: Four Decades of Insights." *Journal of Construction Engineering and Management*, 146(9), 04020110.

Neve, H., Wandahl, S., Lindhard, S., Teizer, J., and Lerche, J. (2020). "Learning to see value-adding and non-value-adding work time in renovation production systems." *Production Planning & Control*, 1-13.

Reinbold, A., Seppänen, O., and Peltokorpi, A. (2020). "The Role of Digitalized Visual Management to Empower Selfmanaged Crews in Construction Projects." *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC)*Berkeley, California, USA, 925-936.

Rocha, C. G. d., Formoso, C. T., Tzortzopoulos-Fazenda, P., Koskela, L., and Tezel, A. "Design Science Research in Lean Construction: Process and Outcomes." *Proc., 20th Annual Conference of the International Group for Lean Construction*San Diego, California, USA.

Simon, H. A. (1996). *The sciences of the artificial*, MIT Press, Cambridge, Mass.

Singh, V. V., Tommelein, I. D., and Bardaweel, L. (2020). "Visual Tool for Workload Leveling Using the Work Density Method for Takt Planning." *Proc. 28th Annual*

*Conference of the International Group for Lean Construction (IGLC)*Berkeley, California, USA, 865-876.

Tezel, A., Koskela, L., and Tzortzopoulos, P. (2016). "Visual management in production management: a literature synthesis." *Journal of Manufacturing Technology Management*, 27(6), 766-799.

Tezel, A., Koskela, L., Tzortzopoulos, P., Koskenvesa, A., and Sahlstedt, S. (2011). "An Examination of Visual Management on Finnish Construction Sites." *19th Annual Conference of the International Group for Lean Construction*, J. Rooke, and B. Dave, eds.Lima, Peru.

Tezel, A., Koskela, L. J., Tzortzopoulos-Fazenda, P., Formoso, C. T., Alves, T., Neto, B., Viana, D., and Mota, B. (2010). "PROCESS TRANSPARENCY ON CONSTRUCTION SITES: EXAMPLES FROM CONSTRUCTION COMPANIES IN BRAZIL." *18th Annual Conference of the International Group for Lean Construction*, K. Walsh, and T. Alves, eds.Haifa, Israel, 296-302.

Tezel, A., Koskela, L. J., and Tzortzopoulos, P. (2013). "Visual Management in Industrial Construction a Case Study." *21th Annual Conference of the International Group for Lean Construction*, C. T. Formoso, and P. Tzortzopoulos, eds.Fortaleza, Brazil, 471-480.

Valente, C., Brandalise, F., Pivatto, M., and Formoso, C. (2017). "Guidelines for Devising and Assessing Visual Management Systems in Construction Sites." *25th Annual Conference of the International Group for Lean Construction*Heraklion, Greece, 695-702.

Valente, C. P., Pivatto, M. P., and Formoso, C. T. (2016). "Visual Management: Preliminary Results of a Systematic Literature Review on Core Concepts and Principles." *24th Annual Conference of the International Group for Lean Construction*Boston, Massachusetts, USA.

van Aken, J., Chandrasekaran, A., and Halman, J. (2016). "Conducting and publishing design science research: Inaugural essay of the design science department of the Journal of Operations Management." *Journal of Operations Management*, 47-48, 1-8.

Wesz, J. G. B., Formoso, C. T., and Tzortzopoulos, P. (2018). "Planning and controlling design in engineered-to-order prefabricated building systems." *Engineering, Construction and Architectural Management*, 25(2), 134-152.

Yap, J. B. H., Shavarebi, K., and Skitmore, M. (2020). "Capturing and reusing knowledge: analysing the what, how and why for construction planning and control." *Production Planning & Control*, 1-14.

Sahlberg, J., Lehtovaara, J., and Seppänen, O. (2021). "Implementing Takt Production in Renovation Projects." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 677–686, doi.org/10.24928/2021/0113, online at iglc.net.

IMPLEMENTING TAKT PRODUCTION IN RENOVATION PROJECTS

Jenni Sahlberg[1], Joonas Lehtovaara[2], and Olli Seppänen[3]

ABSTRACT

Renovation projects are a special type of construction projects. The unique features of renovation projects make production control challenging, as they often cause a great deal of variation, resulting in waste in production and reducing profitability. Takt production has been applied to renovation, but its specific suitability and benefits in renovation projects have not been studied widely.

This paper describes a design science study that i) examines the suitability of takt production in renovation projects through literature and interviews, ii) designs a process model for applying takt production in renovation projects, and iii) applies and validates the designed process model in a case project.

The findings imply that takt production can benefit renovation projects. The study highlights the significance of fulfilled prerequisites and well-managed supporting functions in takt production. If these requirements are not fully met, the significance of proactive problem-solving in production control and collaborative practices increases.

KEYWORDS

Design science, lean construction, takt planning and control, renovation.

INTRODUCTION

Renovation projects – that commonly include complex and unpredictable production systems – often suffer from low productivity (Kemmer 2018). Solutions for these productivity problems have been sought from the production planning and control methods within the domain of lean construction. The fundamental aim of lean construction is to employ flow and maximize the value-creation for the customer (e.g., Bertelsen and Koskela 2004). These elements are critical in renovation projects in which poor production flow can lead to chaos, and the customer often has strict limitations for the production schedule and sequence of renovated areas (Kemmer 2018).

The main goal of takt production is to plan and control the production in a way that allows it to proceed in a steady rhythm, leading to increased production flow (resulting in, for example, reduced durations; e.g., Kujansuu et al. 2019) and maximized customer value (Binninger et al. 2017; Haghsheno et al. 2016). Takt production has been mostly studied and applied in interior phases of new buildings (e.g., Lehtovaara et al. 2019; Vatne and Drevland 2016), with some applications in renovation projects such as in interior

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phase and MEP assembly (e.g., Tommelein 2017; Binninger et al. 2018). However, implementation in other renovation work phases, such as demolition, and detailed investigation of specialties of renovation construction, remain scarce. Some argue that takt production can be challenging to implement in projects that hold a large amount of variability (e.g., Vatne & Drevland 2016), while other research presents takt production as an optimal method for reducing variability in these instances while enhancing flow and value-creation (e.g., Tommelein 2017). Nevertheless, takt production's suitability to complex and non-repetitive renovation has not yet been evaluated; therefore, further studies of takt production in this specific domain are needed.

This study's main objective is to evaluate whether takt production forms a suitable production planning and control method for renovation projects, and if yes, what restrictions, preconditions, and benefits might be associated with the method. In addition to evaluating the suitability, a process model of takt production in renovation projects is formed and tested. The study was set to focus on large renovation projects where the general contractor is also responsible for demolition and design management operations (i.e., Design-Build) and in which the future occupant or customer is also heavily involved in the design process, as usually in renovation projects (Aalto et al. 2017). The study is limited to the construction phase; thus, the handover phase is not included in the study.

RESEARCH DESIGN

The study was conducted as a design science research (DSR), which is an iterative research method aiming for developing a solution or a tool for an existing problem (Holmström et al. 2009). DSR starts with a challenge or an interesting opportunity to implement a known practice in a new context, forming a suitable approach for searching for solutions to practical problems like construction management issues (Rocha et al. 2012). Therefore, it is justified to use DSR to implement takt production in complex renovation projects. The study applies a five-step approach of DSR (adopted from Holmström et al. 2009), presented in Figure 1.

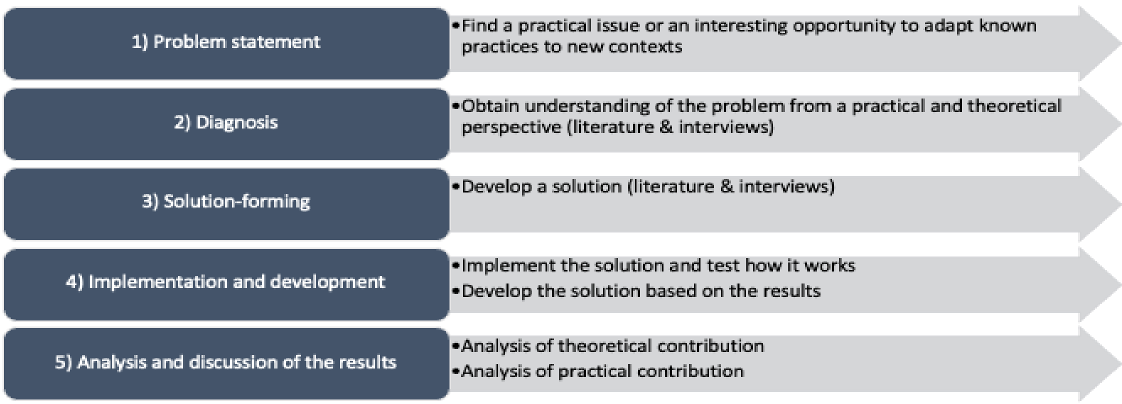

Figure 1: The structure of the research

First, a specific problem is defined, presented in the introduction section. Second, the diagnosis of the problem is conducted based on the literature review (consisting of the relevant takt production and renovation construction literature) and 12 semi-structured interviews, including nine site managers, supervisors and engineers, one representative from an MEP and a demolition company each, and one lean construction consultant. The diagnosis aimed to synthesize information about the prevalent takt production methods and practices in renovation projects, utilizing earlier experiences from case examples, and to gain complementary professional knowledge of the subject. Third, a solution – the process model for applying takt production into renovation projects – was developed. Fourth, the process model was tested through implementation in a complex renovation project. The solution's feasibility was examined through qualitative analysis, including the analysis of the progress of construction and mechanical, electrical, and plumbing (MEP) work tasks, seven semi-structured interviews among the case project organization, accompanied by production meeting, document, and site observations. The first author took an active role in implementing and testing the process model through the fourth phase, participating in planning and controlling the production during the implementation. Finally, the results were analyzed, and the contributions of the study were discussed.

DIAGNOSIS AND SOLUTION-FORMING

TAKT PRODUCTION IN CONSTRUCTION

Three different takt production methods and their previous implementation were considered in the diagnosis; these methods were selected due to the availability of descriptions in international, peer-reviewed journal and conference papers. These methods are Takt Planning and Takt Control (TPTC) (e.g., Binninger et al. 2017), Takt Time Planning (TTP) (e.g., Frandson et al. 2013), and process model for implementing takt production intro ship cabin refurbishment (Heinonen and Seppänen 2016).

While all the methods offer quite a similar approach and a systematic process to follow, certain differences can be found between the methods. TPTC is highly structured and top-down oriented (e.g., Dlouhy et al. 2018a) whereas the collaborative practices of TTP answer more to social needs and commitment process from down to up (e.g., Frandson et al. 2013). The ship cabin refurbishment method focuses on aggressive top-down implementation while aiming for radically small batch sizes. The latter method also offers a clear connection between production flow, value-creation, and management of supporting functions, such as logistics (Heinonen and Seppänen 2016).

Collaborative practices in production planning can increase the level of commitment and the reliability of work (Kujansuu et al. 2019). However, just involving everyone as early as possible does not necessarily ease the process, especially in complex takt production projects (Lehtovaara et al. 2019). Thus, the number of the participants in production planning and control and the timing of their participation should be considered carefully and based on project-specific characteristics (Frandson 2019).

Although clear repetition of processes and a small amount of variability greatly helps the planning and control process (e.g., Haghsheno et al. 2016; Vatne and Drevland 2016), takt production is not only limited to cases with a high amount of repetition and low variability (e.g., Tommelein 2017). Variability can be effectively managed by applying time, capacity, inventory, or plan buffers (Dlouhy et al. 2019), with a preference on capacity buffers that are often underutilized in current planning and control practices (Frandson 2019). By decreasing batch size, production can be paced more tightly, resulting in a decreased duration (Dlouhy et al. 2019). However, with more uncertain and complex projects, control of tightly-paced production can be challenging. For these kinds of projects, an increased amount of buffers are needed (Vatne and Drevland 2016), and reliability in starting data is essential to form a sound takt plan (Tommelein 2017).

As construction production often involves tasks that optimally would proceed in different rhythms or directions (Frandson 2019), TPTC offers phasing as a solution (Dlouhy et al. 2018b). Phasing allows a fluent synchronization of differently orientated phases, aiming for better overall optimization of production (Gardarsson et al. 2019) while maintaining reasonable resource flow and productivity, for example, in MEP installation (Dlouhy et al. 2018b). However, phasing benefits the project only if different phases are coordinated so that prerequisites of all work tasks will be fulfilled (Dlouhy et al. 2018b).

RENOVATION PROJECTS

Renovation projects differ from the construction of new buildings in two significant ways. First, there are special work tasks in renovation construction, including demolition of structures and hazardous materials, structural changes, preservation, and conservation tasks that do not exist in constructing new buildings (e.g., Kemmer 2018; Ma et al. 2015). These tasks require particular professional knowledge of work methods, materials, and safety to plan and execute (Ma et al. 2015).

Second, the unique characteristics of renovation projects should be considered in the planning and control process. According to Kemmer (2018), when entering into a renovation project, an organization should understand the building's current conditions, the full content of the necessary construction tasks, and both the existing and the future operations in the building. It is quite common that the condition of an existing asset is not fully communicated or researched (e.g., Mitropoulos and Howell 2002). As-built conditions are available only after demolition and structural changes phases, creating a vast amount of uncertainty (Aalto et al. 2017) and possibly leading to significant schedule deviations and design changes during the construction. Therefore, the content or the scope of renovation can aggressively change through the production. In addition, the planning and control of operations are strictly connected to value-creation, as the needs of the present or the future occupant and their operations often define the schedule and the sequence of renovation (Kemmer 2018).

INTERVIEWS

Current Practices

According to the interview results, takt production has been implemented so far in renovation projects in various ways. In total, five earlier takt production projects were discussed. In two of them, takt production was abandoned during the control phase due to the lack of earlier takt production experience or several design changes. However, there were also positive experiences, especially in three other projects. Even though these projects were executed with different takt methods, a common factor was that the general contractor was always in the lead and the subcontractors participated in detailed takt planning and takt control phases, in which collaborative practices (like the Last Planner System, LPS; Ballard and Tommelein 2021) or digital tools were utilized.

Prerequisites, Challenges, and Benefits

In addition to mapping the current practices, findings considering prerequisites, benefits, and challenges in applying takt production in renovation projects were gathered. The interviewees highlighted the importance of prerequisites for effective takt production, including the following main points: i) adequate design and other starting information, ii) early procurement so that the necessary preconditions of takt production are written in contracts and contractors can participate in production planning, iii) planning logistics and defining logistic practices in procurement contracts, iv) participation of the whole supply chain including subcontractors and material suppliers, v) commitment of the main contractor’s organization and quality of the daily production control routines with vi) implementation of practices and software that support takt planning and control. It should be noted that most of these prerequisites are valid for any takt projects and just the first one is impacted by special conditions of renovation projects.

According to the interviews, challenges of takt production are connected to the main prerequisites listed above, supporting the results of the literature review. The absence of preconditions leads to a challenging planning process and further unnecessary changes, making-do (Koskela 2004), and waste during the production. The interviewees argued that the benefits of takt production are most visible during the production control. Takt plan is an easily understandable and transparent tool that can generate time savings while increasing commitment and collaboration. Interviewees reported positive outcomes of shortening the overall duration in a hotel and office refurbishments and embraced the transparency of dependencies of work tasks generated by takt production implementation. In addition, preventing accumulated rush and cascading delays at the end of the production was considered to be important. Some of the interviewees argued that the benefits, e.g. time savings are more likely to be achieved in repetitive production.

PROCESS MODEL

Based on the diagnosis, a solution – formed as a process model – was developed. The process model was set to cover the following issues in renovation production planning and control: i) prerequisites, including starting data changes generated from demolition, ii) commitment through collaborative practices, iii) sufficient knowledge and skills through an organization and iv) integration of the support functions of production, e.g., procurement, logistics, and design management. The process model is called *three-phase takt production in renovation projects*. More detailed description of the process model can be found in (*omitted for peer review*)

The process model allows to divide production into particular phases planned and executed individually, including a possibility to apply different takt planning parameters (such as takt time) to different phases (Dlouhy et al. 2018b). The phases of a renovation project are i) preparation, that aims for ensuring the preconditions for the interior phase, ii) interior and iii) finish (Figure 2). Earlier takt production documentation from renovation projects implied that MEP assembly should be integrated with other interior phase tasks (e.g., Tommelein 2017; Frandson 2019). The rest of the tasks are gathered from the interviews and Finnish construction guideline database (Rakennustieto Oy 2011). Notably, there should be a time buffer in between phases e.g. for design update needs occurred during demolition.

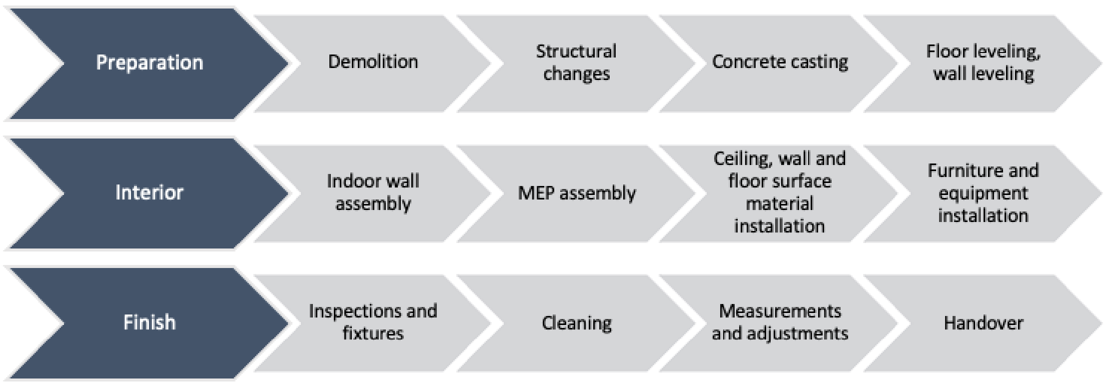

Figure 2: Three-phase takt production in renovation projects

The process model is structured according to the three-level (macro-norm-micro) approach of TPTC (Dlouhy et al. 2018a). The macro level covers process definition and customer priorities (Dlouhy et al. 2018a). In the process model, the macro level includes the three-phase takt production presented in Figure 2, aiming for standardization of the production timeline of renovation projects. In TPTC, the norm level consists of detailed takt and support function planning process and the micro level represents takt production control and coordination on work task level (Dlouhy et al. 2018a). The process model includes step by step instructions for these levels, see (*omitted for peer review*).

The process model is also applicable for projects with inadequate takt production prerequisites, e.g., starting data, because preliminary planning can start before all the procurements are done and some information is still lacking. General contractor is responsible for the whole process and other production participants are included from detailed takt planning phase, adapting collaborative practices on the level that the project size and complexity requires and allows. Increasing the level of commitment (e.g., Kujansuu et al. 2019; Gardarsson et al. 2019), and communication especially in complicated projects (Kemmer 2018) are embraced by implementing collaborative practices (e.g. TTP process, Frandson et al. 2013 or LPS, Ballard and Tommelein 2021).

IMPLEMENTATION AND DEVELOPMENT

CASE DESCRIPTION

The process model was tested by implementing it into a renovation project that included significant risks, i. e. unaccomplished designs, unexposed structures where the major changes were due, a short production planning time, and a customer-defined overall duration. According to Aalto et al. (2017), this is a typical setting in a renovation project, therefore suitable and interesting starting point for the implementation. The case project is an office building from 1994, not including any hazardous materials. The renovation consisted of the full modernization of the office spaces including MEP systems and construction of new stair connections. Also, the façade and the roof were refurbished.

IMPLEMENTATION OF THE PROCESS MODEL AND DATA ANALYSIS

The testing of the process model was executed in two very similar office floors that were punctured by the new stair shafts and a few local changes on façade structure. The floors were divided into four almost identical ~780 sqm takt areas based on the repetitive work and the MEP service areas, and the takt time was set as five days based on the work quantities and required lead time. In addition, the case project was the first takt production project for every participant in the project, and the clear rhythm in a week was considered beneficial. The study included one iteration round of the process model. The three-phased process model and its production planning steps were followed according to the process model from demolition to interior phase. The MEP contractor participated in detailed planning through several comment rounds and LPS meetings which were a chosen collaborative production planning tool in the case project. The implementation was found to be mostly successful. The participants supported the three-level takt production (Figure 2) and argued that it made the occurred deviations of production visible and buffering useful. Some difficulties in following the process model appeared in the control phase, mostly because of the global Covid-19 pandemic restrictions and the organization's lack of previous takt production experience.

The demolition phase was executed according to the plan otherwise, but after exposing the structures, the new stair shafts were found to be different than assumed. Thus, the main delays in the construction tasks were the last 5 percent of the work located around the stair shafts, and it was executed by another work group that focused only on the delayed worktasks. There was also need for a few production control adjustments and a couple of wagons were delayed because of a temporary lack of calculated resources, especially when the second floor started. These adjustments were handled through daily takt control routines and were not updated to the takt plan. In addition, to improve flexibility, three buffer wagons were transferred from the end into the trains during the production. The final version of the takt plan containing the buffer wagons is in Figure 3.

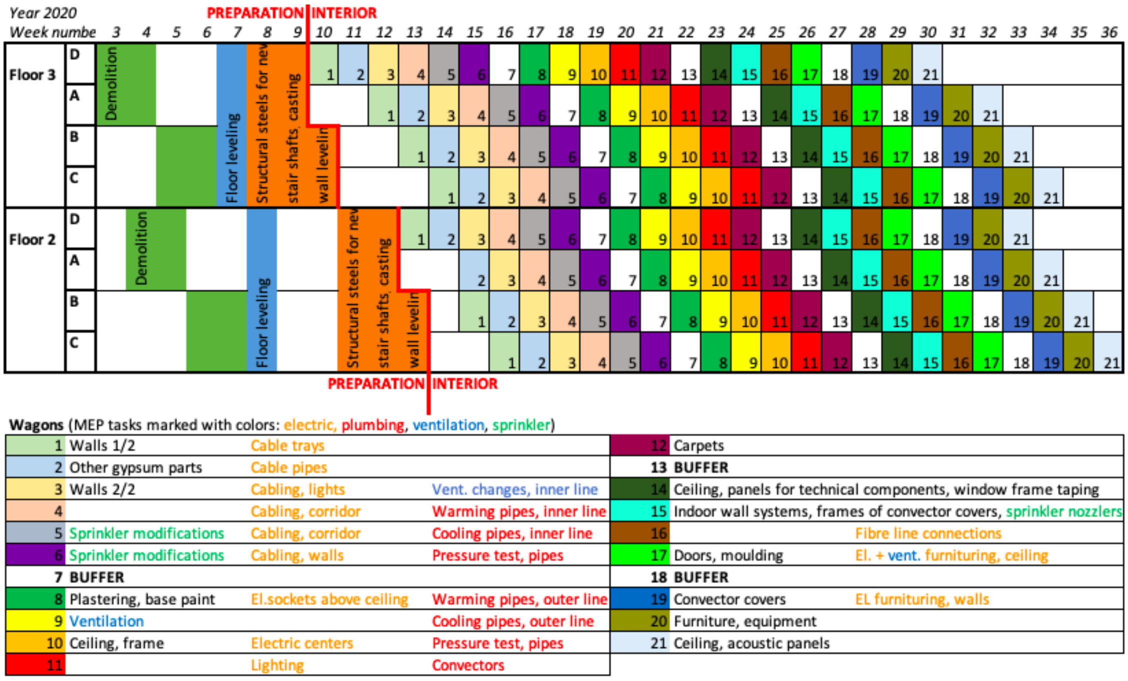

Figure 3: The final takt plan of the case project (preparation and interior phases)

The progress analysis showed that MEP installations started as planned, but electricity assembly started to fall behind soon after cabling tasks were started. The main reason for the delay was the customer's lack of unambiguous information about the requirements of electricity assembly. Thus, design changes occurred during the installation. Plumbing proceeded quite well except for the overlapping production trains that required doubled resources. Ventilation installations were the most challenging task to schedule and execute because the work was done inside the existing fireproofed steel structure intermediate floor. In short, the execution started before and ended after planned dates. The occurred challenges and other delays than the stair shaft related occurred after five weeks of takt production, indicating production control issues.

In addition, the MEP contractor expected more flexibility when the main contractor assumed a full and exact commitment to the takt plan. The takt control meetings were held between the main and the MEP contractor because the other subcontractors followed the schedule quite intuitively. However, the MEP contractor found the level of communication partly inadequate, and the stakeholders had some disagreements that can be a partial cause for issues in production control. Also, collaborative practices in production control were found to be challenging without digital tools, and COVID-19 pandemic put additional challenges on conducting collaboration effectively.

REFLECTION AND DEVELOPMENT OF THE PROCESS MODEL

According to the interviews made amongst the case site organization, the implemented three-phase model was almost unanimously supported, offering a solid base for further development. The interviewees agreed that the timing and the level of their participation in production planning was suitable to the project. In addition, the lead time of the takted areas was reduced by 30 percent compared to the traditional scheduling approach. Major changes to the process model were not suggested due to the promising results. However, specifications to clarify daily production control policies were made so that the process model would be more suitable for the organizations lacking previous takt production experience. Also, the role of participation of an MEP contractor and other partners were suggested to be specified more clearly based on the project specified requirements.

DISCUSSION OF THE RESULTS

Our case study results demonstrate that takt production can be successfully implemented in renovation projects, and even relatively easily if the system possesses clear repetition of processes and a small amount of variability. In the case project, the implementation was set not to cover the whole production but was limited to repetitive areas. The validation of the process model should be continued in different types of renovation projects containing different levels and appearances of repetition and uncertainty.

The study showed the significance of fulfilled prerequisites in takt production. Even though it was found in the case project that takt planning and even takt control can be started with imperfect prerequisite conditions, with better starting data, it would have been possible to create more accurate and reliable plans. If there are significant deficiencies or delays in the prerequisites, an organization should prepare itself to schedule changes and proactive problem-solving during production control. In this case, short-cycled and systematic control of takt production control is extremely essential. If delays occur, an additional crew can execute delayed work tasks following the main train. If these matters are taken care of, the study implies that the predictability and controllability of renovation projects can be improved with takt production.

The case project also showed that the early recognition of bottleneck tasks or a lack of critical input data improves the preconditions for successful takt production. The phasing of the production into three phases according to the process model was found to be a suitable approach. However, all potential distractions and deviations that affect the interior phase should be examined in the preparation phase. In the case project, recognizing the stair shafts as a significant bottleneck earlier would have been a great benefit. Also, a thorough review of the full content and preconditions of MEP work packages, e.g., cabling, should have been done more carefully. Based on the diagnosis and the data analysis, a separate development phase between demolition and construction phases could be considered to allow the implementation of takt production into more uncertain and high-variability areas. In addition, the possibility of classifying design update needs based on their urgency should be considered to minimize the delay. Also, late customer decisions generated significant difficulties to takt production, thus, the management of the customer relationship is a key factor in a successful implementation.

The results demonstrate two different commitment modes of subcontractors. In the case project, the MEP contractor involved in the scheduling through the process model but was not fully committed to the schedule, while other subcontractors worked according to takt schedule even if they did not participate in the planning. This shows that even collaborative practices do not guarantee commitment. Thus, the readiness for implementing takt production should be weighed in the procurement process. A digital software could increase the transparency and trust between stakeholders, being the most significant development suggestion by the MEP contractor.

Finally, when implementing takt production, the previous experience of the key people must be taken in account, as it certainly influences the commitment level towards the method. Based on the case project, it seems important to change practices little at a time and allow the slow development of culture and skills. The role of training and education should be considered, and the complexity of a takt plan can be increased only by teaching and gathering experience about takt production. This was aligned with the claim that the benefits are more likely to be achieved first in repetitive renovation projects.

The limitation of the research was that no data was collected related to flow of resources and materials. In future research, additional data should be collected to analyze if renovation projects impact resource flows in takt production.

CONCLUSIONS

This study was conducted to examine the usability of takt production in renovation projects. The results show that takt production can be a suitable method for renovation projects, even if the prerequisites are not fully accomplished, if production control supporting functions are handled proactively and collaboratively. By including a development phase between demolition and construction phases, takt production could offer a suitable method in planning and controlling projects with more uncertainty and high variability. In addition, phasing of the production was seen as effective in managing deviations that are common in renovation projects. Takt production practices should be implemented incrementally and considering the previous takt production experience of organization to increase the ability to apply takt production also in complex renovation projects containing a high amount of variability.

Future research should study the possibilities of takt production in different kind of renovation projects, including housing, hotel and industrial premises, focusing also on less repetitive production that includes more uncertainty and renovation specific work phases, e.g., abatement and demolition of other hazardous materials and conservation. This can be done according to the process model instructions and approaches presented in previously documented takt methods. In addition, the applicability of different options to increase flexibility should be studied. Further research should also strive for a deeper understanding of the coordination between MEP and construction tasks.

REFERENCES

Aalto, T., Saari, A., Junnonen, J-M. (2017). *Vaativien korjaushankkeiden ongelmat ja niiden torjunta: Vaativien korjaushankkeiden johtaminen -tutkimuksen osaraportti 1*. Tampereen teknillinen yliopisto. Rakennustuotanto ja -talous. Raportti; vuosikerta 22.

Ballard, G., Tommelein, I.D. (2021). *2020 Current Process Benchmark for the Last Planner® System of Project Planning and Control*. University of California, Berkeley.

Bertelsen, S., Koskela, L. (2004). Construction Beyond Lean: A New Understanding of Construction Management. Proceedings (IGLC12). Helsingør, Denmark.

Binninger, M., Dlouhy, J., Haghsheno, S. (2017). Technical Takt Planning and Takt Control in Construction. Proceedings (IGLC25). Heraklion, Greece.

Binninger M., Dlouhy J., Müller, M., Schattmann, M., Haghsheno, S. (2018). Short Takt Time in Construction – A Practical Study. Proceedings (IGLC26). Chennai, India.

Dlouhy, J., Binninger, M. Haghsheno, S. (2019). Buffer Management in Takt Planning – An Overview of Buffers in Takt Systems. Proceedings (IGLC27). Dublin, Ireland.
Dlouhy J., Binninger M., Oprach S., Haghsheno S. (2018a). Mastering complexity in Takt planning and Takt control - Using the three level model to increase efficiency and performance in construction projects. Proceedings (IGLC26). Chennai, India.
Dlouhy J., Oprach S., Binninger M., Haghsheno S. (2018b). Using Taktplanning and Taktcontrol in Production Projects – Comparison of Construction and Equipment Phases. Proceedings (IGLC26). Chennai, India.
Frandson, A. (2019). *Takt time planning as a work structuring method to improve construction work flow*. Doctoral dissertation. UC Berkeley.
Frandson, A., Berghede, K., Tommelein, I. D. (2013). Takt time planning for construction of exterior cladding. Proceedings (IGLC21). Fortaleza, Brazil.
Gardarsson, M. H., Lædre, O., Svalestuen, F. (2019). Takt Time Planning in Porsche Consulting, The Boldt Company and Veidekke. Proc. (IGLC27). Dublin, Ireland.
Haghsheno, S., Binninger, M., Dlouhy, J., Sterlike, S. (2016). History and Theoretical Foundations of Takt Planning and Takt Control. Proc. (IGLC24). Boston, USA.
Heinonen, A., Seppänen, O. (2016). Takt Time Planning in Cruise Ship Cabin Refurbishment: Lessons for Lean Construction. Proceedings (IGLC24). Boston, USA.
Holmström, J., Ketokivi, M., Hameri, A. P. (2009). Bridging practice and theory: A design science approach. *Decision Sciences*, *40*(1), pp. 65-87.
Kemmer, S. (2018). *Development of a Method for Construction Management in Refurbishment Projects.* Doctoral dissertation, University of Huddersfield.
Koskela, L. (2004). Making-Do – The Eighth Category of Waste. Proceedings (IGLC12). Helsingør, Denmark.
Kujansuu, P., Lehtovaara, J., Grönvall, M., Seppänen, O., Peltokorpi, A. (2019). Comparison of Collaboration and Trade Partner Commitment in Takt Implementation. Proceedings (IGLC27). Dublin, Ireland.
Lehtovaara, J., Mustonen, I., Peuronen, P., Seppänen, O., Peltokorpi, A. (2019). Implementing takt planning and takt control into residential construction. Proceedings (IGLC27). Dublin, Ireland.
Linnik, M., Berghede, K., Ballard, G. (2013). An Experiment in Takt Time Planning Applied to Non-Repetitive Work. Proceedings (IGLC21). Fortaleza, Brazil.
Ma, Y.-P., Hsu, C. C., Lin, M.-C., Tsai, Z.-W., Chen, J.-Y. (2015). Parametric Workflow (BIM) for the Repair Construction of Traditional Historic Architecture in Taiwan. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XL-5/W. 25th Int. CIPA Symposium, Taipei, Taiwan.
Mitropoulos, P., Howell, G. A. (2002). Renovation Projects: Design Process Problems and Improvement Mechanisms. *Journal of Management in Engineering*, pp. 179-185.
Rakennustieto Oy. (2011). Ratu 86-0388. Korjausrakentamisen erikoistyöt. Työlajit.
Rocha, C. G. Da, Formoso, C., Tzortzopoulos, P., Koskela, L., Tezel, A. (2012). Design Science Research in Lean Construction: Process and Outcomes. Proceedings (IGLC20). San Diego, California, USA.
Tommelein, I. D. (2017). Collaborative Takt Time Planning of Non-Repetitive Work. Proceedings (IGLC25). Heraklion, Greece.
Vatne, M. E., Drevland, F. (2016). Practical Benefits of Using Takt Time Planning: A Case Study. Proceedings (IGLC24). Boston, USA.

Power, W., Sinnott, D., Lynch. P., and Solorz C. (2021). "Last Planner® System Implementation Health Check." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 687–696, doi.org/10.24928/2021/0119, online at iglc.net.

LAST PLANNER® SYSTEM IMPLEMENTATION HEALTH CHECK

William Power[1], Derek Sinnott[2], Patrick Lynch[3], and Chris Solorz[4]

ABSTRACT

Achieving consistency of Last Planner® System (LPS) implementation is a persistent challenge for owners, contractors, and practitioners alike. This research evaluated the application of all functions of LPS within an Engineering, Procurement, Construction Management and Validation (EPCMV) consultancy and sought to develop a Guideline and Implementation Health Check (IHC) to assist consistent LPS implementation across all company projects. The study adopted a mixed-methods approach utilising case study design and data collected from a literature review, project documentation review, purposeful semi-structured interviews, two pilot implementations, and a focus group workshop conducted within the case company and across two projects.

Findings posit an implementation assessment tool (IHC) should be considered as an aid to sustaining consistent LPS implementation across projects. Construction should strive to standardise its processes (like the IHC introduction) and adopt a 'process improvement' view and mindset. The IHC highlights the critical components of the functions of LPS and allows project teams to check whether each is being utilised effectively. LPS and its functions constitutes a systematic process for construction planning however, best results will only accrue once all components are in place. While the IHC will ensure the physical infrastructure is in place, successful LPS implementation necessitates deeper consideration of how people think, communicate, engage, commit, and collaborate. Successful and sustainable LPS implementations must be founded on a desire and motivation to improve existing delivery processes and necessitate senior management commitment from all stakeholders.

KEYWORDS

Lean construction, Last Planner® System, collaboration, health check.

INTRODUCTION & LITERATURE REVIEW

Uncertainty of workflow has blighted construction execution for decades and has been identified as a shortfall in traditional construction management methodologies (Ballard

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and Howell 2003; Mossman 2019). A dedicated tool of Lean Construction (LC), LPS was created in the early 1990s as a suite of complementary functions for controlling and coordinating site production on construction projects (Ballard and Howell 2003; Daniel *et al*. 2015; Hamzeh *et al*. 2016). Ballard and Tommelein (2016 p.59) posit '…the inspiration for LPS was the discovery of chronically low workflow reliability in construction projects. Consequently, the first step in its development was to improve workflow reliability …to learn how to do what we say we're going to do.' While the importance of LPS is highlighted in the literature, there is little practice description of the '*how to do variety'*, as much comment tends to focus on the pitfalls and factors conducive to success. It is this knowledge deficit that has resulted in academics being unable to provide practitioners with the solutions needed to implement the concepts and principles effectively, implying the effort of actually implementing in practice will be even more difficult to achieve.

The core functions of LPS are master / milestone schedule, phase / pull planning, look ahead and make-ready process, commitment / weekly work planning, daily huddles / coordination, and learning and action (Ballard 2000; Daniel *et al*. 2015; Ebbs and Pasquire 2019). Daniel and Pasquire (2017) suggest little attention has been given towards developing a plan or roadmap for integrating LPS into a project. Effective integration is critical as Power *et al*. (2021 p.48) suggest '…rushed implementations of LPS as 'rescue attempts' are doomed to fail as the overburdening of already overloaded teams with new working practices will provoke resistance to the new methodology.'

Several studies (Daniel *et al*. 2016; Daniel *et al*. 2017; Ebbs *et al*. 2018; Power and Taylor 2019; Hackett *et al*. 2019) argue the consistency of implementation of LPS varies. Ballard and Tommelein (2016), with the publication of '*Current Process Benchmark*…' sought to address inconsistent approaches to implementations (Ebbs *et al*. 2017), emphasising the importance of using all functions to ensure PPC and productivity are linked to the overall milestone schedule (Ballard and Howell 2004; Hamzeh *et al.* 2009; Ballard and Tommelein 2016). The adoption of a standard approach is advised by Daniel and Pasquire (2017, p.16) which avoids each project '…reinventing its own wheel every time'. A consistent and standard approach is essential as Ballard and Tommelein (2016, p. 60) posit LPS '…is a series of interconnected parts. Omission of a part destroys the system's ability to accomplish its functions.' Previous assessment tools focused on improving LPS implementations by addressing reasons for non-completion (RNC) of tasks information (Lagos *et al*. 2019), by focusing on organisational, project and external influences (Ebbs *et al*. 2018), with provision of a Facilitator's Guide (Ebbs and Pasquire, 2019), and by utilising lessons learned from cyclical implementations (Hackett *et al*. 2019).

Based on previous studies there is a need to develop a Guideline and IHC to assist consistent LPS implementation across all projects by asking three research questions: 1) How is LPS implemented in projects; 2) How can implementation of LPS be improved; and 3) What are the possible effects of the improvement measures.

RESEARCH DESIGN

The paper reports on an in-depth case study of an EPCMV consultancy implementing LPS on selected projects since 2015. Inconsistencies pertaining to LPS implementations were observed on recent projects (poor client feedback and lessons learned) and an internal improvement assignment was initiated to develop an understanding of what was required to enable a standardised and consistent LPS implementation across all projects.

This qualitative study utilises a mixed-methods approach with case study design in accordance with Yin (2009). A sequential explanatory approach (Creswell 2009) was adopted, with each stage informing the next phase of the research. Unique sources were purposely sought to increase validity and to provide a wider perspective, as advocated by Yin (2009) and Stake (1995).

Purposefully selected interviewees were familiar with both positive and negative feedback from LPS implementations. These interviews were transcribed and then analysed using a thematic analysis approach and was organised into different themes in accordance with Braun and Clarke (2006); inferences drawn from the emerging themes were checked by triangulation against the literature review findings and against other sources to check their reliability and integrity. An action research approach, in accordance with Eden and Huxham (1996) was taken on one of the pilot implementations (pilot #2) so the effectiveness of interventions could be clearly monitored and measured. Table 1 presents the sources for the research.

Table 1: Research Sequence and Source

Steps	Source	Project and Participants
1	Integrative Literature Review	Lean, Lean Construction Literature & particular focus on past IGLC contributions
2	Project Documentation	Owner feedback, lessons learned,12 EPCMV Company LPS Data from 2017 – 2020. Review PPC on 4 'poor feedback' projects. Company's Lean Group (n=4) assessed & analysed implementation of all LPS functions across 12 projects. (n=12)
3	Purposeful Interviews	Interviews with EPCMV Company members: Ops Director, 2 X Project Manager, 2 X Construction Manager, Last Planner Facilitator. (n=6; all either directly or indirectly involved in the implementation)
4	Develop Guideline & Health Check	Develop Guideline and Health Check. (4 members of the Lean group referencing sources in table 2)
5	Health Check Pilots	Roll out Guideline and Health Check training and trial on two projects. (n=2)
6	Post-pilots Focus Group Workshop	EPCMV Company Members: Ops Director, 2 X Project Manager, Construction Manager, Last Planner Facilitator X 2. (n=6; all either directly or indirectly involved in the implementation)

An integrative literature review was conducted on Lean and LC literature. Four specific projects had received poor feedback on project performance and LPS implementation – PPC was reviewed on these projects. The research team then analysed 12 projects that utilised LPS to assess effectiveness of implementation of all LPS functions. The projects were measured for compliance with the five core functions of LPS: Milestone Scheduling, Phase Planning, Lookahead Planning, Commitment Planning, and Learning (Ballard 2000; Ballard and Tommelein 2016). The implementations were scored on a range from 0 to 5 with: 0 = 'no existence of the function', 3 = 'Partial existence of the function', and 5 = 'Full existence of the function'.

Next, semi-structured purposeful interviews were conducted with six members of the company project execution team to understand the reasons behind the inconsistency and poor feedback. Referencing LC literature, outlined in table 2, a Guideline and

Implementation Health Check (IHC) was compiled by the company's 'Lean Group' (four persons qualified and experienced in Lean and LPS) to assist project teams with implementation of all functions of LPS.

Table 2: Sources and key points for developing the Guideline & Health Check

Source	Key Points
Ballard and Tommelein (2016, p.61) *'Current Process Benchmark...'*	'Functions are the proper work of the system, its jobs. 1) Specifying what tasks should be done when and by whom, from milestones to phases between milestones, to processes within phases, to operations within processes, to steps within operations. 2) Making scheduled tasks ready to be performed 3) Replanning/planning to complete, to achieve project objectives 4) Selecting tasks for daily and weekly work plans—deciding what work to do next 5) Making release of work between specialists reliable 6) Making visible the current and future state of the project 7) Measuring planning system performance 8) Learning from plan failures'.
Daniel and Pasquire (2017) *'LPS Path Clearing Approach'*	Step Actions at the Project Level. Table 1: Production planning and control practice (Planning Best Practice). Table 2: LPS implementation assessment questions.
Ebbs and Pasquire (2019) *'Facilitator's Guide'*	Appendix 3: LPS Facilitator Checklists Appendix 4: Felipe Engineer's LPS Guide Appendix 5: Study Action Team™ Guidance for Facilitators Guide to the Last Planner® System

Training was delivered on the Guideline, and the IHC was trialled on two projects over a 12-week period. After the trial period a focus group workshop was held to review both pilot implementations and to assess next steps. The IHC weekly scores, plus interventions and their outcomes, were presented to the focus group. Limitations exist due to the research being conducted within a single organisation. Bias was mitigated by two researchers being distanced from the projects and unconnected with the case company.

FINDINGS

Research Question 1: How is LPS implemented in projects?

Owner feedback and internal lessons learned sessions suggested haphazard and inconsistent LPS implementation across the case company's projects. Some implementations received plaudits for LPS while others spoke of little, if any, discernible improvement from traditional methodologies. PPC data over 24-week duration from four selected projects (LPS received poor feedback) showed unreliability, unpredictability, and an absence of stability of PPC within the selected projects. PPC generally stayed between 60 and 80 percent, occasionally dropping below 50 percent or rising to over 90 percent. Knowing that PPC is positively correlated to enhanced productivity, this erratic performance is the antithesis of what projects require for enabling smooth and even workflow.

All 12 projects that utilised LPS from 2017 to 2020 were evaluated; mean, median, and lowest scores were calculated; % implementation was attained by calculating the mean values as a % of a perfect score of 5. The summarised findings are presented in table 3.

Table 3: Status of LPS implementation on 12 projects.

Survey Findings Score from 0-5 (0=no, 5=full)	Milestone Planning	Phase Planning	Lookahead Planning	Commitment Planning	Learning
Mean Values	3.7	2.1	2.8	3.7	2.2
Median Values	3.5	2	2.5	4	2
Lowest Values	2	0	2	3	0
% Implementation	73%	42%	55%	73%	43%

Table 3 highlights the inconsistency of application of all functions of LPS. Commitment and Milestone Planning were most used functions with Phase Planning, a critical enabling function of the entire LPS system, least used at 42 percent indicating a major weakness in the implementation. Disappointingly, Lookahead Planning at 55 percent and Learning at 43 percent also point to poor and ad hoc use of key functions of the process. Findings from the purposeful interviews are presented in table 4.

Table 4: Interview findings on inconsistency of LPS implementation

Unaware of advantages accruing from using all functions
LPS support & resource are focused on selected projects (owner mandated)
Lack of focus or ownership towards making the process succeed
Poor trade partner engagement with LPS process
Full implementation not mandated or demanded on all projects
Managers selecting individual functions & discarding others
Owners offering resistance and not participating
Differing interpretations of what LPS is and its benefits
Absence of standardised implementation process or procedure

Interviewees agreed there was an over-reliance on the ‘Lean Team’ supporting LPS on projects; existence of the ‘Lean Team’ removed LPS ownership and accountability from site management and resultingly, trade partners. Additionally, if a budget for ‘Lean Team’ support didn’t exist the site proceeded to use only selected aspects such as a milestone plan and morning huddles. Some owners and managers were more familiar with, and aware of, the advantages of LPS and therefore mandated and supported its use. However, other owners and managers were reluctant to sponsor the implementation. As the company relies on Standard Operating Procedures and Guidelines in its work execution, interviewees suggested the absence of a best-practice Guideline and Implementation Health Check (IHC) was a barrier which, if resolved, could provide an implementation roadmap, consistency, and remove the reliance on the ‘Lean Team’.

Development of Guideline & IHC

Research Question 2: How can implementation of LPS be improved?

The IHC built on existing research sources as referenced in table 2. The specific aim of the IHC was, along with the Guideline, to ensure consistency of application of LPS and to provide weekly feedback identifying implementation gaps, thus, allowing focused improvement. The IHC consisted of 38 prompts or questions across six areas that when responding 'Yes' would confirm its application and 'No' would highlight an area for improvement. Table 5 presents the 38 prompts/questions contained in the IHC.

Table 5: Content of IHC per LPS function

Function	Content
Milestone Planning	Physical/virtual space; information accessible; all functions visible; Master Schedule up to date; all team trained & refreshed within past 6 weeks.
Phase Planning	Plan developed with all trades within last 3 months; logic and sequence validated; pull from milestone; 6 week lookahead aligns; constraints identified; behaviours; flow walk screening for seven flows.
Look Ahead / Make Ready	New week added to lookahead; incomplete tasks brought forward and replanned; constraint log reviewed with lookahead / phase plan; flow walk /new constraints raised; constraints metrics; Tasks Made Ready.
Commitment / Week Work Plan	Communication; attendance; all trades contribution; commitments; 'sound' criteria applied; behaviours; agreed plan communicated.
Daily Huddle	Communication; engagement; correct mark-up; missed tasks addressed; Unplanned work added & impact assessed; parking lot employed; new constraints addressed; behaviours.
Learning & Action / PPC Analysis	PPC visualised & available to all; RNC assessed; recurring RNC root causes; A3 improvement projects enacted.

TRIAL OF IHC

Research Question 3: What are the possible effects of the improvement measures?

The IHC was trialed on two pilot implementations. Pilot #1 was a project involving a single contractor with no handoffs to other contractors. Full LPS training was provided, and the contractor was familiar with the LPS process as they had been participants in the enabling works LPS (run by the case company) for 14 weeks. The contractor implemented LPS with one of the authors attending morning huddles, the weekly coordination meeting, and compiling the weekly PPC and IHC reports. The IHC summary page is shown in figure 1.

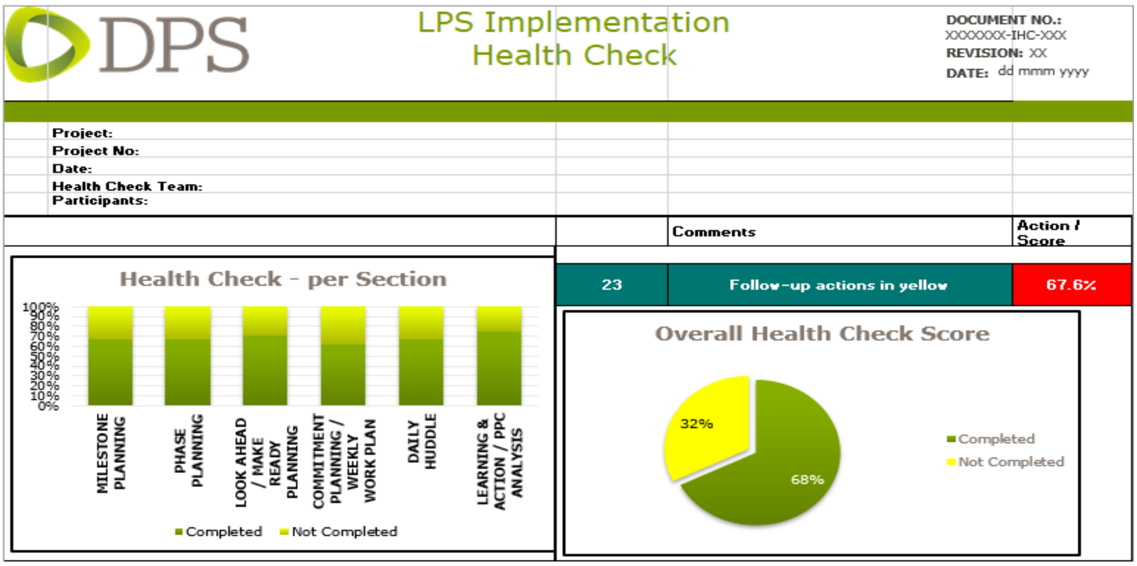

Figure 1: Implementation Health Check summary

The contractor was unwilling to accept the weekly IHC feedback as an improvement opportunity and struggled to understand the value of lookahead planning and constraints identification. A PPC report with detailed reasons for RNC was furnished weekly but the learning and action function of LPS wasn't acted on. Pilot #1 didn't have a collaborative atmosphere; conversations were tense and more adversarial when poor PPC or IHC scores were discussed. LPS was treated as a tool demanded by the owner; the softer social aspects of LPS lay undiscovered as LPS was owned solely by the site manager. A visual correlation between PPC and Health Check is evident in figure 2 (below) and points to PPC performance being influenced by the effectiveness of implementation of all LPS functions, as measured by the IHC. The findings suggest that incomplete implementation (poor IHC score) is constraining PPC achievement.

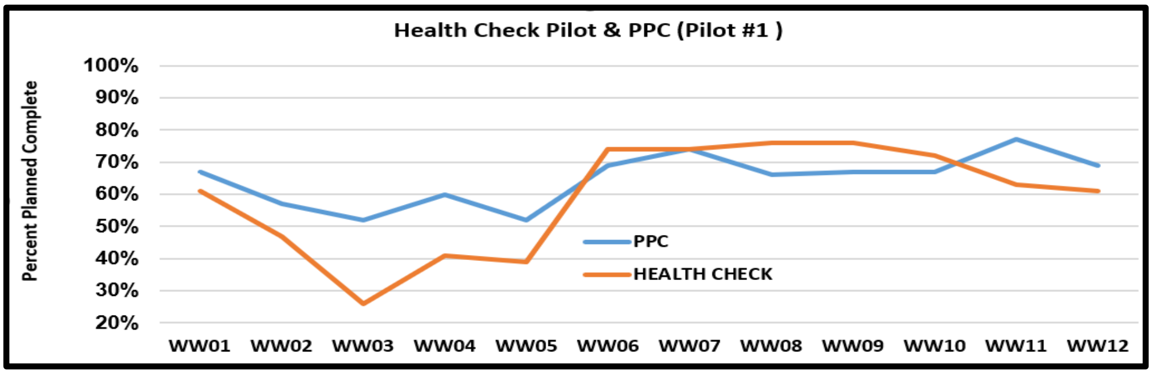

Figure 2: Pilot #1 - PPC & IHC scores.

Pilot #2 was conducted on a warehouse construction project where another author was embedded as a Last Planner Facilitator. The Facilitator had the authority to intervene in the weekly site management and planning process to ensure a full LPS implementation in accordance with the IHC. The EPCMV company's Operations Director was supporting this pilot; this was a key difference from the pilot #1 implementation. Findings from pilot #2 are presented in figure 3.

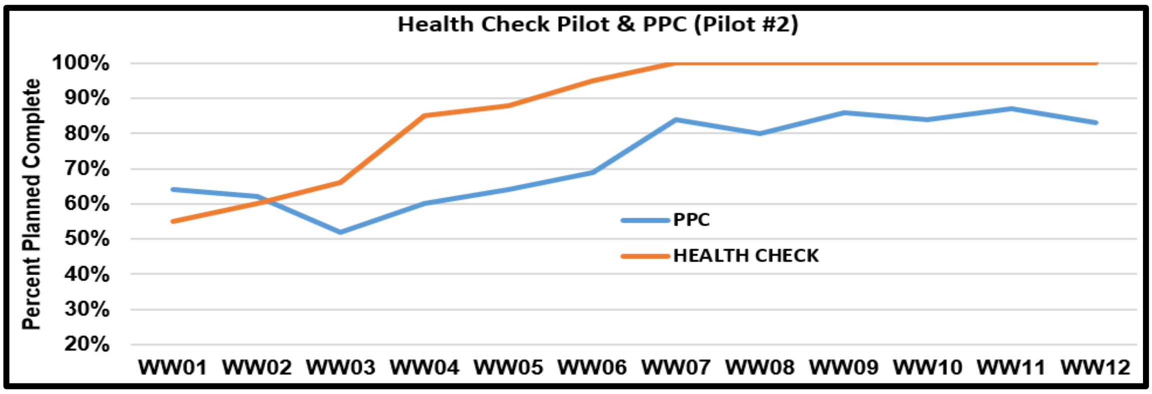

Figure 3: Pilot #2 - Warehouse Project PPC & IHC scores.

Pilot #2 represents how the team (owner, construction management, trade partners) could ensure all functions were implemented. Numerous interventions were applied as improvement opportunities arose when analysing PPC, RNC, and highlighted IHC gaps. Figure 3 presents PPC maintained at over 80 percent when all functions of LPS were implemented and suggests a correlation between a 'full' implementation and higher and more reliable PPC. While both projects are dissimilar in nature, the process of LPS and

IHC should be much easier on pilot #1 (single contractor, minimal design input, sole possession of site and all inputs, low Covid impact) than on pilot #2 (live pharmaceutical facility, owner possession of site, eight trade partners, complex design, international supply chain, high Covid impact as populous site). After the 12-week pilot period expired a focus group workshop was conducted to review the learnings. Table 6 presents the findings.

Table 6: Post-pilot implementation focus group findings

There must be a desire and a will to make the implementation succeed.
Senior management & site leadership support is critical.
Facilitation at early stages is a key enabler.
Education and training should be provided to exhibit the benefits & potential of LPS.
A longer-term view of LPS implementation should be undertaken; not just to address a crisis.
The Health Check is a critical implementation effectiveness measurement tool.

The summary findings in table 6 posit treating LPS solely as a tool to supplement existing methodologies is insufficient and will not deliver optimal results. Adoption of LPS must be linked to and aligned with a motivation and desire to change from traditional delivery methods. Implementing all LPS functions leads to increased and more reliable PPC; PPC is positively correlated to productivity. The structure introduced by the Facilitator when implementing the IHC on the facilitated pilot #2 brought a coordinated routine that encouraged the trades to participate in the planning of the work; the ensuing positive behavioural change enabled a more collaborative working environment. Early facilitation embeds the routine, practice, and language of LPS from the outset. This common and shared understanding is critical to clarifying the Conditions of Satisfaction for the next customer in line, while also maintaining the implementation process. Standardisation of the process (Guideline and IHC) across all projects will ensure consistency and confidence amongst teams. The IHC identified improvement opportunities on both pilot projects. Critically, it was pilot #2 that addressed the opportunities resulting in higher and sustained PPC.

DISCUSSION

The IHC, in conjunction with a competent and knowledgeable facilitator, has been found to be a critical enabler of effective LPS implementation. As embedding and sustaining of LPS is often constrained by limited resources, the IHC offers an opportunity to standardise the process and ensuring a step by step ‘check and act’ sequence is part of the kit. Therefore, it is critical that a consistent LPS process, assisted by the IHC, is developed on all construction projects. In pilot #1, the contractor was contractually mandated to utilise LPS on the project. However, they had neither desire nor motivation to use the IHC findings to enhance their weekly planning process. LPS became a tool-focussed ‘tickbox’ exercise ensuring the contractor was contractually compliant. Contractual terms alone will not provide the underlying motivation and determination to meaningfully implement LPS. Also, despite the IHC and the identification of the improvement opportunities, unless the desire to improve the status quo and to overcome past failures exists, the implementation will not reach full potential. Clearly, there must be a desire and a motivation within the company, the project team, and the owner to ensure LPS will succeed and not end up being another ‘fad’ or partial implementation.

The importance of management commitment, leadership, and alignment of strategy in any Lean implementation is emphasised in the literature. Pilot #2 indicates the positive results (PPC and IHC) from a fully supported implementation, where leaders modelled ideal Lean behaviours. Attendance at morning huddles, attending planning workshops, and seeking to be made aware of RNC and process improvement projects are examples of such behaviours. When site leadership support the LPS process, traditional delivery practices are examined, challenged with a Lean mindset, and consideration of customer, next-customer, and 'Value' begin to infiltrate conversations. It is important the 'softer' elements are in place to ensure the IHC contributes fully to the overall LPS process.

Contractors should not wait for the crisis to occur as a reason to introduce LPS on a project. Rather, they should adopt an innovative approach to improve their delivery processes consistently and continuously. This can be achieved by understanding the value of the IHC contribution towards ensuring consistent and effective implementation. Measuring the implementation effectiveness allows continuous incremental process improvement and fosters a continuous improvement mindset and approach; end to end LPS on projects can underpin broader construction delivery improvement extending by consistency and stability across the supply and value chain.

CONCLUSION AND RECOMMENDATIONS

Diligent implementation of all functions of LPS allied to continuously improving the process delivers better results. This study contributes to academic and practitioner knowledge by presenting how utilising the IHC to improve implementation of all functions of LPS delivers higher and consistent PPC. Construction should strive to standardise its processes (like the IHC introduction) and adopt a 'process improvement' view and mindset. The contribution of this tool is to assist getting the implementation 'effective' from the outset. However, while the IHC will ensure the physical infrastructure is in place (a checklist to ensure compliance with 38 highlighted prompts), successful LPS implementation necessitates deeper consideration of how people think, communicate, engage, commit, and collaborate.

Further research could be utilised to refine, modify, or confirm findings by replicating the study in a larger case population as a means of improving the IHC. Quantitative research could address the measurement of different variables identified in this work.

REFERENCES

Ballard, G. (2000) *The Last Planner System of Production Control*, Doctoral Dissertation, The University of Birmingham, UK.

Ballard, G., Kim, Y., Liu, M. and Jang, J. (2007) *Roadmap for Lean Implementation at the Project Level*, The Construction Industry Institute, Austin, USA.

Ballard, G. and Howell, G. (2003) 'Lean project management', Building Research & Information, 31(2), 119-133.

Ballard, G. and Howell, G. (2004) 'Competing construction management paradigms', Lean Construction Journal, 1(1), 38-45.

Ballard, G. and Tommelein, I. (2016) 'Current Process Benchmark for the Last Planner® System' *Lean Construction Journal*, 57-89.

Ballard, G., Vaagen, H., Kay, W., Stevens, B., and Pereira, M (2020) 'Extending the Last Planner® System to the Entire Project'. *Lean Construction Journal*, 42-77.

Braun, V. and Clarke, V. (2006) Using thematic analysis in psychology.*Qualitative research in psychology*, *3*(2), 77-101.

Creswell, J. (2009) *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. London: SAGE Publications.

Daniel, E., Pasquire, C. and Dickens, G. (2015) 'Exploring the implementation of the Last Planner® System through IGLC community: Twenty-one years of experience'. In: *Proc. 23rd Annual Conference of the International Group for Lean Construction.* Perth, Australia, 153-162.

Daniel, E., Pasquire, C. and Dickens, G. (2016) 'Exploring the Factors That Influence the Implementation of the Last Planner® System on Joint Venture Infrastructure Projects: A Case Study Approach' In:, *Proc. 24th Annual Conference of the International Group for Lean Construction.* Boston, Massachusetts, USA, 20-22.

Daniel, E. and Pasquire, C. (2017) "Last Planner System Path Clearing Approach (LPS-PCA): an approach to guide clients, main contractors and subcontractors in the implementation of the LPS." *Research report for external body. Nottingham: Nottingham Trent University: Publications.* Nottingham, UK.

Ebbs, P., Pasquire, C., and Daniel, E. (2018). The Last Planner® System Path Clearing Approach in Action: A Case Study. In: *Proc. 26th Annual Conference International Group for Lean Construction,* Chennai, India, 724-733.

Ebbs, P. and Pasquire, C. (2019) A facilitators' guide to the Last Planner® System: a repository of facilitation tips for practitioners. Nottingham: Nottingham Trent University.

Eden, C. and Huxham, C. (1996) 'Action research for management research'. *British Journal of management*, 7(1) 75-86.

Hackett, V., Harte, P. and Chendo, J. (2019) 'The Development and Use of Last Planner® System (LPS) Guidance' In: *Proc. 27th Annual Conference of the International Group for Lean Construction.* Dublin, Ireland, 651-662.

Hamzeh, F., Kallassy, J., Lahoud, M., and Azar, R. (2016). 'The First Extensive Implementation of Lean and LPS in Lebanon: Results and Reflections.' In: *Proc. 24th Annual Conference International Group for Lean Construction*, Boston, USA, 33–42.

Howell, G., Ballard, G., and Tommelein, I. (2010) "Construction Engineering—Reinvigorating the Discipline." *J. Construction Engineering and Management*, 137(10) 740-744.

Liu, M., Ballard, G. and Ibbs, W. (2010) "Workflow Variation and Labor Productivity: Case Study", *Journal of Management in Engineering*, 27(4), 236-242.

Mossman, A. (2019) 'Last Planner: 5 +1 Crucial and Collaborative Conversations for Predictable project production planning', *The Change Business Ltd.* Available at: https://www.researchgate.net/publication/321804312_Last_Planner_5_1_crucial_collaborative_conversations_for_predictable_design_construction_delivery_Dec_2017 (Accessed 09 February 2021).

Power, W. and Taylor, D. (2019) 'Last Planner® System and Percent Plan Complete: An Examination of Trade Contractor Performance'. *Lean Construction Journal.* 131-146.

Power, W., Sinnott, D., and Mullin, A. (2021). Improving Commissioning and Qualification Delivery Using Last Planner® System. *Lean Construction Journal*. 36-52.

Stake, R. (1995) *The art of case study research*. Sage.

Yin, R.K. (2009). Case study research: Design and methods (4th ed). Thousand Oaks, CA: Sage.

Mossman, A. and Ramalingam, S. (2021) "Last Planner, Everyday learning, Shared understanding & Rework." *Proc. 29th Annual Conf. of the Int'l Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 697–706, doi.org/10.24928/2021/0137, online at iglc.net.

LAST PLANNER, EVERYDAY LEARNING, SHARED UNDERSTANDING & REWORK

Alan Mossman[1] and Shobha Ramalingam[2]

ABSTRACT

Tasks most likely get done right when the performers' criteria match the criteria of those who receive the completed task (the customers). Knowledge in construction is mostly tacit. Making the tacit explicit is challenging and has to be conversational. Everyday learning and the structured planning conversations in the Last Planner® System (LPS) can help make tacit knowledge explicit. This conceptual paper explores the connections between learning, understandings of criteria and rework in project-based production to understand, *how can we reduce rework on projects that arise from performers' misunderstanding of customer criteria for each task?*

The preliminary findings are a) Less rework will be required when performers can develop a shared understanding of the criteria for each work task with their customers; b) Shared understanding is most likely when the criteria are explicit; c) Everyday learning will enable the process of making tacit information more explicit.

This paper has implications for practitioners as everyday learning and shared understanding will help workers at all levels to continuously share and learn while feeling psychologically safe enough to make mistakes and learn from them. It also suggests further multi-disciplinary research in the area of shared understanding and rework.

KEYWORDS

Reliable promising, Last Planner® System, flow, rework, everyday learning.

INTRODUCTION

Pasquire (2012) discusses *common understanding* and the consequences for production of 'not understanding' the 'what, how and why' to do something and that shared understanding can reduce snagging (punch) lists and the need to revisit work. Pasquire and Court (2013) showed how bringing together the knowledge distributed within a production team appeared to help the team get closer to a *shared understanding* of a project. Pasquire and Ebbs (2017) reiterate the value of shared understanding as an underpinning flow in lean construction. Using the metaphor of machine code, the code that controls the operation of machines, they suggest that, without good machine code, machine output is poor. In human systems, shared understanding is like good machine code. It needs to be supported by good leadership. To establish pre-conditions for communication and collaboration in construction projects, Koskela *et al* (2016) discuss the different meanings associated with the construct *shared understanding*. The article discusses six concepts that are potentially relevant to engaging in meaningful discussion.

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Ideas discussed in these papers are relevant to creating *shared understanding* at task level e.g. situational awareness, standard method, common ground, the importance of paying attention to tacit knowledge and making it more explicit.

In construction projects, *rework* is a significant source of time and cost escalation. Studies suggest 5-10% of project cost is generally spent on rework (i.e. more than the project margin claimed by many lead constructors). Some researchers claim it is over 20% and some rework events are hidden and unreported (Love 2020).

Learning is the basis for improvement. When a mistake is made and learned, people are far less likely to make the same or a similar mistake again (Ferrada *et al*. 2016). Although she makes reference to *After Action Reviews* and similar micro-learning processes, Carrillo (2005), like Ferrada *et al*, writes about macro-level stage-gate or end-of-project lessons-learned systems. The lessons that participants will admit to learning are those that are not too embarrassing and will not trigger a claim from another party. Episodic learning like this contributes little to developing a learning culture.

Everyday learning is the basis for everyday improvement. It leads to small improvements made every day or every week that change the way things are done for the rest of the project. When a mistake is made and learnt from, the chances of making the same mistake again are reduced. This fosters a learning culture in projects and embeds improvements are more likely to be carried over to future projects as ingrained habits. This led us to want to understand ***what stops everyday learning in projects?***

Our literature review throws light on several enablers of learning: leadership, motivation, face-to-face interactions, individual/team/organizational learning; and on disablers such as: time pressure, distance, virtual interactions, lack of management support, cultural differences (Gil and Mataveli 2017, Ferrada *et al*. 2016). Project mood can either support or obstruct learning (Flores 2016). Thus there are multiple constructs to explore. Taking a systems perspective and aligning with the core lean goal of delivering *value*, one significant input is reliable promising — using the promise cycle and success criteria or Conditions of Satisfaction (CoS) (Flores 2013). The process of conversation is nonetheless beset with challenges such as the psychological safety needs of team members (Edmondson 1999) or making *tacit* project knowledge *explicit* (Nonaka 1994). Failure to understand customers' CoS may lead to rework and delay in projects (Ballard 2000; Chiu *et al* 2016). Intuitively, it is therefore intriguing to understand the connection between learning, shared understanding, the CoS and rework in project-based production. This paper thus explores this research question: ***how can we reduce rework on projects that arise from misunderstanding the CoS?*** through literary evidence and experiential insights in the subsequent sections.

METHOD

This is a conceptual paper grounded in theory. Literary evidence is the basis for understanding real-life situations through inductive logic. The researchers' experiential knowledge and insights are an important part of the inquiry and critical to understanding the phenomenon (Sutton and Staw 1995). The focus is on complex interdependencies and system dynamics that cannot be reduced in any meaningful way to a few discrete variables or to linear, cause and effect relationships (Torraco 1997). Mindful of and attentive to system and situation dynamics, this study examines real-world situations as they naturally unfold with a focus on individuals, an organization, a community, or an entire culture. This method is the basis for understanding the connection between shared understanding, CoS and rework and also for future validation. To address the above research question, theoretical insights from literature and experiential evidence are discussed below in the context of the construct ‘understanding’:

‘UNDERSTANDING’

Taking a systems perspective, ‘understanding’ is explored in the following sequence: **1**. Focussing on the production, the promise cycle and the CoS as an *input* parameter for a shared understanding and learning in projects are investigated; **2**. Focussing on the *process*, the challenges in learning with respect to transferability of tacit knowledge and embedded psychological safety issues in teams are explored; **3**. Focussing on the *output*, the impact of poorly shared understanding that may lead to rework, added cost and delay in projects are highlighted and finally, **4**. The insights on shared understanding and rework are integrated for a comprehensive and holistic understanding.

1 ‘UNDERSTANDING’ PRODUCTION AND THE CONDITIONS OF SATISFACTION

Construction projects are a form of production. Production operations are broken down into discrete tasks. Tasks get done when they satisfy the requirements – the Conditions of Satisfaction (CoS) – of the customers for that task. S*ubsequent trades, designers, the lead constructor, end-users, permitting authorities* are all examples of customers for trade teams working on construction sites or in off-site fabrication shops. Customers provide critical inputs to the performers that increase the chances that the performers’ outputs (decisions, designs, product) will be *right-first-time* and can be relied upon.

This means that there is a unique definition of value and unique CoS *for every task within a project* as well as for the project as a whole. Ideally each performer works with their unique CoS for each activity to:

- deliver the work safely and *right-first-time*
  meet the needs of the end-user or purchaser + authors of the directives and
- satisfy the next team(s) &/or individual(s) that rely on the performer’s output.

A successful handover requires the supplier to supply what the customer wants, when she wants it and how she wants it. In this context, effective project participants should understand their own needs and the needs of ***all*** their customers (for whom they provide inputs) and their suppliers, including designers (whose outputs they receive along with the CoS) (see Joseph Juran’s triple role concept in Forbes and Ahmed 2010). *Smooth handovers* from one performer to another are critical to the success of a project, just as they are in a relay race. These handovers are often more than simple transmissions (or transitions). In athletics, those involved in a relay get to practice, review and improve over and over again. It is often the handover that makes, or breaks, a relay team. In projects, every handover is different and opportunities for rehearsal are limited.

On traditional projects, it is generally assumed that the instructions the workers are given are sufficient for them to understand what needs to be done. The problems of traditional construction project organisations have grown worse over the last 50 years as the construction sector has become ever more fragmented and worker employment more casualised (Green 2010). This has resulted (in UK, US, EU, India and elsewhere) in the use of workers who often don’t share the language and culture of site and project managers. The results in linguistic, social, cultural and employment distance between crews and other project team members. This appears to reinforce site and project manager’s tendency to *tell* workers what to do.

On lean projects using the Last Planner System (LPS), work crew leaders decide for themselves what tasks they will do, when and how in ever increasing detail as the time to do a task gets closer. They use a series of structured planning conversations (Mossman 2020) with fellow crew leaders and site managers to do that. These conversations can help create shared understanding (Pasquire and Court 2013). Planning conversations in the 4-8 weeks before planned task delivery are particularly critical. Ramalingam and Mahalingam (2011) describe the role of *boundary spanners* who can facilitate conversations and the emergence of shared understanding.

‘UNDERSTANDING’ THE PROMISE CYCLE

The simplified promise cycle shown in Figure 1 is critical to all forms of production (Flores 2013). It is at the heart of LPS. The structured LPS conversations are designed to make it easy for team leaders to make reliable promises about the work that they and their teams will do in the next period.

Customers make a request of one or more potential performers. Here’s an example: ‘*Hey Mum, can we go for a bike ride today?’* That’s a request to one very special performer. If you are Mum, there may be other things you want to do today and that you expect your daughter to do, such as *tidying her room*. Thus begins a negotiation – what does she mean by *bike ride* (where, how long, when to leave, when due back) and what do you (Mum) understand by *tidy room?* Once you have agreed these things you can agree what will happen and when. In this case you will make promises to each other.

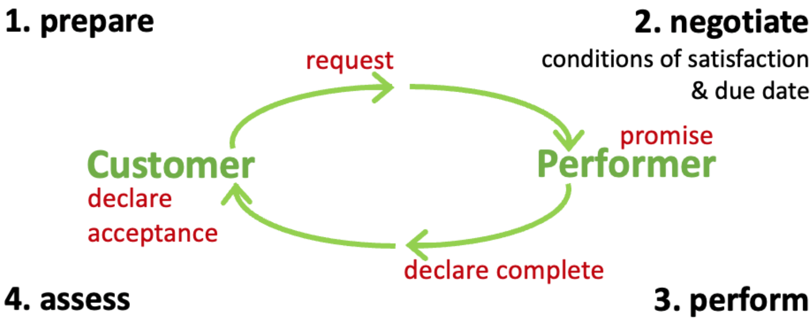

Figure 1: The Promise Cycle (after Flores 2013)

In a work context, the complexity of the negotiation may be greater, yet the agreement of CoS and the delivery date are no less important. If this is not done, the assumptions made by the performer about the CoS may be wrong and the delivery may not satisfy the customer(s). CoS set out the customers’ idea of quality work. If the next trade in line receives quality work, they are better placed to deliver quality work themselves.

2 ‘UNDERSTANDING’ THE CHALLENGES TO LEARNING: KNOWLEDGE TRANSFER ISSUES

Construction projects bring together individuals and teams for a limited time to focus on creating a particular unique and complex outcome quickly. Construction work is embedded in institutionalized project settings where knowledge of regulations such as the operating laws, government rules, design and construction standards are explicit. Normative and cultural-cognitive knowledge such as work practices, local preferences and cultural beliefs tend to remain predominantly tacit (Javernick-Will and Levitt, 2010).

Drawn from different parts of an organisation and generally from a range of organisations, project participants, few of whom will have worked together before, must learn to share their diverse socio-technical expertise, skills and knowledge (Hayek 1945) so that they have a shared understanding of what is to be created. Most of the information and knowledge necessary to complete projects successfully is tacit (see fig. 2) and, according to Nonaka (1994), transfer of tacit knowledge can occur only through shared experiences such as socializing, mentoring or by providing on-the-job training.

On traditional projects, workers, or their trade supervisors, are instructed by site managers who tend to assume 1. that the workers share their tacit understanding of what is required; 2. that they (the instructors) share the tacit knowledge of the requirements' authors and 3. understand the needs of later trades. Workers may also assume that they understand the instructions they receive.

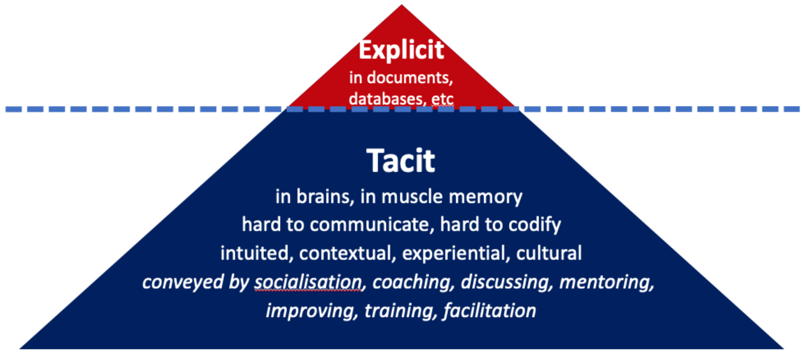

Figure 2: Tacit Vs Explicit knowledge in projects (after Nonaka 1994)

"Projects are embedded in multiple [systems] … which jointly facilitate and constrain project organizing" (Manning 2008). The expectations of each individual's home team or organisation affects their willingness to trust others and share skills, information and knowledge, especially tacit knowledge. The structured conversations of LPS create shared experiences. The standardisation of the structured conversations between projects helps team members re-use their abilities to make their tacit understandings more explicit and to develop shared understandings as they move from project to project.

Leonardi and Bailey (2008) highlight the challenges to shared understanding for transnational teams due to differences in the interpretation of the *implicit* knowledge embedded in digital tools such as the meaning of the symbols or codes used in the tools.

'Understanding' Psychological Safety Needs and Challenges

Many workers feel that it is not safe say "no" to an instruction (Edmondson 1999 talks about *psychological safety*) or to say that they don't understand it, or the CoS. They feel they have to *make-do*, even when this results in sub-standard work. Edmondson (1999) says team 'psychological safety', a belief shared by team members that it is safe to take interpersonal risks, is a pre-requisite for learning. If nurtured carefully, psychological safety will result in a learning culture in which people feel free to speak up, ask for help, or offer an idea. In the face of uncertainty, the need to ask questions, tolerate mistakes and seek help become necessary competencies for learning, innovation and improvement.

3 'UNDERSTANDING' REWORK, COST AND DELAY

Rework becomes necessary when work done fails to match the expectations of a customer. Rework adds to project cost and duration. Tasks have to be completed or, more often, undone and redone using additional labour, materials, tools, equipment and time.

Rework disturbs production flow while the work is corrected. In manufacturing it is easy to insert buffers in the line so that briefly stopping the line in one section of the plant has no effect on other sections. In construction production that is much more problematic.

If this happens too often, the authors' conversations in the field suggest subsequent crews add a time buffer between their start time and the previous crew's declared finishing time or they allow themselves more time to complete. In this way one small delay is magnified and completion is delayed.

Project leaders don't want production workfaces to be idle. Crew leaders don't want their workers waiting for work. The need for rework can result in either or both.

4 SHARED UNDERSTANDING AND REWORK

Figure 3 shows why shared understanding of the directives and CoS is important in a task production process if rework is to be avoided. The directives, including the CoS, are part of the request to the performer(s) of the task and are the basis for assessing the performer's output. Rework is likely to be required when the task output fails to meet the criteria.

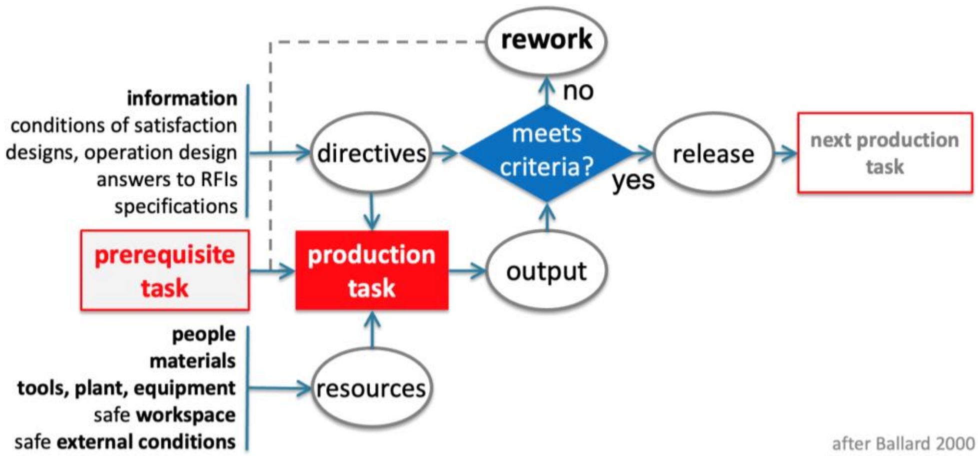

Figure 3: Activity Definition Model for task production (after Ballard 2000)

In order to do their work '*right first time'*, performers need to feel confident that they share their customers' understandings of the criteria. If performers' mis-understand the assessors' criteria, the assessors are likely to require at least additional work and possibly rework. Both result in additional cost and delay to the project overall as well as to the performer. Some performers understand that it is in their interest to ensure that they share the assessors' criteria so that they are better able to do tasks right-first-time.

Written documents and a number of people both within and outside the performers' immediate team hold the knowledge that performers need. Information about what their customers' *value* and the *CoS* that are to be met will come, directly or indirectly, from those customers and via the directives for the task. Unambiguous and explicit directives and CoS are the ideal; in reality they will almost certainly refer to tacit knowledge, possibly assuming that it is explicit and shared (as in "***everyone*** *knows that!"*).

Directives and CoS may draw on normative and cognitive knowledge that could be tacit and open to interpretation. For instance, differences in institutionalized project settings and interpretations informed by *tacitly* held local norms and cultural beliefs can lead to differences in individual interpretations which create rework.

Information is not knowledge. Information may be shared. People can share experiences. A shared understanding of information requires dialogue between stakeholders to establish that it is shared. If you are told something (information) you need to experience it in some way so that it becomes *your* knowledge, and you have *your* understanding (Leonardi and Bailey, 2008). My understanding may not be the same as yours. That's why it's important to check that we have a *sufficiently* shared understanding.

DEVELOPING SHARED UNDERSTANDING

Sharing information is a small but important part of building a shared understanding. Social processes enable performers to share their customers' understanding of what is required. Even if the task will be done by a robot, this social process is necessary to enable the person who programs the robot to understand how to set-up the robot.

The exchange and combination of information leads to the creation of intellectual capital and, as Nahapiet and Ghoshal (1998) suggest, can create organisational learning, a competitive advantage. In the context of projects there are two specific advantages: 1. the project specific advantage of reducing repetition of mistakes enabling the team to deliver the project for less – this aspect is limited to the project. 2. The *meta-skill* of learning to efficiently exchange and combine information producing a competitive advantage for those seeking to work together on future projects. Individuals can develop this skill and the consequent reputation as a good team player that goes with it – and so can companies, divisions, departments and crews that regularly work in projects.

Recent studies by Melissa Valentine and Michael Bernstein on "flash teams" – temporary crowdsourced organisations fluidly convened through open call to solve complex problems quickly (See e.g. Hinds *et al* 2020) are, since the start of the COVID pandemic, relevant wherever teams have to learn effective online collaboration quickly.

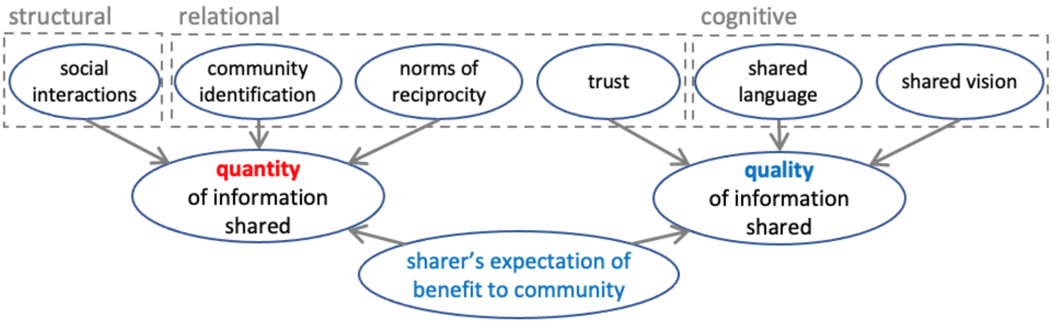

Figure 4: the significant drivers of information sharing. after Chiu et al (2006)

Figure 4 summarises the significant drivers of both the quantity and quality of information sharing. To show factors that affect the quantity and quality of information shared by individuals in virtual on-line communities, Chiu *et al* (2006) used selected drivers from Nahapiet & Ghoshal's (1998) "dimensions of social capital": the *quantity* of knowledge shared is affected by **Structural** Social Interaction ties, the **Relational** norms around reciprocity and the degree to which the individual identifies with the community; the *quality* of the information shared is related to the degree the individual trusts the community, the **Cognitive** degree of shared language and shared vision. Project teams in the workplace, particularly with more people working from home post-COVID, have some similarities with virtual on-line communities.

How does a performer know what the customer wants? – and how does a performer *know that they know* what the customer wants? Production of understanding needs managing and because it involves both explicit and tacit knowledge, it is unlikely this understanding will simply exist. Pre-requisites for *shared understanding* include:

- parties understand that they need shared understanding.
- a psychologically safe way for each party to check that their understanding is *sufficiently* similar to each of the other parties such that they can be *reasonably* confident in the outcome. (This is necessarily a *satisficing* approach (Simon 1956) and presupposes that sometimes we will make mistakes.)

DISCUSSION

Effective promising requires shared understanding of the customer requirements and CoS. Developing shared understanding is a critical step in *making work ready* in the Last Planner System. The initial conversations may happen during *phase planning* (or even earlier) as trade or design teams start to plan handovers from one to the next. On long-lead items some discussion may be necessary prior to ordering to ensure that the supplies and sub-assemblies will meet the CoS. For all activities, CoS will be discussed once the activity is in the *lookahead window*. Absence of shared understanding of the CoS is a constraint on the successful delivery of a task or activity.

The most common metric used in LPS is PPC (Percentage of Promises Completed or Percent Plan Completed). The reason for publishing project PPC data is to help the team as a whole to learn. Everyday learning appears to offer teams a way to improve their LPS metrics such as PPC, Tasks Made Ready (TMR) and Commitment Level (CL) (Ballard & Tommelein 2021). *When PPC gets used as a stick to beat team members with*, workers feel psychologically unsafe, ***learning stops*** and team member's attention shifts from advocacy for the project to protecting themselves from blame, claim or other sanctions.

For shared understanding performers need a way to check that they understand the intent of all the information they are given and the intent of their formal and informal customers. It is an example of reflective work that needs to precede execution.

When performers are clear about their customers' CoS, they are in a position to spot defects in their own work and correct it before passing it on to another trade. When actions are repeated (as in most projects) spotting defects early enables the responsible trade to do it *right first time* in future iterations – i.e. they don't repeat the mistake – as well as correcting the mistake(s) they made initially.

Even if they feel psychologically safe, it is not clear to us whether they will then be more likely to flag up defects – or things that don't look or feel right – in work being passed to them and get it put right before they do anything that would make corrections more difficult. In an ideal world, whether what they flag up is right or wrong, they will be thanked for asking the question. Then they will be more likely to do it again.

Shared understanding online: More and more construction work, particularly that involving designers, is now done online, a trend that COVID has accelerated. For some, this makes it easier to share ideas, information and knowledge. Sharing tacit knowledge as well as experiences (e.g. on local preferences, organizational norms, cultural beliefs) is easier when working face-to-face.

In short, based on all the above findings, 3 propositions are evident in this study which will have to be validated with future studies:

- ***Proposition 1: Less rework will be required when performers can develop a shared understanding of the Conditions of Satisfaction between negotiating parties***
- ***Proposition 2: Shared understanding is most likely when the criteria are explicit***
- ***Proposition 3: Everyday learning will help make tacit information more explicit.***

CONCLUSIONS

In the preparation phase of the Promise Cycle, the customer develops CoS to sit alongside the *request* so that the potential performer knows what is expected. Negotiating the CoS involves making the knowledge explicit. The request + draft CoS is the signal for customer and performer to check that they have a shared understanding of the customer's

CoS and, if necessary, to negotiate the CoS and/or the due date. That discussion will often require the sharing of tacit knowledge and implicit knowledge embedded in the tools in virtual contexts. Codification of the tacit knowledge and making explicit the *imiplicit* knowledge will help create shared understanding.

In LPS, the clarification and negotiation of the CoS happens at various stages, as the time for the work to be done approaches. Failure to (adequately) clarify the CoS with the performer increases the chances that the performer will get it wrong first time → leading to rework, delay and added cost.

Digitisation and online communication can facilitate collaborative transfer of knowledge but it does not guarantee shared understanding as it may erroneously assume shared implicit knowledge and tacit knowledge that is very difficult to share without dialogue, mentoring by knowledge workers or via hard negotiations.

Conditions that appear to facilitate shared understanding of CoS in any context include psychological safety, a project culture that makes time for it and an expectation that workers will not knowingly pass on defective work.

This suggests further propositions for future validation:

- Systematic root cause analysis of rework to establish if lack of shared understanding created the need for rework;
- What makes it easier/more difficult to share understanding of CoS in the context of a construction project – in design, in off-site fabrication, in assembly?
- How can we make it easier for project stakeholders to share tacit knowledge online and to recognise the importance of sharing implicit knowledge to mitigate risk?
- What makes it easier for workers to stop and correct defective work?

REFERENCES

Ballard, G. and Tommelein, I. D. (2021). Current Process Benchmark for the Last Planner® System of Project Planning and Control. *Lean Construction Journal.*

Ballard, H. G. (2000). The Last Planner System of Production Control. PhD Thesis. *University of Birmingham.*

Carrillo, P. (2005). Lessons learned practices in the engineering, procurement and construction sector. *Eng, Construction & Architectural Management*,12, 236–50.

Chiu, Chao-Min, Meng-Hsiang Hsu, Eric TG Wang (2006). Understanding knowledge sharing in virtual communities: *Decision Support Systems*. 42, 1872–1888.

Edmondson, A. (1999). “Psychological Safety and Learning Behavior in Work Teams.” *Administrative Science Quarterly*, 44 (2) 350-383.

Ferrada, X., Núñezb, D., Neyemb, A., Serpellc, A., Sepúlveda, M. (2016) A lessons-learned system for construction project management: a preliminary application, *Procedia - Social and Behavioral Sciences* 226, 302 – 309.

Flores, F. (2013) *Conversations for Action and Collected Essays*. Create Space.

Flores, G. (2016) *Learning to Learn and the Navigation of Moods*. Pluralistic Networks.

Gil, A. J. & Mataveli, M. (2017). Learning opportunities for group learning: An empirical assessment from the learning organization perspective. *J Workplace Learning, 29*(1), 65–78.

Green, Stuart D. (2011) *Making Sense of Construction Improvement*. Wiley Blackwell.

Hayek, F.A. (1945). The use of knowledge in society. *Am. Econ Rev.* 35(4) 519-30.

Hinds, R., Valentine, M., Berg, J., De Celles, K. (2020) *Suddenly Seen: How Virtual Employees Experienced Newfound Equality and Visibility*. Accessed February 26, 2021. https://mvalentine.github.io/pdfs/visibility.pdf.

Javernick-Will, A and Levitt, R (2010) Mobilizing Institutional Knowledge for International Projects, ASCE J Construction, Engineering & Management, 136(4).

Koskela, L., Pikas, E., Gomes, D., Biotto, C., Talebi, S., Rahim, N., & Tzortzopoulos, P. (2016). "Towards shared understanding on common ground, boundary objects and other related concepts." In: *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction*, Boston, MA, USA.

Leonardi PM and D.E. Bailey 2008 Transformational Technologies and the Creation of New Work Practices: Making Implicit Knowledge Explicit in Task-Based Offshoring *MIS Quarterly* 32(2):411-436.

Lincoln, F.H and Ahmed, S.M. (2020). *Modern Construction: Lean Project Delivery and Integrated Practices*, 2edn., Routledge.

Love, P. (2020). Creating a mindfulness to learn from errors: Enablers of rework containment and reduction in construction *Development in the Built Env't* 1.

Manning, S. (2008). Embedding Projects in Multiple Contexts: A Structuration Perspective *Int'l J Project Management* 26(1) 30-37.

Mossman, A. (2020). *Last Planner: 5 + 1 crucial & collaborative conversations for predictable project production planning* 40pp. Accessed March 8, 2021. http://bit.ly/LPS-am-2020.

Nahapiet, J, and Ghoshal, S. (1998) Social capital, intellectual capital, and the organizational advantage, *Acad of Management Rev* 23 (2) 242–266.

Nonaka, I. (1994) "A dynamic theory of organizational knowledge creation." *Organisational. Science*, 5(1) 14–37.

Pasquire, C. L. (2012) The 8th Flow – Common Understanding. *Proc 20th Annual Conference of the International Group for Lean Construction, San Diego, USA.*

Pasquire C.L. & Court, P.F (2013) An Exploration of Knowledge and Understanding - the Eighth Flow. In *Proc 21st Conf. of the Int'l Group for Lean Construction*, Forteleza, Brazil.

Pasquire, C. & Ebbs, P. 2017, 'Shared Understanding: The Machine Code of the Social in a Socio-Technical System' In: *Proc. 25th Ann Conf of the Int'l Group for Lean Construction.* Heraklion, Greece, 9-12 Jul 2017. pp 365-372.

Ramalingam, S and Mahalingam, A. (2011). Enabling conditions for the emergence and effective performance of technical and cultural boundary spanners in global virtual teams**.** *Engineering Project Org. J.* 1(2).

Simon, H. A 1956 "Rational Choice and the Structure of the Environment" *Psychological Rev*. 63(2) 129–138.

Sutton, R. I and Staw, B.M. (1995) What Theory is Not. *Admin Sci Q*, 40(3) 371-84.

Torraco, R. J. (1997). "Theory-Building Research Methods." In Swanson R.A. & E.F. Holton, eds. *Human Resource Development Research Handbook.* Berrett-Koehler.

Barbosa, A.S., and Costa, D.B. (2021). "Productivity Monitoring of Construction Activities Using Digital Technologies: A Literature Review." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 707–716, doi.org/10.24928/2021/0141, online at iglc.net.

PRODUCTIVITY MONITORING OF CONSTRUCTION ACTIVITIES USING DIGITAL TECHNOLOGIES: A LITERATURE REVIEW

Amanda da S. Barbosa[1] and Dayana B. Costa[2]

ABSTRACT

Although the engineering and construction sector is one of the largest in the world economy, it has historically been characterized by a low level of productivity and innovation. Traditional methods for productivity assessment at construction sites, despite being effective, are time-consuming and based on manual data collection and direct observation of activities on-site, which hampers the obtaining of reliable and up-to-date information of activities productivity. To contribute to future research in this area, this study aims to identify and analyze the main existing methods for measuring, analyzing, and improving productivity at construction sites using digital technologies, based on a systematic literature review. A total of 35 papers dated from 2010 to 2021 were selected using Scopus, ASCE Library, and Web of Science databases. Results show that technologies based on computer vision and sensors are the most used by researchers, being able to automate data collection for work sampling and activity analysis, measure inputs, outputs, and cycle times, and monitor factors that can influence workers' productivity. These technologies also have the potential to assist in the development of data collection methods for the assessment of productivity, ergonomics, and worker well-being. This integration, despite valuable, has been little explored in the literature.

KEYWORDS

Waste, flow, time compression, construction productivity, digital technologies.

INTRODUCTION

According to a McKinsey report (Ribeirinho et al. 2020), construction is one of the biggest industries in the world, being responsible for 13% of the global Gross Domestic Product, and yet, even when outside of crises, it does not perform well. Improving the effectiveness of production control has attracted the interest of researchers and lean construction practitioners over the years. In lean construction, production activities are improved continuously with respect to waste and value (Koskela 1992).

With the advent of Industry 4.0, companies have been channelling their efforts to achieve superior performance by advancing levels of automation and interconnectivity (Tortorella et al. 2019). With the incorporation of Industry 4.0 technologies, process

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stability increases and potential issues that jeopardise delivering according to customers' needs can be anticipated (Tortorella et al. 2019). According to Zhao et al. (2019), the use of digital technologies to measure waste on worker, subcontractor and project level could provide significant benefits to an industry plagued with poor productivity. To contribute to future research in this area, this study aims to identify and analyze the main existing methods for measuring, analyzing, and improving productivity on construction sites using digital technologies for automated data collection, based on a systematic literature review.

PRODUCTIVITY MONITORING IN CONSTRUCTION

Definitions of productivity range from industry-wide economic parameters to the measurement of crews and individuals, and each of these measures has its unique purpose (Thomas et al. 1990). According to Thomas et al. (1990), at the project site, contractors are often interested in labor productivity, which can be expressed as the ratio between outputs expressed in specific physical units and inputs expressed in man-hours.

Work sampling, as a technique used to indirectly assess productivity, consists of observing the activities at regular intervals and categorizing them into different work categories to evaluate how time is utilized (Liou and Borcherding 1986). Each observation records what is happening at that instant, and the technique is based upon statistical sampling theory (Thomas et al. 1990). Compared to work sampling, the activity analysis technique includes more detailed observations, provides a more descriptive assessment of the effectiveness of the utilization of workers' time, and can continuously identify the areas for productivity improvements (Cheng et al. 2013).

Regarding the calculation of productivity rates for machinery performing cyclic activities, it is first necessary to estimate the cycle times (Sabillon et al. 2020). On earthmoving activities, the soil amount, which can be estimated based on the number of dump trucks loading and their soil-capacity, and the operating hours are two main aspects that must be considered for productivity monitoring (Kim and Chi 2020).

As it can be noted, traditional methods for productivity assessment at construction sites, despite being effective, are time-consuming and based on manual data collection and direct observation of activities on-site, which hampers the obtaining of reliable and up-to-date information of activities productivity.

RESEARCH METHOD

The research method of this study is a systematic literature review. The research questions to be answered are: What are the most used digital technologies for productivity monitoring in construction sites? How can these technologies help to monitor the productivity of construction activities? What are the main advantages and limitations of the technologies used?

The database used in the study were Scopus, ASCE Library, and Web of Science. The inclusion criteria established were: (1) Papers that have search terms at least in the title, abstract, or keywords; (2) Publications between 2010 and 2021; and (3) Articles published in journals. The exclusion criteria were: (1) Papers not focused on the engineering and construction area, and (2) Publications unrelated to the theme. The final sample consists of 35 selected papers, as shown in Table 1. The search on the database was performed by looking for the following terms:

- Construction AND (productivity OR "work sampling" OR "activity analysis" OR "value-adding time") AND (RFID OR UWB OR bluetooth OR sensors OR accelerometer OR "computer vision" OR "machine learning" OR "deep learning" OR "image processing" OR audio OR microphones).

Table 1: Steps for the definition of the sample and number of papers found

Steps	Data Base		
	Scopus	ASCE	Web of Science
Search for terms	Title, abstract or keywords	Full text	Title, abstract or keywords
Results of the search	471	4916	282
Publications between 2010 and 2021	362	2684	241
Publications on journals	168	1154	164
Remaining papers after removal by exclusion criteria: 35			

The 35 selected papers are distributed into 13 journals (Figure 1a). The journal with the largest number of articles is Automation in Construction, with 13 publications, followed by the Journal of Computing in Civil Engineering appears with 7 publications, and the Journal of Construction Engineering and Management with 4 publications. Figure 1b shows that there were variations in the number of publications over the years. The years with the largest number of publications were 2014 and 2019, with six papers on each. The papers were grouped according to the technologies used to collect and analyze productivity data. 16 publications (45.7% of the sample) used sensor technologies, 16 (45.7%) used technologies based on computer vision, and 3 (8.6%) used technologies based on audio signals.

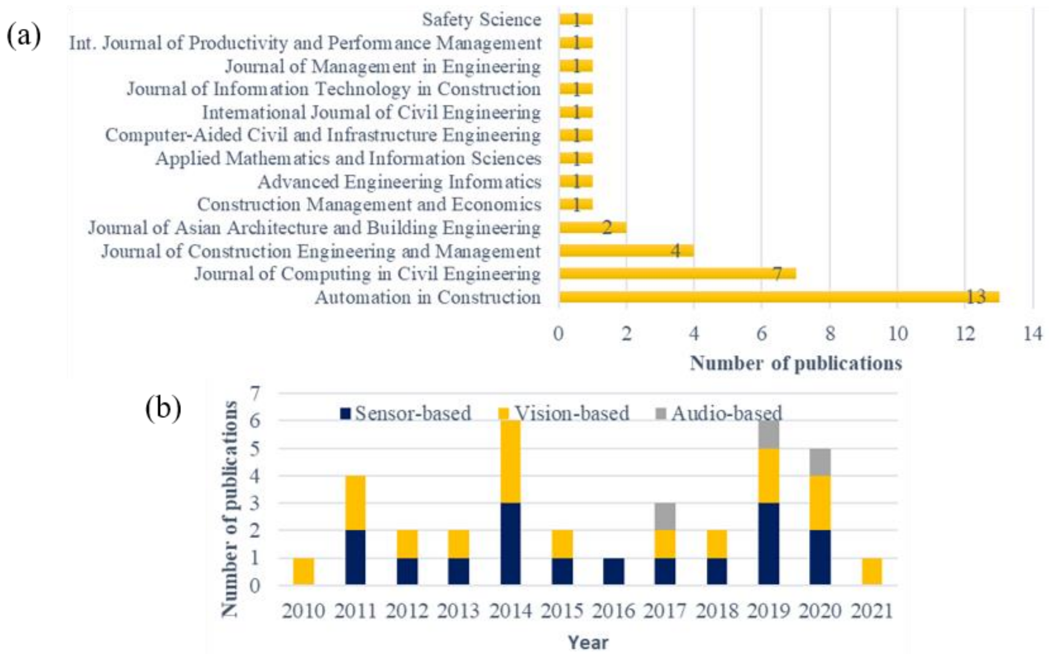

Figure 1: Distribution of publications (a) by journal, and (b) by year and type of technology used

METHODS USING COMPUTER VISION-BASED TECHNOLOGIES

Table 2 presents the 16 papers in the sample that use methods based on computer vision. Video-based activity analysis requires methods for detecting and tracking resources, and procedures for activity recognition (Liu and Golparvar-Fard 2015). Gong and Caldas (2010) present a video interpretation model that extracts productivity information from the video of a concrete column pour operation in real-time. Gong and Caldas (2011) extend this model to non-cyclic construction operations. Gong et al. (2011) classify the actions of workers and equipment on videos into categories that may be used for activity analysis. However, these authors pointed out challenges with gesture recognition on computer-based approaches.

According to Liu and Golparvar-Fard (2015), training and testing models used in computer-vision methods for activity analysis requires a large amount of empirical data which is not yet available to the research community. To address this limitation, these authors propose crowdsourcing the task of workface assessment from jobsite video streams with the assistance of a web-based marketplace platform. Despite that, applying crowdsourcing to workface assessment can be challenging due to the complexity of construction operations and the lack of formal taxonomy to describe activities (Liu and Golparvar-Fard 2015).

Table 2: Papers that use computer-vision-based technologies

Authors	Subject monitored	Scope
Calderon et al. (2021)	Excavators	Activity analysis
Kim and Chi (2020)	Excavators and dump trucks on earthmoving activities	Activity analysis
Roberts et al. (2020)	Workers performing bricklaying and plastering	Activity analysis
Kim et al. (2019)	Dump trucks on earthmoving activities	Measurement of work hours, cycles per hour, and quantity installed
Roberts and Golparvar-Fard (2019)	Excavators and dump trucks on earthmoving activities	Activity analysis
Luo et al. (2018)	Workers performing rebar and formwork	Work sampling
Bügler et al. (2017)	Equipment on earthmoving activities	Activity analysis and measurement of quantity installed and work hours
Liu and Golparvar-Fard (2015)	Workers and equipment on concrete placement operations	Activity analysis
Khosrowpour et al. (2014)	Workers performing interior drywall operations	Activity analysis
Lee et al. (2014)	Workers performing formwork	Measurement of quantity installed and work hours
Lee and Hong (2014)	Construction workers	Measurement of work hours
Ranaweera et al. (2013)	Tunnel liners	Measurement of tunnel construction productivity in terms of shift production
Bai et al. (2012)	Workers tying rebar	Work sampling and analysis of workers' efficiency
Gong and Caldas (2011)	Workers and equipment on various construction activities	Activity analysis
Gong et al. (2011)	Backhoe and workers in formwork activities	Activity analysis
Gong and Caldas (2010)	Concrete bucket on a concrete column pour application	Activity analysis

Some papers focus on automated measurement of inputs and outputs to calculate the productivity of activities. Lee and Hong (2014) developed an image processing algorithm that analyzes and collects construction man-hours that can be used as the input factor for estimating productivity. Lee et al. (2014) developed algorithms for measuring installed work quantity and working hours of construction workers. The productivity data is linked with the 4D BIM model, which helps to predict construction scheduling for management purposes. Bügler et al. (2017) proposed a method for estimating the productivity of soil removal by combining photogrammetry to measure the volume of the excavated soil, and video analysis to generate statistics regarding the construction activities.

Pose estimation techniques, commonly used in research on construction worker ergonomics, have also gained prominence among productivity studies. Bai et al. (2012) developed a human pose analyzing algorithm that automatically determines the efficiency of work-face operations. Khosrowpour et al. (2014) and Roberts et al. (2020) used RGB visual data to detect and track workers' skeleton features to interpret and analyze their activities. Calderon et al. (2021) leveraged articulated 3D models of construction equipment in tandem with vision-based pose estimation methods to train and perform vision-based activity analysis.

The use of multiple cameras at different locations on-site can minimize problems related to occlusions on vision-based methods (Roberts and Golparvar-Fard 2019; Kim and Chi 2020). Surveillance cameras may not provide as detailed information as pose estimation methods, but can reduce costs with the use of cameras that already exist on construction sites. Bügler et al. (2017) and Kim et al. (2019) used surveillance cameras for productivity analysis of equipment on earthmoving activities, while Luo et al. (2018) used surveillance videos to track workers and conduct an automated work sampling.

One of the advantages of vision-based methods is that videos are understandable by any visually able person, provide detailed information, and allow reviews by managers away from the work sites (Liu and Golparvar-Fard 2015). Visual data contains information about not only the physical movements of workers and equipment, but also their visual features and spatial-contextual natures (Kim and Chi 2020). On the other hand, computer vision algorithms are sensitive to environmental factors such as occlusions, lighting, and illumination conditions (Cheng et al. 2017). Shaking of cameras caused by wind, and blur of images caused by rain, snow, and fog represent additional challenges for equipment and worker action recognition (Gong et al. 2011). Besides that, a single camera can only cover a limited field of view. To fully cover a large construction job site, it would be necessary to install multiple cameras in various locations (Cheng et al. 2017).

METHODS USING SENSOR-BASED TECHNOLOGIES

Table 3 will present the 16 papers in the sample that use sensors to collect productivity data. The use of body-worn sensors such as accelerometer, gyroscope, and magnetometer that enable the measurement of workers' posture and motions has gained greater attention for construction activity monitoring. According to Joshua and Varghese (2011), accelerometers are resilient and robust in difficult conditions compared with image sensors, besides having a small size, good accuracy, and reasonable power consumption.

Another advantage is that they can be embedded in wristbands to classify activities performed with hands, such as masonry (Joshua and Varghese 2011; Ryu et al. 2019), ironwork, and carpentry (Joshua and Varghese 2014). Ryu et al. (2020) investigated whether journeymen adopt different work techniques that are safer and more efficient than those of apprentices using an accelerometer, a gyroscope, and a magnetometer, and found that journeymen have more advanced working methods concerning safety and productivity. Other studies used accelerometers embedded in smartphones to measure the operational efficiency of excavators (Ahn et al. 2015) and to detect activities of workers to obtain the proportion of time spent in each activity (Akhavian and Behzadan 2016).

Real-Time Location Sensors (RTLS) such as Radio Frequency Identification (RFID) and Ultra-Wideband (UWB) draw attention from researchers and practitioners because of their technological maturity, cost-efficient infrastructure, and ability to operate without line of sight (Cheng et al. 2017). Cheng et al. (2011) used UWB to analyze the time trajectories of workers and to perform automated work sampling. Costin et al. (2012) used

RFID to track the efficiency of a buck hoist operator and material lift system for transportation. Zhao et al. (2019) applied Bluetooth Low Energy (BLE) to analyze the share of uninterrupted presence of workers in work locations, which is a necessary condition for value-added time, although not all time the workers spend in work locations is necessarily value-adding.

Table 3: Papers that use sensor-based technologies

Authors	Sensors used	Subject monitored	Scope
Lee et al. (2020)	Accelerometer, gyroscope, magnetometer, and a heart rate sensor	Workers performing material handling tasks	Study of the influence of physical strain and psychological stress on workers' productivity
Ryu et al. (2020)	Accelerometer, gyroscope, and magnetometer	Masons	Study of the influence of body loads and level of experience on productivity
Jassmi et al. (2019)	Sensors of blood volume pulse, respiration rate, heart rate, etc.	Workers on various construction processes	Study of the relationship between workers' emotional status and productivity
Ryu et al. (2019)	Accelerometer	Masons	Measurement of cycle time of actions
Zhao et al. (2019)	BLE	Workers on various construction processes	Work sampling
Lee and Migliaccio (2018)	Heart rate sensor	Workers installing a raised deck	Study of the relationship between physical strain and productivity
Hwang and Lee (2017)	Heart rate sensor	Workers on various construction processes	Study of the inflluence of direct and indirect work on workers' physical demands
Akhavian and Behzadan (2016)	Accelerometer and gyroscope	Workers on various construction processes	Work sampling
Ahn et al. (2015)	Accelerometer	Excavators performing utility work, moving wastes, demolishing, etc.	Work sampling
Ibrahim and Moselhi (2014)	GPS and accelerometer	Equipment on earthmoving operations	Measurement of quantity installed, work hours, and cycle time
Joshua and Varghese (2014)	Accelerometer	Iron workers and carpenters	Work sampling
Gatti et al. (2014)	Heart rate and breathing rate sensor	Workers assembling a raised deck	Study of the relationship between productivity and physical strain
Cheng et al. (2013)	UWB and accelerometer	Workers assembling and disassembling a raised deck and building a wall	Work sampling
Costin et al. (2012)	RFID	Workers and elevator buck hoists	Recognition of non-value adding time associated with the use of the elevator
Cheng et al. (2011)	UWB	Workers, equipment and material	Work sampling
Joshua and Varghese (2011)	Accelerometer	Workers performing masonry activities	Recognition of productive activities

Although RTLS sensors can be useful for a variety of applications, without interpreting the activities and purely based on location information, deriving workface data is challenging (Liu and Golparvar-Fard 2015). Based on this issue, Cheng et al. (2013)

attempt to automate the process of activity analysis by fusing information on body posture and the location of workers performing repeated activities. While accelerometers were mounted on a chest belt, UWB tags were placed on the participants' helmets for location tracking. In this method, the identification of direct work activity requires the participants to be present in the work zone and to have a high posture angle.

Other studies use biosensors in wearable devices to analyze factors that affect the productivity of construction workers. Heart rate (HR) is one of the physiological signals most used to study the influence of physical strain on productivity (Gatti et al. 2014, Hwang and Lee 2017; Lee and Migliaccio 2018). Jassmi et al. (2019) also used blood volume pulse, respiration rate, galvanic skin response, and skin temperature to assess the effect of the emotional status of workers on their productivity level. In the study of Lee et al. (2020), HR, activity levels, and sleep quality were monitored to examine how physical strain and psychological stress affect unskilled construction worker productivity and safety performance. Despite being promising, Joshua and Varghese (2011) highlight that the use of too many sensors may be uncomfortable for the subject and can interfere with normal or spontaneous activity.

METHODS USING AUDIO-BASED TECHNOLOGIES

Table 4 presents the papers of the sample that use methods based on audio signals. Audio has been investigated by researchers as input data for recognizing activities of construction heavy equipment that generate distinct acoustic patterns while performing routine tasks (Cheng et al. 2019). Cheng et al. (2017) propose a system that records sounds generated by construction equipment by using commercially available microphones and classifies operations in productive or major activities and non-productive or minor activities. Cheng et al. (2019) presented an audio-based activity recognition model tested under various hardware and software settings. Sabillon et al. (2020) proposed an audio-based system for estimating cycle times of construction equipment for multiple days of operation.

Table 4: Papers that use audio-based technologies

Author	Equipment monitored	Scope
Sabillon et al. (2020)	Dozer, grader,backhoe excavator, and excavator	Measurement of cycles per hour
Cheng et al. (2019)	Compactor, dozer, grader, excavator, and mixer	Measurement of cycles per hour
Cheng et al. (2017)	Backhoe, wheelloader, mini excavator, dozer, hydraulic hammer, dumper, breaking up asphalt, and excavator	Automated recognition of productive and non-productive activities

The application of audio signal processing techniques in the construction management area is still in the early stages of development (Cheng et al. 2019). Compared to visual and kinematic data, sound provides certain advantages: a single microphone can cover larger areas without the need to be directly attached to a machine, and the processing of audio files is computationally less expensive compared to processing images and video files (Sabillon et al. 2020). However, the existence of background noise might be a negative factor for the algorithms, and certain types of construction machinery do not generate distinct sound patterns during operation (Cheng et al. 2017; Sherafat et al. 2019).

DISCUSSION AND CONCLUSIONS

A systematic literature review was carried out to identify and analyze the main existing methods in the literature for productivity monitoring on construction sites using digital technologies. The use of tools to automate techniques such as work sampling and activity analysis allows the identification of waste related to time spent on non-value-adding activities and enables the simplification of steps in a process, therefore being of great importance for lean construction research. However, this paper has the limitation of having analyzed specific categories, not presenting a broader approach on the topic.

Results show that technologies based on computer vision and sensors are the most used for productivity monitoring on construction sites. These technologies can automate data collection for the processes of work sampling and activity analysis, as well as to measure inputs and outputs, and monitor physical and emotional factors that can influence workers' productivity. Audio has been used for monitoring equipment productivity, especially for measuring cycle times. However, there are still few studies in this category.

Computer vision algorithms have made great advances in recent years, mainly with the use of deep learning techniques. Despite this fact, the detection of fine movements is still a challenge for vision-based methods. Pose estimation techniques, widely used in ergonomics studies, are capable of analyzing movements in a more detailed way. Due to their origin, pose estimation techniques have a great potential for studies of productivity monitoring integrated with ergonomics analysis. Regarding the use of sensors, further studies are needed to overcome the challenge of relating the worker's location to the type of work being performed, which could be done through the integration of RTLS with kinematic sensors. Studies using physiological signals have great potential to demonstrate the influence of stress and physical demand on workers' productivity.

Thus, as can be seen in Figure 2, there is an opportunity to combine the technologies of computer vision-based and sensor-based methods to provide evidence regarding the integrated management of productivity and safety and their impacts on the production process. This integration, despite being of great value, has been little explored in the literature.

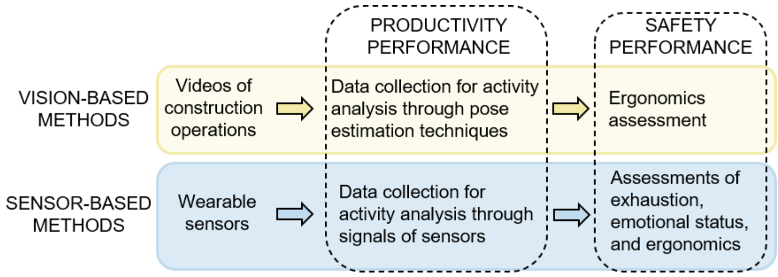

Figure 2: Workflow for integration of productivity and safety monitoring using digital technologies

REFERENCES

Ahn, C. R., S. Lee and F. Peña-Mora (2015). "Application of Low-Cost Accelerometers for Measuring the Operational Efficiency of a Construction Equipment Fleet." *J. Comput. Civ. Eng.* 29.

Akhavian, R. and A. H. Behzadan (2016). "Smartphone-based construction workers' activity recognition and classification " *Autom. Constr*. 71: 198–209.

Bai, Y., J. Huan and S. Kim (2012). "Measuring Bridge Construction Efficiency Using the Wireless Real-Time Video Monitoring System" *J. Manage. Eng.* 28: 120-126.

Bügler, M., A. Borrmann, G. Ogunmakin and P. A. Vela (2017). "Fusion of Photogrammetry and Video Analysis for Productivity Assessment of Earthwork Processes" *Comput. Aided Civ. Inf. Eng.* 37: 107–123.

Calderon, W. T., D. Roberts and M. Golparvar-Fard (2021). "Synthesizing Pose Sequences from 3D Assets for Vision-Based Activity Analysis" *J. Comput. Civ. Eng.* 35(1).

Cheng, C.-F., A. Rashidi, M. A. Davenport and D. V. Anderson (2017). "Activity analysis of construction equipment using audio signals and support vector machines" *Autom. Constr.* 81: 240–253.

Cheng, C. F., A. Rashidi, M. A. Davenport and D. V. Anderson (2019). "Evaluation of Software and Hardware Settings for Audio-Based Analysis of Construction Operations" *Int. J. Civ. Eng.* 17: 1469–1480.

Cheng, T., J. Teizer, G. C. Migliaccio and U. C. Gatti (2013). "Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data" *Autom. Constr.* 29: 24–39.

Cheng, T., M. Venugopal, J. Teizer and P. A. Vela (2011). "Performance evaluation of ultra-wideband technology for construction resource location tracking in harsh environments" *Autom. Constr.* 20: 1173–1184.

Costin, A., N. Pradhananga and J. Teizer (2012). "Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project" *Autom. Constr.* 24: 1-15.

Gatti, U. C., G. C. Migliaccio, S. M. Bogus and S. Schneider (2014). "An exploratory study of the relationship between construction workforce physical strain and task level productivity" *Const. Manag. Econ.* 32: 548-564.

Gong, J. and C. H. Caldas (2010). "Computer Vision-Based Video Interpretation Model for Automated Productivity Analysis of Construction Operations." *J. Comput. Civ. Eng.* 24.

Gong, J. and C. H. Caldas (2011). "An object recognition, tracking, and contextual reasoning-based video interpretation method for rapid productivity analysis of construction operations." *Autom. Constr.* 20: 1211-1226.

Gong, J., C. H. Caldas and C. Gordon (2011). "Learning and classifying actions of construction workers and equipment u sing Bag-of-Video-Feature-Words and Bayesian network models" *Adv. Eng. Inform.* 25: 771–782.

Hwang, S. and S. Lee (2017). "Wristband-type wearable health devices to measure construction workers' physical demands " *Autom. Constr.* 83: 330–340.

Ibrahim, M. and O. Moselhi (2014). "Automated productivity assessment of earthmoving operations" *J. Inf. Technol. Constr.* 19: 169-184.

Jassmi, H. A., S. Ahmed, B. Philip, F. A. Mughairbi and M. A. Ahmad (2019). "E-happiness physiological indicators of construction workers' productivity: A machine learning approach" *J. Asian Archit. Build. Eng.* 18: 517-526.

Joshua, L. and K. Varghese (2011). "Accelerometer-Based Activity Recognition in Construction." *J. Comput. Civ. Eng.* 25: 370-379.

Joshua, L. and K. Varghese (2014). "Automated recognition of construction labour activity using accelerometers in field situations" *Int. J. Prod. Perform. Manag.* 63: 841-862.

Khosrowpour, A., J. C. Niebles and M. Golparvar-Fard (2014). "Vision-based workface assessment using depth images for activity analysis of interior construction operations" *Autom. Constr.* 48: 74-87.

Kim, H., Y. Hama, W. Kim, S. Park and H. Kim (2019). "Vision-based nonintrusive context documentation for earthmoving productivity simulation" *Autom. Constr.* 102.

Kim, J. and S. Chi (2020). "Multi-camera vision-based productivity monitoring of earthmoving o perations" *Autom. Constr.* 112.

Koskela, L. (1992). Application of the New Production Philosophy to Construction. Finland.

Lee, C., J. Som and S. Lee (2014). "A System Model for Analyzing and Accumulating Construction Work Crew′s Productivity Data Using Image Processing Technologies" *J. Asian Archit. Build. Eng.* 13: 547-554.

Lee, S. and M. Hong (2014). "Implementation of Man-Hours Measurement System for Construction Work Crews by Image Processing Technology" *Appl. Math. Inf. Sci.* 8: 1287-1293.

Lee, W., G. C. Migliaccio, K.-Y. Lin and E. Y. W. Seto (2020). "Workforce development: understanding task-level job demands-resources, burnout, and performance in unskilled construction workers" *Saf. Sci.* 123.

Liou, F.-S. and J. P. Borcherdin (1986). "Work sampling can predict unit rate productivity." *J. Constr. Eng. Manage.* 112: 90-103.

Liu, K. and M. Golparvar-Fard (2015). "Crowdsourcing Construction Activity Analysis from Jobsite Video Streams" *J. Constr. Eng. Manage.* 141.

Luo, X., H. Li, D. Cao, Y. Yu, X. Yang and T. Huang (2018). "Towards efficient and objective work sampling: Recognizing workers' activities in site surveillance videos with two-stream convolutional networks." *Autom. Constr.* 94: 360-370.

Ranaweera, K., J. Ruwanpura and S. Fernando (2013). "Automated Real-Time Monitoring System to Measure Shift Production of Tunnel Construction Projects." *J. Comput. Civ. Eng.* 27: 68-77.

Ribeirinho, M. J., J. Mischke, G. Strube, E. Sjödin, J. L. Blanco, R. Palter, J. Biörck, D. Rockhill and T. Andersson (2020). The next normal in construction McKinsey & Company.

Roberts, D., W. T. Calderon, S. Tang and M. Golparvar-Fard (2020). "Vision-Based Construction Worker Activity Analysis Informed by Body Posture " *J. Comput. Civ. Eng.* 34.

Roberts, D. and M. Golparvar-Fard (2019). "End-to-end vision-based detection, tracking and activity analysis of earthmoving equipment filmed at ground level" *Autom. Constr.* 105.

Ryu, J., A. Alwasel, C. T. Haas and E. Abdel-Rahman (2020). "Analysis of Relationships between Body Load and Training, Work Methods, and Work Rate: Overcoming the Novice Mason’s Risk Hump " *J. Constr. Eng. Manage.* 146.

Ryu, J., J. Seo, H. Jebelli and S. Lee (2019). "Automated Action Recognition Using an Accelerometer-Embedded Wristband-Type Activity Tracker" *J. Constr. Eng. Manage.* 145.

Sabillon, C., A. Rashidi, B. Samanta, M. A. Davenport and D. V. Anderson (2020). "Audio-Based Bayesian Model for Productivity Estimation of Cyclic Construction Activities " *J. Comput. Civ. Eng.* 34.

Thomas, H. R., W. F. Maloney, R. M. W. Horner, G. R. Smith, V. K. Handa and S. R. Sanders (1990). "Modeling construction labor productivity." *J. Constr. Eng. Manage.* 116: 705-726.

Tortorella, G. L., R. Giglio and D. H. Van Dun (2019). "Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement." *Int. J. Oper. Prod. Manag.* 39.

Zhao, J., O. Seppänen, A. Peltokorpi, B. Badihi and H. Olivieri (2019). "Real-time resource tracking for analyzing value-adding time in construction." *Autom. Constr.* 104: 52-65.

Al Barazi, A., Seppanem, O., Pikas, E., Lehtovaara , J., and Peltokorpi, A. (2021). “Enhancing Internal Vertical Logistics Flows In High-Rise Construction: An Exploratory Study.” *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 717–726. doi.org/10.24928/2021/0143, online at iglc.net.

ENHANCING INTERNAL VERTICAL LOGISTICS FLOWS IN HIGH-RISE CONSTRUCTION: AN EXPLORATORY STUDY

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ABSTRACT

Vertical logistics systems are important for enhancing production performance in high-rise buildings (HRBs). However, researchers studying vertical logistics have focused on examining the flow of individual resources in isolation. Only a few studies adopt a holistic approach to optimizing the flow of resources. For example, research on the combined effect of the number, characteristics, and rules of elevators uses and break rooms' location on the production system's performance remain scarce. Methods and tools like agent-based modelling (ABM) and simulation could be used to study and predict vertical logistics systems' performance holistically. This research uses hypothetical strategies to investigate opportunities to enhance performance and develop more effective vertical logistics systems. The proposed agent-based model and simulation is validated with a simple, hypothetical takt plan. The simulation results show that the logistic system's performance varies when changing parameters like the number of elevators and the location of break rooms. This research's main contribution is a new way to study these systems and potentially enhance their performance. Furthermore, possibilities to maximize performance and remove logistical bottlenecks are suggested.

KEYWORDS

Vertical transportation systems, internal logistics, simulation, agent-based, production planning and control.

INTRODUCTION

Effective high-rise construction depends on the vertical transportation system's performance. The system can substantially affect the production schedule as it limits the

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time available for work or delays the transportation of the resources (Jung et al. 2017; Park et al. 2013). A vertical transportation system is used to move workers to their work locations during working hours. Elevators are also used for moving other resources such as materials and equipment consumed by production tasks. Increased performance of vertical transportation systems is necessary to minimize waste.

One essential peculiarity in construction, compared to plant-based manufacturing, is that instead of product flowing through the production line, the productive resources flow through the product (Sacks 2016). That is, the planning, coordination, and organization of productive resources, in addition to production operations, to flow through the building is very important. It is especially relevant in high-rise construction projects, where the physical distance of travel and associated time is significantly higher than in other building types.

Although there is previous work on high-rise logistics, they tend to focus on an individual strategy such as elevator zoning (e.g., Jung *et al.*, (2017)). In real high rise projects, a combination of strategies is required, and to the authors' knowledge, there is no previous work that has attempted to identify and include. This study explores vertical flows as an emergent property of takt based construction production plan. An agent-based model is used to study the interactions between these flows. The model could be used in high rise projects to study, pre-plan and determine the performance of hypothetical strategies for vertical transportation systems. The model may bring insights for the construction planners to examine the role of changing combinations of system variables, including, for example, the number of elevators, the site working policy, and when the material elevator can be used to transport workers, on system performance. As such, it may be used by companies and planners to update their current planning methods and produce better plans.

BACKGROUND

SIMULATION OF VERTICAL LOGISTICS SYSTEMS IN HIGH-RISE BUILDING

This study focuses on the internal phase of construction production. The vertical logistics during the internal construction phase is achieved through different means, including elevators and cranes. It is important to select the right number of elevators with the appropriate speed, capacity and manage the elevators' control rules, including the service range, zones, usage, and methods of calling the elevators, to optimize vertical transportation.

Vrijhoef et al. 2018 simulated workers' time usage and examined five strategies that could affect workers' productive time. One strategy included increasing the number of restrooms by one and the elevators by one. These interventions helped to increase the productive time on site. However, the role of material delivery, traffic on different floors and the impact of changing the break rooms' locations were not considered.

Jung *et al.*, (2017) used ABM to study the effects of zoning and sky-lobby control strategies on the performance of vertical transportation systems. The main finding was that there is no one best strategy suitable for all kinds of traffics and that the design of the elevator system should vary according to the construction project phase. The study did not, however, examine how the location of breakrooms, number of lifting elevators, and material lifting strategies affect the site traffic.

There are many metrics to assess the elevator system's performance in the building's operation phase, however, these metrics are not suitable for the construction phase because no particular patterns for traffic exist (Jung *et al.*, 2017). Also, these metrics ignore workers waiting time, queuing length, and the total travel time when workers' traffic exceeds the vertical transportation system's capacity (Siikonen, 1997).

Moreover, it is important in construction to evaluate each elevator operation efficiency separately and manage the traffic accordingly. This is particularly evident when the performance, service range, and elevators' characteristics are different. This limitation stresses the need to emphasize the worker's time to arrive at their destination, mainly during peak time traffic. If the workers spend more time arriving at their destination, their overall productivity decreases accordingly. Thus, a measure for vertical transportation system performance should consider assessing the time needed by every worker to reach their destination.

One of the challenges in studying vertical transportation is that the historically used methods for evaluating vertical transportation, like deterministic simulation, or discrete event simulation, fall short in modelling the site conditions. The usage of complex science methods like ABM can help to overcome these limitations.

RESEARCH METHODS

As the main output of this research is an agent-based simulation model for construction vertical transportation systems, the design science research methodology is chosen (Holmström et al. 2009). The selected methodology assumes gradual and iterative development and evaluation of the artefact, i.e., the simulation model in this research. After each development iteration, focus group interviews were organized to collect feedback from researchers and practitioners to develop the model further.

ABM is a computer simulation technique used to examine how system rules and patterns emerge from individual agents' behaviours (Epstein et al. 1996). ABM is a suitable tool to describe complex systems' behaviour. It employs a "bottom-up" approach and creates artificial agents representing entities with the ability to perceive and interact with each other and their environment. In other words, in ABM, the interaction of system components or agents' behaviours determines the whole system's behaviour. The agent could be an autonomous individual or an entity that recognizes each other as heterogeneous rather than identical. They evolve and adapt to their surrounding environment. Also, they can communicate, make autonomous decisions, and behave stochastically.

Few recent works have used ABM to bring insights to construction. For example, ABM is used to assess the impact of production control methods and information flow on production (Ben-Alon and Sacks 2015). Also, ABM has been used to study the design workflow at the intersection of social and process aspects (Hattab and Hamzeh 2016). Furthermore, ABM helped the project controller simulate a project's status within the Weekly Work Plan (WWP) to achieve the desired performance (Shehab et al. 2020).

This model is built using Python open-source programming language and Python library for Agent-based modeling (MESA), which rely on object-oriented programming concepts. The results of each step of simulation are extracted as data frame (table-like data structure) and then plotted using Python data analysis and visualization libraries, including Pandas, Seaborn, and NumPy.

A simple takt plan to illustrate the progress of HRB production was used for this purpose. The takt plan contains information on the simplified structural, exterior, and interior phases of a 40-floor HRB (see Figure 1). The authors created the plan based on a hypothetical HRB case with hypothetical values for variables. These initial values were validated in workshops with industry representatives and provided a basis to assess the proposed concept's feasibility. These variables will be further validated in future studies.

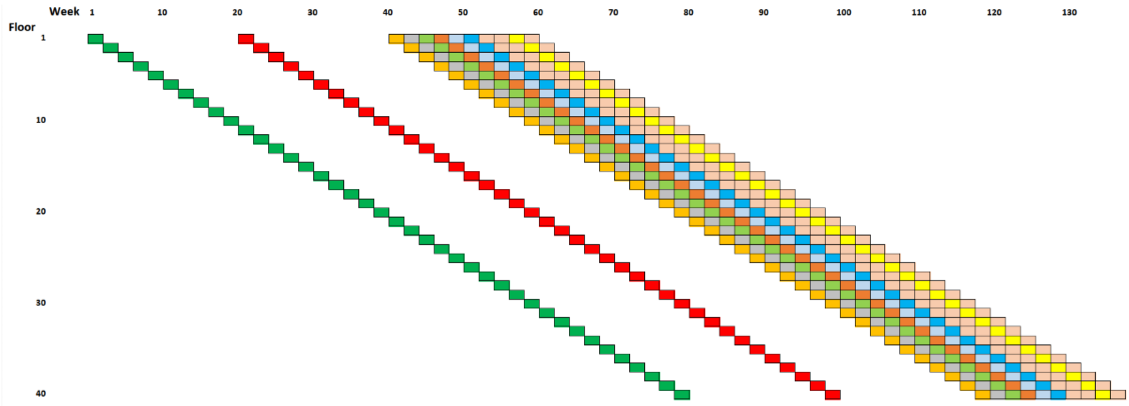

Figure 1 Takt plan with floors on the vertical axis and time (weeks) on the horizontal axis.

DEVELOPING A PROOF OF CONCEPT MODEL THROUGH A TAKT PLAN

The simulation presented in this paper focuses on building a proof of concept and demonstrates the utility of using the agent-based methodology for decision-making. The designed model was used to assess the impact of combinations of strategies, including the number and locations of elevators and break rooms and material delivery strategies in HRB. The parameters that are integrated to develop ABM model for different strategies are shown in Table 1.

As the metrics used to assess elevators' efficiency in the operational building are inappropriate for the construction stage, a new metric called system latency is suggested in this study. We define it as the average time required by the transportation system, including elevators and staircases, to fulfil workers' intentions, e.g., the time taken to reach a break room since that intention was declared.

This also means that intentions and the status of workers have been distinguished from each other. The statuses are the states that workers go through to fulfil their intentions. For example, if the worker is on the first floor and wants to go to a breakroom on the fifth floor, the worker intends to reach the breakroom. However, the worker has many different states to fulfil this intention, including waiting for the elevator, getting in the elevator, waiting for the breakroom's availability (space). The utilization rate index is also used to assess the average percentage of time workers' spent in their working location.

Table 1 Parameters to construct different scenarios of vertical logistics strategies.

ID	Parameters	Explanation
1	Number and type of lifts	The number of installed elevators at a given time.
2	Elevators range	Which floors are served with each elevator?
3	Elevator's usage	Materials/logistics or people
4	Material lifting strategies.	As part of the structural works cycle in weekends
4	Break room's locations	On every 5th and 10th floor breakrooms in site
5	Elevators ordering options.	One button for each elevator or other methods
6	Waste production	Consideration for waste flow
7	Probability of using the elevator	i.e., faster elevators or elevators with more range
8	Location of material storage	One floor or many
9	Location of waste disposable	One floor or many
10	Height: 10, 30 and 50 floors	By changing the time wagons move up.

With 40 takt areas (1 floor equals 1 takt area.), 12 takt wagons, 10-day takt time, and 10-story buffer between structural, exterior, and interior phases, the total duration of the hypothetical project is 138 weeks. The information on work wagons, their need for material logistics, and the number of workers for each wagon are presented in Table 2. The logistics represent a roughly estimated number of material packages that can fit in one elevator needed per one week of work per wagon. A correction factor of 1.2 was included to consider other workforce and visitors to the site, such as supervisors and client representatives.

Table 2 Work distribution within wagons

Wagon	Wagon Description	Logistics	Workers	Correction Factor
1	Structure	0	20	1,2
2	Exterior	0	12	1,2
3	Drywall both sides & HVAC, ELEC, ceilings	6	10	1,2
4	Floor screeding	4	4	1,2
5	Wall levelling and painting	2	4	1,2
6	Ceiling equipment, sockets and switches,	2	5	1,2
7	Kitchen wall & floor tiling	6	4	1,2
8	Floor laminate installation, door and floor	4	4	1,2
9	ELEC, Household equipment installation and	6	5	1,2
10	Cleaning, Supervisor inspection	6	3	1,2
11	Functionality checks	2	2	1,2
12	Handover	0	1	1,2

The construction phase after structure erection, when the vertical logistics rely mostly on elevators, is evaluated. That is, the evaluation of the cranes' role is neglected. On average, the elevator can accommodate 10 people at a time or one person carrying a material package. The elevator takes one minute (one simulation step) to move from one floor to another, considerably slower than in reality. This simplification was made to ease the simulation for the pilot study. The simulation step is connected with the elevator speed (1 step = 1 minute), and simulated elevators move up or down in every step, depending on the elevator demand. Workers also go up/down using stairs with the speed of 1 floor/min. The worker uses the elevator if they are carrying a material package and cannot use the staircase. These parameters were determined in workshops with industry representatives who had experience in takt planning and worked on Finnish high-rise construction sites.

The primary information and agents that are modelled include:

- The model itself, acting as a container of all other agents, time, and spaces.
- Workers for each wagon
- Materials needed for each wagon
- Elevators
- Break rooms: On every 5th and 10th floor versus break rooms in the site office
- Number and type of lifts and rules of lift
- Number and location of storage areas

The values of parameters that are used in the HRB are shown in Table 3. Breakrooms are mainly used during lunch and coffee breaks. The number of these areas and their locations are considered variable. The time spent on the break was assumed to follow a triangular distribution with a mean of 12 min for a coffee break, 30 minutes for a lunch break, and 10 minutes for other types of breaks. Thus, the simulation's distinctive areas depict workspace, storage, elevators, break areas, and lunch areas.

Table 2 Parameters used in the model.

ID	Parameter Name	Value	Max	Min	Unit	Probability
1	Probability of going to nearest	50 %				
2	Elevator capacity	10			persons	
3	Elevator speed	1			floors/min	
4	Storage room capacity	6			persons	
5	Break room capacity	unlimited			persons	
6	Lunch break duration	30	25	45	minutes	triangular distribution
7	Lunch break start	240	210	270	minutes	triangular distribution
8	Coffee break duration	12	10	30	minutes	triangular distribution
9	Coffee break start	120	100	150	minutes	triangular distribution
10	Coffee break2 start	420	400	450	minutes	triangular distribution
11	Picking material duration	15	35	10	minutes	triangular distribution
12	Break duration	15	5	30	minutes	triangular distribution
13	Floors by stairs	3	1	5	floors	triangular distribution
14	Work duration	120	5	180	minutes	triangular distribution
15	Workday steps	510			minutes	-

RESULTS

In total, 54 simulation runs in two iterations were conducted in this pilot study. The generated data were analyzed and visualized. KPIs were calculated after simulating one week per scenario. The investigated 27 scenarios are formed from the combinations of the following parameters:

- The numbers of elevators: two, four, and six.

- The break rooms' locations: only ground floor, every fifth floor, and every 10th floor
- Simulation starting days are 200, 400 and 600

The strategy titled 2EV – Br5th in Figure 2 means that the site has two elevators and break rooms on every fifth floor. Similarly, the 4EV-BrGr site strategy has four elevators and one break room on the ground floor. All other strategies visualized in Figure 2 are encoded similarly.

System latencies ranged from 1 minute to a maximum of 8 minutes. On average, since the announcement of their attention, most workers reached their destinations in less than two minutes. There are only a few instances where the system took more than 8 minutes to fulfil intentions.

As the wagons move up, the system latency increases. The increase in the physical distance from the ground floor increased the reliance on elevators and caused increased latency. The maximum system latency is around 8.5 minutes when the structure wagon is on the 60th floor, and the building had two working elevators with one break room on the ground floor. When the structure wagon is on the 20th floor, many other wagons are close to the ground floor, and according to our previously explained assumptions, some workers will use the stairs more frequently. This reduces the reliance on elevators and reduces system latency significantly. In the same way, the utilization rates increase when the wagons are close to the ground floor. For all strategies with the structure wagon on the 20th floor, the utilization rate ranges between less than 70% to around 75%.

When the structure wagon is on floor 40th, the maximum utilization rate is achieved by having four elevators and break rooms every 5th floor (6EV-Br5th) with materials delivery out of working hours with an average utilization rate, from two iterations, close to 68 %. This also applies when the structure wagons are on floors 20th and 60th. The model estimates an increment in utilization rate by around 20% compared to the strategy with two elevators and one break room on the ground floor. Adding elevators and break rooms also reduced the latency time tremendously. For example, when the structure wagon is on the 40th floor, adding four elevators and break out rooms on every 5th floor reduced the latency time 8 times from an average of ~4 to ~0.5 minutes, as shown in the figure (2EV-BrGr vs 6EV-Br5th).

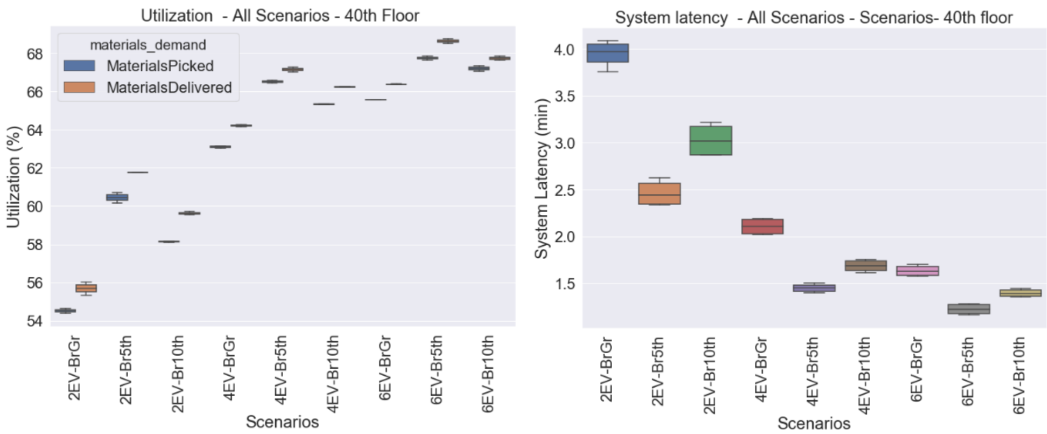

Figure 2 System latency and utilization rate when structure wagon is on 40th floor.

DISCUSSION

The system's performance was studied by changing one parameter or a combination of parameters as part of the strategy. The results showed a significant correlation between system variables and the overall performance of the vertical transportation system. It was possible to increase the utilization rate ca 18% by changing the system's variables. The simulation model helped to quantify the impact of these changes on system performance. This could provide construction planners better understanding and tangible evidence regarding the importance of each variable.

It was found that the method of material delivery affects the overall utilization rate. For example, the utilization rate increased about 2% for the strategy 2EV-Br10th when materials are delivered out of working hours. Overall, it was found that delivering materials outside working hours increased the utilization rate and decreased system latency. However, the addition of elevators had a more significant impact.

Adding elevators increased the utilization rate for all scenarios. The increase in the utilization rate was not linear. For example, compared to the 2EV-BrGr, the utilization rate for the strategy 4EV-BrGr was around 9% higher and, when compared to the 6EV-BrGr, the utilization rate for the 2EV-**BrGr** was 2.8% higher, signifying the difference between adding 2 and 4 elevators. The impact of adding elevators on system latency was similar to the utilization rate. The system latency decreased in none linear manner as the number of elevators increased. The optimal number of elevators can be determined based on evaluating and balancing the expected gains against the costs. Also, adding break rooms enhanced the performance of the system. Adding break rooms had a lower impact on system performance than the number of elevators but more than the selected material delivery method.

An interesting finding is cases where more elevators rendered equal or even less the overall performance than the cases with fewer elevators. This is evident in the cases 4EV-Br5th vs 6EV-BrGr also in 4EV-Br10th vs 6EV-BrGr. According to this, the planner can further build on this result to decide between the best strategies.

The magnitude of the impact of each variable on cost and waste can be evaluated against the estimates. For example, assuming that workers spend 5 hours in their workplace, an increase of 18 % in utilization rate would account for an approximate reduction in time wasted out of working place by 54 minutes for each worker. If the site has 40 workers, this accounts for 36 hours total reduction in the wasted transportation time in one day and 7200 hours in 200 days. Suppose this time is value-adding, and considering that the cost of worker/h is ten euros, this sums up to 72000 euros of savings. This amount could then be compared, i.e., with the cost of elevators and installing the elevators.

LIMITATIONS

The proof-of-concept model is subject to several limitations to be addressed in future research. For example, no distinction between external and internal elevators was made. The external elevator must have an operator and his time of operating the elevator is by definition non-value adding. Also, the speed of elevators in this research is considered all equal and slow for construction elevators. In reality, speeds differ, and elevators are faster. Similarly, the speed 1 floor/min of workers using the stairs is also slow. The metrics like system latency and utilization represent the average values for all floors. Distinguishing system performance based on the height of floors is important to have better and more accurate understanding for the results.

In the current model, the simulation time is one week, per which the average performance is calculated. However, this approach averages out the performance during the peak times and different types of traffic, i.e., upward, downward, and mixed traffic. In future research, it is critical to consider the system's performance at peak times in addition to the average performance.

The model parameters and values, including the hypothetical takt project case, were evaluated through workshops with industry partners. In future research, the model should be implemented in real case projects both in the pre-planning phase, where the model could be used to investigate alternative vertical transportation strategies, and the construction phase, where the existing logistics system's performance is monitored. Data from elevators and resource positioning systems could be collected in high-rise building projects to track the performance.

FUTURE RESEARCH

ABM and simulation were used to evaluate complex vertical logistics systems and predict hypothetical systems' performance. The model generated results that were validated in workshops with industry participants by visualizing the agents' movements. Also, the results were validated internally and numerically by comparing the generated numbers and metrics with those in real projects. However, further internal and external validation is needed. External validation should be made with the industry partners by comparing the model results with a real case study.

Other parameters could be integrated and tested to understand their impact on the overall performance. For example, the simulation model could be developed to quantify the effect of changing takt times or takt strategy. The impact of errors and omissions in design could also be studied as workers move to seek more information from other trades or supervisors.

The model should be flexible and configurable for a specific actual project and before the elevators are installed. This could be done by iterating through strategies with multiple elevators' schedules and characteristics of elevators. We have already started using the model to support decision-making in two real high-rise construction projects. Our initial experience from two ongoing case studies indicates that it is possible to get data for calibrating the model. This will include analyzing the time spent by workers on each space throughout the day and waiting after elevators, as suggested by our industry partners. The model could form a basis for a digital twin of logistics process where parameters are updated in real or close to real time based on the system's actual behavior.

CONCLUSION

Construction processes embody complex systems' behaviours. Simulation is one of the methods used to understand complex systems, yet it is not often utilized in construction research. This work has created and implemented a simple simulation model that can predict some performance metrics for vertical construction logistics systems despite the limited work done under this scope. The proof of concept showed promising results that do not deviate much from reality. The model is expected to help the construction teams in their decision-making and quantify the impact of different decisions and policies. Such an approach to decision-making is expected to result in savings and benefits.

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REFERENCES

Axelrod, R. (1997). *The complexity of cooperation. Agent-based models of competition and collaboration*.

Barney, G., and Al-Sharif, L. (2015). *Elevator traffic handbook: Theory and practice: Second edition*. Elevator Traffic Handbook: Theory and Practice: Second Edition, Taylor and Francis Inc.

Ben-Alon, L., and Sacks, R. (2015). "Simulating and vizualising emergent production in construction (Epic)using agents and BIM." *Proceedings of IGLC 23 - 23rd Annual Conference of the International Group for Lean Construction: Global Knowledge - Global Solutions*.

Cederman, L.-E. (1997). *Emergent actors in world politics : how states and nations develop and dissolve*. Princeton University Press.

Epstein, J. M., Axtell, R., and 2050 Project. (1996). *Growing artificial societies : social science from the bottom up*. Brookings Institution Press.

Hattab, M. Al, and Hamzeh, F. (2016). "Analyzing Design Workflow: An Agent-based Modeling Approach." *Procedia Engineering*, Elsevier Ltd, 510–517.

Jung, M., Moon, J., Park, M., Lee, H. S., Joo, S. U., and Lee, K. P. (2017). "Construction worker hoisting simulation for sky-lobby lifting system." *Automation in Construction*, Elsevier B.V., 73, 166–174.

Macy, M. W., and Willer, R. (2002). "From Factors to Actors: Computational Sociology and Agent-Based Modeling." *Annual Review of Sociology*, Annual Reviews, 28(1), 143–166.

Park, M., Ha, S., Lee, H. S., Choi, Y. K., Kim, H., and Han, S. (2013). "Lifting demand-based zoning for minimizing worker vertical transportation time in high-rise building construction." *Automation in Construction*, Elsevier B.V., 32, 88–95.

Sacks, R. (2016). "What constitutes good production flow in construction?" Construction *Management and Economics*.

Shehab, L., Ezzeddine, A., Hamzeh, F., and Power, W. (2020). "Agent-Based Modelling and Simulation of Construction Crew Performance." *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC),* International Group for Lean Construction, 1021–1032.

Vrijhoef, R., Dijkstra, J. T., and Koutamanis, A. (2018). "Modelling and simulating time use of site workers with 4d BIM." *IGLC 2018 - Proceedings of the 26th Annual Conference of the International Group for Lean Construction: Evolving Lean Construction Towards Mature Production Management Across Cultures and Frontiers*.

Sharma, A. and Trivedi, J. (2021). "Application of Information Theory in Last Planner® System for Work Plan Reliability." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 727–736, doi.org/10.24928/2021/0147, online at iglc.net.

APPLICATION OF INFORMATION THEORY IN LAST PLANNER® SYSTEM FOR WORK PLAN RELIABILITY

Anjali Sharma[1], and Jyoti Trivedi[2]

ABSTRACT

Last planner system® (LPS) is an effective tool for continuous monitoring and improvement of the planning. One of the main parts of LPS is the constraint removal discussion. Identifying and removing the constraints before the execution can influence the reliability of the plan and can ultimately improve the project performance. Previous research works have indicated the use of Information theory to quantify the effect of constraint removal discussion on the performance of the weekly work plan while using Percentage Plan Complete (PPC) as an indicator of work plan reliability and considering a limited range of constraints categories. Earlier studies have proved that Task Anticipated (TA) and Task Made Ready (TMR) are better indicators of the project duration than PCC. In this paper, the researchers have used information theory to assess the effect of the constraint removal discussion on PPC, TA, and TMR of the construction projects while considering a wider range of constraints. The results signified that the important constraint categories vary for improving PPC and improving TA & TMR. Identifying and discussing the main constraint categories could improve the work plan reliability indicators up to 18%. The framework can be used repeatedly and the results can contribute in improving the effectiveness of weekly meetings in the future.

KEYWORDS

Last planner® system, constraint analysis, make-ready planning, work plan reliability, information theory.

INTRODUCTION

The last planner system was designed by Glenn Ballard and Gregory Howell using the action research approach in the early 1990s'. Construction professionals have been using it widely in the architecture, engineering, and construction (AEC) industry for over two decades. Unlike the critical path method (CPM) the LPS uses pull driven scheduling approach to improve the planning reliability (Dave, Hämäläinen, & Koskela 2015). One of the main features of LPS is the constraint removal discussion. Research works have proved that identifying and removing the constraints prior to the execution can influence the reliability of the look-ahead plan and ultimately improve the project performance (Hamzeh et al. 2015).

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Lindhard and Wandahl (2012) specified nine types of constraints – Design availability, Material availability, Worker availability, Equipment availability, Space availability, Completion of predecessor activities, External conditions (weather related), Safe working conditions, and Unknown working conditions. It is a difficult task for a planner to identify the constraints and discuss them properly with various project stakeholders; in the weekly meeting within a limited time. Thus prioritizing the constraints before the weekly meetings can result in improved workflow reliability. Javanmardi et al. (2020) used information theory to quantify the effect of weekly meetings on just the PPC of the project using a limited number of constraints. The Information theory is a mathematical representation of the transmission and processing of information through communication (Shannon 1948). The research work of Hamzeh et al. (2015) has proved task anticipated (TA) and task made ready (TMR) to be more accurate representative of the project duration than PPC.

The goals of this research were - (1) To quantify the effect of weekly constraint removal discussions on the quality of the work plans, (2) To identify the important constraint categories for improvement of the work plan reliability indicators (PPC, TA and, TMR) using the Information theory, (3) To assess the discrepancy in the important constraint categories for different work plan reliability indicators. The researchers used information theory to quantify the collected data from three sites for five weeks.

LITERATURE REVIEW

Jang and Kim (2008) identified that workflow reliability is highly correlated with the performance of the look-ahead process by using a statistical analysis method. Their research identified a positive correlation between the performance of the look-ahead process and the PPC while using PCR (Percentage Constraint Removal) to assess the performance of the look-ahead planning process. Liu et al. (2011) proved that by implementing LPS, the workflow reliability can be increased which will eventually lead to a significant increase in labour productivity. Another research verified that workflow reliability and schedule performance are significantly correlated while using a quantitative analysis approach by performing two case studies. The paper verified that an increase in PPC suggests an improvement in workflow reliability. (Olano, Alarcón, and Rázuri 2009).

Hamzeh et al. (2019) discovered that projects tend to run behind the scheduled milestones due to poor performance in (1) making tasks ready and removing constraints, (2) committing to critical tasks, and (3) matching load to capacity. A latest research proposed a few new matrices and revealed a mismatch problem between load and capacity resulting in wasted resources due to poor allocation strategies in weekly work plan that negatively impacted project performance. Another research showed (Hamzeh et al. 2019). Shehab et al. (2020) have developed a simulation model to modify planned production rates and to generate a more realistic production rate named Improved Production Rate (IPR). The proposed model proved to be useful as a basis for a decision support system for planners to evaluate the reliability of their planned production rates.

Javanmardi et al. (2020) identified the lack of research to quantify constraint removal discussions and how they affect the work plan reliability. They used information theory to identify the information gain and its transmission efficiency to identify its effect on the work plan reliability. The research used *only PPC as the indicator of work plan reliability* while using a *limited set of constraints*. Recently identified more accurate indicators of work plan performance - TA and TMR were not considered (Hamzeh et al. 2015).

METHODOLOGY

The research included six phases in twelve steps (refer Figure-1). In the first two phases extensive study was performed on LPS related works, which lead to defining the topic, identification of research gaps and determining the objective and scope of work. Third phase was to find case study sites. In fourth phase the data collection was done in two steps - (1) the frequency of constraint removal discussions during the weekly meetings were recorded, and (2) various work plans were collected to compute the values of work plan reliability indicators. In the fifth phase the data analysis was performed in two steps - (1) the performance indicators were divided into two groups using the k-means clustering algorithm, and (2) constraint removal entropy, performance indicator's entropy, mutual information between constraint removal and indicator, and information gain from constraint removal discussions were calculated. In the final phase the researchers identified the important constraint categories and their impact on various work plan reliability indicators was calculated for each site.

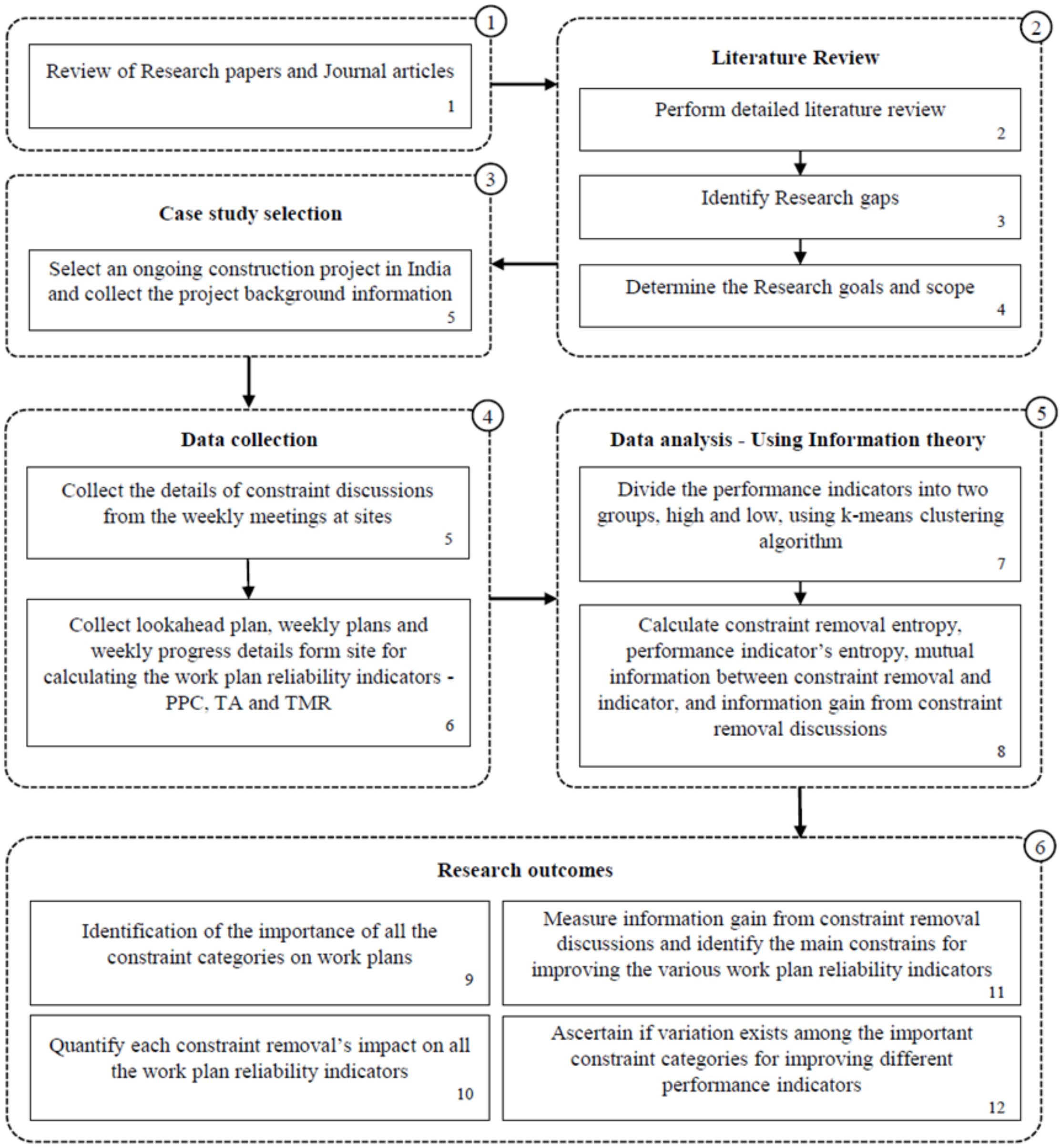

Figure 1: Flowchart of research methodology

CASE STUDIES

Various construction organizations across the nation were approached with an aim of exploring their live construction projects as case studies. The organizations which responded positively were selected as case studies. Two case studies were of a national level contracting firm, while the other case study was of a local city contractor. The details of these sites and their weekly meetings are given in the table below:

Table 1: Details of case studies

	Case study 1	Case study 2	Case study 3
Type	Residential	Industrial	Residential
Built-up area	23,000 sqm	3,10,000 sqm	17,000 sqm
Status of work during data collection	Finishing	Finishing	RCC, Finishing
Contractor	C1	C1	C2
Avg. Duration of weekly meetings	54 minutes	65 minutes	38 minutes
Avg. nos. of participants	18	22	8

All the case study sites were using LPS upto different extent. The level of implementation was as shown in Table 2.

Table 2: Level of implementation of LPS

LPS Component	Case Study - 1	Case Study -2	Case Study - 3
Phase Scheduling	Not Implemented	Not Implemented	Not Implemented
Look-ahead Planning	Partial Implementation	Partial Implementation	Not Implemented
Weekly Planning	Implemented	Implemented	Implemented
Analysis and Continuous Improvement	Implemented	Implemented	Partial Implementation

The phase scheduling was not implemented in any of the projects. Contractor 1 (C1) had implemented the look-ahead planning by involving the last planners and identifying constraints at an early stage. Whereas on the site of case study-3 the look-ahead planning stage of LPS was not implemented. The last planners were not involved and constraints were not identified at look ahead stage. The look-ahead plan was prepared by extracting the master schedule. The weekly planning was done at every site. At sites of case study-1 & 2 analysis and continuous improvement was fully implemented. The site personnel used to identify the reason of delays and for future improvement a plan was made on monthly basis. On the site of case study-3 only the reasons of delay were identified, which showed partial implantation of the last component of LPS.

DATA COLLECTION

The researcher collected discussion data by attending the weekly meetings for five weeks. For the purpose of these research it had been considered that all the decisions affecting the performance of the work plan are discussed only in the weekly meetings.

The other part of data collection consisted of collecting the lookahead plan, weekly plan and the actual weekly progress from site in order to calculate the performance indicators – PPC, TA and TMR. The formula used for the performance indicator calculation are:

$$Percentage\ Plan\ Complete = \frac{Number\ of\ tasks\ executed\ in\ a\ week}{Total\ number\ of\ tasks\ planned\ for\ a\ week} \times 100\%$$

$$Task\ Anticipated = \frac{Number\ of\ anticipated\ tasks\ from\ look\ ahead\ plan}{Total\ number\ of\ tasks\ on\ weekly\ work\ plan} \times 100\%$$

$$Task\ Made\ Ready = \frac{Number\ of\ completed\ tasks\ out\ of\ anticipated\ tasks}{Total\ number\ of\ tasks\ on\ weekly\ work\ plan} \times 100\%$$

In the data collection the constraint categories has been classified into nine types - X1 to X9. The undiscussed constraint category for each site has been not taken into consideration. The crosstab between the week and the constraints category represents the number of times a certain category of constrain was discussed for the activities in the next weekly plan. The value of the performance indicators for the next week is presented.

Table 3: Constraint Removal Discussion & work plan reliability indicators for case study 1

Week	X_1	X_2	X_3	X_4	X_5	X_6	X_8	PPC	TA	TMR
1	3	4	5	2	3	5	3	72%	82%	62%
2	0	1	3	0	3	3	2	67%	75%	46%
3	1	3	2	0	0	4	2	85%	75%	48%
4	1	1	2	0	1	4	3	72%	82%	66%
5	0	3	2	0	4	2	2	68%	72%	46%

Table 4: Constraint Removal Discussion & work plan reliability indicators for case study 2

Week	X_1	X_2	X_3	X_4	X_5	X_6	X_8	PPC	TA	TMR
1	1	3	5	1	0	1	1	79%	83%	52%
2	1	1	3	0	1	0	0	77%	80%	48%
3	0	4	5	1	1	3	0	85%	70%	38%
4	2	2	4	1	0	2	0	70%	86%	39%
5	0	2	3	1	0	2	0	74%	65%	26%

Table 5: Constraint Removal Discussion & work plan reliability indicators for case study 3

Week	X_1	X_2	X_3	X_4	X_5	X_6	X_8	PPC	TA	TMR
1	0	0	2	0	2	1	0	89%	86%	76%
2	0	1	2	1	4	2	0	68%	87%	52%
3	0	2	3	1	3	0	0	74%	74%	50%
4	1	1	2	0	3	0	0	78%	69%	52%
5	2	0	4	0	4	0	2	56%	72%	33%

Here; X_1 - Design availability, X_2 - Material availability, X_3 - Worker availability, X_4 - Equipment availability, X_5 - Space availability, X_6 - Completion of predecessor activities, X_7 - External Conditions (weather related), X_8 - Safe working conditions, X_9 - Unknown working conditions

DATA ANALYSIS

The collected data was processed using Information theory, for which the following steps were followed (Shannon 1948):

1. As discussed in the data collection chapter, a cross-tab is generated between every *X* (i.e. X_1, X_2, ..., X_9) and *Y (performance indicators - PPC, TA & TMR)*. Each cross-tab display the distribution of *X* tab against *Y* tab.
2. The performance indicators are classified in two distinct non-overlapping categories using the k- means clustering algorithm *(by NCSS 2020 software).*
3. Add rows and columns at the end and take the sum of all rows and columns of the cross-tabs generated in the previous step.
4. Calculate Joint and Marginal probabilities by dividing every cell of cross-tabs in step (ii) by the total sum.
5. Calculate joint and marginal entropies using the following equation:

$$H(X,Y) = \sum_{i=1}^{m_x} \sum_{j=1}^{m_y} p(x_i, y_j) \log_2 \frac{1}{p(x_i, y_j)} \; bits$$

6. Calculate every X and Y entropies using the following equation and summing marginal entropies calculated in step (v).

$$H(X) = \sum_{i=1}^{m} p(x_i) \log_2 \frac{1}{p(x_i)} bits$$

7. Calculate the mutual information using the following equation based on the results of steps (v) and (vi).

$$I(X,Y) = H(X) + H(Y) - H(X,Y) \; bits$$

The data analysis was done for all three case study for each of the performance indicators (PPA, TA, and TMR). Here an example of detailed analysis for the TA of Case study 1 has been presented.

The following table shows the clustering results achieved by k-means analysis using the NCSS 2020 software. The results of TA values were classified into two categories A and B. Group A has TA of 82%. Category B has an average TA of 74% with values ranging from 72% to 75%.

Table 6: Constraint removal discussion and TA categorization for case study-1

Week	X_1	X_2	X_3	X_4	X_5	X_6	X_8	TA	Category
1	3	4	5	2	3	5	3	82%	A
2	0	1	3	0	3	3	2	75%	B
3	1	3	2	0	0	4	2	75%	B
4	1	1	2	0	1	4	3	82%	A
5	0	3	2	0	4	2	2	72%	B

Here; X_1 - Design availability, X_2 - Material availability, X_3 - Worker availability, X_4 - Equipment availability, X_5 - Space availability, X_6 - Completion of predecessor activities, X_7 - External Conditions (weather related), X_8 - Safe working conditions, X_9 - Unknown working conditions

By following the calculation steps enlisted in this chapter the *H(X)*, *H(Y)*, *H(X,Y)* and *I(X,Y)* were calculated. The results can be seen in the following table:

Table 7: Entropy and mutual information for TA for case study-1

Constraint	H(X)	H(X) Rank	H(Y)	H(X,Y)	I(X,Y)	I(X,Y) Rank
X_1	1.52	3	0.97	1.92	0.57	2
X_2	1.52	3	0.97	1.92	0.57	2
X_3	1.37	5	0.97	1.92	0.42	6
X_4	0.72	7	0.97	1.37	0.32	7
X_5	1.92	1	0.97	2.32	0.57	2
X_6	1.92	1	0.97	2.32	0.57	2
X_8	0.97	6	0.97	0.97	0.97	1

Here Entropy of constraint discussions *H(X)* represents the information gained by observing the frequency of constraint discussions. Entropy of performance indicators *H(Y)* signifies the information gained by observing the value of performance indicator. The Joint Entropy *H(X,Y)* quantifies the information gained by observing both - the frequency of discussion of a particular constraint and the performance indicator. Mutual Information *I(X,Y)* signifies the quantify the information gained about a performance indicator by observing the frequency of discussion of a particular constraint category.

For identification of the main constraint categories affecting the work plan reliability a graph of Mutual information *I(X,Y)* vs. the Entropy *H(X)* was plotted as shown in Figure 2. The dotted lines shows the average values of entropy and mutual information.

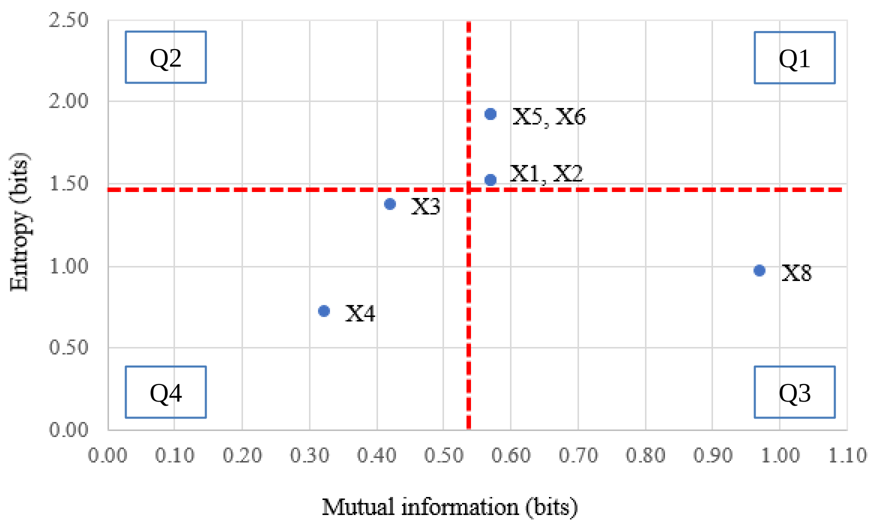

Figure 2: Mutual information vs. Entropy for constraints for case study-1 (TA) (Based on the theory adapted from Javanmardi et al. (2018); Javanmardi et al. (2020))

The constraint categories in the 1st quadrant are both important for TA improvement and discussed effectively. Thus the site team should continue discussing them in the same manner. In this project, discussion of Design availability, Worker availability, Completion of predecessor activity, and Safe working conditions are in this category.

In the 2nd quadrant, the constraint categories were less important for TA improvement but discussed effectively. Such constraint categories shall be addressed by the participants briefly with less effort in the future. No such constraint categories are present here.

The constraint categories in the 3rd quadrant are important for TA improvement but were not discussed effectively by the participants. Unsafe working conditions fall in this quadrant. For instance, the scaffolding work for painting work of ceiling was not meeting the safety standard. Due to which the performance indicator value suffered. Despite its massive effect on the work plan reliability, the constraint was not discussed enough.

In the 4th quadrant, the constraint categories were less important for TA improvement and were discussed briefly. Equipment availability and worker availability were discussed briefly and they didn't have a significant impact on the TA. Prioritizing the constraint discussion in this way will assure that sufficient information for TA improvement is gained during the meetings.

To quantify the effect of constraint removal on Improvement of work plan reliability the relative importance of each constraint category was calculated using the following formula:

$$\text{Relative importance of a constraint category} = \frac{\mathrm{I}(x_1, y)}{\Sigma_i \mathrm{I}(x_i, y)}$$

The relative importance is then multiplied by the overall Performance Indicator improvement, which is the difference between the average performance indicators of Groups made by k-means analysis. For instance, Relative importance of $X_8 \times$ Performance indicator (TA) improvement is equal to $0.24 \times 8\% \simeq 1.9\%$.

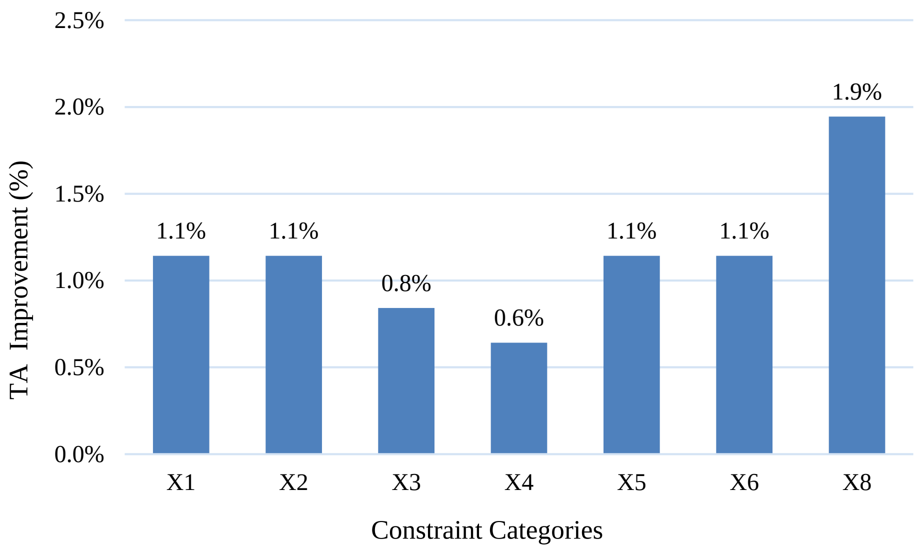

Figure 3: Expected TA improvement by various constraint categories for case study-1 (Based on the theory adapted from Javanmardi et al. (2020))

To quantify the effect of constraint removal on the improvement of work plan reliability the relative importance of each constraint category was calculated. The barchart shows that discussions on Safe working conditions (X_8) had the highest (1.9%) contribution to the TA improvement, followed by a 1.1% improvement from Design availability (X_1), Material availability (X_2), Space availability (X_5), Completion of predecessor activities (X_6). This indicates that removing constraints related to safe working conditions will have the highest positive impact on the TA.

The data analysis was performed in the same manner for all the performance indicators of each case study.

CONCLUSION

The data analysis performed using the Information theory identified the most and least important constraint categories affecting the work plan reliability. It will help the project managers in conducting more effective weekly meetings with defined agenda. The quantified values of the expected improvement in performance indicators (PPC, TA, and TMR) helped in understanding the importance of efficient constraint removal discussions. The study can be applied to any construction project using LPS anywhere in the world.

The results of case study-1 indicated that design availability, material availability, space availability, and completion of predecessor activities were the four most important constraint categories for improving work plan reliability. The analysis signified that the removal of these four constraints could improve PPC by 11%. For TA and TMR the important constraints for increasing the work plan reliability were safe working conditions and design availability. These two categories can improve the TA and TMR by 3% and 6%, respectively. The important categories for PPC and TA-TMR were different.

The results of case study-2 showed that material availability, worker availability, and completion of predecessor activities were the three most important constraint categories for improving work plan reliability. The analysis revealed that the removal of these three constraints could improve PPC by almost 6%. For TA and TMR the important categories were design availability, material availability, and completion of predecessor activities. These three categories can improve the TA and TMR by 13% and 12%, respectively. Again the important categories for PPC and TA-TMR were found to be different.

The results of case study-3 indicated that completion of predecessor activities and material availability were two main important constraint categories for improving the work plan reliability. The analysis signified that the removal of these two constraints could improve PPC by almost 9%. For TA and TMR the important constraints for increasing the work plan reliability were safe working conditions and completion of predecessor activities. These two categories can improve the TA and TMR by 8% and 18%, respectively. Again the important categories for PPC and TA-TMR were different. A direct effect of the project parameters (area, duration of a meeting, etc.) and the LPS implementation level on the results have not been discovered in any of the case studies.

The results proved that the important constraint categories for improvement of TA and TMR varies from the important constraint categories for PPC improvement. This research is applicable to any construction project applying the LPS anywhere in the world. The result of the analysis only indicates the important constraint categories at a particular stage of the project. That means the main constraint categories can vary for various stages of execution. The important constraint categories while working on the basement level will be different from the important constraint categories in the finishing stage of the project. Thus the analysis has to be repeated as the project progresses from one stage to another. The organizations may apply this analysis to their projects at every stage and the results can be used to create a database of important constraint categories at various stages of the project.

It was observed that few of the constraints were interrelated. For example, due to absence of the labours the plumbing work could not be finished, which shows material related constraints. Fixing of pipes was a predecessor activity for other finishing activities and due to fewer labours the plumbing work could not be finished. As a result, the successor activities couldn't get complete. These inter-relations can be studied to enhance the outcomes of the research.

In this research, the constraint removal discussion were counted based on frequency regardless of the duration of discussion. Future research work can look into finding a way to incorporate the time aspect in the data analysis.

REFERENCES

Ballard, G. (2000). "The Last Planner System of production control." *PhD. Diss*., Univ. of Birmingham, Birmingham, UK.

Dave, B., & Hämäläinen, J., & Koskela, L. (2015). "Exploring the Recurrent Problems in the Last Planner Implementation on Construction Projects." *Proc., The Indian Lean Construction Conference (ILCC 2015)*, Mumbai, India, 6-7.

Hamzeh, F., Ballard, G., & Tommelein, I. D. (2012). "Rethinking Lookahead Planning to Optimize Construction Workflow." *Lean Construction Journal 2012*, 15-34.

Hamzeh, F., El Samad, G., Emdanat, S. (2019). "Advanced Metrics for Construction Planning." *Journal of Construction Engineering and Management*, 145(11), 1-16.

Hamzeh, F., Al Hattab, M., Rizk, L., El Samad, G., & Emdanat, S. (2019). "Developing new metrics to evaluate the performance of capacity planning towards sustainable construction", *Journal of Cleaner Production*, 225, 868-882.

Hamzeh, F., Saab, I., Tommelein, I. D., & Ballard, G. (2015). "Understanding the role of "tasks anticipated" in lookahead planning through simulation." *Automation in Construction*, 49(Part A), 18-26.

Hamzeh, F., Zankoul, E., & Rouhana, C. (2015). "How can "tasks made ready" during lookahead planning impact reliable workflow and project duration." *Construction Management and Economics*, 33(4), 243–258.

Jang, J. W. & Kim, Y. W. (2008). "The Relationship Between the Make-Ready Process and Project Schedule Performance." *Proc., 16th Annual Conference of the International Group for Lean Construction*, Manchester, UK, 647-656.

Javanmardi, A. , Abbasian-Hosseini, S. A., Hsiang, S. M. & Liu, M. (2018). "Constraint Removal and Work Plan Reliability: A Bridge Project Case Study." *Proc., 26th Annual Conference of the International Group for Lean Construction*, Chennai, India, 807-817.

Javanmardi, A. , Abbasian-Hosseini, S. A., Liu, M. & Hsiang, S. M. (2020). "Improving Effectiveness of Constraints Removal in Construction Planning Meetings: Information-Theoretic Approach." *Journal of Construction Engineering and Management*, 146(4).

Lindhard, S. & Wandahl, S. (2012). "Improving the Making Ready Process - Exploring the Preconditions To Work Tasks in Construction." *Proc., 20th Annual Conference of the International Group for Lean Construction*, San Diego, USA, 18-20.

Liu, M., Ballard, G., & Ibbs, W. (2011). Work Flow Variation and Labor Productivity: Case Study. *Journal of Management in Engineering*, 27(4), 236-242.

Olano, R. M., Alarcón, L. F., & Rázuri, C. (2009). "Understanding the relationship between planning reliability and schedule performance - A case study." *Proc., 17th Annual Conf. of the Int. Group for Lean Construction*, Taipei, Taiwan. 139-153.

Shannon, C. E. (1948). "A mathematical theory of communication." *Bell system technical journal*, 27(3), 379-423.

Shehab, L., Ezzeddine, A., Hamzeh, F., & Power, W. (2020). "Agent-Based Modelling and Simulation of Construction Crew Performance." *Proc., 28th AnnualConference of the International Group for Lean Construction*, Berkeley, California, USA, 1021-1032.

McHugh K., Koskela L., and Tezel A. (2021). "Reality Capture Connecting Project Stakeholders." *Proc. 29th Annual Conference of the International. Group for Lean Construction (IGLC),* Alarcon, L.F. and González, V.A. (ed.), Lima, Peru, pp. 737–746. doi.org/10.24928/2021/0148. Available at www.iglc.net.

REALITY CAPTURE CONNECTING PROJECT STAKEHOLDERS

Kevin McHugh [1] Lauri Koskela[2], and Algan Tezel[3]

ABSTRACT

Digital media and point cloud captures have been used extensively in the mapping and surveying fields. As technology has advanced digital photographic and Lasor scanning information can be captured on site and processed rapidly. This has led to developing software that can use the processed information, for reconstructing it with the help of photogrammetric methods and connecting it to the 3D Building Information Model (BIM). This paper will review the effectiveness of reality capture digital process in a pandemic situation.

Reality Capture (RC) is becoming an important part of the information dynamics on construction projects. Lidar, Drone imagery, Laser scanning and Photogrammetry captures are now used extensively to document the construction process. Platforms that can, host, and overlay and compare scans and photographs to BIM models and 2D plans have been developed. RC provides a rich source of imagery that can also be used to support the production control process. Designers and project managers can focus on value added work utilizing the latest project imagery to co-ordinate and collaborate and to assist developing short term look ahead plans and validate prepared work plans. As a result of the Covid-19 pandemic worldwide societal and industrial shutdowns occurred the reduce the spread of disease. As industry returned safeguards had to be developed to protect workers and prevent the spread of disease. This paper outlines how a RC strategy that has been developed as a countermeasure to fragmented teams caused by the Covid-19 pandemic and how RC can be used to increase engagement by project stakeholders on construction projects in a post pandemic digital era. This paper discusses how digital tools can support established lean construction process and how action research can assist the continued development of new processes.

KEYWORDS

Reality capture, BIM, Last Planner® System, digital construction.

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INTRODUCTION

Construction projects are complex, constantly evolving, task-based endeavours. As a result, the construction industry has been investing in technology to assist with project monitoring. Traditional project management methods have resulted in poor productivity with unpredictable results. The main reason for this is that modern projects consist of many fragmented teams and integrate supply chain dependencies(Bølviken and Koskela 2016,Dave et al. 2015a) Studies have highlighted the potential of using 3D mapping of construction sites and buildings from unmanned aerial systems (UASs) imagery to assist in management tasks (Golparvar-Fard et al. 2011). Providing a similar process to use imagery to map internal structures would boost productivity for internal works.

There is increased interest into digital visual management utilizing Building Information Modelling (BIM), Laser scanning and photogrammetric methods. These are not new technologies; however, the improvements of digital processing and storage provides greater connectivity and functionality for captured images. These methods include image-based sensing technologies (i.e., Reality Capture) and 3D remote sensing technologies (i.e., robotic total stations), Global Positioning Systems (GPS), Radio Frequency Identification (RFID), bar codes, Ultra-Wide Band (UWB) and laser and distance ranging—LADAR) (Golparvar-Fard et al. 2011).

Visual management (VM) is the practice of visualizing information or displaying requirements to set directions (Eaidgah et al. 2016). VM is used to support construction management such as production management, safety management, performance management, workplace management (housekeeping) (Tezel et al. 2016). Recent developments of vision engines and portable 360° cameras have facilitated interior mapping technology that can be utilized internally in a building under construction (Pica and Abanda 2021). It is also possible to collect construction data using indoor positioning system. Data collection can be improved using Internet of Things (IoT) applications and real time imagery from drones and helmet cameras (Tang et al. 2019). A concern for data collection is that it can be often incomplete and inadequate (Zhong et al. 2015), where often only a fraction of operational disturbances are recorded in site meetings, and the progress reports, which can prevent effective communication.

As a result of the Covid-19 pandemic teams were dispersed and fragmented due to health restrictions. This disrupted the social interactive site based collaborative process. This paper will show how RC tools can support the Last Planner® System by providing the current situational picture. Mapping images to plans and further linking them to the model provides data that can be used rapidly for co-ordination as it reflects the current project conditions which improves the quality of the planning.

LITURATURE REVIEW

Lean methods and tools that can be supported using RC along with wider digital tools are reviewed to demonstrate how RC can support LC in a digital environment. The review of literature highlights how RC support social interactions and can support lean construction to improve the quality of communication and planning.

LEAN CONSTRUCTION

Lean Construction (LC) is a holistic approach for managing construction projects, identifying the dependencies and promote collaboration between project stakeholders to manage the flow of information and work that is required to maintain effective work flow.Meetings are designed in a collaborative way where people gather in a 'big room' where interaction between project stakeholders is encouraged (Dave et al. 2015b). This process moved to virtual cloud-based meeting platforms. Meetings were carried out in a digital 'Obeya' room where collaborative planning was aided by digital visual management. Images, drawings, and 3D BIM models were used to inform and communicate planned works between trade contractors (Majava et al. 2019). The rooms help to arrive at decisions faster, provide a framework for waste elimination and asset logistical and sequencings issues.(Nascimento et al. 2018)

During the collaboration process, developing trust helps reduces tensions between stakeholders and altogether improving collaboration performance. Building trust can involve differing interpretations. For example, common understanding in business was seen as a fundamental factor in developing and accepting trust (Kasper-Fuehrera and Ashkanasy 2001). The review and presentation of current project imagery promotes real collaboration between teams.

THE LAST PLANNER® SYSTEM

The Last Planner® System (LPS) (Ballard 2000)is used for managing production control on construction projects. The system relies on a collaborative management approach where tasks are co-ordinated collectively in short term cycles. Another key component is the review of Planned Percent Complete (PPC) which measures the effectiveness of the current planning cycle. This part of the system can be supported by utilizing visual management tools such as BIM, scanning and photographic imagery to provide unambiguous information that can be interpreted to support the planning process and provide the basis for highlighting areas of improvement (Xu et al. 2020).

VISUAL MANAGEMENT

Visual Management(VM) has an important role to play in providing clarity and availability of information, especially in face of the complexity of construction projects (Brady et al. 2018) Digital VM tools can acquire, sort and present large amounts of acquired project data in a form that can be easily accessed and interpreted by project stakeholders. Often a barrier for successful collaboration is the lack of information to accurately communicate the current project status to allow participants to collaborate and demonstrate productivity levels(Dave et al. 2010). The acquisition of sufficient amount and detail data is time consuming and as a result is not captured as regularly; usually, weekly, or monthly reports are gathered. The status information is not current, and it is not in a format that would help stakeholders (Soibelman et al. 2008).

The development of the BIM model is an integral component of the production control system. Properly developed and managed, BIM-centric project delivery makes available high fidelity, geometrically and positionally accurate, uniquely identifiable building component data sets together with a wealth of descriptive and operable metadata (Tang et al. 2019). The model is a collaborative platform which evolves in line with the construction programme.(Nascimento et al. 2018) The familiarity of the BIM model to all trade contractors allows facilitates the use of the model to assist collaborative meetings.

SITUATIONAL AWARENESS

Ambiguity and a lack of the current situational awareness is a hindrance to LPS collaborative meetings, that often require follow up site meetings to verify or to replan short term work post meeting. Communication between stakeholders is inconclusive where quantities and make ready needs are not fully realised and therefore are not raised correctly.(Reinbold et al. 2020) Situational awareness can be supported by the collection and access to multiple picture files and access to real time images. This ability increases the productivity of management and trade contractors to access the correct information to support the decision-making process.

Utilizing RC platforms allows access to real time images which can be reviewed and analysed by all project teams at any time. The chronological arrangement and display of captured images are important. These images can be access and reviewed to provide insights into construction and design. This improves the quality of collaboration and improves communication channels which in turn reduce errors. This has increased project transparency which has increased the quality of collaboration and the effectiveness of meetings. If process transparency is successfully implemented, most problems, abnormalities, and types of waste that exist can be recognized to allow remedial measures to be taken (Saurin et al. 2008).

CASE STUDY

BACKGROUND TO THE CASE STUDY

The emergence of the Covid-19 pandemic in late 2019, affected Ireland in early 2020. As a result, a national lockdown was implemented to control the spread of the virus. This closed all non-essential workplaces including all construction project. To safely reopen construction projects measures were needed to be put in place to control the number of operatives on the project by introducing remote working for managerial staff and shift working for operational staff.

Increased team fragmentation was observed as a practical gap in the collaborative planning process which was used prior to the pandemic. This was a new constraint for the production planning process, both for the preparations and co-ordination of work plans and in the execution of these plans. This challenged the existing project production control system that relied on collaborative and social interaction for the preparation and execution of planned tasks. RC techniques that supported external work co-ordination capturing images using UAVs was identified as a possible solution, thus OpenSpace was identified to capture and use 360° images for internal works.

To include remote teams all collaborative meetings were moved to on-line meeting platforms. Drone imagery and laser scanning has been used on the project and continued to assist with external infrastructure planning. Internal images were captured by mounting a 360° HD camera on a hardhat and syncing your location to a floorplan to OpenSpace.

Daily schedule of internal image capture walks quickly provided an extensive catalogue of 360° images. These images were processed by 'OpenSpace' and displayed on a project plan for navigation and aligned to a BIM viewer for comparison. The first author conducted participatory action research to apply and combine digital tools to support the lean practices and visual management tools that were relied upon thus far on the project. Chevalier and Buckles (2013) contend that researchers contribute an important set of skills through their active involvement, including the ability to make sense of group dynamics and to identify the need for change. The first author managed the production control system for the project and was involved in the design and implementation of the production controls pre and post pandemic.

CASE STUDY SCOPE

OpenSpace was the RC platform selected to capture and manage 360° images for the project internal works. The project is a single storey Data Center that consisted of 8 data halls with an internal area of 57,000m2 and administration building of 5,800m².

The pandemic imposed severe operational changes to the project with teams working remotely, split team rotas working on-site and offsite and teams that previously worked together split into shifts. The Covid-19 pandemic restricted the movements of key personnel to the project and similarly restricted the movements of on-site craft workers and supervision. Capturing 360° images and syncing these images to the project floor plans and BIM model provided a digital creative space to collaborate, providing the ability to navigate through the project linking images with the floor plans and aligning the 3D model with the floorplan so that project photographs and model imagery could be compared.

Production Control

The basis of the project control system was to represent all aspects and review the current project activities and highlight dependencies with all project stakeholders. Design and technical information requirements were identified for project tasks where logistic and resource information were also required.

Pandemic restrictions meant that Design, Construction and Quality inspection teams were further fragmented. This challenged the existing collaborative production control system were project teams convened regularly. The existing system relied on face to face 'Big room' meetings. RC bridged the gap and allowed stakeholders to engage and interact and communicate effectively with each other. The challenge was to understand and present the production analysis data and relate this to work in progress. The availability of such massive data creates new opportunities to identify production bottlenecks and make an effective production plan through data-driven approaches (Posada et al. 2015)

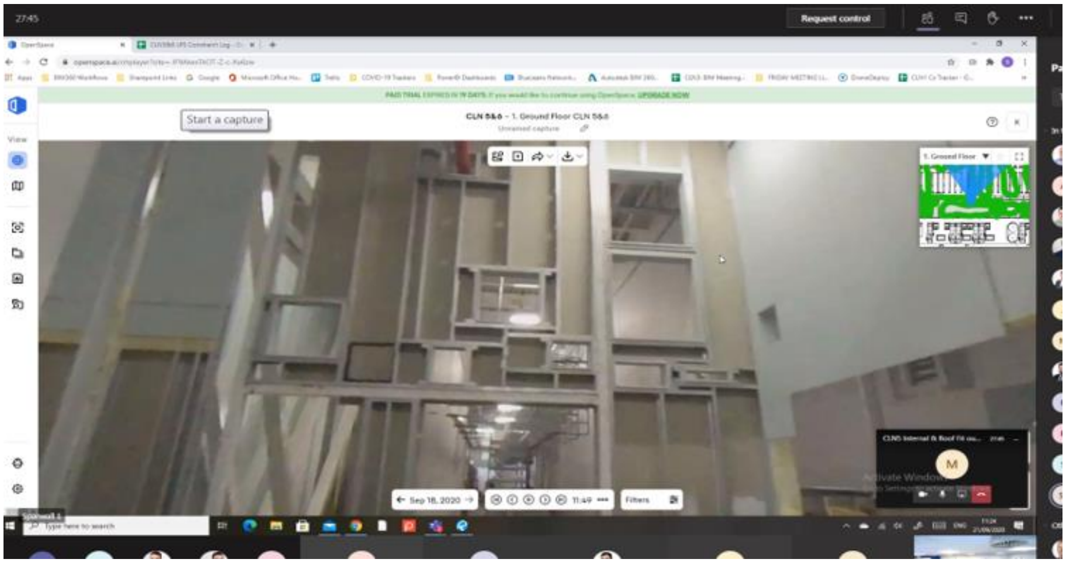

Figure 1 Virtual 'Big room' meeting

Area co-ordination could be maintained by all teams communicating using OpenSpace. Remote workers still operate effectively and communicate in area co-ordination meetings. This ensures all activities are planned and co-ordinated safely. Digital platforms were been used to produce short term planning and weekly planning activities to support the LPS. RC tools allowed teams to manage the look ahead planning and the review of planned percent complete (PPC) tasks. This assisted the improvement of work sequencing and sizing. Time and labour factors could also be discussed to manage labour utilisation and ensure operational safety. (see Figure 1).

This transparency improved the quality of the production plans. Supervisors could share their knowledge to address and communicate issues and opportunities. This increased the trust between project teams and allowed them to collaborate more effectively. The remote working virtual collaboration was highly visual, and the quality of the interaction was maintained by the immersive 360° photographs and the comparison to the BIM model. This allowed discussions to flow as participants could navigate through the building virtually while comparing images to past images and the BIM model.

DESIGN MANAGEMENT

A key principle for LC is to maximise value and minimise wastes. Design and inspection are critical functions for determining value. Design and technical product information approval are prerequisites for construction tasks. Managing the development of shop drawings and technical documents is key for maintaining a robust production control system.

RC connected design and construction teams to allow them to collectively manage and sequence design and co-ordination activities. As work progressed design teams can observe completed works and identify and communicate design requirements for the next planned construction phase. Look ahead planning for design activities mirrors the production look ahead so that design resources are efficiently utilized to ensure design activities are completed in advance of the planned construction activities.

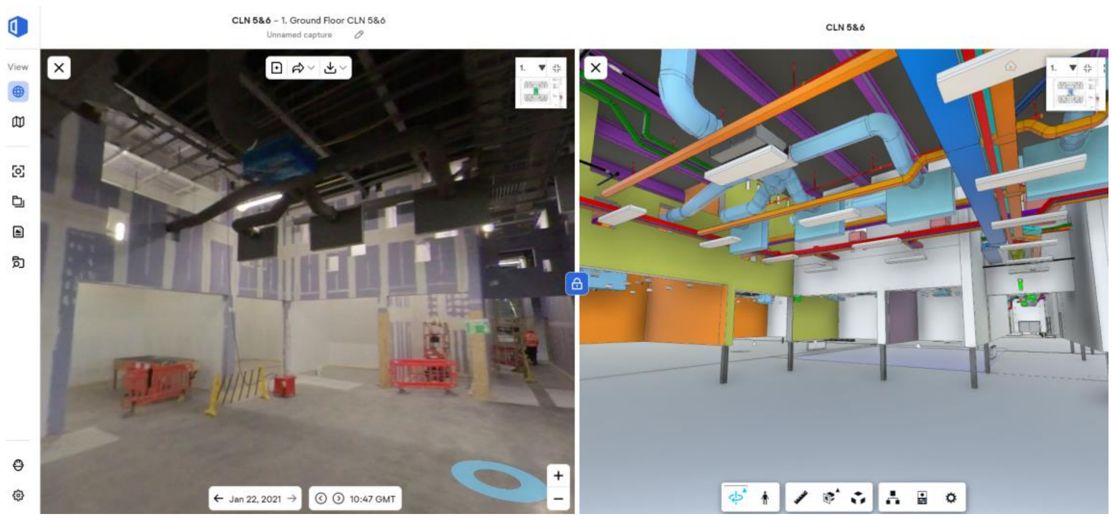

Figure 2 BIM Model Comparison

As part of the design quality reviews, the progress of construction tasks could be reviewed and updated in the design LPS where quality teams could review and confirm quality hold points, where follow on works cannot proceed without inspection of the preceding works. Therefore, inspections could be identified and scheduled in line with production plans to ensure continuity and progress tasks effectively (see Figure 2).

DISCUSSION

The deployment of the internal RC process was identified to fill a practical gap observed in the project management systems. RC successfully connected teams that were now working remotely or separated by different shift patterns. This reintegrated teams into the prevailing collaborative production management system that the project was successfully using prior to the pandemic. The ability to navigate virtually through the current state of the project increased the engagement between on-site and off-site teams by providing a common platform to review and understand the current situational picture.

The primary tool for production control is the LPS. Team engagement and commitment are critical for successful implementation of the system. RC supported the LPS allowing fragmented project teams to participate fully in the look ahead and review sections of the system. The trial was successful as the number of activities that were observed tracked and completed daily increased from the pre pandemic numbers and the planned percent complete (PPC) was unchanged and ranged from 70 to 80%. The initial scope of the trial was quickly exceeded, and the images were introduced into project diaries and project status reporting.

RC has potential to further support the LPS by providing quantifiable metric comparing image captures providing quantifiable production information. The capture and processing times for these solutions have decreased rapidly, allowing quicker access to images, which assists an agile production control system by providing measurable production information that can be accessed and reviewed in near real time.

The use of RC underpins LC practices and supports a collaborative process. Utilizing the latest available data and imagery can improve accountability and therefore improve the engagement in the planning process. RC allows teams to evaluate and improve if is used in the right environment where continuous improvements are encouraged and supported. The simplicity of the software and the enhanced availability of information in the field and in the office allowed teams to interact together in a positive and collaborative manner. The availability of real time information allowed teams to effectively progress BIM meetings, package meetings and area co-ordination meetings, also considering that these collaborative meetings are attended by non-site-based personnel. It provides a large volume of valuable information that is accessible and easily interoperated. This supported the LPS, allowing teams to co-ordinate and communicate effectively and by providing a review of completed works that provided productivity insights.

However, the predominant current adversarial contracting arrangement does not allow full transparency which in turn restricts the access to information is an issue where teams would like greater access. With further maturity of collaborative contracting and the further digitization of construction, RC can effectively support planning design and execution of construction tasks.

The continued digitisation of construction will provide further digital integrations into project site management. Hybrid post pandemic solutions will embrace digital visual management and integrate these into hybrid visual management solutions. However, digitization should underpin the social collaborative LC approach where information is used to understand productivity rather than direct operational decisions using data alone. Where RC has increased transparency and can provide historic information to validate payments or intercede in dispute resolution it is important to protect the information and share it as a collaborative tool.

CONCLUSION

The deployment of OpenSpace was initiated to counteract the restrictions on movements of project team members. RC was proposed as a solution to continue to use LC effectively by reintegrating dispersed team members and allow them to continue to collaborate remotely. The platform was easy to use and required no additional onsite processing. The RC reviews formed part of each discipline’s project meetings and increased the clarity of team communication.

The ability to interrogate images and to compare revisions of the image and the model browser function increased the situational awareness and allowed fragmented project to collaborate. The quality of the information increased the engagement between project stakeholders.

Digital construction and digital lean construction are at the cutting edge of industry innovations. Capturing and analyzing rich forms of data are coming into focus in the industry. Providing a lean philosophy of capturing enough information at the right time and presenting actionable data will connect fragmented construction teams and improve productivity. However, the large volume of competing platforms and management paradigms present a challenge to information management in construction.

This research was limited to using RC to support the LPS and collaborative planning. The author was responsible for the LPS on the project and potential improvements were noted anecdotally from other project disciplines. However, the potential to integrate RC into digitally management tools and providing near ‘live’ information can improve the effectiveness of all project operations. RC will remain an important addition to the digital management structure in the post pandemic era. Digital media will continue to evolve with further potential integrations of sensor technology and image recognition technology which also can be used to support LC in a digital era.

REFERERENCES

Ballard, H. G. (2000). “The last planner system of production control.” PhD thesis, University of Birmingham, U.K.

Bølviken, T., and Koskela, L. (2016). 'Why Hasn’t Waste Reduction Conquered Construction?' In:, 24th Annual Conference of the International Group for Lean Construction. Boston, Massachusetts, USA, 20-22 Jul 2016.

Brady, D. A., Tzortzopoulos, P., Rooke, J., Formoso, C. T., and Tezel, A. (2018). “Improving transparency in construction management: a visual planning and control model.” *Engineering, Construction and Architectural Management*, Emerald Group Publishing Limited, Bradford, United Kingdom, 25(10), 1277–1297.

Chevalier, J. M., and Buckles, D. J. (2013). *Participatory Action Research: Theory and Methods for Engaged Inquiry*. Taylor & Francis Group, London, United kingdom.

Dave, B., Boddy, S., and Koskela, L. (2010). Improving Information Flow within the Production Management System with Web Services.,18th Annual Conference of the International Group for Lean Construction, 14-16th July 2010, Haifa, Isreal.

Dave, B., Kubler, S., Pikas, E., Holmström, J., Singh, V., Främling, K., Koskela, L., and Peltokorp, A. (2015a). “Intelligent Products: Shifting the Production Control Logic in Construction (With Lean and BIM).” In:, Seppänen, O., González, V. A. & Arroyo, P., 23rd Annual Conference of the International Group for Lean Construction. Perth, Australia, 29-31 Jul 2015,341–350.

Dave, B., Pikas, E., Kerosuo, H., and Mäki, T. (2015b). “ViBR – Conceptualising a Virtual Big Room through the Framework of People, Processes and Technology.” *Procedia Economics and Finance*, 21, 586–593.

Eaidgah, Y., Maki, A. A., Kurczewski, K., and Abdekhodaee, A. (2016). “Visual management, performance management and continuous improvement: A lean manufacturing approach.” *International Journal of Lean Six Sigma*, Emerald Group Publishing Limited, 7(2), 187–210.

Golparvar-Fard, M., Bohn, J., Teizer, J., Savarese, S., and Peña-Mora, F. (2011). “Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques.” *Automation in Construction*, 20(8), 1143–1155.

Kasper-Fuehrera, E. C., and Ashkanasy, N. M. (2001). "Communicating trustworthiness and building trust in interorganizational virtual organizations." *Journal of Management*, SAGE Publications Inc, 27(3), 235–254.

Majava, J., Haapasalo, H., and Aaltonen, K. (2019). "Elaborating factors affecting visual control in a big room." *Construction Innovation*, Emerald Group Publishing Limited, London, United Kingdom, 19(1), 34–47.

Nascimento, D., Caiado, R., Tortorella, G., Ivson, P., and Meiriño, M. (2018). "Digital Obeya Room: exploring the synergies between BIM and lean for visual construction management." *Innovative Infrastructure Solutions*, 3(1), 19.

Pica, D., and Abanda, F. H. (2021). "Emerging BIM-3D-Laser Scanning Integration in Construction Practice." *Collaboration and Integration in Construction, Engineering, Management and Technology*, Advances in Science, Technology & Innovation, S. M. Ahmed, P. Hampton, S. Azhar, and A. D. Saul, eds., Springer International Publishing, Cham, 345–350.

Posada, J., Toro, C., Barandiaran, I., Oyarzun, D., Stricker, D., Amicis, R. de, Pinto, E. B., Eisert, P., Döllner, J., and Vallarino, I. (2015). "Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet." *IEEE Computer Graphics and Applications*, 35(2), 26–40.

Reinbold, A., Seppänen, O., and Peltokorpi, A. (2020). "The Role of Digitalized Visual Management to Empower Selfmanaged Crews in Construction Projects." Berkeley, California, USA, 925–936.

Saurin, T. A., Formoso, C. T., and Cambraia, F. B. (2008). "An analysis of construction safety best practices from a cognitive systems engineering perspective." *Safety Science*, 46(8), 1169–1183.

Soibelman, L., Wu, J., Caldas, C., Brilakis, I., and Lin, K.-Y. (2008). "Management and analysis of unstructured construction data types." *Advanced Engineering Informatics*, Intelligent computing in engineering and architecture, 22(1), 15–27.

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., and Gao, X. (2019). "A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends." *Automation in Construction*, 101, 127–139.

Tezel, A., Koskela, L., and Tzortzopoulos, P. (2016). "Visual management in production management: a literature synthesis." *Journal of Manufacturing Technology Management*, Emerald Group Publishing Limited, 27(6), 766–799.

Xu, S., Wang, J., Shou, W., Ngo, T., Sadick, A.-M., and Wang, X. (2020). "Computer Vision Techniques in Construction: A Critical Review." *Archives of Computational Methods in Engineering*.

Zhong, R. Y., Huang, G. Q., Lan, S., Dai, Q. Y., Chen, X., and Zhang, T. (2015). "A big data approach for logistics trajectory discovery from RFID-enabled production data." *International Journal of Production Economics*, 165, 260–272.

De La Torre, J.R., Taboada, L.J., and Picoy, P.E. (2021). "Road Construction Labor Performance Control Using PPC, PCR and RNC During The Pandemic." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 747-756. doi.org/10.24928/2021/0166, online at iglc.net.

ROAD CONSTRUCTION LABOR PERFORMANCE CONTROL USING PPC, PCR AND RNC DURING THE PANDEMIC

Jorge R. De La Torre[1], Luisa J. Taboada[2], and Pool E. Picoy[3]

ABSTRACT

At the beginning of 2020, the Coronavirus pandemic had various countries negatively affected in the development of their economic activities, as their industries had to interrupt production, hindering their performance and economic development. Before this occurrence, it was known that the evolution of construction labor performance on site was minimum and had high indicators of variability. Due to this, extensive literature reviews have presented Last Planner® System as a methodology to mitigate and improve performance, mostly, in building construction. However, this deficiency presents itself with more frequency in road projects and worsens because of the pandemic.

Having this said, it is important to control labor performance during the sanitary crisis in road projects. Therefore, in this context, the objective of this investigation is to validate the use of Last Planner® System methodology indicators (Percentage of Plan Completed and Percentage of Constraint Removal) as mechanisms of labor control.

The findings evidence a direct relationship between improving indicators of Last Planner® System and a better labor performance while meeting budgeted yields.This in turn has validated the use of Last Planner indicators. Regarding the Reasons for non Completion, the impact of external factors merits and additional investigation due to frequency of occurrence.

KEYWORDS

Last Planner® System, lean construction, variability, performance, labor.

INTRODUCTION

The start of 2020 has seen a major decline in economic development world wide, the global pandemic has seen many nations interrupt or in some cases halt all of their activities. After a process of disruption and adaptation to the new normal by taking preventative measures against the virus, industries have tried to resume their rhythm of their work. However, achieving previous performance standards has proven to be challenging due to the addition of man hours allocated to comply with health protocols such as temperature control and disinfection. This has increased the amount of work hours

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in activities that do not provide value to production but are essential. The construction sector nominates such hours as Non-Contributory Time (TNC).

This new reality impacts particularly the construction industry due to the nature of the execution of its activities involving of numerous specialized work force teams which work together to achieve the goals of construction projects (Cost, time, quality) (Sinesilassie et al. 2018). In adition, these past years, the construction industry has been critizicized and compared to other industries due to the reduced evolution of labor performance and the few tools established to control and improve them, which leads to wastes in the processes causing cost overruns and decreased productivity (Bølviken and Koskela, 2016). This was identified by Ballard and Howell in 1992 (Hackett et al. 2019). As shown in Figure 1, while all norwegian industries improve the productivity of their work force, in terms of value added per working hour, there exists a declining trend in labor productivity of on-site construction Activities (Ahmad et al. 2020).

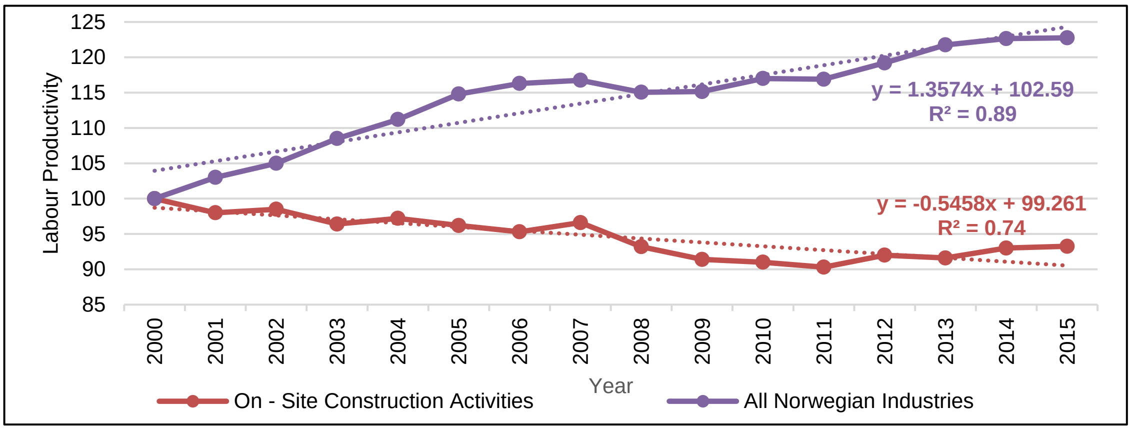

Figure 1: Labour productivity of on-site construction (Figure 15 in Ahmad et al., 2020)

This defect stands out even more in the face of the new normal, due to the increase of TNC and Karunakaran et al. (2019), indicate that it is more frequent in road works due to its longitudinal nature; however, the literature has been limited, for the most part, to address variability through none traditional tools in building construction. According to their research, the causes of variability in road works depend on factors that cause delays in the work flow. These are poor project planning and scheduling, design changes during execution, underground electrical and sanitary networks, material shortages, material and equipment failure, poor communication and interaction, weather, inadequate construction methods, inexperienced contractors and poor site investigation.

According to Radzi et al. (2020), the inefficient performance is found between the most common and significant impacts faced by road construction projects when constraints are not dealt with. Their study proposes that projects that have previously taken care of constraints have imporved scheduale performance by 22%, productivity improvement of 29% and 21% less changes during the execution compared to other projects that do not deal with their constraints. i.e. they have less variability. Therefore, this research will use the percentage of constraint removal (PCR), an indicator proposed by Jang and Kim (2007) as a measure for the make-ready process.

Last Planner® System (LPS) is a methodology based off the philosophy of Lean construction (LC) of which's' primary objective is to obtain a reliable workflow through anticipated identification of constraints. According to Ballard and Tommelein (2016), a reliable workflow is achieved by eliminating waste and reducing variability, thus improving the work force performance. This reliability can be measured through the percentage of plan completed (PPC) and the performance of resources. In addition, managemental level (work management, plan, task and sequence of work), human resources (labor loyalty, stability of human resources, work force), rework and weather are some of the factors that determine 64.23% of the reliability of the work flow (Zhang et al. 2017).

On the other hand, according to Li et al. (2019) LC techniques have a positive impact on cooperation between workmen and their supervisors to complete tasks and suggest ways to improve processes, as well as in interactions with customers, which provides a collaborative environment that improves project performance. It is worth mentioning that researchers have experienced time and cost savings due to LC. Liu and Ballard (2008) highlight that in the face of a high PPC trend, the contractor achieved cost improvements of 24%. Similarly, Dallasega et al. (2016), demonstrated a labor savings of 8% compared to the initial estimate when applying LPS in their case study.

Due to the scarce evolution of labor performance, the few tools that have the capacity to control it and the higher incidence of variability in road projects, this research seeks to demonstrate, within the context of the new normal, the relationship between the control of labor performance of the case study (road project) and the indicators PPC, PCR and reasons for non compliance (RNC), as well as to answer the question: Is it valid to use the indicators PPC, PCR and RNC as a control mechanism of labor performance in road construction within the new normal?

METHOD

The methodology of this research (Figure 2) was applied to a road work (roads and sidewalks) executed in the city of Lima, capital of Peru, during the last quarter of 2020.

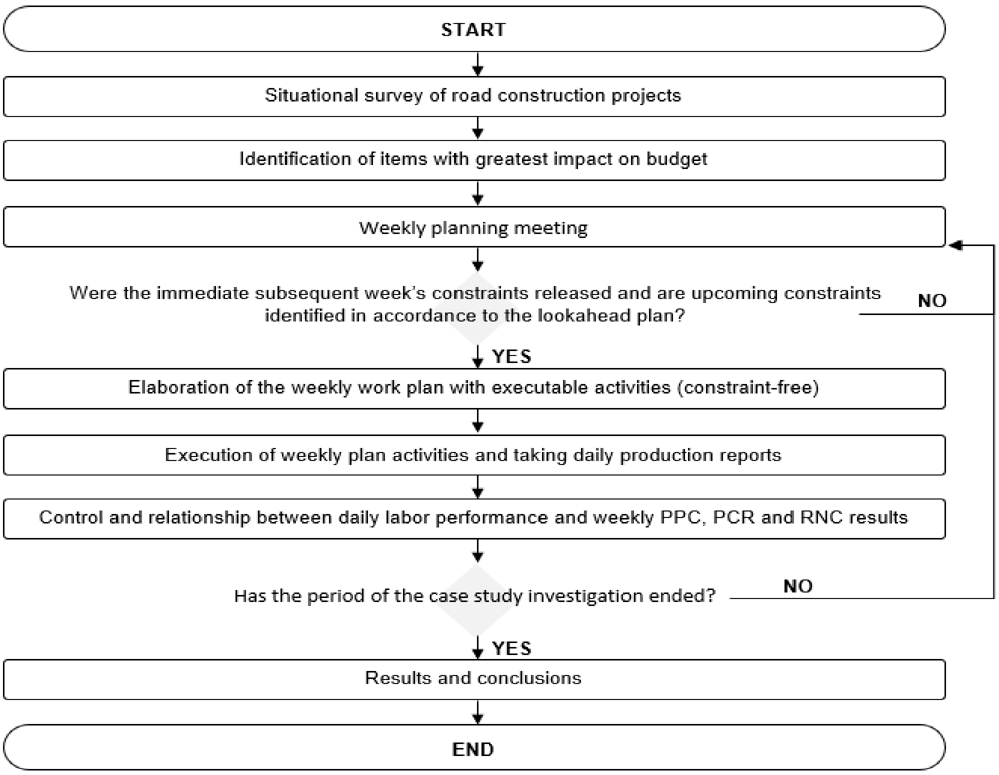

Figure 2: Flowchart of Research Process

As a first step, a situational survey of road works was made, then the items in execution that had the greatest impact on the budget were identified, with which weekly planning meetings were started for the 6-week period of execution of activities. These meetings were held at the end of each week. In these meetings, activities were updated and constraints were analyzed according to the LookAhead; and activities free of constraints were planned for the following week. Also, the PPC, PCR, RNC indicators and the actual labor performance of the control items of the completed week were evaluated.

Figure 2 represents the methodology used for the control of the labor performance of a road project within the context of the new normal using as a mechanism the PPC and PCR indicators and RNC for decision making oriented to continuous improvement.

Situational Survey of Road Construction Projects

The survey was conducted among 40 professionals from 16 construction companies specializing in road projects during the new normal, from which it was found that 21% of the respondents, according to their experience, believed that the inadequate composition and size of crews is a factor that negatively impacts labor performance (Figure 3).

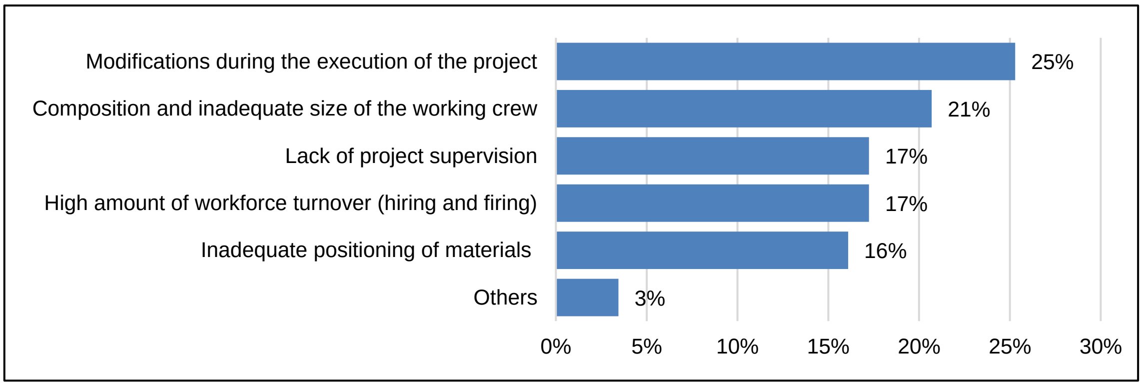

Figure 3: Factor of variability of the labor performance

Likewise, 22% of the professionals rated Waiting or Downtime as the waste with the greatest impact on labor performance. (Figure 4).

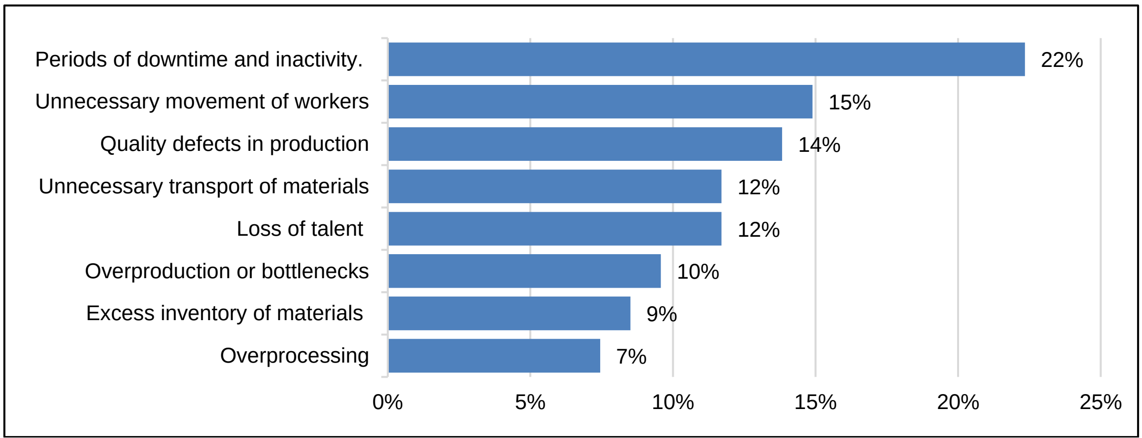

Figure 4: Waste with the greatest impact on labor performance

In addition, Figure 5 shows that, according to specialists, the average Productive Time (TP), i.e., that which the time that workers add direct value to production of executed activities., represents 50.45% of the activities performed at the construction site.

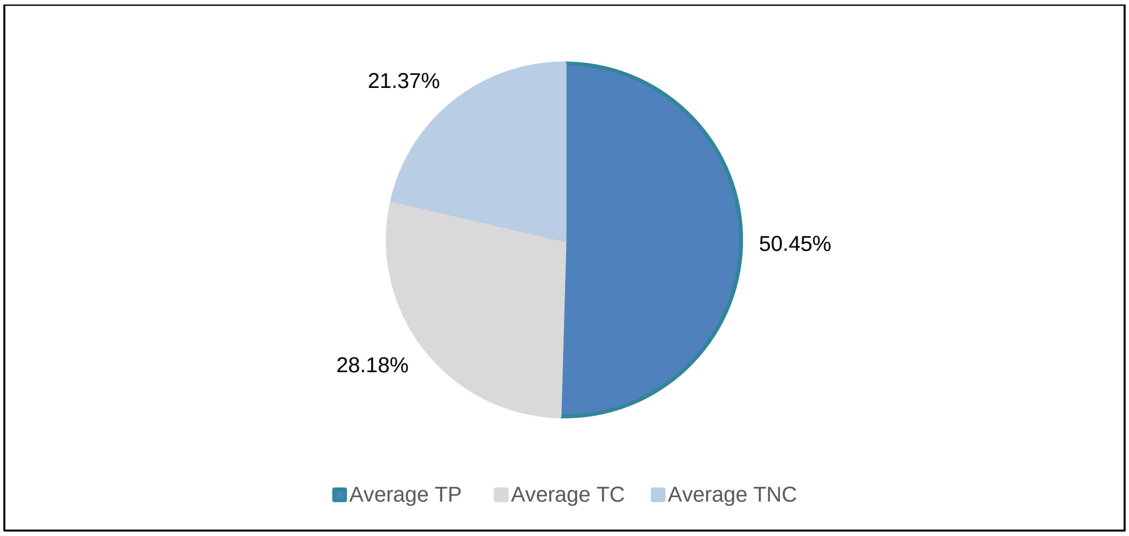

Figure 5: Distribution of types of work times in road projects in the context of new normality

Table 1 presents the causes and consequences of variability provided by road project specialists.

Table 1: Causes and consequences of variability in labor performance. Source: Own elaboration.

Causes	Consequences
Poor planification	Waits, unresolved constraints
Incompatibility between tecnical file and field reality	Rework, cost overuns, and new studies.
Natural disasters	Imposibility of work realization due to rain
Incompatibility in layouts	Delays and reschedualing of work
Indefitions imputed to the client	Time extensions and cost overuns
Climate change	Not being able to asphalt or pur pavements
Not having a complete report of interferences	None budgeted extra labor
Lead time of resources	Delay
Hiring of unqualified personnel, deficient programing	Low performance
Lack of planning and control of production	Working without clear goals, which implies greater costs and possibly missing the deadline.
Underground interference in urban areas	Halt of work due to new activities which require resolution

These survey results provided a situational overview of road works and guided the PPC and PCR indicators towards a controlled labor performance within the context of the new normal.

IDENTIFICATION OF ITEMS WITH THE GREATEST INCIDENCE

Table 2 shows the items that were under execution during the study period. Under the criterion of controlling the labor performance of those that add the most value to the project, the first seven items with the greatest impact on the budget were selected

Table 2: Activities being carried out during the study period

N°	Item description	% impact on budget
1	Rigid Pavement	34.76%
2	Granular Sub-base H=20 cm	5.66%
3	Concrete Sidewalks	4.40%
4	Pavement painting	2.99%
5	Asphalt Contraction Joint Sealing	1.50%
6	Excavation to subgrade in Loose Material	1.20%
7	Demolition of Flexible Pavement	1.18%
8	Installation of guardrails	1.17%
9	Painting of guardrail	1.17%
10	Ready-mixed concrete for curbs	0.97%
11	Excavation and pouring for vertical sign	0.89%
12	Ready-mixed concrete for parapets	0.48%
13	Cleaning of pavements	0.36%
14	Retaining wall	0.33%
15	Concrete sewer	0.21%
16	Speed bumps	0.19%

WEEKLY PLANNING MEETING

These meetings were held at the end of each week. In these meetings, the LPS indicators and the yield curves of the control items were evaluated; and the planning for the following week was done. In that sense, the agenda was divided into two parts:

Executed Week Review

- **Percentage of Plan completed (PPC):** Indicator to verify compliance with the activities of the Weekly Plan for the week executed (Ballard and Tommelein, 2016).
- **Reasons for Non Compliance (RNC):** Qualitative indicator through which decisions are made and corrective actions are taken with respect to the activities of the PPC that were not complied with. It also contributes to the continuous improvement of the system (Ballard and Tommelein, 2016).
- **Percentage of Constraint Removal (PCR):** This indicator verifies compliance with the weekly scheduled release of constraints, allowing the determination of executable tasks (Lagos et al., 2019).

In addition, performance curves were developed in order to establish the relationships between the weekly results of PPC, PCR and labor performance.

- **Labor performance curves:** This graph identifies whether the labor resource meets the expected performance (input/output), according to the budget, because if the accumulated performance is higher than the budgeted performance, more man-hours (input) are being used than expected, which translates into cost overruns. This tool is based on data obtained from daily production reports of the control items, which indicate the composition of the work crew (workmen quantity), the amount of production (output) and the hours used for this.

Immediate Post Week Planning

- **Weekly work plan:** Detailed work plan for the following week. It is elaborated with activities free of constraints (Executable Tasks).
- **Constraint analysis:** Performed with information of each constraint that compromises the execution of an activity, identified in the lookahead, in order to determine the time and responsible for releasing it.
- **Lookahead Plan:** Planning whose time horizon should be equivalent to the time it takes for the most critical constraints to be lifted, so that these are identified and resolved in time. For the case study the time horizon was 3 weeks.

RESULTS

The results show that the lower the PPC and PCR (Figure 6 and 7), the performance is higher, which translates into inefficient use of resources and cost overruns. This is due to the fact that, in the event of non-compliance with the release of constraints, the workflow is interrupted, which implies greater use of labor resources.

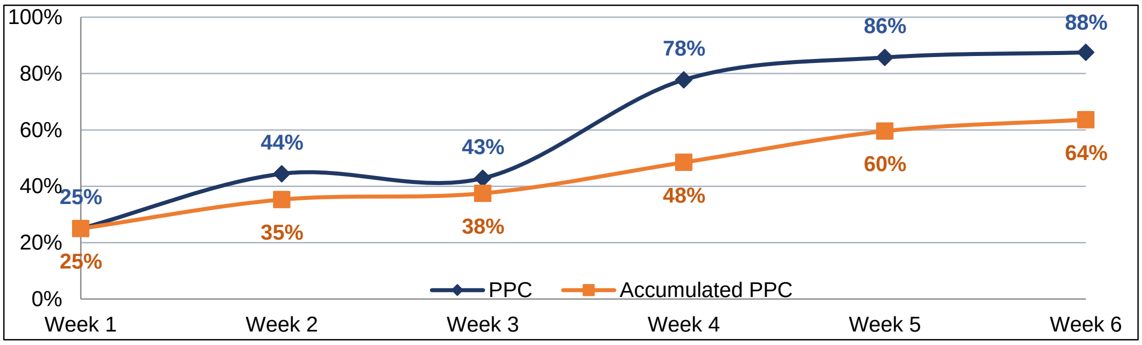

Figure 6: Study Period PPC Graph

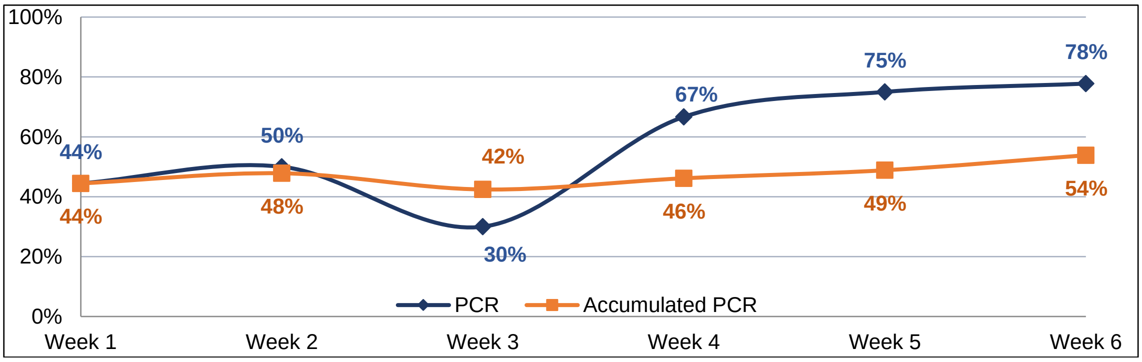

Figure 7: Study Period PCR Graph

The improvement in performance begins in week 3 (Figure 8), at which point the PPC and PCR tend to rise, which is explained by timely decisions and actions regarding labor and release of constraints.

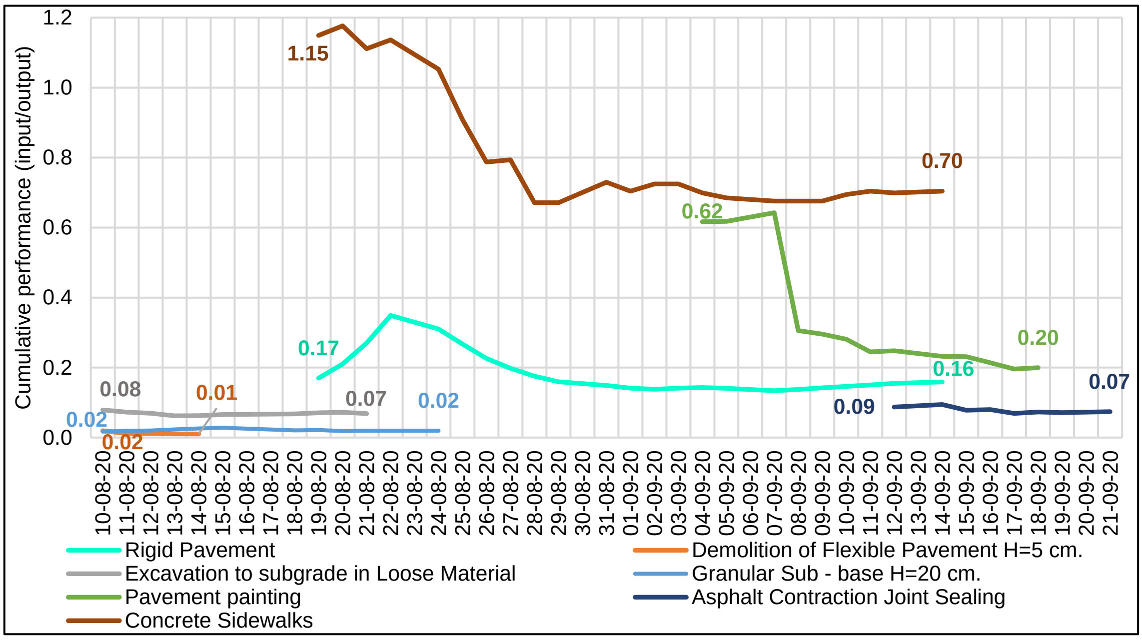

Figure 8: Labor performance curves

It is worth mentioning that some decisions involved more workmen, however, the labor performance was aligned with the budgeted performance of each control item, i.e., the system minimized labor cost overruns, which shows that it was able to control its performance within the current situation, as well as improve production speed, considering 8 hours of daily work (Table 3). This last finding is attributed to the weekly analysis of PPC and PCR results and the identification of RNCs to contribute to decisions aimed at continuous improvement of the workflow.

Table 3: Results cumulative labor performance curves

Item description	**Workmen Nr. (a)**	**Labor Performance (input/output)**			**Production speed (output/day)**		
		Budgeted	**Start (b)**	**End (c)**	**Start** $\frac{1}{b/(a\times 8)}$	**End** $\frac{1}{c/(a\times 8)}$	**Increase**
Rigid Pavement (m^2)	18	0.16	0.17	0.16	848	905	7%
Demolition of Flexible Pavement (m^2)	6	0.19	0.02	0.01	2464	4657	89%
Excavation to subgrade in Loose Material (m^3)	3	0.09	0.08	0.07	305	350	15%
Granular Sub-base H=20 cm (m^2)	5	0.04	0.02	0.02	2340	2037	-13%
Pavement painting (m)	8	0.64	0.62	0.20	104	320	208%
Asphalt Contraction Joint Sealing (m)	14	1.13	0.09	0.07	1287	1512	17%
Concrete Sidewalks (m^2)	7	0.71	1.15	0.70	49	80	63%

Finally, with respect to the RNCs identified during the current health situation, the most frequent are the external ones with 42% (Figure 9), since roadworks present factors specific to the type of project that can cause interruptions in the work flow throughout its development, which is why the labor performance is variable. Specifically, the irregularity of vehicular flow and frequent interference with residential access during the new normality was identified, as well as with services such as public lighting poles within the roadway and subway power lines. Therefore, it is recommended that before the start of a road project developed during the current situation, information about these factors be taken, since they represent a constraint and by taking action to release them, a workflow without interruptions and with better labor performance would be achieved.

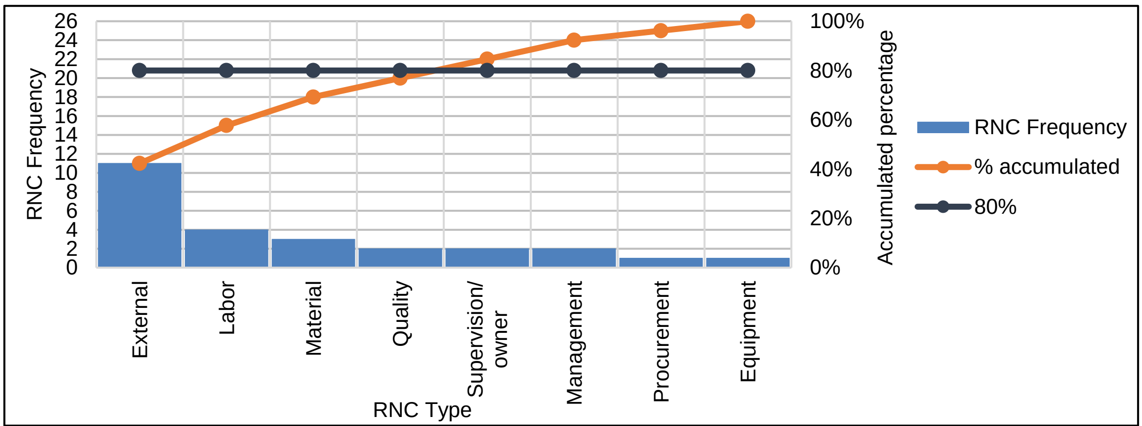

Figure 9: RNC Pareto Chart

CONCLUSIONS

- It was found that the monitoring of labor performance of road construction projects through the PPC, PCR and RNC indicators generated a positive impact on improving labor performance in road projects developed during the new normal.
- It was verified, according to the Pareto chart, that in the new normality, the greatest source of RNCs are: External, labor, materials and quality with a cumulative percentage of 80%.
- Specific external RNCs during the study period were found to encounter heavy and light traffic problems in the work areas, as well as interference with residential access and domestic public services.
- Better PPC and PCRd were found to be directly related to a labor performance in line with the Budget.
- It was found that when the PCR tends to be higher the PPC is also higher, since the best decisions made during the constraint analysis minimized workflow interruptions by improving labor throughput.
- It was found that low PPC and PCR, translates into and inefficient labor performance which in turn leads to higher cost overruns for the road project.
- A 24% to 64% improvement in PPC resulted in up to 67.74% improvement in the work force performance of the pavement painting control line item.
- This study contributes to existing knowledge and practice, in the context of the pandemic, by validating the methodology for monitoring and optimizing the

performance of the road construction work force using LPS indicators and collecting RNCs characteristic of the type of work and the health crisis.

REFERENCES

Ahmad, S. B. S., Mazhar, M. U., Bruland, A., Andersen, B. S., Langlo, J. A., and Torp, O. (2020). Labour productivity statistics: a reality check for the Norwegian construction industry. *International Journal of Construction Management*, *20*(1), 39–52. doi.org/10.1080/15623599.2018.1462443.

Ballard, G., and Tommelein, I. (2016). *Ballard_Tommelein-2016-Current-Process-Benchmark-for-the-Last-Planner-System*. 1–42.

Bølviken, T., and Koskela, L. (2016). *WHY HAS N ' T WASTE REDUCTION CONQUERED CONSTRUCTION ? 2*, 3–12.

Dallasega, P., Marcher, C., Marengo, E., Rauch, E., Matt, D. T., and Nutt, W. (2016). A decentralized and pull-based control loop for on-demand delivery in eto construction supply chains. *IGLC 2016 - 24th Annual Conference of the International Group for Lean Construction*, 33–42.

Hackett, V., Harte, P., and Chendo, J. (2019). The development and use of last planner® system (LPS) guidance. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, 651–662. doi.org/10.24928/2019/0101.

Jang, J. W., and Kim, Y.-W. (2007). Use of Percent of Constraint Removal to Measure the Make Ready Process. *Proceedings IGLC-13*, *July*, 529–538. https://www.iglc.net/papers/details/497.

Karunakaran, S., Malek, M. A., and Ramli, M. Z. (2019). Causes of delay in construction of highway projects: A review. *International Journal of Civil Engineering and Technology*, *10*(2), 2374–2386.

Lagos, C. I., Herrera, R. F., and Alarcón, L. F. (2019). Assessing the Impacts of an IT LPS Support System on Schedule Accomplishment in Construction Projects. *Journal of Construction Engineering and Management*, *145*(10), 04019055. doi.org/10.1061/(ASCE)CO.1943-7862.0001691.

Li, S., Fan, M., and Wu, X. (2019). Lean construction techniques and individual performance. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, 1469–1477. doi.org/10.24928/2019/0136.

Liu, M., and Ballard, G. (2008). Improving labor productivity through production control. *Proceedings of IGLC16: 16th Annual Conference of the International Group for Lean Construction*, 657–666.

Radzi, A. R., Rahman, R. A., Doh, S. I., and Esa, M. (2020). Construction readiness parameters for highway projects. *IOP Conference Series: Materials Science and Engineering*, *712*(1). doi.org/10.1088/1757-899X/712/1/012029.

Sinesilassie, E. G., Tabish, S. Z. S., and Jha, K. N. (2018). Critical factors affecting cost performance: a case of Ethiopian public construction projects. *International Journal of Construction Management*, *18*(2), 108–119. doi.org/10.1080/15623599.2016.1277058.

Zhang, L., Chen, X., and Suo, Y. (2017). Interrelationships among critical factors of work flow reliability in lean construction. *Journal of Civil Engineering and Management*, *23*(5), 621–632. doi.org/10.3846/13923730.2016.1217921.

Daliri, S., Young, B.K., and Lædre, O. (2021). "Last Planner® System on The Minnevika Bridge Project." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 757–766, doi.org/10.24928/2021/0167, online at iglc.net.

LAST PLANNER® SYSTEM ON THE MINNEVIKA BRIDGE PROJECT

Sajad Daliri[1], Brendan K. Young[2], and Ola Lædre[3]

ABSTRACT

Construction companies around the world have adopted the Last Planner® System (LPS) to reduce variability, increase workflow and improve reliability on their projects. This study explains the implementation of LPS in an infrastructure (railway bridge construction) project. Strengths and weaknesses of the implementation were examined and possible measures to overcome the experienced challenges were discussed. Finally, attitude changes towards the LPS during the project were measured.

Data was collected through case-specific observations, semi-structured interviews with open-ended questions, and two surveys. The findings revealed that the project benefitted from implementing LPS, but benefits could have been reinforced if critical team members had participated continuously in the necessary meetings, followed the system without resistance and maintained their commitments. Additionally, LPS on the Minnevika bridge project was the novel start and detected challenges are often experienced by every organization at the beginning of implementation of a new system. Indeed, the Minnevika bridge project can be considered as a point of departure and being persistent will help the parties to benefit even more in the next project.

KEYWORDS

Last Planner® System, challenges, infrastructure, attitude.

INTRODUCTION

Since the construction industry plays a vital role in economy, society, environment (Ansah et al. 2016), reducing waste and increasing productivity is important. The existing failures reported in the traditional project management help define the requirements for a new approach. This approach has been adapted to the construction industry, namely lean construction (Pellicer et al. 2015). The Last Planner® System is one of the most popular lean tools which has been used in construction to improve management and control, reduce urgent procurement requests, improve the performance(Alarcón et al. 2011), and for continuous monitoring of planning efficiency (O. AlSehaimi et al. 2014).

Several of the largest construction companies in Norway have shown their interest in LPS or what they call "Collaborative Planning (Veidekke and Kruse Smith), Trimmed Construction (Skanska) and Collaborative Project Execution (Nymo)" in their operations

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(Kalsaas and Grindheim 2014). PNC Norge AS, the company under-study, is one of these organizations that has implemented LPS on their Minnevika bridge project to improve planning and control, reduce uncertainty, take advantages of efficient collaboration among contractors and subcontractors, and measure the weekly project progress. When it comes to LPS implementation, the specific cultural barriers such as attitude to work could show up (Johansen and Porter 2003). However, by considering cultural analysis tools and measurements, it is possible to find out the factors of success or failure of certain practices in cultural conditions (Ravi et al. 2018). A significant number of case studies of implementation of LPS in projects exists, but few have investigated the participants' attitude changes towards LPS implementation on an infrastructure project who have adopted the LPS for the first time. Therefore, the following research questions were formulated:

- How is the Last Planner® System practiced on the Minnevika bridge project?
- What are the strengths and weaknesses of the LPS process on the Minnevika bridge project?
- How have the involved parties' attitudes towards challenges changed during the implementation of LPS?

After the introduction section, the research methods are explained. Then, the literature review concentrates on LPS stages and challenges. The case study findings are presented and discussed before the research questions are answered in the conclusion section.

LITERATURE REVIEW

LAST PLANNER® SYSTEM COMPONENTS

Last Planner® System is a holistic and cascade system that helps construction companies improve planning reliability, production performance, and workflow on construction sites (Hamzeh,2011). The integrated components of this system include milestone planning, phase planning, look-ahead planning, weekly work planning, and learning (Ballard and Tommelein, 2016).

Milestone planning

The front-end planning process that, besides defining the project milestones and the required length of time for performing each activity, provides an overview of entire tasks that should be executed throughout the project (Daniel et al. 2017).

Phase planning

By utilizing the milestone planning and incorporating input from different project parties (direct involvement of the contractors, sub-contractors, clients, and other stakeholders), reliable construction planning will be developed at this stage to cover each project phase as a reverse phase scheduling back from important milestones (Hamzeh et al. 2012).

Look-ahead planning

It is medium term planning approximately six weeks in advance and screens for constraints in eight flows, which includes resources, information, equipment, material, prerequisites, safe workplace, external conditions (Koskela 2000) and common understanding (Pasquire and Court 2013) before passing the activities into production on site in order to increase construction flow. (Daniel et al. 2017).

Weekly work planning

The weekly work planning takes place every week with the involvement of last planners in order to review the commitments planned in the previous week. It involves making a schedule for the week ahead and defining the detailed assignments that should be performed during that week (Pellicer et al. 2015).

Learning

Measuring the reliability of the plan that is directly related to the productivity (Pellicer et al. 2015) is possible by applying measurement indicators such as; Percentage Plan Complete (PPC) for evaluating the proportion of commitments that are delivered on time and the reason for non-completion (RNC) in order to learn from the mistakes and avoid them in future (Ballard and Tommelein 2016).

LAST PLANNER® SYSTEM CHALLENGES

Many construction companies have made attempts to take advantage of the LPS. However, it should be noted that besides the numerous benefits of this tool, many organizations face significant implementation obstacles (Ballard et al. 2007; Viana et al. 2010). As Hamzeh (2011) stated *"researchers in the field of change management and lean have reported attempts of many organizations to implement lean practices. However, most companies either failed or only partially achieved lean production in its true form*". According to Hamzeh (2011), both general and local factors can impact implementation of LPS. General factors relate to the execution of a new method and include: human resources, organizational inertia, resistance to change, technological barriers. Local factors relate to project circumstances and include; relatively new experience in lean methods, traditional project management methods, the newness of LPS to team members, lack of leadership, and team chemistry. Similarly, Porwal et al. (2010) categorized the challenges into two parts; 1. Challenges faced during the implementation phase such as lack of training, partial or late implementation of LPS, lack of support and contractual structure. 2. User challenges, for instance, lack of commitment and attitude toward the new system, lack of collaboration, extra resources or time consuming, and lack of understanding of new system. It should be noted that the most LPS challenges tend to be related to the softer aspects of implementation including organizational process and people (Dave et al. 2015). Kassab et al. (2020) followed the initial implementation of LPS on the Minnevika Bridge Project and Table 6 lists the challenges they identified.

RESEARCH METHODS

To answer the research questions, data was collected through case specific observations, semi-structured interviews with open-ended questions, and two surveys. An initial literature study was carried out to identify the core components of LPS and the challenges related to implementing LPS. Findings from literature were used when establishing an interview guide and formulating the survey questions.

The Minnevika bridge project was selected as a case study since it is one of the first infrastructure projects in Norway to implement LPS. It consists of 2 abutments and 18 piers standing on 268 Ø1016/20 mm steel tube friction piles. When opening for traffic in August 2023, this 836m long concrete bridge will be the longest in Norway. It is part of the Norwegian railway operator BaneNor's Eidsvoll Nord-Langset 4.5 kilometer double-track rail development that in addition to the Minnevika bridge includes a short tunnel and three short bridges. A joint venture was established between Hæhre AS and PNC

Norge AS to deliver the total project. Within the joint venture, PNC Norge acts as the main contractor for the Minnevika bridge.

The first author was employed as a trainee on the Minnevika project and supported the LPS facilitator both in the weekly work meetings and with preparing the LPS documentation. The first author was an participant-observer who followed the guidelines of Saunders et al. (2009) while conducting observations. Notes were taken from the observations of 9 weekly work meetings. The second author was an ordinary participant in these meetings, but not an observer. These two authors' participation led to an in-depth knowledge about the project but may also have led to a biased analysis despite attempts to avoid it.

Three semi-structured interviews were collected during the LPS implementation with two site managers and one project planner. The interview questions were structured after the three research questions.

Two more or less similar surveys were distributed in February 2019 and November 2020 with the same participants. The first survey was answered by 8 participants and the second by 9. Findings from the first survey are reported by Kassab et al. (2020). Collecting data with the two surveys conducted with an interval of one year allowed for a longitudinal study to be presented here.

FINDINGS

LPS IMPLEMENTATION ON THE MINNEVIKA BRIDGE PROJECT

The implemented LPS on the Minnevika bridge project consists of a Milestone plan, Look-ahead plans and the Weekly work plans. The contractor's site managers and supervisors established the Milestone plan at the beginning of the project. The milestones are tied to the major activities in the project. The Milestone plan represents the top of the plan hierarchy and decides the room for manoeuvre in the Look-ahead plan and the more detailed Weekly work plan.

With the Milestone plan as the starting point, the Look-ahead plans were established. The contractor used the milestone plan to map the bridge construction activities from the beginning to the end by pull planning principles. The mapping included an identification of all activities that had to be completed to reach each milestone. The necessary order, the duration and the critical path for these activities were identified. Then, a pull planning of the activities from their last date of completion was carried out. The respective first possible start date for the activities on the critical path gave the available time. Hopefully the available time is sufficient. The team used this backwards – or reverse – planning of the workflow to establish the Look-ahead plan from the milestone plan. Look-ahead plans on the Minnevika bridge project were for six weeks ahead and required representatives of the main contractor and the subcontractors to plan reliably and identify constraints.

The construction managers, site engineers, production team, HSE representatives, partners and subcontractors participated in the Weekly Work Plan (WWP) meetings. On the Minnevika bridge project, the term Production Evaluation and Planning (PEP) is used for the activities that correspond to the LAP and WWP described in literature. The agenda in the PEP meeting had standard headings: evaluation of the previous week, checking the Reason for Non-Completion (RNC) of trades (part of handover management between the trades, and the Minnevika project use the term Variance Analysis), Order and safety **(**analyse the safety issues on the construction site), Risk matrix (risks/constraints with corresponding probability and consequences), Action Plan (with responsibles and deadlines, to mitigate risks and promote opportunities), LAP, WWP, and Logistics.

The contractor measured the following Key Performance Indicators (KPI): Percent Plan Complete (PPC) overall, PPC per trade, Milestone Completion, Variance Analysis (or RNC), Top Three Variances, and Problem Solving. The indicators were tracked and used in order to increase productivity and learning from mistakes.

THE LPS ON MINNEVIKA COMPARED TO LPS IN LITERATURE

The Last Planner® System on the Minnevika bridge project consists of five components described as essential in literature, namely milestone planning, backwards planning, look-ahead planning, weekly work planning and measurements for learning. Even though the contractor only applied LPS in the execution phase and not in the design phase, the core components of LPS were in place.

Table 1: LPS components on the Minnevika bridge project

	Milestone plan	Phase planning	Look-ahead planning	Weekly work planning	Measurement & Learning
In place	✓	✓	✓	✓	✓

STRENGTHS AND WEAKNESSES OF LPS – EXPERIENCES FROM MINNEVIKA

To understand the productivity and efficiency of LPS on the Minnevika bridge project, it is vital to determine the benefits and drawbacks of the system from the participants' perspective who were involved in implementation of LPS. After analyzing the notes from the participant observations and the transcripts from the interviews with the project team, it seemed that the strengths overweighted the weaknesses. A majority of the project participants' experienced LPS for the first time, and they thought that if LPS were implemented on future projects with the same participants some of the weaknesses would fade away more or less by themselves. During the interviews, the strengths and weaknesses of the LPS execution as well as possible solutions for the shortcomings were examined. The results related to the milestone plan, lookahead plan, weekly work plan and KPIs are described in table 2-5 below, respectively. Each table is followed by a discussion.

Of those weaknesses identified – both for the Milestone, Look-ahead and Weekly work plan – many of them seemed to be the result of irregular attendance of participants in the meetings. An observation was that it often was the same participants that did attend and and the same that did not. Put in other words; some participants were not loyal to the plans, and their unloyalty spoilt potential benefits for all. The success of LPS demands that all – or at least most – of the participants act loyal.

A measure to overcome the challenges related to the Milestone plan in table 2 – that emerged during the observations and interviews – was to review the milestones periodically. A periodic review would remind the participants about the main milestones in the project and prevent that the short-term look-ahead planning occupied all attention.

Table 2: Strengths and weaknesses of the Milestone plan

Strengths	Weaknesses
• Higher level management uses it to track project progress • Suitable as report to the client • Gives a target plan on the entire project • Can be used when prioritising which activities can be delayed and which can be speeded up	• Does not include all activities on site • Can be forgotten since it is not in everyday use

Table 3: Strengths and weaknesses of the Look-ahead planning

Strengths	Weaknesses
• The involved parties cooperate on a reliable detailed plan for decisions, activities and resources with the critical path benefitting the project as a whole for. • Planning on whiteboard with colourful sticky notes helps visualize the process and improve understanding • Helps participants to reflect and plan clearly	• It sometimes creates a short-term focus • Since Look-ahead planning is time consuming it can lead participants to rush into the actual planning

Suggested measures to mitigate the challenges in table 3 related to Look-ahead planning at the Minnevika bridge project included to increase consciousness about how the six-week look-ahead plan fits the Milestone plan. The milestone plan should to a larger extent have been used as a reference for the continuous look-ahead planning, as the milestone plan was not always consulted when the look-ahead plan was updated to match progress on site. The result was that the updated look-ahead plan was not fully aligned with the milestone plan. However, since the updated look-ahead plans were not substantially changed, the missing alignment was not expected to cause future problems. Another suggested measure was to assign people to activities, and thereby increase consistency in who was responsible for the planning.

Table 4: Strengths and weaknesses of the Production evaluation and production planning (PEP)/Weekly work plan (WWP)

Strengths	Weaknesses
• A weekly meeting that helps the team coordinate both internally with partners and with the subcontractors • One meeting substitutes separate meetings with individual subcontractors • Allow discussions on all issues with involved parties • Make the production team commit to the plan • Participation in planning motivates the foremen • Participants with different perspectives provide input to appropriate solutions	• Some supervisors did not attend the meetings • Time consuming (around two hours) • Parts of the meetings were irrelevant to some participants • Rotational working schedules distort continuous participation

It is not easy to ask experienced managers to adopt new ways of management, and that caused the weaknesses of the PEP meetings listed in table 4. The best way to convince these managers to spend the necessary time is by convincing them of the benefits of the system. During the observations, some benefits appeared. As one of site managers explained: *"The PEP meeting helps us to have one coordination meeting instead of having meetings one by one with all our partners and subcontractors separately. Now we get everyone in the same room and when a problem comes up, we have more people to contribute and look at it from different angles to make better solutions"*. Another measure that appeared during the observations and the interviews is to put more efforts into establishing the PEP meeting schedule. The meeting schedule must be aligned with the relevant participants' presence on site, and not at least with which time of the day that works best for the participant's rotation, their tasks on site, and their meeting schedule.

Table 5: Strengths and weaknesses of the KPI

Strengths	Weaknesses
• Supports communication of lessons learned • Prevents repetition of mistakes • Comparison of progress compared to plan • Reveals reliability of the superior plan	• Hard to attract the participants' attention to the KPI • Participants usually do not analyse and track changes after PEP meetings

The KPIs were measured, but as identified in Table 5, the participants in the PEP meetings were not eagerly embracing the entailing opportunities. A suggested measure to overcome the weaknesses was to demonstrate how the measurements of Percent Plan Complete (PPC), Milestone Completion, Variance Analysis (Reasons for Non-Completion), and Top Three Variances could be used to improve the workflow for the participants.

MEASURING THE INVOLVED PARTIES' ATTITUDES DURING THE PROJECT

To measure changes in the participants' attitudes towards the LPS, two surveys were distributed to project participants with around one year interval. Both surveys contains questions based on challenges identified by Kassab et al. (2020), who reported the findings from the first survey. When distributing the surveys with one year interval, it was possible to observe how attitudes changed after the participants acquainted themselves with the LPS. The changes in average score (from 1= very low to 5= very high on a Likert Scale) from February 2019 to November 2020 are given in Table 6.

Table 6: To what extent do you think each of the following challenges is considered as a critical challenge on the Minnevika Bridge project during execution phase (average scores from 1-5)? (developed from Kassab et al. (2020))

Challenges	Feb 2019	Nov 2020
1. Maintaining people's commitment to be part of the process and take the system seriously	3.50	3.22
2. Lack of transparency in the interfaces between project team members	2.25	2.77
3. Resistance to the system	2.25	3.22
4. The language barriers	1.63	2.00
5. Non-participation of critical team members	2.85	3.22
6. The decisions and input are primarily provided by top-level management, such as site managers	3.00	2.88
7. Fear of responsibility (mainly from lower-level management)	3.00	2.22
8. Doubt (about overall performance and benefits behind the LPS)	1.63	2.77
Challenges	**Feb 2019**	**Nov 2020**
9. Misunderstanding of the basic concepts of the LPS	2.00	2.22
10. The time commitment required to participate in the weekly meeting	1.75	2.77
11. Lack of engagement	1.63	2.00
12. Disruption	1.63	2.33

ATTITUDES HAVE CHANGED

When comparing the scores from February 2019 with the scores from November 2020, it appears that the scores have changed after a year. Three of the challenges originally identified by Kassab et al. (2020) are considered to have become less critical after a year. **Maintaining participants' commitment to be part of the process and to take the system seriously** was the main challenge during the first stage of LPS implementation and is still one of the three top challenges. It has become slightly less significant with time. Similarly, **the decisions and input are primarily provided by top-level management, such as site managers** and **Fear of responsibility (mainly from lower-level management)** have followed the same trend. One reason why these challenges are considered less critical after a year may be that the project team has gained more experience with LPS after one year, and that the participants see that LPS is practiced according to theory.

The comparison of the scores from the first survey with the scores from the second survey reveals – somewhat surprisingly – that nine out of twelve challenges are considered to have become more critical after a year. The nine challenges are **Lack of transparency in the interfaces between project team members**, **Resistance to the system**, **The language barriers**, **Non-participation of critical members**, **Doubt (about overall performance and benefits behind the LPS)**, **Misunderstanding of basic concepts of the LPS**, **The time commitment required to participate in the weekly meeting**, **The lack of engagement** and **Disruption**. These challenges are maybe considered more critical after a year, as the participants realise that the promised benefits of LPS are not manifesting as quickly as hoped for. In addition, the project team might have experienced that LPS's charm of novelty has faded during the year, and that implementation of LPS requires persistence. They need to put in resources to make LPS work, and the resources may outweigh the benefits for projects that implement LPS for the first time. The next project may not need that much resources to realise the benefits.

The suggested explanations for why three challenges have become less critical (more experience and LPS practiced according to theory) could have been used to explain a decrease in the nine remaining challenges as well. However, the nine other challenges increased. The other way around, the suggested explanations for why nine challenges have increased (promised benefits not manifesting, charm of novelty has faded out, implementation requires persistence and resources outweigh benefits) could have been used to explain an increase in the three. The exact reasons for why three challenges decreased, and nine challenges increased were not in-depth investigated.

CONCLUSIONS AND FUTURE WORK

This paper set out to answer three research questions, namely, 1) how is the Last Planner® System practiced on the Minnevika bridge project, 2) what are the strengths and weaknesses of the LPS process on the Minnevika bridge project from participants' perspectives and 3) how have the involved parties' attitudes towards challenges changed during the implementation of LPS. The answers to these three research questions are based on the findings from studying the implementation of LPS on one railway bridge construction project and are considered valid for other infrastructure projects that plan to implement LPS for the first time.

The answer to the first research question is that the contractor on the Minnevika bridge project has implemented five core components described by literature as essential, namely milestone planning, phase planning, look-ahead planning, weekly work planning and measurements for learning.

The participants recognise typical strengths of LPS and have experienced improved planning and control during the execution phase. Some project team members did not invest as much resources in following up LPS as others, but if they had done so the typical strengths could have been reinforced. Despite that some participants did not put sufficient efforts into LPS, the implementation resulted in improved coordination between the contractor and the partners, and between the contractor and the subcontractors. The participants believed that if they implemented LPS more faithfully on their next project, several of the experienced weaknesses would fade and strengths could probably even be boosted because of the training they acquired on the Minnevika project.

The answer to the third research question about how have the involved parties' attitudes towards challenges changed during the implementation of LPS, is that three observed challenges are considered to have become less critical while nine challenges are considered to have become more critical. Since the project team has gained experience with LPS and see that it works, the three challenges are less critical. Since the project team also sees that making LPS work demands continuous effort, the other nine challenges are considered more critical after a year. Successful implementation of LPS not only relies on the application of the full version of the tool, but also on changes in mindset and project team participation. LPS does not represent a quick fix.

The Minnevika bridge will open for traffic in August 2023. To collect more data and quality assure the conclusions in this study, it is recommended to carry out more interviews and distribute a third survey to measure the attitudes towards LPS right before the project is finished. The third survey should look for the exact reasons why some challenges decrease and some increase by time.

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REFERENCES

Alarcón, L. F., Diethelm, S., Rojo, O., and Calderón, R. (2011). "Assessing the impacts of implementing lean construction." *Revista Ingeniería de Construcción*, 23(1) 26–33.

Ansah, R. H., Sorooshian, S., and Mustafa, S. B. (2016). "Lean Construction: An Effective Approach For Project Management." *ARPN Journal of Engineering and Applied Sciences.,* 11(3) 1607-1612.

Ballard, G., Kim, Y.-W., Liu, M., and Yang, J. (2007). "Roadmap for Lean Implementation at the Project Level." *The Construction Industry Institute.,* p.426

Ballard, G., and Tommelein, I. (2016). "Current Process Benchmark for the Last Planner System." *Lean Construction Journal.,* 89 57-89.

Daniel, E. I., Pasquire, C., Dickens, G., and Ballard, H. G. (2017). "The relationship between the last planner® system and collaborative planning practice in UK construction." *Engineering, Construction and Architectural Management*., 24(3) 407–425.

Dave, B., Hämäläinen, J.-P., and Koskela, L. (2015). "Exploring the Recurrent Problems in the Last Planner Implementation on Construction Projects." *Institute for Lean Construction Excellence.*

Hamzeh, F. (2011). "The Lean Journey: Implementing The Last Planner ® System in Construction." *Proceedings of the 19th Annual Conference of the International Group for Lean Construction, IGLC* 13-15.

Hamzeh, F., Ballard, G., and Tommelein, I. (2012). "Rethinking Lookahead Planning to Optimize Construction Workflow." *Lean Construction Journal (LCJ).*, 2012 15–34.

Johansen, E., and Porter, G. (2003). "An experience of introducing last planner into a UK construction project."

Kalsaas, B. T., and Grindheim, I. (2014). "Integrated Planning Vs. Last Planner System." *22nd Annual Conference of the International Group for Lean Construction, IGLC* 639-650.

Kassab, O., Young, B., and Lædre, O. (2020). "Implementation of Last Planner® System in an Infrastructure Project". *28th Annual Conference of the International Group for Lean Construction, IGLC.,* 517-528.

Koskela, L. (2000). "An exploration towards a production theory and its application to construction". *VTT Technical Research Centre of Finland, Espoo.*

AlSehaimi, A.O., Fazenda, P.T., and Koskela, L. (2014). "Improving construction management practice with the Last Planner System: a case study." *Engineering, Construction and Architectural Management*., 21(1) 51–64.

Pasquire, C., and Court, P. (2013). "An Exploration Of Knowledge And Understanding - The 8th Flow." *22nd Annual Conference of the International Group for Lean Construction, IGLC* 43-52.

Pellicer, E., Cerveró, F., Lozano, A., and Ponz-Tienda, J. L. (2015). "The Last Planner System of Construction Planning And Control As A Teaching And Learning Tool." *INTED2015 Proceedings, 9th International Technology, Education and Development Conference.,* 4877-4884.

Porwal, V., Fernandez-Solis, J., Lavy, S., and Rybkowski, Z. (2010). "Last planner system implementation challenges." *Proceedings of the 18 Annual Conference International Group for Lean Construction, IGLC* 548–556.

Ravi, R., Lædre, O., Fosse, R., Vaidyanathan, K., and Svalestuen, F. (2018). "The Last Planner System: Comparing Indian and Norwegian Approaches." *26th Annual Conference of the International Group for Lean Construction.*, 381–391.

Saunders, M., Lewis, P., and Thornhill, A. (2009). "Research Methods for Business Students. Pearson Education."

Viana, D. D., Mota, B., Formoso, C. T., Echeveste, M., Peixoto, M., and Rodrigues, C. L. (2010). "A Survey on The Last Planner System: Impacts And Difficulties For Implementation Brazilian Companies." *18 th Annual Conference of the International Group for Lean Construction.*, 497-507.

Hamerski, D. C., Fernandes, L. L. d. A., Porto, M. S., Saurin, T. A., Formoso, C. T., and Costa, D. B. (2021). "Production planning and control as-imagined and as-done: the gap at the look-ahead level." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 767–776, doi.org/10.24928/2021/0169, online at iglc.net.

PRODUCTION PLANNING AND CONTROL AS-IMAGINED AND AS-DONE: THE GAP AT THE LOOK-AHEAD LEVEL

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ABSTRACT

The Last Planner® System (LPS) of Production Control is widely acknowledged as fit to tackle the complexity of construction projects. However, the implications of complexity in the implementation of LPS itself have not been investigated. Those implications are investigated in this paper by exploring the gap between production planning and control-as-imagined and as-done at the look-ahead level. For that purpose, a case study was conducted in the refurbishment of a department store in which the LPS was implemented. Data collection involved document analysis, participant observation at the look-ahead and short-term planning meetings, and unstructured interviews. The Functional Resonance Analysis Method (FRAM) was used for modeling variability and interactions between the managerial functions at the look-ahead planning level. Results indicated several differences between production planning and control-as-imagined and as-done, which reflect hidden activities required for the removal of constraints. These activities took time and effort from managers and therefore they can partly explain why the LPS was not strictly followed as-imagined in theory.

KEYWORDS

Last Planner® System, look-ahead planning, production planning and control, complexity, FRAM.

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INTRODUCTION

Construction projects can be usually regarded as complex systems (Bertelsen 2003), as they have many interrelated components (e.g. stages, technologies, stakeholders, etc.) which also interact with their environment (Dekker et al. 2013). In turn, the Last Planner System (LPS) is a production planning and control model, which is based on Lean concepts and principles that have been adapted from repetitive manufacturing into the construction domain (Ballard and Tommelein 2012). The LPS overcomes, to some extent, the limitations of traditional project management approaches (Koskela and Howell 2002) and has been associated with successful outcomes when applied to complex construction projects (Castillo et al. 2018).

The removal of constraints is a core process for the production of reliable plans in the LPS (Hamzeh et al. 2012). It is carried out at the look-ahead planning level, which typically has a planning horizon from 4 to 12 weeks and aims at making ready work packages, i.e., free of pending constraints so as they can be assigned to production teams in the short-term planning level (Ballard, 2000). Constraints may be related to labor, space, equipment, design, safety, among other resources. In fact, the same work package can be associated with several constraints and therefore there may be a non-linear relationship between the number of work packages and the number of constraints. Furthermore, the removal of constraints is likely to be recursive as the removal of a primary constraint (e.g. equipment) may trigger the need for removing other upstream constraints (e.g. maintenance of existing equipment). As such, it is reasonable to expect that the removal of constraints is also a complex process itself, likewise other LPS activities.

In this paper, this complexity is investigated in light of the concepts of work-as-imagined and work-as-done, which were proposed by Hollnagel (2012). Work-as-imagined (WAI) refers to the various assumptions, explicit or implicit, that people have about how work should be done, being often prescribed in procedures or standards. By contrast, work-as-done (WAD) refers to how something is actually done, either in a specific case or routinely (Hollnagel 2015). Previous studies, both in the construction industry (Penaloza et al. 2020) and in lean manufacturing systems (Soliman and Saurin 2020), have shown that the WAI and WAD concepts are applicable to managerial processes. Patriarca et al. (2021) coined the term WAx in order to convey the pervasive nature of these concepts. Understanding the gap between WAI and WAD is important for two main reasons: (i) it usually indicates that successful outcomes do not necessarily occur because people are behaving according to WAI (Hollnagel 2015); and (ii) wide gaps suggest considerable scope for improvement (Perkins et al. 2010).

Therefore, this study aims to investigate the gap between production planning and control-as-imagined (based on the original version of the LPS) and production planning and control-as-done (based on how it is applied in practice) at the look-ahead level. This investigation sheds light on taken-for-granted assumptions underlying the LPS.

LITERATURE REVIEW

CONSTRUCTION PROJECTS AS COMPLEX SOCIO-TECHNICAL SYSTEMS

Complex socio-technical systems are formed by a large number of diverse and dynamically interacting elements, such as people, materials, equipment, and procedures (Hollnagel 2012). These interactions give rise to variability and uncertainty, which are present in most construction projects (Koskela 2000).

In addition, some factors amplify the complexity of construction processes such as the fragmentation of the construction industry and the ever-growing demands for fast, safe, low cost, and high-quality projects (Gidado 1996). Thus, coping with complexity has been more and more part of everyday work in construction project management (Formoso et al. 2015).

Penaloza et al. (2020) pointed out some typical attributes of complexity in the construction industry, such as the gap between WAD and WAI, the influence of the external environment, and the interactions between construction stages. According to Melo and Costa (2019), the understanding of WAD in construction is often overlooked by managers; standardized operating procedures are devised for compliance purposes instead of providing useful guidance to those at the front line of construction activities.

FUNCTIONAL RESONANCE ANALYSIS METHOD (FRAM)

Hollnagel (2004) conceived FRAM as a method to model complex systems. One of the main roles of FRAM is to model how different functions in socio-technical systems relate to each other (Hollnagel 2012). FRAM is based on the following main principles (Hollnagel 2012):

- The equivalence of successes and failures: things that go well and things that go wrong have the same causes. Acceptable and unacceptable outcomes are due to the ability of organizations and individuals to adjust to expected and unexpected circumstances.
- Approximate adjustments: work is continuously adjusted to the existing conditions (resources, time, tools, information, requirements, opportunities, conflicts, interruptions). These adjustments are made by individuals, groups, and organizations at all levels, and will be approximate rather than perfect.
- Emergence: the variability of multiple functions can combine in unexpected ways, leading to nonlinear effects. Thus, both failure and normal performance are emergent, rather than a resulting phenomenon, as they cannot be attributed or explained solely based on the functioning or non-functioning of specific components.
- Functional resonance: the combined everyday variability of various functions can sometimes create a functional resonance, thereby producing unexpected results. Functional resonance is the detectable variability (e.g. accidents or wastes) that otherwise remains hidden in everyday work.

FRAM application involves five steps (Hollnagel 2012):

1. To define the purpose of FRAM analysis, which can be, for example, an investigation of a past event, a risk assessment of a new system, or an evaluation of design changes;
2. To identify and describe the functions of the system according to six aspects (input, output, preconditions, resources, time, and control);
3. To describe the variability of the functions, taking into account what is expected to happen (or what happened, in the case of a past event) with the output of each function in terms of time (too early, on time, too late, not at all) and precision (precise, acceptable, imprecise);

4. To aggregate the variability of individual functions, by assessing couplings between functions – couplings occur between the output of a function and any of the other aspects of downstream functions;
5. To devise practical measures for improving the work system design, if necessary.

RESEARCH METHOD

Case study was the research strategy adopted in this investigation. It is an appropriate strategy as this study aims to understand a current phenomenon in its context (Branski et al. 2010).

The initial step was the selection of a relevant case study. As the main selection criterion, we sought a construction project in which there was an explicit intention of fully using the LPS. Thus, a refurbishment project for a department store in Brazil, in which the LPS was implemented by demand of the owner, was selected. An additional benefit of choosing this project was the ease of access to data sources as one of the authors was involved in the planning and control process. The unit of analysis was the managerial functions that made up the look-ahead planning level. More specifically, this study focuses on those functions during the process of removing constraints.

Next, FRAM was used to model the functions involved in the removal of constraints, considering two work packages: (i) installation of the fire pipe support system; and (ii) mezzanine assembly. At the time of data collection, the former package had been 100% complete, while the latter was delayed. The first one was selected due to the wide variety of managerial functions that were necessary to make the work package ready. The second was selected as it involved much variability, which allowed the exploration of variability propagation across the planning process. Although the content of the work packages and the corresponding variabilities were different, the managerial functions involved in the removal of constraints were similar, thus facilitating meaningful comparisons.

The FRAM models reflected production planning and control-as-done at the look-ahead level, which then set a basis for comparison with production planning and control-as-imagined by the original version of the LPS (Ballard 2000; Tommelein and Ballard 1997; Ballard and Howell 1998; Ballard and Howell 2003). The original LPS version was adopted as a basis for comparison because there were no formally documented standards specifying how construction planning was expected to occur in the construction project – the contractor itself also adopted the original LPS as its imagined approach.

Three sources of evidence were used: documents, participant observations, and unstructured interviews (i.e. informal conversations). The documents analyzed were the look-ahead and short-term plans. Participant observations took place in planning and control meetings for 3 months. A total of 12 look-ahead meetings (2 hours each) and 12 short-term meetings (1 hour each) were attended by one of the researchers. Participant observations offered plenty of opportunities for unstructured interviews with some of the project staff in order to understand how managerial functions related to constraint removal were undertaken.

DESCRIPTION OF THE CONSTRUCTION PROJECT AND THE EXISTING PLANNING AND CONTROL SYSTEM

The study took place during the refurbishment of a commercial building in a shopping mall (department store focused on the sale of apparel) of approximately 1,500.00 m². The majority of the work carried out in the construction site involved finishing activities.

These activities were carried out by 15 subcontractors during a period of 3 months. Most of those activities had a high degree of interdependency between them.

The existing planning and control system was strongly based on lean principles and concepts. However, most of the participants involved in this construction project were experiencing the implementation of those principles and concepts for the first time. A Production System Design was developed before starting the construction stage. Look-ahead planning meetings occurred every two weeks and short-term planning meetings were held weekly.

RESULTS

FRAM MODELS

Figure 1 presents a model of the functions involved in the removal of constraints for the work package "Installation of the fire pipe support system", while Figure 2 presents a similar model for the work package "Mezzanine assembly". In both models, 19 functions to make a work package ready were identified. The sequencing of the functions is represented from the top to the bottom and from the left to the right, while the functions are represented by hexagons. The hexagons with yellow borders are related to the preparation of the construction plans, which are part of long-term, look-ahead, and short-term planning levels. The hexagon with red borders represents the work package execution, which is the last function of the models. In the traditional FRAM representation, the name of the functions appears inside each hexagon. However, for better visualization in this paper, a coding system was adopted (Table 1).

In Figures 1 and 2, the functions are categorized according to six of the preconditions for starting a construction task proposed by Koskela (2000), which are: construction design, components and materials, workers, equipment, connecting works, and space.

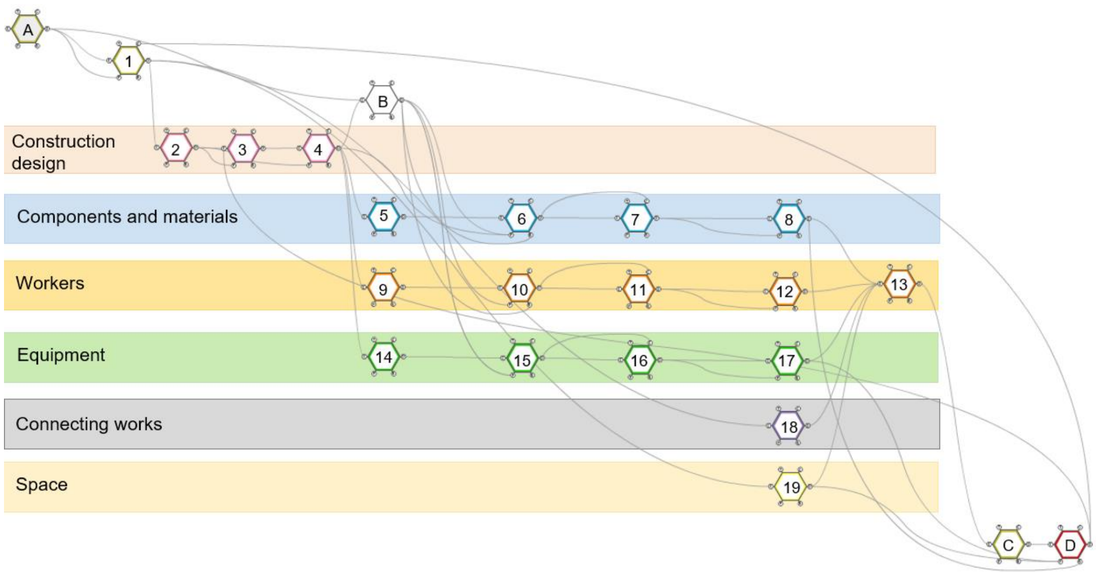

Figure 1 – Functional model for the removal of constraints: work package "Installation of the fire pipe support system"

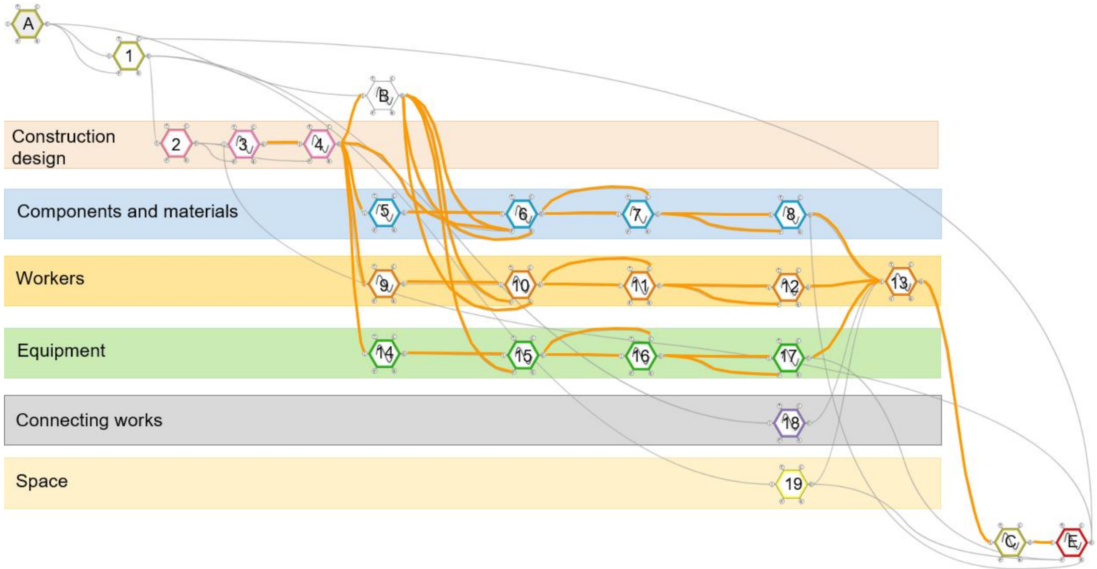

Figure 2 – Functional model for the removal of constraints: work package "Mezzanine assembly"

Table 1 – Names of the functions presented in Figures 1 and 2

	Function		Function
A	Produce long-term plan	11	Perform induction training
1	Produce look-ahead plan	12	Check workers availability
2	Check construction design availability	13	Conduct a price quote for equipment rental
3	Study construction design	14	Rent equipment and schedule the delivery
4	Check the quantity of materials	15	Check the delivery of equipment
B	Check financial resources availability	16	Check logistics for equipment transportation
5	Conduct a price quote for materials	17	Check the conclusion of previous work packages
6	Purchase materials and schedule the delivery	18	Check space availability
7	Check the delivery of materials	19	Make commitment
8	Check logistics for materials' transportation	C	Produce short-term plan
9	Perform job interviews to compose the work team	D	Installation of the fire pipe support system
10	Hire workers and schedule the start of work on site	E	Mezzanine assembly

The functions are coupled to each other through their outputs (O) – they are connected to one or more of the other five aspects of the downstream functions, namely Input (I), Time (T), Precondition (P), Resource (R) or Control (C). In the studied models, the outputs of the initial function "Produce the long term-plan" are "Long-term meeting held", "Cash flow generation", and "The long-term plan". As presented in Figures 1 and 2, these outputs connect to the input and the precondition of the function "Produce the look-ahead plan", and the input of the function "Check financial resources availability".

The waves inside several functions indicate the existence of output variability and the yellow lines denote the propagation path (Figure 2). It is worth noting that, for the model in Figure 2, the work package was not completed due to a compatibility problem in the construction design. The problem started with variability in the output of the function "Study construction design" and propagated throughout almost all downstream functions, resulting in the non-completion of the work package. As the design incompatibility was not identified at its source, some managerial functions had to be performed twice to make the work package ready for the next short-term planning cycle (e.g. check workers availability, check the conclusion of previous work packages, and check space availability).

DISCUSSION

The results of this study pointed out that the production planning and control as-done was substantially different from the production planning and control as-imagined (Table 2).

Table 2 - Production planning and control-as-imagined x Production planning and control-as-done

Production planning and control-as-imagined	**Production planning and control-as-done**
The precondition categories for a construction task are independent on each other	The preconditions categories for a construction task depend on each other
The process of removing the constraints is simple	The process of removing the constraints is complex
There is a formal workable backlog	There is not a formal workable backlog
Constraints are identified by looking for upcoming work packages	Constraints are identified by looking for upcoming groups of work packages
All constraints are formally identified and removed	Some constraints are informally identified and removed – i.e., these constraints are not anticipated and documented in the planning meetings
All constraints are removed before starting the work package	Some constraints are removed while the execution of the work-package is in-progress

In the original version of the LPS, the precondition categories for a construction task are typically approached independently. However, this study indicates they are highly interdependent, which facilitates variability propagation. The failure to remove one constraint can affect the removal of other constraints for the same work package as occurred in work package B.

Furthermore, in the LPS as-imagined, the processes for removing constraints are not discussed in depth, which suggests that they are tacitly considered as simple. In this study, the large number of functions required to remove constraints (19 for a single work package), combined with the interdependencies and variabilities, suggests that this process is complex. In turn, in the LPS as prescribed by Ballard and Howell (1998), there must be a formal workable backlog, while in the case study, there was not. A workable backlog consists of a set of work packages that have their constraints removed (Ballard, 2000). The lack of that backlog made room for problems such as the scheduling of work packages that still had constraints. On the other hand, if the said workable backlog was in place the number of functions for the removal of constraints would be even larger, demanding even more planning effort from managers. This may partly explain why the workable backlog was not planned.

Another example of the gap between as-imagined and as-done refers to the short-term planning meetings, in which professionals quickly scanned the list of constraints in the look-ahead tool and identified those groups of activities that had no pending constraints – this is in contrast to the as-imagined approach of analyzing constraints for each individual work package. Furthermore, some of the work packages scheduled at the short-term meetings had no parallel with those discussed during look-ahead planning meetings – this means that the removal of their associated constraints, if occurred, was mostly informal.

However, identifying constraints by looking at groups of activities has two implications. The first one is that some specific constraints for a specific work package can be overlooked. For example, if in a group of activities called “doors”, there is a door with a different specification (e.g. a door with a special lock), this can be neglected during the material purchasing managerial function. The other implication is that the total number of constraints may appear to be lower than it is, concealing the time and effort required for their removal. On the other hand, the practice of identifying constraints by looking at groups of activities saves effort as some constraints are associated with more than one work package. Consequently, removing these constraints could result in more than one made-ready work packages. For example, a single managerial function can be performed to provide equipment for several work packages, e.g. a scissor lift can be used for various activities related to the installation of electrical, air conditioning, and fire protection systems.

In addition, there is a difference related to the timing at which the constraints are removed. Different from the original version of the LPS, in which all constraints are removed before the execution of the work package (supporting the creation of a formal workable backlog and related activities), in this study, some constraints were removed while the work package was in-progress.

CONCLUSIONS

This paper discusses the results of a case study aimed at analyzing the gap between the production planning and control-as-imagined and the production planning and control-as-done. In this investigation, the FRAM was used to model the production planning and control-as-done and to analyze the variability propagation throughout the look-ahead managerial functions. The results suggest differences between what is prescribed by the original version of the LPS and how it was applied in practice in the case study, focusing specifically on the look-ahead level. One of the limitations of this study is the fact that it is based on a single case study. Therefore, the results cannot be generalized. Further studies are required to understand if the gaps identified in this study are recurrent on other construction projects and if they reflect fundamental limitations and under specification in the theory of LPS.

REFERENCES

Ballard, G. (2000). "The last planner system of production control." *PhD Diss*., Faculty of Engineering., University of Birminghan., Birmingham, United Kingdom.

Ballard, G., and Howell, G. A. (1998). "Shielding production: essential step in production control." *Journal of Construction Engineering and Management*., 124(1) 11-17.

Ballard, G., and Howell, G. A. (2003). "An update on last planner." In: Proc. 11th Ann. Conf. of the Int´l. Group for Lean Construction, Blacksburg, United States.

Ballard, G., and Tommelein, I. D. (2012). "Lean management methods for complex projects." *Engineering Project Organization Journal*., 2(1-2) 85-96.

Bertelsen, S. (2003). "Construction as a Complex System." In: Proc. 11th Ann. Conf. of the Int´l. Group for Lean Construction, Blacksburg, United States.

Branski, R., Aurellano, R., and Lima Junior, O. (2010). Metodologia de estudo de caso aplicada à logística. In: Congresso de Pesquisa e Ensino em Transportes, 24., 2010, Salvador. Anais... Salvador, 2010.

Castillo, T., Alarcón, L. F., and Salvatierra, J. L. (2018). "Effects of last planner system practices on social networks and the performance of construction projects." *Journal of Construction Engineering and Management*., 144(3).

Dekker, S., Bergström, J., Amer-Wåhlin, I., and Cilliers P. (2013). "Complicated, complex, and compliant: best practice in obstetrics." *Cognition, Technology and Work*., 15(2) 189–195.

Formoso, C.T., Bølviken, T., Rooke, J., and Koskela, L. (2015). "A Conceptual Framework for the Prescriptive Causal Analysis of Construction Waste." In: Proc. 23th Ann. Conf. of the Int´l. Group for Lean Construction, Perth, Australia.

Hamzeh, F., Ballard, G., and Tommelein, I. D. (2012). "Rethinking Lookahead Planning to Optimize Construction Workflow". *Lean Construction Journal*., 15-34.

Hollnagel, E. (2004). "Barriers and Accident Prevention". Ashgate Publishing., Aldershot, United Kingdom.

Hollnagel, E. (2012). "FRAM, the functional resonance analysis method: modelling complex socio-technical systems. Ashgate.

Hollnagel, E. (2015). "Why is work-as-imagined different from work-as-done?" In: Resilient Health Care: The resilience of everyday clinical work. Ashgate, 249-264.

Hopp, W. J., and Spearman, M. L. (2000). "Factory physics." McGraw-Hill., New York.

Koskela, L. (2000). "An exploration towards a production theory and its application construction." *PhD Diss.,* University of Technology., Espoo, Finland.

Koskela, L., and Howell, G. A. (2002). "The underlying theory of project management is obsolete." In: Proc. Of the PMI research conference., Seattle, Washington, United States.

Perkins, L. N., Abdimomunova, L., Valerdi, R., Shields, T., and Nightingale, D. (2010). "Insights from enterprise assessment: How to analyze LESAT results for enterprise transformation." *Information Knowledge Systems Management*., 9(3-4), 153-174.

Patriarca, R., Falegnami, A., Costantino, F., Di Gravio, G., De Nicola, A., & Villani, M. L. (2021). WAx: An integrated conceptual framework for the analysis of cyber-socio-technical systems. Safety science, 136, 105142.

Peñaloza, G. A., Saurin, T. A., & Formoso, C. T. (2020). Monitoring complexity and resilience in construction projects: The contribution of safety performance measurement systems. Applied ergonomics, 82, 102978.

Soliman, M., and Saurin, T. A. (2020). "Lean-as-imagined differs from lean-as-done: the influence of complexity." Production Planning & Control., 1-18.

Tommelein, I. D., and Ballard, G. (1997). "Look-ahead planning: screening and pulling." University of California, Berkeley, California, United States.

Dahlberg T.Ø. and Drevland F.(2021). "Preventing the Parade of Delays in Takt Production." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 777–786, doi.org/10.24928/2021/0175, online at iglc.net.

PREVENTING THE PARADE OF DELAYS IN TAKT PRODUCTION

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ABSTRACT

In recent years, takt has become an increasingly more common method to structure work in construction projects. Because of the tight coupling of activities in takt, ensuring that activities are done on time is crucial. The literature stresses having good takt plans and discusses how to react to delays in the takt production. However, there exists little literature about how site management can work proactively during takt execution to prevent delays.

This paper presents a case study of Consto – a major construction company in Norway – and their experience working proactively to prevent takt production delays. The paper identifies several causes for delays experienced in the company and several approaches used in the case company to prevent them.

We found that if delays were not prevented, they tended to propagate and compound through the production system, leading to a parade of delays. Furthermore, working proactively to prevent delays is contingent on having a high degree of buy-in and commitment from all trades participating in the takt. A key to achieving this was to involve all the trades in the takt planning process actively.

KEYWORDS

Lean construction, takt, production planning and control.

INTRODUCTION

In recent years, takt has become an increasingly common method in construction projects. Takt is a method to structure work on site (Frandson et al. 2013). The method entails dividing the building into takt areas with approximately the same amount of work and then let a trade work undisturbed by others in each area. All trades are given the same amount of time in all areas – the takt time – before they hand over the area to the following trade. The implementation of takt planning in construction is often visualized as a train with connected cars moving through the takt areas (Haghsheno et al. 2016; Haugen et al. 2020). The cars contain a production unit – e.g. a trade – working in the takt area undisturbed by other participants. Takt relies on a close coupling between the trades. Time buffers between the trades are typically minimized. It is, therefore, crucial for a trade to finish their area in time to not cause further delays for the following trades.

Tommelein et al. (1999) present the Parade of Trades game to illustrate the impact workflow variability has on trades at construction sites. The trades are sequentially

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dependent. Thus, an unreliable workflow will result in work stations – i.e. train cars in takt – being unable to realize their full production capacity and therefore lead to waste. As we show in this paper, not properly ensuring a reliable flow in takt production will result in a parade of delays – as in Location-Based Management System (LBMS) is referred to as cascading delays (Seppänen 2009).

The literature underlines the importance of the takt planning process to make a robust takt plan to prevent production delays (Frandson et al. 2014). However, Haghsheno et al. (2016) claim that the takt plan is not a fixed document, but a plan developed throughout the project. Binninger et al. (2017) suggest adjustment mechanisms to deal with the disruption in the takt plan's execution. Common for all their suggested adjustment mechanisms is that they are implemented after a delay already has occurred in the plan. There is a dearth of information in the literature about how delays can be prevented, after the takt plan is made.

The purpose of this paper is to look at how managers on site can prevent delays proactively in executing the takt. To do so, we present a case study of a major construction company in Norway, Consto. The paper starts by presenting the theoretical background for the paper. After that, we outline the methodology for the case study. In the result section, we present causes for delays in takt identified in the case study and the different approaches used in the case company to avoid these delays. The discussion section considers the overall implications of our findings. Finally, we present the paper's conclusion and suggest further work.

THEORETICAL BACKGROUND

There are various approaches to takt production. However, according to Frandson et al. (2013), all takt planning procedures have in common that they evolve a rough production plan into an increasingly detailed and finalized production schedule throughout the iterations. The literature refers to two major approaches – *takt time planning* (TTP) and *takt planning and takt control* (TPTC) (Lehtovaara et al. 2020). The two approaches have much in common. They differ in how takt areas are defined and the degree of trade involvement in the planning process. TTP areas are formulated by finding the smallest repetitive sections of the operation, while TPTC areas are formulated by finding similar work densities. TTP emphasizes trade participation in the overall decision-making phase, while TPTC prioritizes the client's desires as a key planning criterion and prefers predetermined and streamlined control behaviour.

In TPTC, the takt production is controlled through daily takt meetings (Haghsheno et al. 2016). The frequent handovers in the production allow accurate and short-cycled control of individual work; deviations from the plan will disturb the takt and be visible at the handover. This fact makes it possible to react to the disruption at an early stage. However, not all changes to the plan are deviations. A takt plan is not a fixed schedule but rather an execution plan evolving throughout the project. Binninger et al. (2017) propose adjustment mechanisms to absorb disruptions or changes in framework conditions. The long-term goal is to reduce the need for adjustments by continuous learning and better predictions in the takt planning.

One of (Binninger et al. 2017)'s adjustment mechanisms is train stoppage. Train stoppage means that every car stops their work until the reason for the delay is dealt with. This mechanism follows the Jidoka principle from Toyota Production System, also called autonomation (Womack and Jones 2003).

The literature suggests that takt can be combined with the use of the Last Planner System to improve production control (Binninger et al. 2017; Frandson et al. 2014; Kalsaas et al. 2015; Schöttle and Nesensohn 2019; Seppanen et al. 2010). The Last Planner System (LPS) is a staple of production planning and control within Lean Construction. LPS increases plan reliability by identifying what work *should* be done and ensures that it *can* and *will* be done (Ballard 2000). Schöttle and Nesensohn (2019) stress using LPS in all phases of construction to achieve production flow. They argue that it is critical to design a production system that spans from design till handover to the client for a project to succeed.

An important mechanism of LPS is that the people doing the work are involved in planning the work to ensure that plans are feasible in production. Another mechanism is the lookahead process. It makes upcoming work ready for production by analyzing constraints and removing them. Additionally, the system aims to match the workload and capacity within the production system.

Related to takt, Location Based Manager System (LBMS) is another method to structure work on site by dividing the building into work areas (Frandson et al. 2015). In contradiction to takt, LBMS allows trades to keep a steady crew size in production by adjusting the time used in each area to match the labor. A control mechanism in LBMS is to track production in every area and compare it with the planned production using flowline diagrams. By assuming that the current production continues, LBMS forecasts if the area will be finished in time or if measures are needed to increase productivity. Also, compared to takt, LBMS uses more time buffers to reduce the risk of deviations and to prevent cascading delays in production.

According to Seppänen (Seppänen 2009), cascading delays are chains of dependent problems that occur in production. Cascading delays are caused by resource delays, working out-of-sequence, and space congestion due to several trades working in the same areas. In LBMS, cascading delays affect the workflow on site. However, does it not tend to delay the overall schedule of the project due to buffers implemented.

Seppanen et al. (2010) proposed that cascading delay chains should decrease by combining LBMS with LPS. They found that LPS mechanisms as weekly plans and lookahead schedules complemented LBMS's control mechanisms by giving early warnings of potential, upcoming disruption to the production.

Regarding dealing with delays in takt, the literature mainly describes mechanisms that are retroactive. One notable exception is the use of LPS. The literature suggests LPS can complement takt production with proactive control mechanisms (Frandson et al., 2014). However, while the literature on LBMS describes the benefits of mechanisms such weekly meetings and lookahead planning, the takt literature contains few details on how the LPS proactively helps to maintain production in takt. Nor does the literature consider cascading delay chains in takt and how they affect the takt production.

METHODOLOGY

This paper is based on a case study of the Norwegian contractor Consto. The Consto group consists of 15 regional companies and operates nationwide. Their first experience with takt was building the A-wing at the University Hospital of North Norway in Tromsø – a complex project that started in 2015 and finished in 2018. Since 2015, they have used takt in several projects across the country, and they have developed their own strategy and procedures to plan and execute takt production.

To investigate Consto's practices and experiences, we interviewed seven informants with key roles, such as project managers, site superintendents, and foremen. Consto suggested informants with experience using takt. The informants came from different companies under the Consto umbrella. They had between them experience from ten unique project organizations using takt on a hospital, an airport project, and several apartment buildings and schools. All project examples used design-build contracts, with Consto responsible for the design phase as well as execution. In some of the projects, all the trades were sub-contracted. However, in most projects, Consto had their own trades crews for either carpentering or concrete or both. We used semi-structured interviews lasting between 45 minutes and two hours. These contained questions to reveal challenges in takt production and how they work to overcome, prevent, and learn from them.

We analyzed the interviews using a thematic coding approach per Robson and McCartan (2016). All interviews were transcribed, and the informants' statements were tagged with codes that identified what topic or theme. Some of the codes were predefined based on preliminary studies; however, the majority rose from the gathered data. After that, we grouped related codes into major themes before we placed all the themes into two main categories: causes for delays and elements for preventing these delays.

Also, we did a limited document analysis on internal brochures and presentations on the topic of Consto's planning and control approach, *Involverende Bygging i Consto* (Eng: Involving Construction in Consto). The purpose of the document analysis was to investigate Consto's building strategy and internal guidelines on implementing takt.

RESULTS

This section presents the findings from the case study. The interviews were the primary source for these. Unless explicitly noted in the text, all the presented results stem from these. We have divided the findings into two categories: causes for delays and elements for preventing these delays.

CAUSES FOR DELAYS

Deliveries and logistics

According to the informants, one of the main reasons for delays in takt productions is late deliveries to the building site. Delay of delivery of materials, equipment, tools and other requirements prevent cars from completing their work in the takt area before the handover to the next car. The missing delivery or unfinished work will often affect the next car directly. However, sometimes the effect of the delay appears only later in the production.

Delayed deliveries can result from unexpected conditions such as bad weather, incidents or even a pandemic. However, in many cases, the reason for deliveries being late is that they are ordered too late. Trade contractors tend to postpone orders to maintain the opportunity to add on more materials or equipment to save shipping cost. Instead of making the orders as soon as possible, the participants postpone the orders as much as possible. It turns out that it is hard to evaluate when the last deadline for ordering is, and, in some cases, the contractors outright forget to make orders because of this waiting tactic.

On the other hand, too early deliveries to the building site are also reasons for delays in the takt production. Materials or equipment stored at the site takes up space and need resources such as workers, time, and planning. Using the takt areas as storage space inhibits the production directly, while using transport areas such as hallways or stairs slows down the logistic. An informant expressed that a significant challenge in takt is to handle the areas that are combined takt and transport areas to prevent the previously mentioned scenario. Also, dedicated storage areas slow down logistics due to deliveries needing more transfers than if delivered directly to the work area.

Errors

Building errors is another reason for delays in takt production. Errors require rework and tearing down the existing product, often leading to damage to trades' finished work in the takt area. Such occurrences cause a chain of correction work that affects the progress in the takt area.

Interestingly, many informants did not consider building errors to delay the takt because the correction work was handled outside or parallel to the takt production. However, later in the interviews, all informants admitted to correction work often tended to cause delays later in production. We found that congestion of correction work shortly before the planned completion of a takt area was often the reason for not completing the area on time.

Incorrect estimation

From the analysis, we discovered that if the input to the takt planning work is incorrect, it can lead cars working too slowly related to the plan and not finishing with the work in a takt area on time. Underestimated amount of work or areas not adequately sorted cold be causes for the delays. For example, floor plans are often used as the primary documents while planning the takt. Variables like room height can easily be forgotten in the process and cause more work or need for equipment – such as lifts – to complete the area.

According to one informant, overestimating efficiency was a cause for working too slow according to the project's plan. However, this is not a common problem, and other informants said that efficiency is often higher than expected in takt due to the high degree of repetition in work.

Available staffing and crew

We found that a lack of workers can be a reason for cars not being completed in time. The informants mentioned the constant need for more labor in the Norwegian construction industry as a cause for short-staffing in takt production periods. There is also a challenge with temporary labor replacing workers drilled in the cars' repetitive work. Sometimes, one worker needs two temp workers as a replacement, not because the temp workers are not qualified, but because the takt train's efficiency is tied to repetition.

An additional reason for a lack of workers is illness or injuries. Especially crucial for cars with small contractors and few workers. For example, if a car contains only one worker who gets an injury that makes it impossible for them to keep working the next takt time, the risk of not completing the takt area is high. As mentioned, it is not easy to find a replacement on short notice, and if one manages, it can be hard keeping up the required efficiency.

Communication and key roles

We found internal communication problems to be an underlying cause for delays. The main problem is replacing key roles and staff between the takt planning process and the start of the takt production, or later in the production itself. The informants emphasized that the takt planning process is more than just the end-product, the takt plan. The planning process is where all the takt production trades anchor the main goals and notions of collaborating. Being part of the process is vital for feeling ownership of the project and committing to the takt plan.

It is not easy to make people have ownership and commitment to the takt plan without involving them in the takt planning process. The informants claimed that this is why it is crucial to involve the right people from every trade in the takt planning process. The people in the planning process need to have a sufficient understanding of how the work is done and, at the same time, be able to plan. For example, when a trade representative is a manager with little or no attachment to the workers who will do the work. They often fail to consider essential parts of the work in the planning, and then they fail to communicate the importance of the plan to the workers. The result is the workers and crew leaders on the construction site lacking ownership and commitment.

PREVENTING DELAYS

In the case study, we found several different approaches to prevent takt production delays. A similarity between all approaches is that they all benefit from a high degree of involvement from the trades with the takt planning and in the production phase. All the informants agreed that making disruptions, abnormal production, or uncertainties visible as soon as possible is crucial for preventing delays in takt. In the following, we will present the main strategies identified for preventing takt delays.

Weekly meetings

Some informants acknowledged that weekly meetings with all takt production trades were a key tool to prevent delays. The meetings included a status update from all trades and a lookahead planning discussion for the next three weeks focusing on the first one. Some informants recommended doing the meeting halfway through the one-week takt time so that the trades had time to discover potential delays and at the same time had sufficient time to do measures before the handover of the takt area.

The projects used several measures to correct issues identified in the weekly meetings. For example, some to ensure sufficient capacity, levelling up the work crew with more power to increase productivity and assigning overtime work. Other to find solutions to deal with obstacles such as late deliveries. Here, the typical approach was to get together all the relevant actors – e.g. trades and suppliers – and develop a plan of action to ensure minimal impact on the takt plan.

On the other hand, some informants reported having challenges with the weekly meetings. They had experienced trades showing up unprepared to clarify the status on site and look ahead to the following weeks. In some cases, the trades were described as too positive regarding their production halfway through the takt time and would not report potential delays in the meetings. The trades gambled on production speed increasing in the second half of the takt time without doing any measures, which often led to delays. Another concern was that the weekly meetings alone could not handle all challenges at a dynamic construction site. There is a need for more frequent meetings to distribute information and involve the trades. Many of the project organizations interviewed in this study claimed that Daily Huddle is a tool to meet these needs.

Daily Huddle

Many of the informants mentioned Daily Huddles as a significant tool to handle the day-to-day obstacles on site. They described Daily Huddles as a 15-minute meetings series taking place every morning out on the site. All participants on site, inside and outside the takt production, are represented. The Daily Huddle is a tool to distribute and gather information such as upcoming deliveries or production disruptions. In this way, solutions, especially to logistics challenges on site, can be solved effectively immediately after the challenge becomes visible, instead of waiting for the weekly meeting.

We found that some project organizations used Daily Huddle in combination with the weekly meetings. In contrast, others had gone over to relying solely on Daily Huddle as the production control and involvement mechanism. The projects that used only Daily Huddle saw no need for further involvement from the trades. Prioritizing the Daily Huddle led to increased benefits from them. The key was to involve the right roles with a good overview of the whole construction process and decision-making mandate in these meetings.

Consto's crew leader for carpentry typically led the Daily Huddle in projects that used both meeting series types. On the other hand, in projects using only Daily Huddle, the site superintendent led the meetings. By involving key roles such as the site superintendent and, in some cases, even the project manager in the Daily Huddle, chains of commands shortened, information flow increased, and the time from a challenge becoming visible to it being solved was reduced.

Prioritizing the time after the meeting, and solving the identified issues right away, was vital to benefit from the Daily Huddles. For example, in one project, nobody in the project organization was allowed to schedule appointments until one hour after the Daily Huddle. This rule ensured that they had the time to deal with potential needs that occurred in the meeting.

Planning phase

Another finding is that a well-structured handover process from design to execution can help prevent delays in the takt production. Some of the project organizations had used a meeting series called the 16-12-8-4-1 meeting series for this purpose. This series is parallel to the takt planning process. The main goal is to ensure that the design's detail level is sufficient and that the preconditions for construction are adequate.

The internal document *Involverende Bygging i Consto* states that the 16-12-8-4-1 series consists of five meetings 16, 12, 8, 4, and 1 weeks before the takt production starts. The first and the second meetings included the design team and the main contractor Consto. In the third meeting, eight weeks before the takt start, the design team hands over the drawings to the main contractor and sub-contractors. The last two meetings of the series focus on ensuring that the drawings are sufficiently detailed for construction. The last meeting of the series also ensures that all constraints for starting the takt have been removed.

All the informants in the study emphasized that the key to a smooth takt production is to ensure every participant feels ownership and commitment to the takt plan and that they are working towards the same overall goal. This ownership feeling and commitment can be created in the takt planning by involving the trades in the process. We found that it is essential to spend enough time on the takt planning so that crucial issues in the takt production are identified and solved. According to the informants, the project organization should strive to guarantee that the people who will actually do the takt production – i.e. crew leaders – are involved in the planning.

Often, Consto, as the main contractor, will be significantly more experienced and knowledgeable about planning than the sub-contractors. According to the informants, it can then be a good idea for them to help the trades in their planning. Some informants revealed that they sometimes had sat down with single trades and, for example, made very detailed logistic plans to maintain site workflow.

To prevent delays related to deliveries, we found it beneficial to ensure orders are placed before the takt production starts. With takt, every trade knows what and where to produce when and can easily convert the takt plan into a delivery plan. Some informants said that fewer delivery related problems occurred when they had made sure that the trades in the takt had made their orders before the production started. They also said that any changes to the deliveries after order placement, was often no problem for the supplier as long they were made in sufficient time before the delivery. Also, with occurrences of delays, they had experienced few issues related to postponing deliveries from the supplier.

DISCUSSION

CAUSES FOR DELAYS

The causes for delays found in this paper are arguably not only related to takt production but construction in general. They align with earlier findings in the literature, especially, findings related to delays in LBMS. There are many similarities between the two work structuring methods – takt production and LBMS. Therefore, it is not surprising that the methods face similar challenges to maintain production. However, a unique factor for takt production is the tight coupling between activities and little or no time buffers to absorb variability. Therefore, we would argue takt is the more fragile production system of the two, with less room to implement necessary measures to prevent delays before handovers between trades, leading to unfinished takt areas being handed over.

According to our findings, handing over unfinished takt areas tends to lead to more delays later because of irrational work sequences and correctional work – i.e., it leads to what we would call a *parade of delays.* The parade of delays is similar to Seppänen's cascading delay chains in LBMS. However, a parade of delays in takt production is more likely to affect the overall delay in the project due to the differences between the work structuring methods previously discussed. Once a delay has occurred in takt production, it requires taking measures straight away to not delay the overall schedule in the project. For example, the literature points to train stoppage as a solution to prevent these handovers of unfinished takt areas. However, train stoppage cannot fully prevent a parade of delays. A train stoppage will cause an overall delay. It delays the takt plan one takt period, a delay which will not be made up without other measures.

Both cascading delays and the parade of delays relates to the principle of jidoka, in the sense of not letting a deficient product pass through the production line – it causes more waste than just fixing the problem straight away. Therefore, it is crucial to strive to prevent delays instead of reacting to them when they occur.

PREVENTING DELAYS

The literature suggests that the key to flow in production is to design a production system that spans from the design phase to the handover to the client. The 16-12-8-4-1 meeting series aims to deal with the transition between the design and production phases by gradually involving the trades in production. This gradual transition helps the trades familiarize themselves with the design and quality assure it, making production plans – e.g. the takt plan – more reliably. In particular, the meeting series can help prevent delays such as building errors and incorrect estimation.

Planning the logistic on site is key to keeping the flow in the takt production. The takt plan makes it easier to make visible where the different trades will be working at specific times but need to be complemented by additional planning of non-value creating activities such as transportation of materials and supplies. From the case study, one of the most challenging parts of logistics was handling takt areas that are also transport areas such as hallways and stairs. The challenge was to maintain progress in the area and, at the same time, not cut the supply to other takt areas. A key idea of takt is to let every car work undisrupted in the takt area. Any transport through the area will interfere with this. While transport through production areas is a well-known challenge in construction, it has been poorly covered in previous studies on takt and is an area that warrants more research.

The control work of the takt production through Weekly Meetings and Daily Huddles harmonizes well with the Last Planner System's mechanisms. Our findings are in concurrence with previous studies. Weekly Meetings and Daily Huddles are effective tools in combination with takt production. We found that the Daily Huddle is a tool that can deal with disruptions at a very early stage and solve the day-to-day challenges at the site. Our findings underline that it is crucial to involve people with the necessary overview and mandate to make the Daily Huddle effective. Setting aside time for key roles – such as the site supervisor – to deal with minor issues every day can be time-saving in the long run because it prevents parades of delays. Prioritizing the Daily Huddle made the Weekly Meetings superfluous.

A finding in this paper is that the necessary commitment and ownership in the project for the trades can be created through the takt planning process. However, doing so requires the trades to be involved in the process. Among the approaches described in the literature, TTP will serve this purpose better than TPTC.

CONCLUSION AND FURTHER RESEARCH

The purpose of this paper was to look at how managers on site can prevent delays proactively in executing the takt. To achieve this purpose, we conducted a case study of Consto - a major Norwegian contractor.

This paper confirms findings from previous studies that the key to smooth takt production is the takt planning process. The takt planning process is where the takt production participants build ownership and commitment. A good process is crucial for establishing good communication in the execution phase. Good communication enables detecting and dealing with potential issues before they cause takt delays. Also, the handover from design to production is essential to prevent delays. The 16-12-8-4-1 meeting series is an effective tool for quality assuring the design and making the trades familiar with it.

The consequences of a parade of delays in takt production can be significant. Instead of reacting to delays, delays should be prevented. Even with a healthy takt planning process, we found frequent trade involvement throughout the execution phase necessary to prevent delays. Daily Huddles and Weekly Meetings are tools that improve information distribution, logistics and ensure all preconditions are met for carrying out the takt production on site. We found that it is crucial to involve people who have an overview perspective of the project and decision-making mandate to make these meetings effective. It is also beneficial to set aside enough time after these meetings to solve any needs or issues brought up.

This paper has identified several causes for delays in takt, and approaches for preventing them. Having used a qualitative case study strategy, we have no quantitative data on how often these delays occur or how effective the various approaches prevent these delays. Based on this paper's limitations, more research is needed on how to prevent takt production delays effectively. We suggest further investigation to measure the effect the Weekly Meetings and Daily Huddles have on preventing delays in takt production.

We have in this paper looked at only one Norwegian contractor. Other proactive measures by management on site in other companies should be identified. Also, there is a need to investigate if the delay causes and the prevention approaches are culturally dependent.

REFERENCES

Ballard, G. (2000). “The Last Planner System of Production Control.” The University of Birmingham, UK.

Binninger, M., Dlouhy, J., Steuer, D., and Haghsheno, S. (2017). “Adjustment Mechanisms for Demandoriented Optimisation in Takt Planning and Takt Control.” *25th Ann. Conf. of the IGLC*, Heraklion, Greece, 613–620.

Frandson, A., Berghede, K., and Tommelein, I. D. (2013). “Takt Time Planning for Construction of Exterior Cladding.” *21th Ann. Conf. of the IGLC*, Fortaleza, Brazil, 527–536.

Frandson, A., Berghede, K., and Tommelein, I. D. (2014). “Takt-Time Planning and the Last Planner.” *22nd Ann. Conf. of the IGLC*, Oslo, Norway, 571–580.

Frandson, A. G., Seppänen, O., and Tommelein, I. D. (2015). “Comparison Between Location Based Management and Takt Time Planning.” *23rd Ann. Conf. of the IGLC*, Perth, Australia, 3–12.

Haghsheno, S., Binninger, M., Dlouhy, J., and Sterlike, S. (2016). “History and Theoretical Foundations of Takt Planning and Takt Control.” *24th Ann. Conf. of the IGLC*, Boston, Massachusetts, USA, 53–62.

Haugen, C. G., Lædre, O., and Aslesen, S. (2020). “Takt Performance Indicators.” *28th Ann. Conf. of the IGLC*, Berkeley, California, USA, 457–468.

Kalsaas, B. T., Skaar, J., and Thorstensen, R. T. (2015). “Pull vs. Push in Construction Work Informed by Last Planner.” *23rd Ann. Conf. of the IGLC*, Perth, Australia, 103–112.

Lehtovaara, J., Seppänen, O., Peltokorpi, A., Kujansuu, P., and Grönvall, M. (2020). “How takt production contributes to construction production flow: a theoretical model.” *Construction Management and Economics*, Routledge, 39(1), 73–95.

Robson, C., and McCartan, K. (2016). *Real World Research*. Wiley, Hoboken.

Schöttle, A., and Nesensohn, C. (2019). “The Beauty of a Phase-Overlapping Last Planner System® With Incorporated Takt.” *27th Ann. Conf. of the IGLC*, Dublin, Ireland, 441–450.

Seppänen, O. (2009). “Empirical research on the success of production control in building construction projects.” Aalto University, Finland.

Seppanen, O., Ballard, G., and Pesonen, S. (2010). “The Combination of Last Planner System and Location-Based Management System.” *18th Ann. Conf. of the IGLC*, Haifa, Israel, 467–476.

Tommelein, I. D., R.Riley, D., and A.Howell, G. (1999). “Parade Game: Impact of Work Flow Variability on Trade Performance.” *Journal of Construction Engineering and Management*, 125(5), 304–310.

Womack, J. P., and Jones, D. T. (2003). *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. Free Press, New York.

Kortenko, S., Koskela, L., Tzortzopoulos, P. & Haghsheno, S. (2021). "Can Last Planner® System Help to Overcome the Negative Effects of Design-Bid-Build?" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 787–796, doi.org/10.24928/2021/0184, online at iglc.net.

CAN LAST PLANNER® SYSTEM HELP TO OVERCOME THE NEGATIVE EFFECTS OF DESIGN-BID-BUILD?

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ABSTRACT

The design-bid-build (DBB) procurement method has negative effects on construction projects. To find out whether those effects found in the literature appear in the field and to find ways to overcome them, nine interviews with practitioners from the architecture, engineering and construction industry have been conducted.

It was found that building a lean culture in the DBB projects and/or setting up a management system that acknowledges lean ideals can help to overcome the negative effects of DBB. Using compatibility assessments of teams and "add-ons" to the standard contracts such as FAC-1 (Framework Alliance Contract) or Construction Manager at Risk were also mentioned as ways to overcome the problems existing in DBB environment.

It was found from the interviews that Last Planner® System supports tackling the existing problems of DBB in number of ways. It enables building lean culture in the DBB projects through improving communication, visualization, transparency and collaboration, building trust, enhancing mood and relationships, as well as overcoming claim culture. It does help to minimize the negative effects of the DBB procurement method on construction projects.

KEYWORDS

Last Planner® System, design-bid-build, cost-led procurement, collaboration, action research.

INTRODUCTION

Kortenko et al. (2020) divided the direct and indirect negative effects of design-bid-build (DBB) procurement method on construction projects into two groups, "flow interruptions"

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and “low margins”. The underlying question motivating that research was whether Last Planner System (LPS) could help to fix those DBB problems.

The ability of LPS to mitigate DBB problems is not fully understood; the applicability of LPS in the DBB context has even been questioned. Matthews & Howell (2005) see DBB as a constraint to the implementation of the Lean Project Delivery System. Dos Santos & Tokede (2016) find that LPS may not be applicable to DBB. To gain deeper understanding in that area, interviews with nine practitioners from the architecture, engineering and construction (AEC) industry have been conducted. Main topics discussed were DBB and its effects on construction industry; the means of improving DBB projects; scheduling/planning; LPS in DBB environment and its ability to tackle DBB problems. The aim of this interview study is to understand: *“Does LPS, if used in a DBB project, help to tackle the negative effects of the DBB environment?”*

METHOD

When the nature of a phenomenon is not completely understood, Meredith (1998) suggests that answering questions of ‘why’ (understanding) around the topic is needed, instead of ‘what’ (identification) and ‘how’ (explanation). Interviews enable the researcher to explore unique participants’ experiences (Meredith 1998) and to understand the meanings that they assign to various phenomena (Cooper & Schindler 2008). To answer the research question, nine exploratory interviews with practitioners from the AEC industry have been conducted between 9th and 20th of November 2020.

The interviewees were selected based on their overall experience in the AEC industry and their LPS experience. Each interviewee has both types of experience for 10 years or more. The aim was to cover different countries to avoid bias associated with local construction markets, their regulations and traditions. Therefore, interviews were conducted with practitioners from four counties: USA, UK, Germany, and Norway. Information about the interviewees is presented in Table 1.

Table 1: Interviewees: Party Represented and Current Position

Interviewee’s Code Number	Party that Interviewee Represents in the AEC Industry	Interviewee’s Position
1	General contractor	Development manager
2	General contractor	Director of lean construction
3	Client, General contractor	Lean construction consultant
4	Client, Designer, General contractor	Consultant
5	Client	Consultant
6	Client	Consultant
7	Academia	Professorial position
8	General contractor	Consultant
9	General contractor	Consultant

The interviewees were informed that their answers would be anonymized and used for academic purposes. They obtained a list with initial questions in advance. The planned length of the semi-structured interviews was 60-75 minutes, at the end it varied from 55 to 80 minutes, with one interview taking 125 minutes. All the interviews were organized and recorded via MS Teams. The recordings were transcribed verbatim. Only the research team has access to the recordings and transcripts. The transcripts were then categorized using MS Excel sheets.

The answers about the nature of DBB, its effects on construction industry and possible solutions to improve the DBB environment with lean thinking were then categorized into sub-topics, summarized and generalized. The preliminary findings from the manual analysis of these topics are presented below. Other topics discussed in the interviews are not included in this paper. Direct quotations are a basic source of raw data in qualitative research that reveals the informants' emotions, thoughts, experiences, and basic perceptions (Patton 2002). Direct quotations have been used to vividly transmit the respondents' views and opinions about using LPS in the DBB environment.

This study is a part of an ongoing PhD research. Action research (e.g., Iivari & Venable 2009) is used as the overall research strategy for this study.

LITERATURE REVIEW

Kortenko et al. (2020) grouped the direct and indirect negative effects of the DBB procurement method on construction projects into two categories, "flow interruptions" and "low margins". These are both consequences and contributors to the following problems: fragmentation of the industry, poor constructability, lack of responsibility for the whole project, hindrance of learning, securing own contract, transferring risk, claims, short-term goals, change orders, silo thinking, lack of improvements, uncooperative behavior, opportunistic behavior, and lack of trust (ibid.).

Possible solutions to overcome the shortcomings of traditional procurement through novel forms of contract and organization have been widely discussed. Heidemann & Gehbauer (2010) analyze advantages of the Integrated Form of Agreement in the USA and the Alliancing Agreement in Australia. Naoum (2003) describes positive impacts of Partnering on the UK construction projects. Cheng & Johnson (2016) discuss successful implementation of the Integrated Project Delivery (IPD) in the USA and Canada. Even using some of the IPD principles improves performance in construction projects (Jenkins et al. 2020). However, sometimes it is not possible to use other forms of procurement than DBB: there are legal, cultural, behavioural, technological and financial barriers against implementing multi-party agreements (Dargham et al. 2019).

FINDINGS

The main findings from the interviews can be divided into three categories. First, the negative effects that DBB has on construction projects. Second, the ways of overcoming these effects in the DBB environment. Third, how can LPS, being used in the DBB environment, help to address these effects.

NEGATIVE EFFECTS OF DBB

DBB, by definition, means a separation of designers and contractors contractually and in time, at least partially, and is usually based on "the lowest bid wins" mentality. The effects of these DBB "features," as viewed by the interviewees, are presented below.

Effects from the Contractual Separation

Contractual separation of the companies involved in the construction process leads to managing of each company's risks separately. When risks occur, companies tend to try to shift their risks to the third parties. *"Contractor is against designer, designer against* *owner, contractor against owner, and everyone against everyone... That leaves nobody out,"* as Interviewee 2 puts it. So, finally, all the companies in the construction project supply chain are pulled into a risk shifting mindset. Interviewees note that securing the contracts and shifting the risks are incentivized by DBB contracts. Interviewee 7 calls the relationships between an architect, an owner, and a contractor *"a triangle of hate."* Interviewee 6 argues that the companies cannot be blamed for this behavior *"because that's the way the contract is set up. It's a mess." "There is risk shifting instead of risk management,"* as Interviewee 3 formulates. Every company involved in the construction process prices its risks. As Interviewee 6 states, *"Risk is a commodity... People are trading risk in DBB."* The risk will manifest finally, but by that time the client will already have paid all the companies the contingencies that they have added to their contract prices to manage their risks. *"If risk was managed collectively, there would still be insurance, but there would be one insurance policy, not 27, 53 or how many the number of delegations that have been through this system is,"* Interviewee 5 explains. But that does not mean that somebody will deal with the problems occurred. At some point, according to Interviewee 5, *"Risk is delegated to the level, below which it cannot be managed."* If some company finally sees a risk, it is incentivized *"to throw up your hands and say, 'Not in contract, not in scope',"* Interviewee 2 states and continues, *"There's not even a requirement of when they need to tell you that they see a conflict in a field or in the documents. Typically, they just have to tell you if they notice it. Therefore, people tell you things are going wrong when it impacts them directly. But by then it's too late."*

Contractual separation of the companies also leads to them having different goals. Absence of a common goal and companies' focus on their own parts of the project leads to *"knowledge silos, meaning the borders, walls between different parties,"* as Interviewee 4 formulates. Not having a common goal, parties are optimizing their own parts due to the economic reasons. *"And all that they're worried about is their own piece of the puzzle. Often at the expense of neighboring pieces of the puzzle, they maybe make decisions that suboptimize their piece, but actually are detrimental to the project overall. So, I think that that mentality can extend very easily down through those chains,"* as Interviewee 7 describes it. Interviewee 1 agrees with that, *"You are more focused on your part and maybe lack the whole picture." "Every party has then its own monetary view on the construction project,"* Interviewee 4 states. Designers and contractors having different goals are set up for conflicts, Interviewee 3 gives an example of such a conflict, *"As a designer, you need to manage your risks. You try not to be that explicit in your drawings, so that there's flexibility of later adjustments. But for a general contractor or a construction manager, it's important to have detailed drawings to minimize cost risks."*

A shared understanding is often missing. This derives from the silos in which the parties are working and from a lack of the whole picture of the project. It creates conditions for rework. Interviewee 4 says that *"the emphasis on the own targets of the different parties involved might be more difficult to integrate in DBB projects as you have more parties, more interfaces than you have in collaborative or integrated approaches."* It also implies for a shared understanding of the interfaces, for example, between two trades on site. Interviewee 5 gives an example, *"Without a shared understanding the workers who are executing a particular task have no guarantee that their work will be accepted when it's done. Because they don't know what the next team in line is, what the designer or the client wants from them. Yes, they've got something written down in a specification, but have they interpreted that specification in the same way that it was written? It's no guarantee that they would have done that."*

When asked about the atmosphere in DBB projects, its culture, environment in which people interact, interviewees often mention words with negative connotations such as *"aggressive," "not pleasant," "untransparent," "not supporting," "not collaborative," "confrontational," "disrespectful," "protective," "not explicit."* Further, people tend to *"hide information"* and *"have hidden agenda."* Interviewee 7 describes project participants' behavior in DBB environment as *"self-preservation."* This self-preservation leads to poor transparency, hidden information and, again, to unforeseen problems in the processes. Interviewee 2 links this behavior with the legal pressure because companies know that *"lawsuits can entail, it makes people put the walls up and be very protective and keep information."*

Interviewees express their concerns about missing collaboration and poor communication in the DBB environment. As Interviewee 2 formulates, *"The word 'collaboration' never shows up in traditional DBB contracts, so why would people work together?"* As Interviewee 6 states, *"DBB contracts inhibit collaboration. They shouldn't, but they do."* Interviewee 3 agrees, *"There is a lot of waste in communication processes. It creates a certain tension in teams because everybody sees that the project isn't progressing that much or as it should, and everybody tries not being blamed for their work. So, they don't take risk, they don't share ideas. But instead, they try to shift work, shift risks to other participants and try to get their desk clean instead of solving the problem."* Another issue that comes into play is the way the schedules are prepared. When a contract is signed, a schedule is usually a part of the contract. These schedules are normally prepared without collaboration with the contractors. Once a contract is signed, it is asked, *"We have a plan, why do we need to get together?"* as Interviewee 6 explains.

Effects from the Separation in Time

The fact that designers and contractors are separated in time, at least partially, means that contractors cannot be involved in the design process. It leads to several problems.

General contractor representatives argue that the decisions made by designers early in the process influence the buildability and cost-effectiveness. If some decisions have been made already, it is more difficult for the contractors to bring their know-how to the process, to use optimization, prefabrication, to use their knowledge and technologies to possibly accelerate the construction. As Interviewee 2 puts it, *"The improvement in performance is not incentivized in the DBB contracts."*

Because of poor constructability, there is rework in design. It, again, leads to blaming other parties, change orders, additional costs, and delays because usually one must have some iterations in all the design stages again to change something. By that point of time, however, the designers normally do not have budget left to make these changes. Here, again, the conflicts between the designers and contractors appear. Contractors want the designers to change or improve the design, designers want the contractors to take care of the designs themselves or just tell them to follow the existing decisions. Interviewee 1 describes some projects in the US construction market, *"When it came to the detailed engineering part, my impression was that they had to do a lot of the detailed engineering once more, all over again because there were so many things they haven't thought of. And they lacked a feedback from the general contractor once he saw the drawings. And then they had to turn it all over and do it once more, a lot of it. That's counterproductive."*

Additional work coming from the errors in drawings or specifications are big issues for contractors because clients typically do not see these tasks as an additional scope. These discussions about the scope might be very time- and money-consuming.

Interviewee 1, a general contractor representative, estimates these discussions at tens of millions of euros for the company and adds that they *"need to go to court with some clients because of this"*. Interviewee 8, another general contractor representative, adds that *"you think about your own scope, you just want to do what is in your scope and nothing more, because if you do something more, you don't get paid for it"*. As Interviewee 2 states, *"You do the minimum that's required ... and you protect yourself."*

Effects from the "Lowest Bid Wins" Mentality

One of the ideas behind DBB is "the lowest bid wins". This, however, does not necessarily lead to minimizing the cost of the project. Interviewee 7 explains, *"People don't realize some of the problems that are created ... by the siloed system of DBB. So, that initial number might be really good. The final cost, the ultimate cost… is different."*

Interviewee 2 describes a situation when an owner changes a design team after an initial programming phase to create design documents with an idea to minimize project costs and argues that it disrupts the process and increases the number of interpretations of the documents, drawings, specifications, requirements, *"You can engage another set of people… to interpret those documents again. So, every time that they think they're doing things to save money, they are really just increasing their costs."*

Interviewee 2 adds that choosing a contractor based on the lowest price does not consider the past record of the company and its qualifications and thus is not ensuring the future quality of the product.

Many interviewees find that DBB is encouraging claim culture. There are economic reasons for it as the companies' margins are low. Interviewee 9 finds that *"DBB encourages contractors and trade partners to overlook any gaps in the design so that they can change order for it later. If they're putting attention to it now, it will just make their cost higher and lessen their chances of getting hired."*

HOW CAN THE NEGATIVE EFFECTS OF DBB BE OVERCOME?

The interviewees were asked about the countermeasures to the problems created by the DBB structure: "If the integrated forms of procurement, multi-party agreements cannot be used, how can the existing problems within the DBB projects be overcome?" To understand why these procurement methods are not being used in particular cases is not a part of this study. We want to understand what can be done to address the potential problems if the use of DBB in a particular project has already been decided.

First, the interviewees suggest building a lean culture in the projects. It can be arranged by an owner. Principles, under which an owner is managing a project, might then influence the whole supply chain. It is recommended to set up a management system that appreciates alignment of the project goals, visualization of the work, collaboration between the participants, and use of the pull systems when planning the work. Many interviewees refer to strong leaders who can build such a culture, even if they do not call it "lean". These leaders can be on all sides: clients, designers, contractors, consultants.

Second, even in the DBB environment it is possible to use behavior and compatibility assessments before nominating companies for the project. The goal here is to build a high-performance team that will work collaboratively. Workshops with potential designers and contractors might be arranged. Obviously, it is difficult to do that without willingness from a client side, and the lowest bid should not be the sole criteria.

Third, the interviewees mention alternatives or "add-ons" to the traditional DBB contracts that allow engaging the contractors in the design process earlier. These are Framework Alliance Contract (FAC-1) and Construction Manager at Risk (CMAR).

FAC-1 is a flexible meta-contractual model which regulates and manages the relations between different parties that are not directly associated over a contract (Di Giuda et al. 2020). In the CMAR delivery model, the owner still has separate contracts with construction manager and designer; construction manager is taking performance risk and responsibility by owning the trade contracts (Bilbo et al. 2014). Both models engage the contractors earlier in the design process.

From our point of view, LPS cannot help to overcome all the negative effects that DBB has on the construction environment, but it can help to create a project culture where some of these effects can be addressed and minimized. LPS enables and supports the first two suggested solutions to improve DBB environment and can be used with FAC-1 contract and CMAR procurement method. The interviewees support these ideas.

HOW DOES LPS SUPPORT BUILDING A LEAN CULTURE?

It is clear from the interviews that LPS helps to solve some of the DBB problems. But is it LPS itself that solves that problems? Interviewee 4 states, *"If you have a stable successful project, it doesn't matter, with lean or without lean. You will have a good atmosphere. And that's the only reason why people say, 'We had a great atmosphere.' No, you only had a great atmosphere because a project was running well, otherwise it would be the same as before."* Interviewee 9 agrees with that, *"It's not LPS itself that is influencing the atmosphere. LPS enables that to happen, but you could follow LPS and do really poor job. It's really the team leadership that matters. It can be a superintendent, it can be a project manager, it could even be one of the subcontractors, if they stand up, take the lead and say, 'Let's be intentional about this, let's behave this way,' that can foster that. But if you don't have anyone doing that, and if you don't have people focusing on reliable commitments, they're not focusing on the right conversations within LPS, then it won't matter."* Therefore, when we say further, "LPS improves…" or "LPS influences…", it means that using LPS enables that to happen, but to be successful, projects will still need strong leaders, dedicated teams, experienced clients.

LPS improves communication. *"It makes people talk,"* as Interviewee 2 puts it. LPS creates a forum where the information exchange takes place direct and efficiently. People are having conversations that would normally take them far more time, if they would have used phone calls, e-mails, or even direct face-to-face communication between two parties. Regardless of the contract, if people are given an opportunity to express in words and to put on a sheet of paper their thoughts that are visible to everybody involved in the process, it improves communication between these people. Interviewee 6 says, *"You're asking people for their input. You are not pushing your program on them. It just turns on in their head, especially people who are new to it because they've never been involved in anything like this. They've never been asked what they needed, what they wanted."*

Being together in the same physical space, where the LPS sessions take place, for example, a big room, creates transparency. Interviewee 1 explains, *"Being physically close to each other, sitting close to each other in the same office for some days a week, is the best solution. Because there are so many details in construction projects, there are so many clarifications you need. And also, it's easier to develop some sort of trust. When you see a person face-to-face, it is harder to make a promise you know you can't fulfil than when you give it on phone or by e-mail."*

The design and construction processes are being visualized by LPS. Visualization reduces complexity. It is beneficial for all the parties involved in the process to see what will happen next to them in that process. Pull planning and make-ready process create shared understanding and show a common goal, e. g. the next milestone in the process.

Interviewee 2 claims that *"the team changes the complexity of the project. Our plan depends on the contractors and their capability, experience, labor availability. There are so many factors."* It means that those involved in a construction project have to act as a team and acknowledge all its members. LPS does that through creating a plan with the very people who are working in a project. Interviewee 5 underlines the social processes behind the LPS, *"What I've been trying to do throughout is get people to understand that construction is a social process. We need to use really solid social processes, particularly the promise cycle to manage the way the work works. And we want you to be in a really sound position, when you're called on to make promises. We're not going to ask you to make promises until a week or so, maybe less, before the work is due to be done."*

When asked about their input, participants tend to feel involved in the planning process and are eager to contribute. LPS improves the reliability of the promises and thus helps to build trust between the participants. Interviewee 5 describes it, *"LPS provides levels of information that makes it easier to trust. The promise cycle is the basis for building trust." "It helps people build stronger relationships,"* Interviewee 9 explains and continues, *"It helps enhance, I guess, your feeling of relationship, friendship, bonding. And it influences how you are interacting in another meeting, how you are interacting in the field. You start actually care about each other. All that soft things that we never bother to pay attention to in construction."* Interviewee 4 adds, *"People are curious. People are interested, they want to know what this is, they want to learn and to explore it, they want to find out if that can also work for them."*

When asked about the atmosphere in the LPS sessions, interviewees use words with positive connotations: *"open," "transparent," "motivating," "positive," "energetic."* LPS also improves the mood of participants, builds a team. It comes with conversations, shared understanding, building trust, improved reliability, making commitments. Leaders should start behaving differently, the others will then be pulled into new collaborative environment. Interviewee 5 says, *"Managing moods is really important for leadership on projects. If the mood is right, then people are learning. If the mood is wrong, people stop learning."* Interviewee 3 describes this open and transparent environment, *"It's an atmosphere where everybody can speak about assumptions, risks, and ideas. Nobody needs to present perfect solutions. We're very fine with communicating the possibilities instead of solutions."* It means that risks are being discussed and managed collaboratively.

How does a good LPS session look like? For Interviewee 2, *"It should be noisy, people should be talking to each other, people should be told to shut up because they're getting too noisy… Those conversations are happening with a lot of activity. If you're in the back of the room filming it, you just see like a flurry of people moving to the board, away from the board, back, having side conversations, negotiating, changing information. It needs to be messy. I think the family dinner is probably the best analogy. If it's not going well, it's going to look like a library."* For Interviewee 5, *"The meetings need to be crisp, courteous and very much to the point. It's very easy to get lost in taking too much time over it, but it's about learning how to go through the process quite quickly."*

Interviewees find that LPS helps to overcome a claim culture in construction. People have an opportunity of raising hand and talking about the possible hindrances in advance. Moreover, during the pull planning process, the companies name their prerequisites, during the make-ready process they are removing constraints together. Interviewee 5 describes it, *"I do think that LPS discourages claim culture in that it gives the companies* *the chance to buy in to the plan. After they are bought in to it, if they've been a part of the creation of it, making claims against it now is almost to claim against yourself and your own involvement."* Interviewee 5 adds, *"LPS helps to overcome claim culture, because the documentation is really clear, and everyone's got access to the data. So, it should be a lot easier to keep the project on time which reduces the risk of a claim."* However, Interviewee 4 separates between claims due to hindrances which may decrease and claims due to design changes and process changes. The latter ones will not be influenced by LPS: *"How can you avoid them if the client wants to change something and she or he has the power to do so? But what you can do is you can mitigate design changes if you can manage to identify the customer value properly. And of course, LPS will not help you in that. Because LPS is a methodology for managing the schedule. Not for managing cost and not for managing the quality. Of course, if you have a proper schedule, you will have a passive impact on the cost and the passive effect on the quality, but not an active one."*

DISCUSSION

LPS does not solve all the negative effects created and supported by DBB because some of them are programmed, they are in the nature of DBB. LPS cannot tackle these attributes of DBB, but it helps to minimize some negative effects.

For instance, if FAC-1 (or a similar scheme) is not being used, designers and contractors will be separated contractually. Thus, the companies will still be managing their contracts and risks separately. However, LPS creates a forum where the common risks can be identified beforehand and therefore can be managed more efficiently. In phase pull planning and look-ahead planning, risks are being made visible and can be discussed between all the parties involved in a particular project phase.

Even if LPS is used in all stages of a project, the designers will still be separated from the contractors in time, if FAC-1 or CMAR are not being used. It means that the contractors will not bring their input into design decisions, therefore, a tension between the designers and contractors might still be there. However, during the look-ahead process in the construction phase, the input needed from the designers can be structured, scheduled and justified by the work sequence in the construction phase, which can support the flow in producing the drawings needed on the construction site.

Using LPS will also not ensure qualifications of the companies involved in the project delivery. However, LPS can help to reveal how a potential team will work together if used in separate workshops before nominating the contracts.

It is important to emphasize that LPS itself does not necessarily help to improve DBB project environment, but creates prerequisites for such an improvement. LPS can be seen as an enabler, as a tool that can help the leaders to create a collaborative culture and to organize their cooperation with the companies involved in a construction project. If used with traditional mindset, without understanding of lean ideals, LPS can become a cargo cult in hands of those believing that just having sticky notes on a board will help them to avoid the traditional project problems and bring them to a project success. It will not.

CONCLUSIONS

Nine interviews with LPS practitioners from the AEC industry have been conducted. The interviewees support the literature findings that DBB has negative effects on construction projects. The interviewees name several ways of improving DBB contracts, such as building a lean culture in a project and/or setting up a management system that acknowledges lean ideals, using assessments of the teams, using “add-ons” to the DBB contracts, such as FAC-1 or CMAR. LPS cannot help to overcome all the problems created by DBB, but it can support the ways of improving DBB suggested by the interviewees. LPS enables building lean culture in the DBB projects through improving communication, visualization, transparency, collaboration, building trust, enhancing mood and relationships, and overcoming claim culture. It therefore does help to minimize the negative effects of DBB procurement on construction projects.

REFERENCES

Bilbo, D., Bigelow, B., Escamilla, E. & Lockwood, C. (2014). “Comparison of Construction Manager at Risk and Integrated Project Delivery Performance on Healthcare Projects: A Comparative Case Study.” *Int. J. Construct. Educ. Res.*, 11(1), 40–53.

Cheng, R. & Johnson, A. (2016). *Motivation and Means: How and Why IPD and Lean Lead to Success*. Minneapolis: Lean Construction Institute and Integrated Project Delivery Alliance. Accessed March 30, 2021. https://hdl.handle.net/11299/198897.

Cooper, C. R. & Schindler, P. S. (2008). Business Research Methods, McGraw-Hill, Boston, USA.

Dargham, S. A., Hatoum, M. B., Tohme, M. & Hamzeh, F. (2019). “Implementation of Integrated Project Delivery in Lebanon: Overcoming the Challenges.” *Proc. of the 27th Ann. Conf. of the Int’l Group for Lean Construction*. Dublin, Ireland, 917–928.

Di Giuda, G. M., Giana, P. E., Schievano, M. & Paleari, F. (2020). A Collaborative Approach for AEC Industry Digital Transformation: A Case Study, The School of Liscate. In: Della Torre, S., Bocciarelli, M., Daglio, L. & Neri, R., eds. (2020). *Buildings for Education: A Multidisciplinary Overview of The Design of School Buildings*. Cham: Springer, 175–184.

Dos Santos, G. F. & Tokede O. O. (2016). “Last Planner System-From Theory to Implementation.” *Proc. of the 10th Cost Engineering, Quantity Surveying & Project Management World Congress*. Rio De Janeiro, Brazil, 305–318.

Heidemann, A. & Gehbauer, F. (2010). “Cooperative Project Delivery in an Environment of Strict Design-Bid-Build Tender Regulations.” *Proc. of the 18th Ann. Conf. of the Int’l Group for Lean Construction*. Haifa, Israel, 581–587.

Iivari, J. & Venable, J. (2009). “Action Research and Design Science Research – Seemingly Similar but Decisively Dissimilar.” *ECIS 2009 Proceedings*, 73.

Jenkins, G., Smith, J. P., Bingham, E. & Weidman, J. (2020). “Application of Integrated Project Delivery Practices in Residential Construction.” *Proc. of the 28th Ann. Conf. of the Int’l Group for Lean Construction*. Berkeley, California, 769–781.

Kortenko, S., Koskela, L., Tzortzopoulos, P. & Haghsheno, S. (2020), “Negative Effects of Design-Bid-Build Procurement on Construction Projects.” *Proc. of the 28th Ann. Conf. of the Int’l Group for Lean Construction*. Berkeley, California, USA, 733-744.

Matthews, O. & Howell, G. A. (2005). “Integrated Project Delivery An Example of Relational Contracting.” *Lean Construct. J.*, 2(1), 46–61.

Meredith, J. (1998). “Building Operations Management Theory through Case and Field Research.” *J. Oper. Manage.*, 16, 441–454.

Naoum, S. (2003). “An Overview into the Concept of Partnering.” *Int. J. Project Manage.*, 21(1), 71–76.

Patton, M. Q. (2002). Qualitative Research & Evaluation Methods, Sage Publications, Thousand Oaks, California, USA.

Grönvall, M., Ahoste, H., Lehtovaara, J., Reinbold, A., and Seppänen, O. (2021). "Improving Non-Repetitive Takt Production with Visual Management." *Proc. 29th Annual Conference of the International. Group for Lean Construction (IGLC29)*, Tommelein, I.D. and Daniel, E. (eds.), Lima, Peru, pp. 797–806. doi.org/10.24928/2020/0195. Online at: iglc.net.

IMPROVING NON-REPETITIVE TAKT PRODUCTION WITH VISUAL MANAGEMENT

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ABSTRACT

Takt production is gaining increasing visibility in the construction industry. To further improve the current takt production practices, visual management tools could offer improved efficiency in the production control phase. However, the effects of visual management in takt control setting have not yet received much attention in research.

This study aimed to investigate the effects of various visual tools in a takt production setting to gain knowledge on how these tools could aid takt control efficiency. The research utilized a design science research approach to create visual management tools and iterate them based on feedback. Interviews, site observation, and takt progress tracking were used to evaluate the implemented tools.

The findings indicate that workers on site want to be more aware of the production plan, and information helps them to work in the right location at the right time. To help workers, visual management tools need to recognizable, explicit, and contain correct and up-to-date information. However, there are cultural issues related to implementation, especially on the need for information going through foremen to crews.

KEYWORDS

Visual management, takt control, lean construction, takt production, production planning and control.

INTRODUCTION

Compared to other industries, construction productivity development has remained low (Forbes & Ahmed, 2011). Takt production is the most recent production planning and control method introduced to answer the productivity problem (Heinonen & Seppänen, 2016; Chauhan et al., 2018). Indeed, studies of takt production have shown potential in increasing production flow, also contributing positively to productivity (Lehtovaara et al., 2021).

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The term “takt” originates from manufacturing, denoting a constant time in which individual production activities should be finished (Hopp and Spearman, 2011). In construction, takt production consists of planning and control functions. Takt planning aims to identify repetitive processes in production and to balance them to decrease variability, forming a central element to establish flow-efficient production (Dlouhy et al., 2016). It is also essential to sustain flow-efficient through production by continuously controlling and improving the system (Lehtovaara et al., 2021).

Several benefits related to takt production have been reported in the literature. Yassine et al. (2014) argued that lead time will shorten, construction costs will diminish, and waste is reduced, while productivity is increased (Vatne & Drevland, 2016). In addition, takt production has been documented to increase transparency, ease communication between subcontractors, and enable more even production while making production forecasting and control more accurate (Frandson & Tommelein, 2014; Dlouhy et al., 2018). Studies of takt production have emphasized takt planning function, while takt control has had a lesser role. Lehtovaara et al. (2021) presented a theoretical model which proposes that takt control enables reducing rework, making-do, and re-entrant flow. Increased stability and reliability, problem-solving, and transparency are effects of both effective takt control and continuous improvement. Although Schöttle and Nesensohn (2019) presented challenges with lack of commitment in takt control. Reasons for the lack of commitment were lack of coordination, lack of understanding the production system and missing information from own company.

One possible way to potentially leverage the positive effects of takt control and continuous improvement is the adoption of visual management (VM) tools. VM is defined by Greif (1991) as the use of information in a visual manner to those who are executing the task in a way that the information can be retrieved at a glance and immediately be transferred to the task execution. VM tools could improve the transparency regarding the task to be executed, resulting in a better and more continuous production flow. VM aims to transform the workplace and task execution into self-explanatory, self-ordered, and self-regulated action while facilitating continuous improvement (Galsworth, 1997). This results in transparency, discipline, management by facts, simplification, and unification, and creating shared ownership (Tezel et al., 2009).

The adoption of VM could increase production transparency and enable more effective identification of waste and disruptions in the production flow (Formoso et al., 2002), which are also associated with Lean Production (Liker, 1997). VM as a part of lean thinking has been a vital management approach to increase information distribution, bringing more transparency to the construction site, and enabling pull production approaches with more simple and targeted communication tools (Koskela et al., 2018).

VM tools can be relatively simple, like a board that has information and visual aids such as production plans (Tezel et al., 2015). Valente et al. (2018) introduced standardized worksheet cards that include information about what work needs to be done and where and the time it takes to complete and sequence steps. Another tool in their study was a constraint analysis board that includes a picture of layout, schedule of activities, and constraints, which supports collaboration between stakeholders. Valente et al. (2018) also pointed out in their proposed model that the final step is to make visual tools visible, which needs to be taken into account in the design of visual tools. These design decisions could include issues such as color, shape, texture, and symbols. (Valente et al., 2018)

It could be argued that takt production and VM objectives are closely aligned. Takt production is used to plan and control the pace with which the processes should happen

(Lehtovaara et al., 2021). VM can be used to communicate the requirements to workers and explain who is to execute what and when, providing a transparent view of production flow and how an individual's work can contribute to completing the project objectives. Contribution can produce a positive side effect of increasing the ownership of the tasks and the workers' commitment to continuous improvement with more self-managed and proactive crews (Reinbold et al., 2020).

Inspired by this evident but little investigated synergy of takt production and VM, this study aims to implement VM tools and monitor whether they improve takt control process, and further examine how VM can be harnessed to support takt control most efficiently. Three VM tools were implemented and individually analyzed. The goal is also to improve these VM tools as part of the takt control process.

The remainder of the paper is structured as follows. Next presented is the introduction of research method and the case study, in which the VM tools are implemented. The iteration process of creating the tools and the central results are introduced in the findings. Then, the overview of VM on the project and analysis of the tools' effectiveness is discussed. Finally, conclusions are presented by assessing study implications and avenues for future research.

RESEARCH METHODS

The research strategy of this paper is design science research, which aims to create a foundation for pragmatic research and solve practical challenges (Dresch et al., 2015); effectiveness of VM and takt control is a practical challenge on site and needs a pragmatic research approach. According to Holmström et al. (2009), in design science research, the aim is to create an artefact used to resolve a problem and meet a specific goal.

The design science research was carried out by utilizing a case study. According to Yin (2009) the need for a case study is when a phenomenon is studied in an actual context. In this study, the context is an ongoing construction site. The study structure mimicked the process described by Holmström et al. (2009). The first phase was problem defining. The problem in this study was site workers lack of commitment to takt production and understanding of the takt plan. The second phase was the refinement of the solution. The artefacts in this research are the specific VM tools which are used to display takt on site. The artefacts were created together with site personnel and were compared with literature about VM. The main requirement for these tools was to make them simple. The artefacts will be presented in the findings section, where the iteration process and VM tools updates will be shown. In the final phase, theoretical suggestions on how to use the information in practice were created, which is presented in the discussion section.

The case project for this study is a new 135 500 sqm2 shopping center. Construction time is from the beginning of 2019 to the spring of 2022. The shopping center has three stories with over 80 different shops, restaurants, and services. Production planning for the interior phase has been done by takt planning collaboratively with subcontractors. The interior phase has been divided into two parts, with the first part consisting mainly of MEP-frame works, interior walls, and painting of the inner roof, with a takt time of 5 days. The second part consists of work activities mainly of finishing work and ending to MEP functioning testing with a takt time of 2 days. The takt area size has been reduced for the second part of the takt plan to consist of a retail space-specific takt area.

Data collection was mainly conducted by structured interviews on-site, site observation, and tracking of takt wagons in the test area. The test area was set for takt areas 1 to 6 on the ground floor's west and east side, respectively. Figure 1 shows the test area with a green line and how it was divided into takt areas. The areas chosen needed to have a similar layout, area size, and takt work activities. VM tools were implemented in the west area. East area was used as a comparison area with the traditional process to compare data. The interviews were conducted on site and in total of 36 subcontractors' workers were interviewed, in which 21 worked in the west area and 15 in the east area. The interviews consisted of two parts: the first part of the interviews included questions about how well takt related requirements were met on a scale of 1 (bad) to 5 (excellent), and the second part included questions about VM. The questions and results are presented in the findings section.

Takt progress tracking was done by analyzing completion rates for each takt wagon. Takt wagons analyzed were from the test areas and the tracking was conducted for eight weeks.

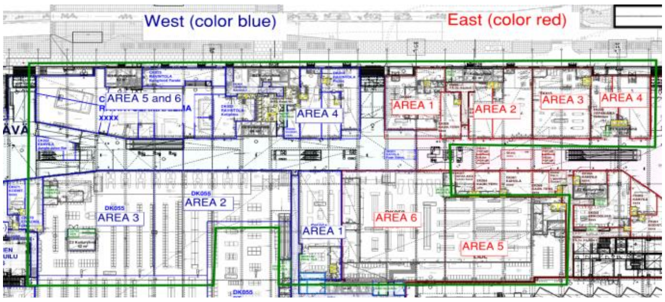

Figure 1. Test area

FINDINGS

Three VM tools were tested on the site. The main focus was on VM tools that aid the individual workers. The implemented VM tools were (1) takt plan visible to site, (2) takt wagon visualization through takt cards, and (3) takt area markings on site. In addition, crew colorings were used to complement these three tools. These VM tools on site are shown in Figure 2. Next, the tools and the iteration process are introduced.

TAKT PLAN VISIBLE TO SITE

Takt plans that were put on site on a takt board included the whole project's takt schedule and takt areas, shown in Figure 2. These takt boards were placed on three floors and two per floor, one for the west block and one for the east block. After some discussion on site with the subcontractors, the information of supervisors per section and foremen controlling different takts were updated as the first iteration on the takt boards. Takt boards were the first VM tools set up on site, and their implementation was done earlier than the other tools. In addition, one takt board in the main lobby at the site was updated as a second iteration to contain information on a three-week schedule for each subcontractor. The three-week schedules were updated weekly.

Takt plans visible on site got positive feedback early on from the subcontractors, and they felt that the information was important. Interviewees felt that the takt boards were easily accessible and found on site. Most of the interviewees also felt the takt plan was easily understandable, but some felt that it was hard to understand. Adding subcontractors' three-week lookahead plans on the takt boards was seen crucial for maintaining work flow as part of takt control. It also helped to make the takt plan more understandable for those who thought the whole takt plan was hard to understand. Takt boards were also used as a tool for coordination with the general contractor's foremen and subcontractors' team leaders as well as coordination between subcontractors. The interviewees pointed out that the significance of production plan in production control is lesser when the worker is further in the subcontracting chain.

Figure 2. Visual management tools shown on site.

TAKT WAGON VISUALIZATION THROUGH TAKT CARDS

The initial idea of takt cards was developed from Kanban cards, takt wagon visualization from an observation of two construction projects in San Francisco[6] , and the need to show more detailed information to the working crews. Most of the information displayed on the takt cards are issues that were discussed in the takt planning meetings but never really visualized on site. The main focus of takt cards was to make them visually recognizable. Before the first iteration, takt cards contained a lot of information but were later simplified. An example of a takt card is shown in Figure 2.

The first iteration of takt cards, which were implemented on site, included information about preconditions, tasks inside the takt, resources needed for the wagon, inspections done within the wagon, and handover date. Through feedback, the second iteration was to add a three-week lookahead plan, which contained the information about the next two takt wagons in the takt area. The three-week lookahead plans were placed beside the takt cards, which were located near the entrance to the takt areas, to be easily visible to people who seek information. The entrace to takt areas was seen as the optimal location for takt cards by interviewees. The third iteration considered making the takt cards more visible. An information board was made and previously mentioned items were added on it as well as a lamp and takt area room identification numbers. This iteration made the takt card as a whole more recognizable as it was bigger in size and had a lamp to gain more attention.

Some of the takt wagons are straightforward work that do not need a lot of information, and the takt boards are enough, as few interviewees pointed out. However, takt cards were seen useful if the cards were bigger and only contained essential information for crews. If there is too much non-essential information the tool was seen as unnecessary. The takt cards were seen to need more instructions. The information should be clear, not too complicated, and recognizable. Essential information for takt control was schedule information about prerequisites of tasks in takt, currents task details, and the next takt wagon. The research area had different sized takt areas and the interviewees thought that

[6] Grönvall, M. 2019. Tahtituotannon implementointi toimitilarakentamisessa. (Master's Thesis).

the takt cards work better in smaller areas in the finishing phase, with multiple tasks in one takt. The study also pointed out that VM system in non-repeatable takt production requires a lot of work to have the real-time information when done manually. Using takt cards for every takt area in the project would scale the problem.

TAKT AREA MARKINGS ON SITE

The initial idea for takt area markings was to spray the outlines of the area on the floor and use columns to show the area with a paper tag. Due to COVID-19 restrictions, the research was delayed, and most of the areas already had natural boundaries by interior walls. After discussions with the project members on how to show the takt areas on site, the thought was to implement the room numbers by projecting the numbers with light, but it wasn't possible due to time limits of this study. Finally, the takt areas were tagged with the room identification numbers and space purpose or name on columns in the area, as shown in Figure 2.

Through iteration of takt cards, the room identifications were attached to the same board as the takt cards. Most parts of the test areas were smaller spaces with only one entrance to the area. With larger areas that had to be split into different takt areas, f.e. west areas 2 and 3, the takt area markings should be shown more visually. Takt area markings should be visible from every side of the area, and the marking should not be only in one place. One interviewee also thought that the takt area outlines should be more visible, but it also depends on what work is done in the area. Area markings with room or area identification helped workers to mark where they had been working. The site layout was mostly seen as easily understandable. Overall, takt area markings with the help of takt boards with project layout and takt areas were seen as essential for takt control. Most workers gave good grades for the visualization and clarity of takt area markings as the average was 4,19 out of 5. Subcontractors working in the larger areas gave worse feedback as mentioned above.

CREW COLORING RELATED TO TAKT WAGONS

Crew coloring was done to match takt cards and takt wagons in the schedule with the color of the company's clothing or logo to make it visually easier to recognize where a crew is needed to be and to control the work. One example is the interior wall subcontractor with red clothes, so their takt and takt card is red. Interviews indicated that most thought that the takt schedule was clear and that some subcontractors did not see their takt cards in the right place. It shows that colors used for takts made it also beneficial to keep track of where their own work was going. Using of colors may have many meanings which was pointed out by a interviewee. The interviewee thought that a green takt card meant that the area was finished by this subcontractor. Although it was a color for the electricity subcontractor and it resulted in the misunderstanding of takt cards.

IMPLEMENTATION RESULTS

Takt progress tracking showed that the west area which implemented VM tools had better average progress. The area had 11% higher results on completed takt wagons than the control area. The challenge with analyzing progress tracking and the effect on takt is the external impact of Covid-19 on subcontractors' resources. This also affected completion progress as the results started decreasing, as the production was running behind from week 5 of testing onward.

Table 1 presents that takt production features were on a good level in the opinion of interviewees, even though production was running late. There was not a straightforward correlation between VM tools and takt plan progress, but as production started running late of the takt schedule, the need for VM tools also started decreasing. This was due to the fact that because the progress tracking was not accurate anymore, the workers partially lost their interest towards the tools. One finding in conflict is that the workers only thought that VM tools help a bit, even though most of them thought there should be more VM information on site. The results were impacted by takt cards not being in real-time and by delays with progress.

Table 1. Interview questions and results

Questions	Results
How well the following are met: work preconditions, clarity of schedule, takt areas and work content, working without interference.	4.3 (west) & 4.1 (east)
Have you seen or used VM tools earlier?	5 had seen (14%)
Do VM tools support your work?	"Helps a bit"
Should the VM tools be located close to workplace or inside site office?	Close to work place on site (91%)
Would you like more VM information on site?	53% would want more information
Could you help to create VM tools that support your work?	50% could help to create VM tools

As summary, the three VM tools provided benefits for production control, but they also need to be developed further to reach full potential. Takt boards were seen to have the most positive effect on production. They made the production plans understandable to most of the workers. Takt boards were also a place for daily coordination of production control. However, takt cards did not achieve their full potential in this study and need further development. The main focus on takt cards is to make them visual and located in a central place to gain attention from workers. Takt cards were seen as a useful tool if they have the right information, which can differ for different takts, takt areas, or crews. Takt area markings with the aid of takt boards were seen essential for takt control. Simple signs like room identifications on columns were seen as an adequate solution. It is important to use takt area markings that suit best for the takt area and are visible from different sides if it is an open space. Color coding in visualizing takt plan on site needs to be made clear, since different colors can create misunderstanding.

DISCUSSION

Tezel et al. (2015) presented that VM tools should be simple and have visual aids like plans. This matter was seen important with takt boards on site. Valente et al. (2018) also presented the benefit of using boards as supporting collaboration between stakeholders. The study showed that using takt boards enables coordination on site, likely decreasing rework and re-entrant flow and increasing transparency and identification of disruptions. These benefits of VM in production flow were also pointed out by Liker (1997) and Formoso et al. (2002). These introduced benefits also have a positive effect on takt control. The problem with some parts of the interviews compared to observation and conversations is that the interviewees did not completely understand takt boards as VM tools.

Takt cards were not used to their full potential and were not recognizable enough in size, which brought the problem of giving enough information to the subcontractor.

Valente et al. (2018) presented that the final step is to make tools visible, which is an important aspect also highlighted in this study. Takt cards were manually changed, which brings the problem of having the updated card on site. Updating takt cards should be digitalized in the future, as Reinbold et al. (2020) pointed out. The challenge of takt cards not being real-time is also present if the work isn’t completed as in the production plan. The challenge of not having real-time information is also introduced by Reinbold et al. (2020). It brings up trust issues, as interviews also pointed out. Results indicate that if takt cards' information is not in real-time, it decreases trust in overall VM tools for takt control. One aspect that challenged the thought of takt cards decreasing the need to contact foremen was, that the information needed isn’t shown in takt cards. To solve these problems it is essential to ensure the right level of information that benefits the workers.

Takt production itself gave sound basis for the implementation of VM tools. The general feedback from subcontractors was that takt schedules were visually clearer and easier to understand than traditional schedules. Most of the tools' information was already present and only needed to be made visually recognizable on site. In the beginning, it was challenging to get the workers on site to understand VM tools and the connection to their work, which made it challenging to see the results of these tools. At a takt planning meeting, the tools were introduced for subcontractors foremen and management, and they felt that VM tools are good extra information but not essential. The information given is not that needed since the subcontractors' supervisors tell the crews where to go and what needs to be done. However, the interviews revealed that actually, the crews on site want more information.

At the time of introducing the tools, the supervisors did not have a clear understanding of the tools. The adoption of VM tools during the production phase in construction sites is still low (Tezel et al., 2011), the request for more visual tools and more information from the production perspective points out that a cultural change is necessary and that the information needs to be better located and distributed in the construction sites. The correlation of VM tools with takt production can be seen from interview results and takt progress tracking. When takt progress decreased, the need for VM tools also decreased. It is understandable since the tools' information is not correct, which decreases the overall need for information.

A broader introduction of VM tools on the site would be needed. It is important to think of the most efficient and easy way to educate VM methods. The process of VM implementation should start early. In a takt production project, VM implementation can be started when starting the takt planning phase with subcontractors. This way, the tools are more familiar early on, as the results point out. VM tools were a bit confusing for the subcontractor crews when implemented in the middle of the project. Iteration and testing of these VM tools are also important since the workers might not know what is needed or what they want before they see the right tools, making it challenging to start implementing these tools. The interviews showed that VM tools' need is there, but what information it should include is still unclear, which makes it challenging to develop these tools.

Some interviews pointed out the strong culture in the construction industry that the foremen should give all the work instructions for the crew. In some interviews, VM tools were not thought to have an impact because the crews would only do as their foreman says. In this sense, VM aims, as presented by Galsworth (1997), were not met. However, the result of not having self-regulated crews is common in construction (Reinbold et al., 2020). This brings up a problem in implementing and controlling takt production since some foremen didn’t really instruct the crews on what takt production is. In this case, the only way to be controlling the work is through the foreman, which means that the foreman needs to be controlling all the time. The study points out that the VM information is there, but it may not be known how to use it or not show the right information for some subcontractors. VM tools and the information it contains should be thought off collaboratively at the beginning of the project to ensure that crews get the information needed.

CONCLUSIONS

This study aimed to gain knowledge and understanding of VM as part of takt control, as little research exists on how VM tools can support takt control on site in the most efficient way. The study was conducted by implementing and iterating three VM tools on site. The data was collected by triangulation of interviews, work progress observations, and site observations.

VM needs to be introduced early on at the site and collaboratively develop the tools. In takt production, VM tools can help when the information given is clear, recognizable, right and in real-time. VM tools are easy to implement in takt production because takt production plans themselves are visually more understandable than traditional schedules.

Takt boards helped different stakeholders on site to solve problems and coordinate work. They were seen as essential for takt control. Takt cards were seen as being helpful when the information is right and the tool is visible enough, but they still need to be improved to reach full potential for takt control. Takt area markings improve understanding and finding the takt area, which reduces waste in work and makes takt control more efficient.

VM should be implemented in more projects to test which tools and information is needed and most efficient for workers. The lack of real-time information in the project brings up trust issues in VM tools overall. The culture of the information management practices needs to change, and with the help of VM on site, there will be more user experiences and knowledge of VM.

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REFERENCES

Chauhan, K., Peltokorpi, A., Seppänen, O & Berghede, K. 2018. ”Combining Takt Planning with Prefabrication for Industrialized Construction.” Proceedings (IGLC 26). Chennai, India, 848-857.

Dlouhy, J., Binninger M., Oprach, S. & Haghseno S. 2016. “Three-Level Method of Takt Planning and Takt Control – A New Approach for Designing Production Systems in Construction.” Proeedings (IGLC 24). Boston, MA, USA, sect.2, 13-22.

Dlouhy, J. 2018. “Large scale project using takt planning and takt control-creating and sustaining multitasking flow.” (IGLC 26).Chennai, India, 1334-1343.

Dresch, A. Lacerda, D. & Antunes Jr, J. 2015. Design Science Research. A Method for Science and Technology Advancement. Springer International Publishing Switzerland 2015.

Forbes, L. & Ahmed, S. 2011. Modern Construction Lean Project Delivery and Integrated Practices. Taylor & Francis Group.

Formoso, C. T., Santos, A. D. & Powell, J. 2002. “An Exploratory Study on the Applicability of Process Transparency in Construction Sites”. Journal of Construction Research, 3(1), 35-54.

Frandson, A. G. & Tommelein, I.D., 2014. “Development of a takt-time plan: a case study.” In Construction research congress 2014. Reston, VA: American Society of Civil Engineers, 1646-1655.

Galsworth, G.D. 1997. “Visual Systems: Harnessing the Power of Visual Workplace”, New York, USA, AMACOM.

Greif, M. 1991. “The Visual Factory: Building Participation through Shared Information”, Productivity Press, Portland.

Heinonen, A. & Seppänen, O. 2016. “Takt Time Planning: Lessons for Construction Industry from a Cruise Ship Cabin Refurbishment Case Study”. Proceedings (IGLC 24). Boston, MA. USA, sect. 1. 23-32.

Holmström, J., Ketokivi, M. & Hameri, A-P. 2009. “Bridging Practice and Theory: A Design Science Approach”. Decision Sciences, Volume 40.

Hopp, W. J. & Spearman, M. L. 2011. Factory physics. Long Grove, IL: Waveland Press.

Koskela, L., Tezel, A., & Tzortzopoulos, P. 2018. “Why visual management?” Proceedings (IGLC 26). González, V.A. (ed.), Chennai, India, pp. 250–260.

Lehtovaara, J., Seppänen, O., Peltokorpi, A., Kujansuu, P. & Grönvall, M. 2021. “How takt production contributes to construction production flow: a theoretical model”, Construction Management and Economics.

Liker, J. 1997. "Becoming Lean: inside stories of US manufacturers", productivity press, Portland / OR.

Reinbold, A. , Seppänen, O. & Peltokorpi, A. 2020. “The Role of Digitalized Visual Management to Empower Selfmanaged Crews in Construction Projects”. Proceedings (IGLC 28). Berkeley, California, USA. pp 925-936.

Schöttle, A. & Nesensohn, C. 2019. “The Beauty of a Phase-overlapping Last Planner System with incorporated Takt.” Proceedings (IGLC 22). Dublin, Ireland, pp. 441–450.

Tezel, A., Koskela, L. & Tzortzopoulos, P. 2009. “The Functions of Visual Management.” International Research Symposium, Salford, UK.

Tezel, A., Koskela, L., Tzortzopoulos, P., Koskenvesa, A. & Sahlstedt, S. 2011. “An Examination of Visual Management on Finnish Construction Sites” In (IGLC 19). Lima, Peru.

Tezel, A., Koskela, L., Tzortzopoulos, P. & Alves, T. 2015. Visual Management in Brazilian Construction Companies: Taxonomy and Guidelines for Implementation. Journal of Management in Engineering 31(6).

Vatne, M. & Drevland, F. 2016. “Practical Benefits of Using Takt Time Planning: A Case Study”. Proceedings (IGLC 24). Boston, MA. USA, sect. 1., 173-182.

Yassine, T., Bacha M., Fayek, F. & Hamzeh, F. 2014. “Implementing Takt-Time Planning in Construction to Improve Work Flow”. Proceedings (IGLC 22). Oslo, Norway.

Yin, R. 2009. Case Study Research. Design and Methods. Fourth Edition. Vol. 5. SAGE Publications Inc.

Fischer, A., Grimm, N., Tommelein, I.D., Kessler, S., and Fottner, J. (2021). "Variety in Variability in Heavy Civil Engineering." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 807–816, doi.org/10.24928/2021/0204, online at iglc.net.

VARIETY IN VARIABILITY IN HEAVY CIVIL ENGINEERING

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ABSTRACT

This paper presents a characterization of heavy civil engineering in the context of lean construction and Industry 4.0. Production characteristics of earthworks are compared with those of multi-story construction. The paper focuses on the equipment use of specialty foundation contractors and shows the variety in variability encountered in the Kelly pile drilling process, as described by industry experts. The authors identify seven sources of variability that affect production performance, classify each one by type, and then describe technologies to harness them. The paper critically examines design considerations in a production system that highly depends on equipment and highlights that advances in implementation of Industry 4.0 will demand ongoing effort in reconfiguring such systems.

KEYWORDS

Lean construction, earthwork, heavy civil engineering, process, value stream, variability.

INTRODUCTION

Industry 4.0 envisioned as Germany's high-tech strategy plan for 2020 and characterized by digitalized production optimized using artificial intelligence (AI) (Lasi et al. 2014), challenges the construction industry to adopt digital technologies in order to address its ever-increasing complexity (McKinsey 2017). However, industry digitalization and optimization is slow due to construction-specific constraints (e.g., Günthner and Borrmann 2011, Schöberl et al. 2020) such as diverse use of technologies in stand-alone applications (lacking interoperability), variety of proprietary platforms, lack of uniform interfaces for documentation and coordination, and lack of digital mapping of processes. A key lesson from lean production is that a pure adaptation of technologies does not optimize a process (Lander and Liker 2007). Rather, process flows must be understood

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in detail to eliminate waste (Rother and Shook 2009). So, while equipment-driven operations have been designed around optimization of equipment use, and the cost of equipment outweighs other costs in their operation, factors other than equipment cost minimization play a role in overall process optimization.

This paper focuses on pile drilling, a heavy equipment-intensive application. The Kelly drilling method, widely-used for pile production, uses a rotary drilling rig ("rig" in short) to make large-diameter bored piles up to 3 m (DIN EN 1536) (Figure 1). This method repeatedly drills and removes soil. Other methods for pile production exist, e.g., the Continuous Flight Auger (CFA) method (Brown 2004, 2005). CFA production is optimized for continuous movement of soil and concrete: soil is transported upward via the auger and concrete is transported downward via a hollow core inside the auger. Unlike the Kelly method, CFA does not have the same range of application in pile design so one is not an exact substitute for the other.

Figure 1: Rotary drilling rig at test site of Bauer Group in Schrobenhausen, Germany (Pictures by Fischer, A.)

Noting that few documents describe the Kelly pile production process and its variabilities, the authors posed three research questions: *What are key differences between (foundation) civil engineering and multi-story building construction in terms of application of lean principles? Which variabilities influence the Kelly drilling production? How may these be addressed by Industry 4.0?*

RESEARCH METHOD

To answer these questions, the authors conducted semi-structured interviews with nine experts from three German specialty foundation contractors involved in the different construction phases: Two estimators, one purchasing agent, two equipment schedulers, two construction managers, and two foremen. The experts were asked to describe their method for producing a Kelly pile in the design-, project preparation-, and execution phase. To supplement this knowledge, Grimm (2020) (a co-author of this paper) searched the literature to identify means of estimating production rates of earthmoving and pile driving operations the research questions.

RELATED WORK

CHARACTERISTICS OF MULTI-STORY AND HEAVY CIVIL CONSTRUCTION

Variability in construction results from variation within and between process interactions (Howell et al. 1993). Process interactions may depend on shared resources, such as cranes in multi-story construction. Cranes are pacemakers, largely responsible for material flow, and used by many stakeholders on-site (Tommelein and Beeche 2001, Friblick et al. 2009, Dallasega et al. 2015). Monitoring crane operations is therefore important when trying to design work standards to reduce variability (Fazinga et al. 2016). When comparing multi-story construction with heavy civil engineering, a key difference is that the latter deals as much with the sharing of resources as it does with the interdependence between them.

Differences pertain to characteristics of in-situ production, the number of different task types, the number of subcontractors working concurrently, and work space requirements depending on the equipment. As part of heavy civil engineering, earthworks are widely discussed in the literature. For example, Kirchbach et al. (2014) describe earthwork production composed of the following material flow: material excavation and loading by excavators, material transportation by trucks, and spreading with bulldozers, where the (cost) deciding factor is the process involving the excavator. To measure production flow, Haronian and Sacks (2020a, 2020b) distinguish between discrete elements (building construction) and layered elements (earth movement). Kalsaas (2012) adapts Overall Equipment Efficiency (OEE) as a metric but emphasizes the need to consider the entire production system, i.e., isolated consideration of the equipment is not sufficient. The importance of the worker, even in equipment-intensive work is shown by the work of Ruiz et al. (2020), whose implementation of 5S led to a demonstrable improvement in working conditions. Kirchbach et al. (2012) confirm that civil engineering, in particular earthmoving, is strongly characterized by uncertainties.

Pile production is known for its dependence on variable and difficult-to-predict geology (Kaplan et al. 2005). However, Rosas et al. (2011) reveals that even though planners complain about the geology's variability, planning mistakes have an even greater effects on forecasts. González et al. (2014) look at geothermal drilling, which, like bored pile production, is characterized by complex processes carried out by highly specialized trades. Established contractual and organizational structures, based on mutual distrust and secrecy, reduce project performance. In contrast to earthmoving, the pile as a product can be seen as a single object, similar to building construction. If one considers the equipment, the rotary drilling rig is less flexible in use compared to the hydraulic excavator. In the following, we investigate the soundness of the common assumption that equipment drive production flow, i.e., that the system is 'paced by equipment' (Haronian and Sacks 2020b).

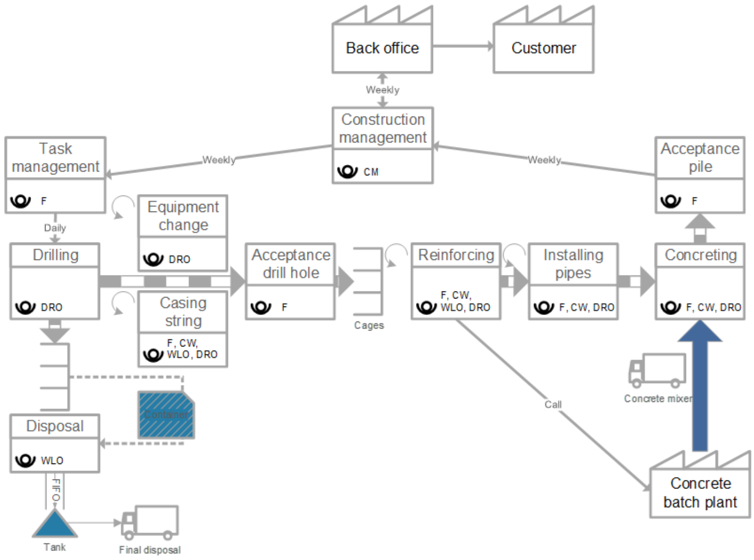
CHARACTERISTICS OF VARIABILITY IN PRODUCT AND PROCESS

Different approaches exist to deal with all this variability. Tommelein (2000) argues that these models are useless if they are not able to address both, the product as well as the process variability in a production system. More specifically, one needs to define sources of variability in a system to identify the adjustments that can be made in order to manage or even improve the system. The product is defined by its parts whereas the process is defined by its activities (Filho et al. 2016, Tommelein 2000). Examples of product characteristics concern, e.g., functionality, configuration, and geometry. Process characteristics concern, e.g., resource assignment and sequencing of activities.

PILE PRODUCTION USING KELLY DRILLING METHOD

The key metric in pile production is the output of pile length produced per day (or piles per day). Based on this value, the number of units of equipment and accessories, such as casing oscillators, is determined based on experience.

Pile production using the Kelly drilling method consists of three main steps: drilling, reinforcing, and concreting, as detailed next. Figure 2 depicts a value stream map of the whole process.



CM: Construction Manager
F: Foreman
CW: Construction Worker
DRO: Drilling Rig Operator
WLO Wheel Loader Operator

Figure 2: Value stream map for pile production using Kelly drilling method

Once the rig has been positioned, the alternating steps of the drilling process start. The equipment picks up the appropriate tool, e.g., an auger (Figure 1 left). The equipment slews and positions itself towards the drilling attachment point. The rotary drive turns in the casing string with the help of the casing drive adapter (Figure 1 right). Lowered with the help of the telescopic Kelly bar, the drilling tool drills as the rotary drive applies the torque on the locked Kelly. Once filled, the drilling tool is pulled out and emptied, usually in a container to ease soil removal from site. In turn, a wheel loader then takes the drill cuttings to the disposal site for further processing. In general, the deeper the drilling tool, the lower the performance due to longer run-in/out times and higher surface friction. For reinforcement, the rebar cage is attached to the auxiliary cable of the rig and setup. The rig then swivels to the drilling attachment point to lower the reinforcement cage. Before concreting starts, the delivery pipes are assembled and lowered into the drill hole. The workers fasten them together. Concrete is placed either directly through the concrete mixer discharge or through a concrete pump/bucket, which requires additional steps. Cutting the casing and delivery pipes is done alternately and often requires extra power from a casing oscillator. The quality of the material is highly dependent on the correct execution (Brown 2004).

SOURCES OF VARIABILITY

The expert interviews and the literature revealed 7 sources of variability.

(1) The design, tied directly to the method and use of resources, depends greatly on the **contractual requirements**. A collaborative partnership is rare between designers, material supplier, and foundation contractors. In the design phase, early involvement of the specialty foundation contractors minimizes the product variability as they may aim to standardize, i.e., length, inclination, and diameter of the piles. All these influence the equipment selection, the auxiliary equipment (casing oscillator), the procedure, and the performance (the longer the pile, the higher the casing friction, the longer the excavations).

Rebar joints should be minimized, if possible, as they entail additional work steps. Specialty foundation contractors work together with material suppliers. Considering the rebar, the delivery and storage of the cages must be in the right sequence (process). Transportation restrictions limit the pile length (product). While concrete contractors are under subcontract to the specialty foundation contractors, in practice, concrete supply will vary. The more flexibly concrete can be called off and the more reliable the transportation is, the better the production flow and the utilization of the rotary drilling rig, but also the quality of the product. In general, increased requirements on the product design characteristics and quality, such as inclined boreholes or floating foundations, determine further process steps, e.g., at which point the inclination needs to be checked.

(2) Variability in the process stems from **environmental influences**, e.g., weather and time, and affect site processes in different ways. Poor conditions can reduce performance by as much as 50-70 % (Girmscheid 2010, Hoffmann and Krause 2016). While the drilling process is stationary, the rig must travel between pile locations. Poor visibility or slippery conditions have less influence on the performance of the drilling than is the case for earthmoving equipment. However, inclement weather conditions, such as strong winds or heavy rain, are unfavorable to the mast’s inclination or the equipment foundation's stability. In addition, the work of construction workers is affected by inclement weather, seasonally and daily (e.g., night time construction).

(3) Environmental influences can be managed by good **site organization** planned in advance. An important part of the site organization is to ensure good time management to achieve high equipment utilization. The time utilization factor provides information on how well the working time is utilized. Reducing factors such as a 50-minute hours (83%) (Bauer 2007, König 2014) are commonly used in special foundation engineering. The influence of site organization is difficult to capture analytically but pertains to factors such as the organization and scope of work, as well as interruptions, maintenance, and repair (Hoffmann and Krause 2016). In special foundation engineering, examples for a good site organization are the provision of spare parts, additional equipment, like casing oscillators, mechanics, buffer time, tight coordination with the concrete supplier.

(4) The **geology** has an enormous influence on the product and process variability. First, the chosen pile design and procedure is based on the soil type. Second, considering the equipment performance, the soil type is included in the theoretical production rate as the volume depends not only on the rated volume but also on the load factor, defined by the fill factor and the swell factor of the material (ISO 1991). In special foundation engineering, the depths of the layer boundaries in the area of the bored piles are based on individual test borings. Practical experience shows that soil layer models give only a very limited prediction of the material present. Moreover, boulders lead to inhomogeneity and disturb the sequence up to a complete standstill. Groundwater also plays a role. The optimum filling level of the tool, as well as the selection of the tool, depend on the soil condition (but also on the operator's skills). Equipment sensor systems help.

(5) A frequently-mentioned process indicator is the equipment operator’s **skills**. Depending on the operator, pile production rate is very high or very low. According to Girmscheid (2010), a novice may reduce it by up to 20-35 %. Experts in special foundation engineering confirm this and back it up with estimates of performance increases of up to 20 % if above-average operators are deployed (independent from existing operator assistance systems). These are decisive for the process. Changing over rotary drilling tools is also complicated and requires a high level of experience. Careful handling of the equipment, such as occasional cleaning of the chains, also helps reduce downtime. Rashidi et al. (2014) cite another factor regarding personnel in the case of bulldozers, the number of consecutive working days. This is also confirmed in special foundation engineering. Experts speak of approximately one week to create a team, and the more well-rehearsed the team is, the greater their performance will be.

(6) Improving the **operating conditions** can help to reduce process variability. Some operating conditions in heavy civil engineering are similar, such as manoeuvrability, or the geodetic height of the construction site. Differences occur considering the distance between the start and endpoints of the load cycle. E.g., targeted loading reduces the production rate up to 10 % (Bauer 2007). In the case of dozers, working in tracks increases it up to 20 % (Girmscheid 2010). In the case of rotary drilling rigs, the distance between the drill holes plays a role as well since with longer distance the pure share of drilling in the working time is reduced.

(7) The degree of **abrasion and failure** must be quantified. Girmscheid (2010) provides an increase up to 80 % for hydraulic excavators. In the case of rotary drilling rigs, the abrasion of tools, such as auger teeth or casing shoes, must be accounted for. In particular, casing shoes have a significant impact on the performance as they remain underground until concreting. Premature abrasion delays reaching the required drilling depth. In softer soils, such as clay, abrasion plays a minor role. The probability of failure of hydraulic excavators during long-term operation is a function of their operating hours (Girmscheid 2010) but the impact of failure is lessoned by preventive maintenance. In the case of rotary drilling rigs, preventive maintenance is all the more important as acquisition and maintenance costs are much higher than for hydraulic excavators.

INDUSTRY 4.0 TOOLS TO ADDRESS VARIABILITY

Industry 4.0 offers opportunities to reduce the seven sources of variability, as described, by providing smart technologies (Oesterreich and Teuteberg 2016, Huang et al. 2021):

Digital models: Building Information Modeling (BIM) provides a digital representation of the construction project (ISO 2018). While widely used in building construction, BIM is not used in heavy civil engineering (Fosse et al. 2016). Instead, Geographic Information System (GIS) may be used to capture the geospatial context of infrastructure systems. The software capabilities of BIM and GIS are increasingly overlapping (Liu et al. 2017). A German initiative is pushing for standardization in special foundation engineering (Germ. Constr. Ind. Fed. 2019).

Internet of Things (IoT): With the help of sensing (e.g., RFID and Bluetooth), entities on site, such as workers, material, and equipment, are connected via the Internet for identification, localization, and performance tracking (Olivieri et al. 2017).

Artificial Intelligence (AI): Machine learning algorithms are used to analyze the increasing flood of data. Ongoing research aims at automatically capturing construction progress (e.g., Bügler et al. 2017, Fischer et al. 2021a).

Simulation: Simulation is a proven tool for testing complex systems and is a key tool for virtual design and construction, albeit not yet widely used in construction practice (AbouRizk 2010, Abdelmegid et al. 2020). Recent approaches address opportunities provided by frequent updates of construction site data (e.g., Louis and Dunston 2017, Akhavian and Behzadan 2018, Fischer et al. 2020, Fischer et al. 2021b).

Table 1 describes how each variability can be harnessed by these technologies.

Table 1: Variabilities in relation to Industry 4.0 tools

	Variability	Digital model	IoT	AI	Simu-lation	Appropriate technologies help…
(1)	Contractual requirements	x			x	gain a better understanding by visualization.
(2)	Environmental influences			x	x	handle weather forecasts.
(3)	Site organization	x	x		x	visualize and test site logistics in advance.
(4)	Geology	x		x	x	visualize the single soil layers to improve reaction time.
(5)	Operator skill		x	x	x	track and analyze personnel's performances.
(6)	Operating conditions		x		x	monitor and virtually test routing strategies.
(7)	Abrasion and failure			x	x	predictive maintenance and capture stochastic failure.

DISCUSSION

Use of Industry 4.0 technologies to reduce variability can help make systems more predictable. Not all variability will be removable, but incrementally the production system will evolve to new future states, each with new system design challenges to be overcome. As the interviews revealed a high degree of human processes on construction sites, a pre- or co-requisite to introducing Industry 4.0 tools, is improving contractual and organizational aspects by using lean management tools. Whereas the multi-story buildings are characterized by the use of cranes challenging the decoupling of different tasks, the earthworks focus is on fleet interaction. In contrast, the foundation-pile activities have been isolated and limited as a one-piece flow line dependent on single machine due to high complexity. The comparison of the application of lean principles, however, shows that even equipment-intensive processes can be improved by focusing the human factors. Transferred, collaborative partnerships involving contractors at an early stage can improve the pile design towards production aspects.

CONCLUSIONS

Special foundation engineering is a competitive field, driven by product and process knowledge. Focusing on the Kelly drilling process in this paper, it was therefore not surprising to not find literature on influencing factors. A comparison with conventional methods in earthmoving and interviews with experts reveal seven sources of variability and derived recommendations. More interviews and additional data collection are in order to lead to more general conclusions, however, this study indicates that process improvements will depend not solely on equipment improvements with Industry 4.0 but on improvements in the socio-technical system as a whole, to fully account for individual people and organizational factors as well. Implementation of lean principles within and between parties can help capture the variability. Standard workflows then serve as a basis for adaptive simulation studies.

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REFERENCES

Abdelmegid, M.A., González, V.A., Poshdar, M., O'Sullivan, M., Walker, C.G., and Ying, F. (2020). "Barriers to adopting simulation modelling in construction industry." *Automation in Construction*, 111, doi.org/10.1016/j.autcon.2019.103046.

AbouRizk, S. (2010). "Role of simulation in construction engineering and management." *J. Constr. Engin. and Manage.*, 136(10), doi.org/10.1061/(ASCE)CO.1943-7862.0000220.

Akhavian, R. and Behzadan, A.H. (2018). "Coupling human activity recognition and wearable sensors for data-driven construction simulation." *J. Information Technology in Construction*, 23, 1-15, https://www.itcon.org/2018/1.

Bauer, H. (2007). *Baubetrieb (Building operations).* Springer-Verlag, Germany.

Brown, D.A. (2004). "Zen and the art of drilled shaft construction: The pursuit of quality." *GeoSupport Conf. 2004*, ASCE, 29-31 Dec., Orlando, Florida, USA, 19-33, doi.org/10.1061/40713(2004)2.

Brown, D.A. (2005). "Practical considerations in the selection and use of continuous flight auger and drilled displacement piles." *Proc. Geo-Frontiers Congr. 2005*, ASCE, 24-26 Jan., Austin, Texas, USA, 1-11, doi.org/10.1061/9780784407783.

Bügler, M., Borrmann, A., Ogunmakin, G., Vela, P.A., and Teizer, J. (2017). "Fusion of Photogrammetry and Video Analysis for Productivity Assessment of Earthwork Processes." *Comp.-A. Civil & Infr. Eng.*, 32(2), 107-123, doi.org/10.1111/mice.12235.

Dallasega, P., Rauch, E., Matt, D.T., and Fronk, A. (2015). "Increasing productivity in ETO construction projects through a lean methodology for demand predictability." IEEE, *Int. Conf. Ind. Engin. and Op. Manage. (IEOM)*, 3-5 March,Dubai, UAE, 1-11.

DIN Deutsches Institut für Normung e. V. (2015). *Execution of special geotechnical work - Bored piles: German version EN 1536:2010+A1:2015.* 93.020, DIN EN 1536.

Fazinga, W.R., Saffaro, F.A., Isatto, E.L., and Kremer, A. (2016). "Difficulties in Work Design in the Construction Sector." *Proc. 24th Ann. Conf. Int. Group for Lean Construction*, 20-22 July, Boston, Massachusetts, USA.

Filho, A.N.M., Heineck, L.F.M., and Costa, J.M. (2016) "Using Lean to Counteract Complexity." *Proc. 24th Ann. Conf. Int. Group for Lean Construction*, 20-22 July, Boston, Massachusetts, USA.

Fischer, A., Balakrishnan, G., Kessler, S., and Fottner, J. (2020). "Begleitende Prozesssimulation für das Kellybohrverfahren (Accompanying process simulation for the Kelly drilling process)." *8. Facht. BMT,* 1-2 October, Dresden, Germany.

Fischer, A., Liang, M., Orschlet, V., Bi, H., Kessler, S., and Fottner, J. (2021a). "Detecting equipment activities by using machine learning algorithms." *Proc. 17th IFAC Symp. Inform. Control Problems Manufact.*, 7-9 June, Budapest, Hungary.

Fischer, A., Li, Z., Wenzler, F., Kessler, S., and Fottner, J. (2021b). "Cyclic update of project scheduling by using equipment activity data." *Proc. 17th IFAC Symp. Inform. Control Problems Manufact.*, 7-9 June, Budapest, Hungary.

Fosse, R., Spitler, L., and Alves, T. (2016). "Deploying BIM in a Heavy Civil Project." *Proc. 24th Ann. Conf. Int. Group for Lean Construction*, 20-22 July, Boston, Massachusetts, USA.

Friblick, F., Tommelein, I.D., Mueller, E., and Falk J.H. (2009). "Development of an Integrated Facade System to Improve the High-Rise Building Process." *Proc. 17th Ann. Conf. Int. Group for Lean Construction*, 15-17 July, Taipei, Taiwan, 359-370.

German Construction Industry Federation (2017). *BIM in Ground Engineering.* Technical Position Paper, Federal Dep. of Ground Engineering. Accessed March 31, 2021. https://www.bauindustrie.de/themen/bundesfachabteilungen/spezialtiefbau.

Girmscheid, G. (2010). *Leistungsermittlungshandbuch für Baumaschinen und Bauprozesse (Performance determination manual for construction machinery and construction processes).* Springer-Verlag, Berlin, Heidelberg, Germany.

González, V., Shahbazpour, M., Toledo, M., and Graell, J. (2014). "Understanding the Supply Relationships of Geothermal Power Generation Projects in New Zealand." *Proc. 22nd Ann. Conf. Int. Group Lean Constr.*, 25-27 June, Oslo, Norway, 1045-1056.

Grimm, N.P. (2020). "Analyse der aktuellen Grundlagen zur digitalen Leistungsermittlung von Baumaschinen (Analysis of the current basics for digital performance determination of construction machines)." *Bachelor thesis*, Chair of Materials Handling, Material Flow, Logistics, Techn. Univ. of Munich, Germany.

Günthner, W. and Borrmann A. (2011). *Digitale Baustelle- innovativer Planen, effizienter Ausführen (Digital construction site - innovative planning, efficient execution).* Springer-Verlag, Berlin, Heidelberg, Germany.

Haronian, E., and Sacks, R. (2020a). "Production Process Evaluation for Earthworks." *Proc. 23rd Ann. Conf. Int. Group for Lean Construction*, 6-12 July, Berkeley, California, USA, 601-612, doi.org/10.24928/2020/0020.

Haronian, E., and Sacks, R. (2020b). "ROADELS: discrete information objects for production planning and control of road construction." *Journal of Information Technology in Construction*, 25, 254-271, doi.org/10.36680/j.itcon.2020.015.

Hoffmann, M., and Krause, T. (2016). "Zahlentafeln für den Baubetrieb (Number tables for construction operation)." Vieweg+Teubner Verlag, Wiesbaden, Germany.

Howell, G., Laufer, A., and Ballard, G. (1993). "Interaction between Subcycles: One Key to Improved Methods." *Journal of Construction Engineering and Management*, 119(4), 714-728, doi.org/10.1061/(ASCE)0733-9364(1993)119:4(714).

Huang, M.Q., Ninić, J., Zhang, Q.B. (2021). "BIM, machine learning and computer vision techniques in underground construction: Current status and future perspectives." *Tunnelling and Underground Space Techn.*, 108, doi.org/10.1016/j.tust.2020.103677.

ISO (1991). *Earth-moving machinery - Machine productivity - Vocabulary, symbols and units.* Int. Organ. for Standardization, Beuth Verlag GmbH, Berlin, Germany, ISO 9245, doi.org/10.31030/2747891.

ISO (2018). *Organ. and digitization of information about buildings and civil engineering works, incl. building information modelling (BIM) – information management using BIM – part 1: Concepts and principles.* Int. Organ. for Standardization, ISO 19650-1.

Kalsaas, B.T. (2012). "Further Work on Measuring Workflow in Construction Site Production." *Proc. 20th Ann. Conf. Int. Group Lean Constr.*, 18-20 July, San Diego, Calif., USA.

Kaplan, H., Elburg, A., and Tommelein, I.D. (2005). "Analysis of Variability in Precasting and Installation of Pile Foundations." *Proc. Construction Research Congress*, 5-7 April, San Diego, California, USA, doi.org/10.1061/40754(183)3

Kirchbach, K., Bregenhorn, T., and Gehbauer, F. (2012). "Digital Allocation of Production Factors in Earth Work Construction." *Proc. 20th Ann. Conf. Int. Group for Lean Construction*, 18-20 July, San Diego, California, USA.

Kirchbach, K., Koskela, L., and Gehbauer, F. (2014). "Digital Kanban for Earthwork Site Management." *Proc. 22nd Ann. Conf. Int. Group for Lean Construction*, 25-27 June, Oslo, Norway, 663-676.

König, H. (2014). *Maschinen im Baubetrieb (Equipment in construction operation)*. Springer Fachmedien Wiesbaden, Wiesbaden, Germany.

Lander, E., and Liker, J.K. (2007). "The Toyota Production System and art: making highly customized and creative products the Toyota way." *Int. J. of Production Research*, 45(16), 3681-3698, doi.org/10.1080/00207540701223519.

Lasi, H., Fettke, P., Kemper, H.-G., Feld T., and Hoffmann, M. (2014) "Industrie 4.0." *Bus. Inf. Syst. Eng.*, 6(4), 239-242.

Liu, X., Wang, X., Wright, G., Cheng, J., Li, X., Liu, R. (2017). "A State-of-the-Art Review on the Integration of Building Information Modeling (BIM) and Geographic Information System (GIS)." *IJGI*, 6(2), doi.org/10.3390/ijgi6020053.

Louis, J. and Dunston, P.S. (2017). "Methodology for real-time monitoring of construction operations using finite state machines and discrete-event operation models." *J. Constr. Engin. and Manage.*, 143(3), doi.org/10.1061/(ASCE)CO.1943-7862.0001243.

McKinsey (2017). *Reinventing Construction: A route to higher productivity*. McKinsey Global Institute, www.mckinsey.com/mgi (March 31, 2021).

Oesterreich, T.D., and Teuteberg, F. (2016). "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry." *Computers in Industry*, 83(4), 121-139, doi.org/10.1016/j.compind.2016.09.006.

Olivieri, H., Seppänen, O., and Peltokorpi, A. (2017). "Real-Time Tracking of Production Control: Requirements and Solutions." *Proc. 25th Ann. Conf. Int. Group for Lean Construction*, 9-12 July, Heraklion, Greece, 671-678.

Rashidi, A., Nejad, H.R., and Maghiar, M. (2014). "Productivity estimation of bulldozers using generalized linear mixed models." *KSCE J. Civil Engineering*, 18(6), 1580-1589, doi.org/10.1007/s12205-014-0354-0.

Rosas, E., Rios, L., and Carrera, D. (2011). "Implementing Last Planner in Open Pit Mining Projects: Case Study." *Proc. 19th Ann. Conf. Int. Group for Lean Construction*, 13-15 July, Lima, Peru.

Rother, M. and Shook, J. (2009). *Learning to see: Value-stream mapping to create value and eliminate muda*. Lean Enterprise Inst., Cambridge, Massachusetts, USA.

Ruiz, C., Castillo, T., and Paredes, M. (2020). "Effects of Implementation of 5S in Heavy Equipment Maintenance Workshops." *Proc. 28th Ann. Conf. Int. Group for Lean Construction*, 6-10 July, Berkeley, California, USA, 589-600.

Schöberl, M., Cai, Z., Fischer, A., and Kessler, S. (2020). "Current Research and Developments for Civil Engineering in Germany." *Current Trends in Civil & Structural Engineering*, 5(1), doi.org/10.33552/CTCSE.2020.05.000601.

Tommelein, I.D. (2000). "Impact of Variability and Uncertainty on Product and Process Development." *ASCE, Proc. Construction Congress VI*, 20-22 Feb., Orlando, Florida, USA, 969-976, doi.org/10.1061/40475(278)101.

Tommelein, I.D., and Beeche, G. (2001). "De-coupling Exterior Cladding Installation from Interior Trades: A Case Study." *Proc. 9th Ann. Conf. Int. Group for Lean Construction*, 6-8 Aug., Singapore.

Lagos, C. I. and Alarcón, L. F. (2021). "Composition and Impact of Reasons for Noncompletion in Construction Projects" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 817–826, doi.org/10.24928/2021/0210, online at iglc.net.

COMPOSITION AND IMPACT OF REASONS FOR NONCOMPLETION IN CONSTRUCTION PROJECTS

Camilo Ignacio Lagos[1] and Luis Fernando Alarcón[2]

ABSTRACT

The Last Planner® System (LPS) uses short systematic cycles of work preparation, short-term execution commitments and identification of Reasons for Noncompletion (RNCs). LPS based software capture quantifiable information that allows to assess RNC impact on execution. RNCs can be categorized using detailed information and their impact can be obtained assessing task progress and compliance. This research aims to determine the main categories, sources and responsible parties affecting compliance, based on empirical data from 25 High-rise Building (HR) and 25 Industrial Construction (IC) projects. Weekly project information representing 22.636 RNCs was assessed to categorize each RNC by type, source and party. The task, commitment and progress information were used to determine their frequency and impact, based on the duration of the affected task and differences between committed and actual progress. The RNC categories were compared across the sample and between HR and IC projects using statistical analyses. Results showed that approximately two in every three RNCs correspond to factors controllable by the main contractor, while collaboration with the client and subcontractors could allow preventing up to 90% of noncompliance issues.

KEYWORDS

Last Planner® System, standardization, reasons for noncompletion, collaboration, reliable promising.

INTRODUCTION

The Last Planner® System (LPS) has been used to manage construction projects in multiple countries for over 28 years (Ballard & Tommelein, 2016). LPS stablishes short cycles of work preparation, commitment, execution and compliance assessment (Alsehaimi et al., 2014) and its use provides quantitative and qualitative information to allow continual improvement on a short-term basis. Its implementation has proven beneficial to increase planning reliability, workflow stabilization, performance across execution and outcomes (Daniel et al., 2015). Also, recent research has found statistically significant correlations between adoption levels, LPS metrics and project performance (Lagos et al., 2019).

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Quantitative research has been limited by the lack of large standardized data samples and, hence, has focused primarily on compliance metrics such as the Percent Plan Complete (PPC) and its relationship to performance (Daniel et al., 2015). Nevertheless, the increasing adoption of IT support systems based on LPS has provided more information, including intermediate planning, work preparation, RNCs and corrective actions, which could be used quantitatively to assess other LPS dimensions (Faloughi et al., 2014). Most LPS research focused on finding causes and sources of noncompliance has relied on single case study analyses or indirect means such as perception surveys to gather information (Daniel et al., 2015). But, most LPS software can allow to standardize and link information, thus, providing ways to use qualitative information such as RNCs in a quantitative way by linking them to performance metrics (Faloughi et al., 2014; Feliz et al., 2014; Lagos et al., 2019). Software like IMPERA automatically link constraints and RNCs to tasks at certain short-term periods, therefore, their impact can be calculated by retrieving short-term performance information for each task (Lagos et al., 2020). This research aims to quantify the frequency and impact of standardized RNC categories to determine where should practitioners and researchers focus the implementation of corrective and preventive actions and how can collaboration help prevent recurring issues.

LITERATURE RESEARCH

Many authors have covered the causes of project deviation throughout the years (Arditi et al., 1985; Assaf & Al-Hejji, 2006; Prasad & Vasugi, 2017). International studies have found that 50 to 70% of projects experience time overruns ranging from 10% to 30% (Assaf & Al-Hejji, 2006; Ullah et al., 2017). Transversal studies based on interviews and surveys have found over 70 empirical causes of deviation (Akinsiku & Akinsulire, 2012; Sambasivan & Soon, 2007), grouped into 10 major categories: Inexperience, Interference, Lack of Resources, Labour Productivity, Design, Financing, Planning, Lack of Compliance of Subcontractors, Equipment and Communication (Sambasivan & Soon, 2007). Theoretical frameworks based on literature reviews of causes of deviation, sources and effects have found that the 42 main cited causes can be attributed to 8 sources that largely correspond to the aforementioned categories, involving clients, contractors, external sources and third parties, which correspond to suppliers of resources, information or conditions (Ullah et al., 2017).

These sources exhibit a direct correspondence to the seven flows presented identified in the Lean Construction perspective: Information, People, Materials, Equipment, Space, Prior Work and External Conditions (Henrich et al., 2007). In fact, LPS research has shown that failure to assess the seven flows at the Lookahead Planning stage reduces the number of executable tasks, which in turn, decreases planning reliability (Ballard & Tommelein, 2016; Bortolazza & Formoso, 2006). A quantitative analysis of 133 projects showed that the impact of workforce shortage, planning and worksite conditions on performance can be traced to deficiencies in constraint management or the removal of RNC sources through corrective actions (Bortolazza & Formoso, 2006). Another study regarding 69 projects showed that 81% of the projects' RNCs were caused by internal controllable factors (Formoso & Moura, 2009).

LPS, which is based on the Lean Construction philosophy, promotes workflow stabilization to reduce waste and improve performance (Ballard & Tommelein, 2016). It stablishes systematics cycles where tasks are assessed in advance to determine if they lack some of the seven prerequisite conditions. If so, a constraint is identified, managed and removed to make that task executable. The set of executable tasks conforms the

Workable Inventory, which is used to stablish short-term execution commitments. Compliance is assessed at the end of each short-term period, through the use of the PPC indicator, to determine workflow reliability and, if any task did not fulfil its commitment, it will be assigned a RNC, which corresponds to a rupture in any of the seven production flows (Ballard et al., 2009).

LPS implementation must follow 5 principles (Ballard et al., 2009): (1) Planning detail only increases when needed to plan, prepare, commit or execute tasks, (2) Planning must be a collaborative effort, (3) Upcoming work is pulled by removing constraints, (4) commitments are traced to assess reliability, and (5) the sources of recurring problems should be systematically removed. These principles are implemented through 5 LPS components (Ballard & Tommelein, 2016): Lookahead Planning, constraint management and work preparation, short-term planning, Reliability assessment and collection of RNCs, and implementation of corrective actions.

Researchers have found that most projects exhibit partial LPS implementations, focusing mainly on the second and fourth components of the methodology (Dave et al., 2015). Hence, project teams are able to stablish commitments collaboratively, monitor compliance and variability, register RNCs and their sources. Although, they lack attention to two key stages: Assessing the needs for effective work preparation through constraint management; and assessing the main sources of recurring problems to focus corrective actions (Lagos et al., 2019). Deficiencies in the implementation of the third and fifth components has been attributed to three factors: Lack of understanding of their relevance; lack of time or resources to collect and assess that information; and lack of standard metrics to assess them (Daniel et al., 2015).

The scarcity of complete implementations, lack of standardized data and effort required to collect it, has forced researchers to focus either on case-study approaches or the use indirect means like surveys and interviews to assess the relationships between LPS components and performance (Brady et al., 2011; Daniel et al., 2015; Dave et al., 2015). Despite those limitations, researchers have found that the increasing LPS adoption leads to performance improvements (Hamzeh & Aridi, 2013), and contributes to aspects such as planning, workforce and site management, collaboration between parties and waste reduction (Alsehaimi et al., 2014). Case study research has also signalled the relevance of weekly collaborative meetings to empower the work-force in stablishing reliable commitments, removing constraints and preventing RNC sources (Soares et al., 2002). Although, researchers have also found that collaboration tends to focus mainly in stablishing short-term commitments instead of the assessment and implementation of work-preparation and RNC reduction actions (Gao & Low, 2014).

Recent research has showed that the use of LPS based support software aids to capture, process and use more information in a standardized and systematic way, especially regarding constraint and RNC management (Faloughi et al., 2014; Lagos et al., 2019). These systems automate data processing to deliver information through graphs and panels, which facilitate their analysis (Dave et al., 2010). Using visual information to promote communication has shown benefits in key processes such as constraint identification, on-site coordination and RNC assessment (Tayeh et al., 2019). This has also contributed to the collection of standardized project samples with quantifiable information regarding elements such as constraints, commitments, RNCs and progress (Faloughi et al., 2014; Feliz et al., 2014; Lagos et al., 2020). Transversal quantitative studies carried out with these samples has allowed to determine statistically significant correlations between constrain management, short-term compliance, RNC occurrence, cost and time performance (Kim, 2019; Lagos et al., 2019). Also, exploratory research showed that quantitative metrics based on constraints and RNC information exhibit correlations with LPS compliance and performance metrics, so that they can be used to assess management and execution performance (Kim, 2019; Lagos et al., 2019, 2020).

METHODOLOGY

The review of over 120 papers published between 1985 and 2020, regarding (1) Causes and sources of deviation and (2) LPS implementation, allowed to determine the opportunity to use standardized project information quantitatively to assess the frequency and impact of RNCs. The use of the software IMPERA was selected since it was developed by the Pontificia Universidad Católica de Chile to support LPS implementation and research (Alarcón & Calderón, 2003). Previous research signalled that most RNCs are caused by internally controllable factors (Formoso & Moura, 2009), hence, the hypothesis "Most RNCs are caused by internally controllable sources" was formulated. Three research questions were established: (1) Which are the most relevant types of RNCs affecting projects which use the Last Planner® System? (2) what is the relative impact of different parties on RNCs? and (3) What percent of RNCs could be prevented by the direct project team? The aim of the research was to determine the main sources, responsible parties and RNC types affecting construction projects, using standardized information captured by the software. A database comprised weekly information from the entire execution scope of 25 high-rise building and 25 industrial construction projects, carried out by 12 Chilean construction companies between 2012 and 2019, was used to assess RNC relevance, composition and impact. The sample was first used in research presented at IGLC28 (Lagos et al., 2020; Lagos & Alarcón, 2020).

COLLECTION AND STANDARDIZATION OF INFORMATION

Standardized information tables regarding the plan, tasks, short-term periods and RNCs were obtained for each project. The plan table contained the type of the project, it's ID, it's initially planned start and end dates, and its actual start and end dates. The tasks table contained a detailed log, including the ID, initial planned dates, current planned dates and the initial, committed and actual progress, of each task in each short-term period of each project. The RNCs table included their ID, the affected task ID, project ID, date of occurrence, type, detailed description and responsible party registered by the project's team for each issue. This information allowed to categorize each RNC, link it to a specific task in a certain short-term period and determine their impact.

The RNCs types were consolidated based on the detailed information available and assigned into eight categories based on the seven flows (Koskela, 2008): Labour, Supply, Worksite Conditions, Productivity, Planning, Engineering and Design, Unforeseen events, and Quality. The responsible parties were classified into four categories, based on similarities of the distinct party registered and the details provided: Main Contractor, Subcontractors, Client, and Third Parties, such as suppliers or external agents. Finally, the sources were categorized as: Internal, if the Main Contractor's direct team could have prevented the issue, or External if it could not have been controlled by them. The sources were determined based on the RNC and affected task details.

ASSESSMENT OF RNC COMPOSITION AND IMPACT

Each project was assessed separately to determine the relevance of each RNC category. The indicator "Relative Frequency Index" (RFI) was calculated in each project as the percent of RNCs belonging to each the category, to assess composition. The Task-Days Impact indicator (TDI), which represented the delay in days caused by a single RNC in a specific task was used to represent the impact of each RNC in the project. The TDI was calculated as the percent difference between commitment and progress, multiplied by the duration of the task. The sum of the TDIs from a specific category in a project was divided by the sum of all its RNC's TDIs to obtain an impact indicator for each category, called the Relative Impact Index (RII). Table 1 shows the calculation of these metrics.

Table 1. Description of RNC metrics

RNC Metric	Indicator	Description
Frequency	N° RNC	$N°\ RNCs_{Category\ i}$
Impact	Task-Days Impact	$TDI = (Planned_{\%} - Actual_{\%}) * Duration_{task}$
Composition	Relative Frequency Index	$RFI = \frac{N°\ RNCs_{Category\ i}}{Total\ N°\ RNCs_{Project\ j}}$
Relevance	Relative Impact Index	$TDI = \frac{\sum_{RNCs\ in\ category\ i} TDI_{RNC\ j}}{\sum_{All\ the\ RNCs\ in\ the\ project} TDI_{RNC\ k}}$

ANALYSIS OF DIFFERENCES BETWEEN PROJECTS AND RNC CATEGORIES

The project types were compared using the average RFI and RII from each group. The normality of each project type sample was assessed using the Shapiro-Wilk's Test (Lagos & Alarcón, 2020). The null hypothesis "the sample follows a normal distribution" was established using a 95% confidence level, so if any of the samples obtained a p-value≤0.05 it meant that it did not follow a normal distribution. If both samples followed a normal distribution, the t-test was used to determine the statistical significance of the differences and, if any of the samples was not normal, the non-parametric Mann Whitney's U test was used instead. In both cases, the null hypothesis "the samples do not present significant differences" was rejected if p>0.05 (Hernández et al., 2006). The RFI and RII from two or more categories within a project type and in the entire sample are co-dependent variables, since an increase in the percent relevance of a category implies a decrease in the relative relevance of the rest of the categories. Hence, the N° of RNCs in each category and the sum of their TDIs, which are independent variables, were used to compare categories against each other. The same process was followed to assess the normality and statistical significance of the observed differences.

RESULTS AND DISCUSSION

The study sample represented 22.636 RNCs from 50 projects, with a minimum of 22 RNCs a maximum of 2845 RNCs per project. The average number of RNCs per short-term period was 9.8, with a minimum of 1.2 RNCs per week and a maximum of 44.1. This section addresses the three research questions separately.

WHICH ARE THE MOST RELEVANT RNC TYPES?

Table 2 shows that labour, supply and worksite conditions represented approximately 55% of the issues and impact in the entire sample. Also, labour, productivity, planning, quality and worksite conditions, which are potentially controllable issues, accounted for approximately 66% of the issues and impact. Although, as Table 3 presents, significant differences were found in RNC composition between HR and IC projects. Controllable types represented 79% of RNCs and 82% impact in HR projects, while only 53% and 52% in IC projects, respectively: However, these results were consistent with the hypothesis.

Table 1. RNC types by frequency and impact

RNC Type	RFI average	RII average
Labour	20,7%	22,4%
Supply	17,2%	16,9%
Worksite conditions	16,9%	16,5%
Productivity	13,1%	12,1%
Planning	11,2%	10,8%
Engineering and Design	10,3%	11,4%
Unforeseen events	6,2%	6,0%
Quality	4,4%	3,8%

Labour and productivity issues were significantly greater in HR projects, while the main issues in IC were Worksite Conditions, Supply and Engineering-Design. These differences can be explained by the nature and conditions of execution in each project type. The IC projects in the sample were brownfields executed in mining or productive sites far from urban locations, meaning that they were carried out while the client continued operations and the supply of resources required longer times. Also, Engineering-Design was provided by the client. In comparison, HR projects were mostly executed in large or mid-size cities, on sites owned by the Contractor or Realtor and with Engineering-Design provided beforehand either by the Realtor or the Contractor. Hence, external and uncontrollable factors were less likely to impact production in HR projects.

Table 2. Comparison of RNC types in HR and IC projects

RNC Type	RFI				RII			
	HR	IC	Delta	p-value	HR	IC	Delta	p-value
Engineering-Design	3%	**17%**	-80%	0,00	4%	**19%**	-79%	0,00
Labour	**33%**	9%	280%	0,00	**37%**	8%	340%	0,00
Planning	11%	12%	-7%	0,44	11%	11%	-5%	0,34
Productivity	**17%**	9%	96%	0,02	**16%**	8%	108%	0,02
Quality	7%	1%	429%	0,00	6%	2%	300%	0,00
Supply	**14%**	**21%**	-32%	0,02	**13%**	**20%**	-34%	0,03
Unforeseen events	3%	10%	-69%	0,03	3%	9%	-71%	0,04
Worksite conditions	11%	**22%**	-49%	0,01	11%	**23%**	-53%	0,00

WHAT IS THE RELATIVE IMPACT OF DIFFERENT PARTIES ON RNCS?

Table 4 shows that the Main Contractor and Subcontractor accounted for 74% of the RNCs and 75% of their impact over the entire sample. Hence, the Client and Third parties contributed significantly less to performance issues than the on-site project team. Although, Table 5 shows differences consistent with the findings from the previous question. The Main Contractor and its Subcontractors produced approximately 96% of issues in HR projects, while in IC projects, they were responsible for 54% of the RNCs and 55% of their impact. These results still corroborate the hypothesis that most issues could potentially be controlled by the direct team, but two findings are worth discussing in more detail.

Table 3. Composition and impact by RNC responsible party

RNC Metrics	Main Contractor	Subcontractor	Client	Third Parties
RFI	45%	29%	18%	8%
RII	45%	30%	16%	9%

First, Subcontractors had a significantly greater impact on HR projects than the Main Contractor and, second, the client was responsible for almost a third of the RNCs in IC project; both results are consistent with the literature findings. A recent study observed that parties tended to act as autonomous agents, unless the Main Contractor ensured a clear understanding of roles and objectives of collaborative LPS instances (Rincón et al., 2019). Thus, if the client and subcontractors are not actively involved in planning and continual improvement, they operate separately from the core team, contributing to noncompliance instances. Transparency, direct communication and collaboration incentives are key to sustain efficient constraint management and RNC removal processes (Brady et al., 2011), therefore, if project teams fail to make constraints and RNC sources explicit, they fail to work as a single interrelated chain of commitments (Porwal, 2010).

Table 4. Comparison of the relevance of each party between HR and IC projects

Responsible parties	RFI				RII			
	HR	IC	Delta	p-value	HR	IC	Delta	p-value
Client	1%	**34%**	-96%	0,00	2%	**31%**	-95%	0,00
Main Contractor	**41%**	**50%**	-19%	0,11	**39%**	**51%**	-24%	0,05
Subcontractor	**55%**	4%	1342%	0,00	**57%**	4%	1395%	0,00
Third parties	3%	12%	-75%	0,13	3%	15%	-81%	0,07

What percent of RNCs are controllable by the project team?

Table 6 shows that internal RNC sources were slightly more predominant than external causes, however, the differences were not sufficient to exhibit statistical significance. These results indicate that sources controllable by the Main Contractor are at least as relevant as external sources in terms of frequency and performance impacts. Table 7 shows that internal sources were also slightly more predominant in HR than in IC projects, which is consistent with the previous findings, although, the differences between the project groups were not statistically significant. Finally, Table 8 shows that internal RNCs were 20% more frequent but only caused 10% more impact, without exhibiting statistically significant differences. These results allowed to conclude that the Main Contractor should be able to prevent at least half of the RNCs observed, but the findings from previous sections demonstrate that close collaboration with the Client and Subcontractors could help to prevent almost 90% of the sources of noncompliance.

Table 6. RNC source analysis

RNC metrics	Internal	External	Difference	p-value
N° RNCs	252	201	20%	0.13
TDI sum	1435	1294	10%	0.27

Table 7. Source comparison between HR and IC projects

Responsible parties	RFI				RII			
	HR	IC	Delta	p-value	HR	IC	Delta	p-value
Internal	**58%**	**53%**	9%	0,38	**55%**	**53%**	4%	0,73
External	42%	47%	-10%	0,38	45%	47%	-4%	0,73

Table 8. Comparison of internal and external sources within each project category

Metrics	HR				IC			
	Internal	External	Delta	p-value	Internal	External	Delta	p-value
N° RNCs	408	322	27%	0.16	95	79	20%	0.22
TDI Sum	2301	2092	10%	0.25	569	492	16%	0.30

CONCLUSIONS

This research aimed to determine the most relevant RNCs categories affecting LPS projects. 22.636 RNCs from 25 high-rise building (HR) and 25 industrial construction (IC) projects were assessed qualitatively and quantitatively to determine the frequency and impact of 8 types, 4 responsible parties and 2 sources of noncompliance. The results showed that two thirds of all the RNCs assessed belonged to types controllable by the core project team. Moreover, approximately 80% of RNCs corresponded to potentially controllable issues in HR projects. The RNCs type differences exhibited between HR and IC projects were explained by the nature and conditions of each project category.

The responsible party analyses were consistent with the previous findings and indicated that approximately 90% of issues were caused by the Main Contractor or its Subcontractors in HR projects, while they were responsible for approximately 55% of the RNCs in the IC sample. The second most relevant party in IC projects was the Client, who was responsible for one in every three issues. Moreover, the source analyses showed that the Main Contractor could have potentially prevented at least half of the RNCs, but that percent could be increased to over 85% of issues if they collaborate closely with the Client and Subcontractors through transparency, direct communication and implementation of correct incentives. Finally, the authors suggest that this research should be continued by expanding the sample, to allow assessing key differences in RNC composition and impact between projects with high- and low-performance and finding means to prevent RNCs.

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REFERENCES

Akinsiku, O., & Akinsulire, A. (2012). Stakeholders' Perception of the Causes and Effects of Construction Delays on Project Delivery. *KICEM Journal of Construction Engineering and Project Management*.

Alarcón, L. F., & Calderón, R. (2003). A production planning support system for construction projects. *11th Annual Conference of the International Group for Lean Construction. Virginia, USA.*

Alsehaimi, A. O., Fazenda, P. T., & Koskela, L. (2014). Improving construction management practice with the Last Planner System: A case study. *Engineering, Construction and Architectural Management*, *21*(1), 51–64.

Arditi, D., Akan, G. T., & Gurdamar, S. (1985). Reasons for delays in public projects in Turkey. *Construction Management and Economics*, *3*(2), 171–181.

Assaf, S. A., & Al-Hejji, S. (2006). Causes of delay in large construction projects. *International Journal of Project Management*, *24*(4), 349–357. doi.org/10.1016/j.ijproman.2005.11.010.

Ballard, G., Hammond, J., & Nickerson, R. (2009). Production control principles. *Proceedings of IGLC17: 17th Annual Conference of the International Group for Lean Construction*, 489–500.

Ballard, G., & Tommelein, I. (2016). Current Process Benchmark for the Last Planner System. *Lean Construction Journal*, *13*(1), 57–89.

Bortolazza, R., & Formoso, C. (2006). A Quantitative Analysis of Data Collected From the Last Planner System in Brazil. *14th Annual Conference of the International Group for Lean Construction Santiago de Chile*, 625–635.

Brady, D., Tzortopoulos, P., & Rooke, J. (2011). an Examination of the Barriers To Last Planner Implementation. *19th Annual Conference of the International Group for Lean Construction*, 13–15.

Daniel, E., Pasquire, C., & Dickens, G. (2015). Exploring the Implementation of the Last Planner® System Through Iglc Community: Twenty One Years of Experience. *Proceedings for the 23rd Annual Conference of the International Group for Lean Construction, Perth, Australia., February 2016*, 153–162.

Dave, B., Boddy, S., & Koskela, L. (2010). Improving information flow within the production management system with web services. *18th Annual Conference of the International Group for Lean Construction*, 445–455.

Dave, B., Hämäläinen, J.-P., & Koskela, L. (2015). Exploring the Recurrent Problems in the Last Planner Implementation on Construction Projects. *Proceedings of the Indian Lean Construction Conference (ILCC 2015)*, 1–9.

Faloughi, M., Bechara, W., Chamoun, J., & Hamzeh, F. (2014). SimpLean: An Effective Tool for Optimizing Construction Workflow. *Proceedings for the 22nd Annual Conference of the International Group for Lean Construction*, 281–292.

Feliz, T., Reed, D., Draper, J., & Macomber, H. (2014). Leveraging software for learning-in-action using commitment-based planning. *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*, 1307–1318.

Formoso, C. T., & Moura, C. B. (2009). Evaluation of the impact of the Last Planner system on the performance of construction projects. *Proceedings of IGLC17: 17th Annual Conference of the International Group for Lean Construction*, 153–164.

Gao, S., & Low, S. P. (2014). The Last Planner System in China's construction industry - A SWOT analysis on implementation. *International Journal of Project*

Management, *32*(7), 1260–1272.
Hamzeh, F., & Aridi, O. (2013). Modeling the last planner system metrics: a case study of an aec company. *Proceedings for the 21th Annual Conference of the International Group for Lean Construction. Fortaleza, Brazil*, 599–608.
Henrich, G., Bertelsen, S., Koskela, L., Kraemer, K., Rooke, J., & Owen, R. (2007). Construction Physics. *15th IGLC - International Group for Lean Construction Conference*, 1–14.
Hernández, R., Fernández, C., & Baptista, P. (2006). Metodología de la investigación. In *McGraw-Hill Interametricana*.
Kim, Y. W. (2019). The impact of make-ready process on project cost performance in heavy civil construction projects. *Production Planning and Control*, *30*(13), 1064–1071.
Lagos, C., & Alarcón, L. F. (2020). Using Percent Plan Completed for Early Success Assessment in the Last Planner System. In I. Tommelein & E. Daniel (Eds.), *Proc. 28th Annual Conference of the International. Group for Lean Construction (IGLC28)*.
Lagos, C., Alarcón, L. F., Basoalto, F., & Del Río, Ó. (2020). Using Reasons for Non-Compliance To Assess Project Performance in the Last Planner System. In I. Tommelein & E. Daniel (Eds.), *Proc. 28th Annual Conference of the International. Group for Lean Construction (IGLC28)*.
Lagos, C., Herrera, R. F., & Alarcón, L. F. (2019). Assessing the Impacts of an IT LPS Support System on Schedule Accomplishment in Construction Projects. *Journal of Construction Engineering and Management*, *145*(10), 1–10. doi.org/10.1061/(ASCE)CO.1943-7862.0001691.
Porwal, V. (2010). *Last Planer System - Areas of application and implementation challenges*. Texas A&M University.
Prasad, K. V., & Vasugi, V. (2017). Delays in construction projects: A review of causes, need and scope for further research. *Malaysian Construction Research Journal*, *23*(3), 89–113.
Rincón, J. L., Fernández-Solís, J. L., Lavy, S., & Du, J. (2019). Effect of Autonomous Agents on Last Planner System Performance in Texas. *Journal of Management in Engineering*, *35*(1), 04018050. https://doi.org/10.1061/(asce)me.1943-5479.0000657
Sambasivan, M., & Soon, Y. W. (2007). Causes and effects of delays in Malaysian construction industry. *International Journal of Project Management*, *25*(5), 517–526. doi.org/10.1016/j.ijproman.2006.11.007.
Soares, A., Bernardes, M., & Formoso, C. (2002). Improving the production planning and control system in a building company: Contributions after stabilization. *Annual Conference of the International Group for Lean Construction*, *10*, 1–12.
Tayeh, B. A., Hallaq, K. Al, Zahoor, H., & Al Faqawi, A. H. (2019). Techniques and benefits of implementing the last planner system in the Gaza Strip construction industry. *Engineering, Construction and Architectural Management*, *26*(7), 1424–1436. doi.org/10.1108/ECAM-01-2018-0039.
Ullah, K., Abdullah, A. H., Nagapan, S., Suhoo, S., & Khan, M. S. (2017). Theoretical framework of the causes of construction time and cost overruns. *IOP Conference Series: Materials Science and Engineering*, *271*(1). doi.org/10.1088/1757-899X/271/1/012032.

PRODUCTION SYSTEM DESIGN

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Lehtovaara, J., Heinonen, A., Ronkainen, M., Seppänen, O., and Peltokorpi, A. (2021). "Takt Production as Operations Strategy: Client's Perspective to Value-Creation and Flow." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 829–838, doi.org/10.24928/2021/0118, online at iglc.net.

TAKT PRODUCTION AS OPERATIONS STRATEGY: CLIENT'S PERSPECTIVE TO VALUE-CREATION AND FLOW

Joonas Lehtovaara[1], Aleksi Heinonen[2], Miika Ronkainen[3], Olli Seppänen[4], and Antti Peltokorpi[5]

ABSTRACT

Takt production is the most recent iteration of location-based production planning and control methods, adopting insights from lean construction and manufacturing operations management literature. In this research, we aim to advance the discussion between these domains further, especially considering the client's viewpoint. We approach takt production as a form of a project's operations strategy, allowing an explicit connection between client value-creation, production flow, and takt planning and control. Five key performance indicators are proposed to aid the client's understanding in assessing (and challenging) the effectiveness and value-creation capability of a specific takt production system. Furthermore, the approach is illustrated by applying it to a master planning phase of a large hospital project. The study has implications for clients and other stakeholders to evaluate their capability to operate with takt production from the lenses of value-creation and production flow. We also hope that the study encourages scholars and practitioners to engage in further discussion with the nature of takt production, observing it from various theoretical and practical viewpoints.

KEYWORDS

Lean construction, takt production, operations strategy, production planning and control, production system design.

INTRODUCTION

Within the last decade, takt production has gained a rapid interest in construction operations management and in the lean construction community. Especially general contractors (GCs) have seen that the implementation of takt production leads to increased production performance. The documented benefits include radical duration reductions of over 50% (e.g., Binninger et al. 2018), increased transparency of communication and effectiveness in production control (Frandson & Tommelein 2014), increased quality and safety (Heinonen & Seppänen 2016), and increased worker productivity (Kujansuu et al.

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2020). Also, other project stakeholders, such as clients (e.g., Dlouhy et al. 2017a), have recently attempted to adopt the method into their practices. Here, client denotes the party responsible for funding and commissioning a construction project.

However, takt production research and development efforts have often been conducted through the lenses of GC and production (flow) effectiveness, with little focus on examining how takt production could most effectively increase value[6] for the client. Even though the client evidently benefits from the increased production effectiveness (such as reduced duration), the missing client's value-driven key performance indicators (KPIs) hinder the possibility of transparently seeing and reaping all the potential benefits of takt production. For a GC, utilizing takt production successfully is an ambiguous promise as there are no specific and measurable requirements for what successful takt production is.

The client's viewpoint has been previously explored, for example, by Dlouhy et al. (2017a), Binninger et al. (2017a), and Haghsheno et al. (2016). In their studies, they rightly argue that the value-creation for the client should be complemented with an adequate process-driven approach. Simultaneously, the process design of takt production should be aligned with the client's value requirements, for example, by recognizing the need to determine takt time and production phasing based on demand and client-determined milestones. Here, takt time serves as a nominator between demand and supply, pacing the production to match customer needs.

Now, we would like to expand these ideas on continuing to build a bridge between the client's value-creation and production flow effectiveness. In this study, we do this by approaching takt production as a form of a project's operations strategy, adopting viewpoints from manufacturing operations management literature, such as from Factory Physics (Hopp & Spearman 2011). We aim to clarify how the client's success can be connected to takt production system's performance through tangible KPIs: this would allow clients to evaluate how different takt production decisions could most successfully promote their project and long-term business goals, to proactively advance flow-efficiency improvement, and also to better understand how capable different service providers, such as contractors, are to succeed with takt production.

The remaining of the paper is structured as follows. First, we look at how takt production could be inspected from the operations strategy perspective. We then propose KPIs that connect value-creation and flow-effectiveness to takt planning and control process. Then, we demonstrate the approach in action through a case example of a takt planning process in a master planning phase of a large Finnish hospital project. Finally, we engage in a brief discussion regarding the implications of the approach and conclude with possible future research avenues.

OPERATIONS STRATEGY APPROACH

In the last three decades, the transformation-flow-value (TFV) (Koskela 1992) theory of construction production has guided the research of planning and control methods towards pursuing flow-efficiency among lean construction research. The research and development of takt production have followed the same path. Indeed, documented cases have reported takt production to improve production flow holistically, especially by

[6] We here follow the definition of Womack & Jones (1996); they define value as something determined by the client, being "a specific product (a good or service, and often both at once) which meets the customer's need at a specific price at a specific time".

promoting good process flow elements such as minimized durations and minimized work in progress (WIP) (e.g., Linnik et al. 2013). As construction processes possess a large amount of waste that is often hidden under overly large time buffers (Ballard & Howell 1998), aggressively focusing on flow-efficiency often has primarily positive effects, leading, for example, to a possibility to reduce waste and to reduce production duration.

While the sole pursuit of flow can be seen as somewhat valuable in itself, only promoting flow can be an inefficient goal if the initiative is not tied to value-creation and the project's desired scope (Pound et al. 2014, Koskela 1992). For example, reducing WIP to an absolute minimum might not result in increased benefits: instead, this reduction would most likely result in a high need for control efforts and WIP starvation, leading to increased costs and reduced performance (Little & Graves 2008). Thus, with no connection to value-creation, solely improving flow might have certain initial benefits but can eventually face diminishing returns (Modig & Åhlström 2012).

In takt production domain, lack of universal capability KPIs hinders contractors' ability to improve their flow-efficiency in a way that is connected to clients' goals. Construction projects form loosely coupled and fragmented systems, in which the production planning and control process are often procured as a "black box" from the contractors (e.g., Dubois & Gadde 2002), often resulting in vague requirements for production performance that are based on guesses and rule of thumbs. The cycle continues as even though production performance can be improved within a project, this information seldom reaches the upstream and the client in the form that could help them improve their requirements for the next project (Henderson et al. 2013).

To shed light on this problem, we take a stance to approach takt production as a project's operations strategy, which considers how to conduct operations in a way that supports the prevailing business case best as possible. We adopt the definition of Pound et al. (2014), as they describe operations strategy as an act of designing, implementing, and controlling the portfolio of ***demand***, ***time, cost, inventory***, ***variability*** [with adequate buffer management], and ***capacity*** to best achieve a company's financial and marketing goals. By applying this definition to takt production, one can design, implement, and control a takt production system that resonates with the project scope and considers the improvement of flow-effectiveness. In the following section, we propose five KPIs to evaluate the effectiveness and value-creation capability of a takt production system and break down how individual components of the system are connected to the KPIs.

TAKT PRODUCTION AND OPERATIONS STRATEGY

PROJECT SCOPE (DEMAND)

We propose the following KPIs for projecting the project scope and for roughly framing the desired product: ***total gross area*** [m2] and ***required quantity of work per gross area*** [h/m2]. Quantity of work per gross area is the amount of work per gross area (e.g., sqm2 of drywall per gross area, acquired from quantity estimations), multiplied by productivity factor (e.g., how long does it take to produce a sqm2 of drywall, acquired from managers' and workers' experienced guesses, previous projects' data, or from public productivity ratio databases). The hours denote total working hours, and the crew sizes are determined separately. Even though the quantity varies between tasks and different project types, it provides a rough but easily comparable indicator for projects with similar scope.

TIME AND COST

The third KPI, ***lead time***, indicates how fast the whole production can be completed from start to finish and matched with client demand (Hopp & Spearman 2011). Short lead time means that the client acquires the product faster while getting more swift returns for their investment. The fourth proposed KPI, ***batch-specific lead time,*** indicates how fast a specific part of production (i.e., an apartment) is completed from start to finish. Shortened batch-specific lead time can be beneficial when the client benefits from paced handover (Dlouhy et al. 2017b), enabling the commission of spaces before the whole product is finished. To decrease (batch-specific) lead times, minimizing variability, non-value-adding activities, and unnecessary (time)buffers is crucial. Together, these two indicators express how timely the production system can respond to the client's needs. Moreover, when the marginal cost for one day of production is known, one can deduce the value of lead time for the client and connect that to the costs. The marginal cost calculation should consider time-related costs of production and opportunity costs of the building operations.

QUALITY AND TRANSPARENCY (INVENTORY)

Transparency of the process and quality of the product increase when information flows through the production organization swiftly, urging the participants to steer the process and solve emerging issues proactively. By increasing production transparency, possibilities for errors, need for rework, and decreased value are reduced, driving for better quality. These benefits can be connected to a setting where the inventory of work is managed effectively and tightly: the work is progressed within small batches, with small WIP, crews working closely together, problems made actively visible and proactively solved (Hopp & Spearman 2011).

Based on the notions above, we propose ***production's tightness***, measured as the average area occupied by a single worker [m2/worker], as a fifth KPI. Tightness is closely connected to effective management of inventory, and when the cost of (poor) quality (such as costs of errors and rework) is known, one can derivate the value of tightness for the client. However, too tight work areas might yield diminishing results when the worker productivity decreases due to congestion (Thomas et al. 2006). Similar to the quantity of work per gross area, the production's tightness also provides a rough but comparable metric between similar types of projects.

VARIABILITY

Production variability indicates how much specific production metrics can deviate from their target amount. Accompanied with waste elimination, managing variability is central in enabling good production flow. In an ideal state all waste and variability are removed, however, in reality all production processes possess at least some degree of waste and variability (Hopp & Spearman 2011), resulting in decreased stability and predictability of the production. To diminish the remaining variability's adverse effects, a portfolio of time, plan, inventory, and capacity buffers can be introduced to the process (Hopp & Spearman 2011, Frandson et al. 2015). As variability can have several different sources and forms, flexible usage of the whole buffer portfolio is essential. The buffers can be implemented first during the process design and then applied as needed during production. Buffers also have varying effects on the presented KPIs, examined below.

Time buffering

Time buffering prevents clashes of work crews and is useful when the process has a great amount of uncontrollable variability but results in longer lead times while hiding problems and hampering transparency (Horman & Thomas 2005). In construction, time buffers are often used as a primary production balancing buffer.

Plan buffering

Denotes moving tasks from the main schedule to a 'secondary schedule' executed with spare time and resources. Reduces trade crews' idle time if they otherwise would have to wait for work, but an excess amount of backlog can result in increased lead time and ineffective inventory management, as the work is moved from the main schedule to more non-critical tasks and the problem-solving can be more easily avoided.

Batch sizing (inventory buffering)

Inventory buffering results in conducting work in larger batch sizes. This leads to an increased amount of simultaneously operated space and tasks, leading to increased WIP. Like time buffers, large inventory allows to prevent clashes between trades and brings flexibility to their work, but simultaneously results in longer lead times with decreased transparency (Little & Graves 2008). With small inventory buffers, the production is observed in tighter cycles, resulting in transparency and urgency to improve the process more proactively. However, a small inventory can also create vulnerability when the system possesses a large amount of uncontrollable variability.

Capacity buffering

Denotes adding more resources to a task than what is necessarily needed. Enables to tackle problems within production proactively, as the excess capacity can be used for solving problems, quality management, and continuous improvement, however, can result in increased costs (Horman & Thomas 2005). Capacity buffers theoretically decrease resource efficiency but increase it over time as problems are proactively solved. In construction, capacity buffers are often avoided as they are believed to increase initial costs.

DESIGN, IMPLEMENTATION, AND CONTROL OF THE PRODUCTION SYSTEM

Takt planning (process design)

Takt planning process consists of balancing buffer portfolio with takt production parameters, namely takt trains and wagons (process and sub-processes consisting of sequenced work tasks), takt time (time given to complete any set of sub-processes in a given location), and takt areas (determined locations in which work tasks are completed within the rhythm of takt time) (Lehtovaara et al. 2021). The selection of these parameters should be based on providing the best combination of client value and production effectiveness; takt planning is not just a method to create a visual plan but also to translate customer need into operative targets. In addition, the process design (and control) should consider the management of capacity (e.g., workers, material, equipment).

Takt control (implementation and control)

Takt control concerns how to implement, measure, and maintain the production system's desired performance. When the planned parameters are also maintained during the production, the desired value is achieved. To steer the production, takt control employs rhythmic production management aiming for steady wagon handoffs, proactive quality management, and visual, collaborative problem solving with root-cause analysis (Frandson et al. 2015). Production can also be steered by adjusting the takt production parameters (Binninger et al. 2017b) and applying or removing buffers. Together, these actions form a basis to steer the production so that the project's scope is meaningfully fulfilled while also providing a transparent way to communicate the production progress for all project stakeholders.

Figure 1 synthesizes the above-described elements, providing insights on the connection between the desired client value, process design, implementation and control, variability management, and the KPIs. It should be noted that the links are somewhat exaggerated as the system always needs to be inspected holistically. Next, we will demonstrate the presented approach in action through a case example.

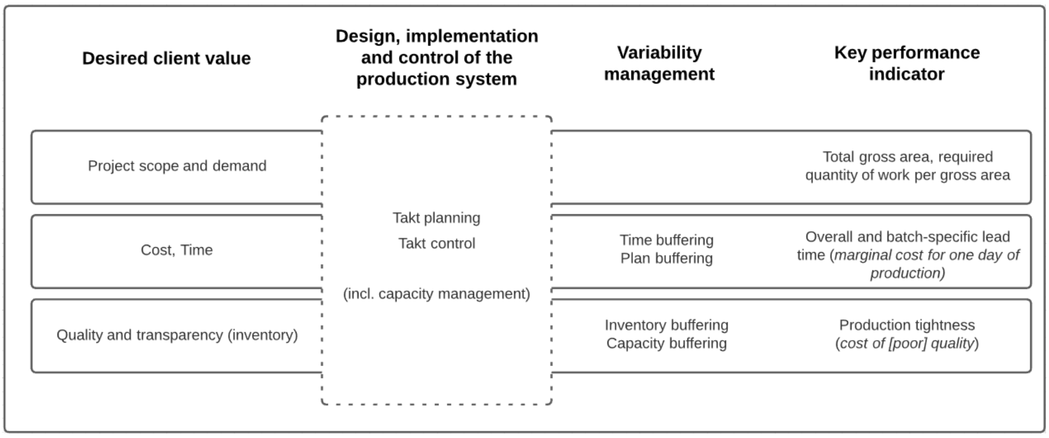

Figure 1: Synthesis of the operations strategy approach

ILLUSTRATIVE CASE EXAMPLE

CASE DESCRIPTION

The presented case is a study for a large hospital project in Helsinki, Finland. The project includes construction of new buildings and renovation of old spaces, consisting of 150,000 m2 of space. The project's overall duration is preliminarily estimated to span eight years and to cost 700 M€. The project is executed with an integrated project delivery method (IPD), in which the integrated project team concurrently performs design and production planning activities. The client has requested potential GC's to employ a takt production approach to seek lead time reduction opportunities and increase transparency during production.

The operations strategy approach was utilized in the master planning phase. The aim was to create a master plan that forms a rough but tangible frame to further help the IPD team conduct target-value-based production preparation. More specifically, the master planning phase's scope was to ensure a basis for transparent, stable, flow-efficient project execution that would provide the best client value. The master planning consisted of three steps, described below.

STEP 1: DATA COLLECTION

The following data were obtained from the preliminary designs, construction manager consultant estimations, references from previous similar projects, and from a national productivity factor database:

- Total gross area by functional areas (m2); based on preliminary designs.
- Required quantity of work per gross area by areas and production phases (h/m2); based on manager consultant estimations and productivity factor database.
- Estimated/desired project lead time and batch-specific lead times (h); based on client's requirements.
- Estimated/desired tightness of the production by phases (m2/worker); based on the previous hospital projects' tightness and average trade crew capabilities.

The obtained variables are presented in Figure 2. The bottom side of the figure (labeled green) also contains initial takt planning parameters for takt planning, which are elaborated below.

Building	Type	gross m2	Quantity of work (hours) per phase						
			Demolition	Earthworks	Foundations	Struct. & exter.	Interior 1	Interior 2	Finishes
East	New building	7 800		4 000	10 000	61 000	15 400	40 200	52 200
Main North 1	New building	24 000		2 000	7 500	83 500	38 500	117 400	156 800
Main North 2	New building	24 000		2 000	7 500	83 500	38 500	117 400	156 800
Main South 1	New building	24 000		2 000	7 500	83 500	38 500	117 400	156 800
Main South 2	New building	24 000		2 000	7 500	83 500	38 500	117 400	156 800
North	New building	11 300		650	7 800	65 000	11 700	55 400	73 500
Building 1	Renovation	6 670	65 500	700	15 200	29 000		26 200	29 500
Building 2	Renovation	8 200	65 500	700	15 200	29 000		43 800	49 500
Building 3	Renovation	7 900	65 500	700	15 200	29 000		41 600	45 900
Total quantity of work			196 500	14 750	93 400	547 000	181 100	676 800	877 800
Estimated tightness (m2 / worker)			100	75	75	120	100	100	100
Takt time (d)			1	5	5	5	1	1	1
Average takt area size (m2)			200	200	200	1000	200	200	200
Amount of wagons			106	9	9	12	19	59	79

Gross areas per functional area (m2) / amount of takt areas in the interior phase)								
K2	K1	1	2	3	4	5	6	7
	820 / 5	1940 / 11	460 / 3	1680 / 10	270 / 2	1680 / 10	270 / 2	420 / 2
3030 / 16	3260 / 17	3130 / 16	2960 / 15	2960 / 15	2940 / 15	2920 / 15	1900 / 10	890 / 5
3030 / 16	3260 / 17	3130 / 16	2960 / 15	2960 / 15	2940 / 15	2920 / 15	1900 / 10	890 / 5
3030 / 16	3260 / 17	3130 / 16	2960 / 15	2960 / 15	2940 / 15	2920 / 15	1900 / 10	890 / 5
3030 / 16	3260 / 17	3130 / 16	2960 / 15	2960 / 15	2940 / 15	2920 / 15	1900 / 10	890 / 5
	320 /2	2720 / 13	2850 14	2860 / 14	2560 / 13			
		1620 / 5	1680 / 6	1130 / 4	1130 / 4	1120 / 4		
	530 / 2	1570 / 7	1570 / 7	1560 / 7	1560 / 7	1410 / 6	10 / 0	
	280 / 1	1560 / 7	1570 / 7	1560 / 7	1560 / 7	1410 / 6	40 / 0	

Figure 2: Obtained data and initial takt planning parameters.

STEP 2: FORMULATION OF INITIAL TAKT PLAN

Based on the input of gross areas, productivity factors, quantities of work, estimated production tightness ratios (Figure 2), accompanied with first guesses of capacity (number of workers) and takt time, the initial version of the plan was created. The outline of the plan and the relations of the KPIs are illustrated in Figure 3. For the initial plan, average takt area sizes (200-1000m2), amount of takt wagons per production phases (9-106pce; calculated as the quantity of work multiplied by production tightness and divided by takt time), and the number of takt areas per functional area (1-16pce; calculated as functional area size divided by takt area size) were obtained as an outcome of scope and production tightness. Also, lead time and batch-specific lead times were obtained as a result.

Batch-specific lead time [h] = Quantity of work [h/m2] x Production tightness [m2/worker]
Production rate [m2/h] = Capacity [n:o of workers] / Quantity of work [h/m2]
Lead time [h] = Total gross area [m2] / Production rate [m2/h] + Batch-specific lead time [h]

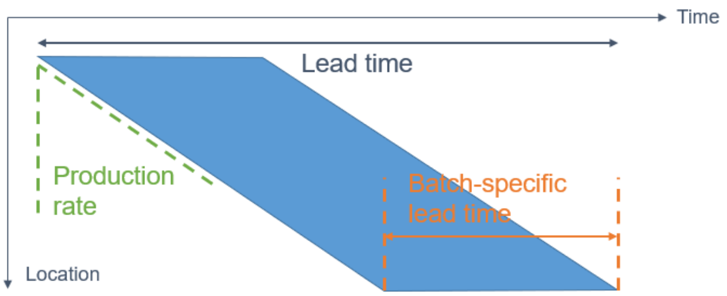

Figure 3: Outline of the initial takt plan

It should be noted that the exact zoning and content of takt wagons were deliberately left undefined in the master planning phase. Instead, the scope of the master planning phase was to obtain rough boundaries for the production rhythm and initial capacity requirements, in which the desired client value is connected to the production flow. Based on these boundaries, the plan will be refined and detailed concurrently with the contractors and other stakeholders in the later planning phases.

STEP 3: ITERATION AND VISUALIZATION OF THE PLAN

After formulating the initial plan, the planning parameters (takt time, amount and size of takt areas, number of wagons) were iterated reciprocally with adjusting the tightness, capacity, and (batch-specific) lead times. Inventory buffers were included by employing relatively sparse tightness ratios (75-120 m2 / worker), and capacity buffers were included by employing a conservative productivity factor. In the master plan, time and plan buffers were mostly avoided, however, some time buffer was scheduled between exterior and interior phases to ensure smooth transitions.

Through iteration, takt planning resulted in a master plan connected to the desired client value, illustrated in Figure 4. In addition to taking into account the value-creation, the parameters were balanced so that all the phases and functional areas could proceed in the same rhythm with little resource fluctuation, enabling smooth production flow. The plan is visualized with a standard takt plan visualization, even though the large number of zones and wagons may make it seem similar to flowline visualization. Nevertheless, the approach differs from other location-based methods (such as the Location-Based Management System) in a way that takt production considers size and number of (takt) areas, as well as the crew composition in takt wagons as flexible parameters, with capacity buffers used as the preferred buffer (Frandson et al. 2015).

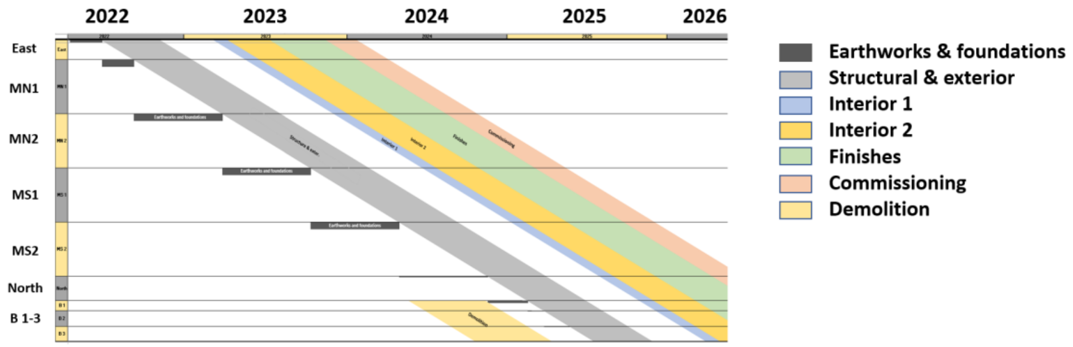

Figure 4: The master takt plan visualization

In summary, the master planning phase resulted in a takt plan that employs a balanced flow between the different buildings and work phases that vary in size and scope. The desired duration, which was a few years less than estimated beforehand, was also achieved in the plan. The resulting plan provides a solid basis for detailed, concurrent target-value-based design and production planning, in which the IPD team further investigates and iterates the presented plans. However, as the case is still in progress, the examination of detailed takt planning and control is left for future research. Hypothetically, the process could be carried on with a similar approach to the norm and micro levels of TPTC (takt planning takt control; Dlouhy et al. 2016) method.

DISCUSSION & CONCLUDING NOTES

In this study, we approached takt production from the lenses of the project's operations strategy, allowing an explicit connection between client value-creation, production flow, and takt planning and control. We hope that the presented approach encourages scholars and practitioners to engage in further discussion with the nature of takt production, observing it from various theoretical and practical viewpoints.

The proactive role of a client helps to put customer value in the center of takt production. In an optimal situation, the client would drive the takt production process and development by assessing the proposed KPIs to form performance requirements, which would guide (general) contractors in designing and controlling the production system. Over the projects, the client should have an increased understanding of what level of value-creation the contractors can provide in certain settings, helping the clients assess demand rates for the projects that are realistic but tight enough to drive contractors to improve their operations management capabilities. Methods to improve these capabilities can be found in other studies, such as takt maturity development by Lehtovaara et al. (2020).

As illustrated through the case example, the approach helped the production planners to justify their decisions in the light of value-creation while providing a solid basis for further collaborative iteration and transparent communication of the plan. However, the case only illustrated the approach in the master planning phase, and future research should address its performance during detailed planning and production phases. We hypothesize that the approach could lead to increased performance within individual takt projects and more efficient long-term improvement; however, this needs validation in future studies. Future research should also address the validation of the proposed KPIs; the focus of the approach and the KPIs was on the value created by the operative functions, however, the value of other stakeholders, such as designers, could also be considered in future development. Moreover, data gathering for these metrics for different takt production use cases is needed to help clients and contractors effectively estimate and compare their projects' success.

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REFERENCES

Ballard, G. and Howell, G. (1998). “What kind of production is construction.” Proceedings (IGLC 6). Guarujá, Brazil.

Binninger, M., Dlouhy, J., & Haghsheno, S. (2017a). “Technical takt planning and takt control in construction.” *Proceedings (IGLC 25).* Heraklion, Greece.

Binninger, M., Dlouhy, J., Steuer, D., & Haghsheno, S. (2017b). ”Adjustment Mechanisms for Demand-oriented Optimisation in Takt Planning and Takt Control.” *Proceedings (IGLC 25).* Heraklion, Greece.

Binninger, M., Dlouhy, J., Müller, M., Schattmann, M., & Haghsheno, S. (2018). ”Short Takt time in construction–a practical study.” *Proceedings (IGLC 26).* Chennai, India.

Dlouhy, J., Binninger, M., Oprach, S., & Haghsheno, S. (2016. “Three-level method of Takt planning and Takt control–A new approach for designing production systems in construction.” *Proceedings (IGLC 24)*. Boston, USA.

Dlouhy, J., Binninger, M., Weichner, L. & Haghsheno, S. (2017a). “Implementation of Lean Construction in Client Organizations – an Analysis of the Status Quo in Germany.” *Proceedings (IGLC 25).* Heraklion, Greece.

Dlouhy, J., Grobler, W., Binninger, M. & Haghsheno, S. (2017b) "Lean Equipment Installation – Potentials of Using Takt Planning." *Proceedings (IGLC 25)*. Heraklion, Greece.

Dubois, A., & Gadde, L. E. (2002). "The construction industry as a loosely coupled system: implications for productivity and innovation." *Construction Management & Economics,* 20(7), 621-631.

Frandson, A., Seppänen, O., & Tommelein, I. (2015). "Comparison between location based management and takt time planning*." Proceedings (IGLC 23)*. Perth, Australia.

Frandson, A., & Tommelein, I. (2014). "Development of a takt-time plan: A case study." *Construction Research Congress 2014.* May 19-21, Atlanta, USA.

Haghsheno, S., Binninger, M., Dlouhy, J., & Sterlike, S. (2016). "History and theoretical foundations of takt planning and takt control." *Proceedings (IGLC 24).* Boston, USA.

Heinonen, A., & Seppänen, O. (2016). "Takt time planning in cruise ship cabin refurbishment: Lessons for lean construction." *Proceedings (IGLC 24).* Boston, USA.

Henderson, J. R., Ruikar, K. D., & Dainty, A. R. (2013). "The need to improve double-loop learning and design-construction feedback loops." *Engineering, Construction and Architectural Management*, 20(3), 290-306.

Hopp, W. J., and Spearman, M. L. (2011). Factory physics. Waveland Press.

Horman, M. and Thomas, H. (2005) "Role of inventory buffers in construction labor performance." *Journal of Construction Eng. and Mgt*. 131(7), 834–843

Koskela, L. (1992). "Application of the new production philosophy to construction." CIFE Technical Report Vol. 72. Stanford university.

Kujansuu, P., Lehtovaara, J., Salerto, S., Seppänen, O., & Peltokorpi, A. (2020). "How Does Takt Production Contribute to Trade Flow in Construction?" *Proceedings (IGLC 28).* Berkeley, USA.

Lehtovaara, J., Heinonen, A., Lavikka, R., Ronkainen, M., Kujansuu, P., Ruohomäki, A., Örmä, M., Seppänen, O. & Peltokorpi, A. (2020). "Takt Maturity Model: From Individual Successes Towards Systemic Change in Finland." *Proceedings (IGLC 28).* Berkeley, USA.

Lehtovaara, J., Seppänen, O., Peltokorpi, A., Kujansuu, P., & Grönvall, M. (2021). "How takt production contributes to construction production flow: a theoretical model." *Construction Management and Economics,* 39(1), 73-95.

Linnik, M., Berghede, K., & Ballard, G. (2013). "An experiment in takt time planning applied to non-repetitive work." Proceedings (IGLC 21). Fortaleza, Brazil.

Little, JC and Graves, S. (2008) "Little's Law." *In: Chhajed, D. and Lowe, T. (eds.) Building Intuition, International Series in Operations Research & Management Science*, New York: Springer, 81–100.

Modig, N., & Åhlström, P. (2012). *This is lean: Resolving the efficiency paradox.* Rheologica.

Pound, E. S., Bell, J. H., & Spearman, M. L. (2014). *Factory Physics for Managers: How Leaders Improve Performance in a Post–Lean Six Sigma World*. McGraw-Hill.

Thomas, H. R., Riley, D. R., & Sinha, S. K. (2006). "Fundamental principles for avoiding congested work areas—A case study." *Practice Periodical on Structural Design and Construction,* 11(4), 197-205.

Womack, J. P., & Jones, D. T. (1996). "Beyond Toyota: how to root out waste and pursue perfection." *Harvard business review,* 74(5), 140-172.

Johansen, P., Christensen. S., Neve, H.H., and Wandahl, S. (2021). "Lean renovation – a case study of productivity, flow, and time improvements" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 839–848, doi.org/10.24928/2021/0150, online at iglc.net.

LEAN RENOVATION – A CASE STUDY OF PRODUCTIVITY, FLOW, AND TIME IMPROVEMENTS

Peder Johansen[1], Søren Christensen[2], Hasse H. Neve[3], and Søren Wandahl[4]

ABSTRACT

Renovation is a particular branch of construction where the production condition is more chaotic and complex than new build. Nevertheless, renovation as a production system has attained less focus than other project types in the Lean Construction community. Moreover, renovation is a significant driver for the green transition. Thus, knowing how to enable high-performing renovation projects is essential to disseminate both in academia and in the industry.

This industrial paper documents the improvement and turnaround of a renovation project faced with cost and time overruns.

The case was changed by implementing first the Last Planner System and daily huddles meeting, and later extending with the implementation of Location-Based Scheduling and a developed concept of visible site management. The entire transformation was monitored as productivity data were collected longitudinally during three years.

The result was a productivity improvement of 54%, achieved even though the contractor capitalized on the productivity improvement by reducing the on-site workforce by 25% and still manage to complete the project one month ahead of the deadline.

KEYWORDS

Lean, renovation, productivity, case study.

INTRODUCTION

Lean construction has often been reported to improve construction projects successfully. However, few case studies of renovation projects exist. In this paper, a case study of a renovation project in which flow and productivity were improved by more than 50% by means of lean construction implementation is reported. It is also the story of a turnaround of a project faced with budget and time overrun. By focusing on flow and productivity improvements, it was achieved to reduce the on-site labor force by 25%, the budget was enforced, and the project was completed one month in advance.

Renovation is a particular branch of construction where the production condition gets even more chaotic and complex than new build (Bertelsen 2003). Recent work by

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Kemmer (2018), Neve et al. (2020), and Tzortzopoulos et al. (2020) sheds light on renovation as a particular production system and points out that the main challenges are: 1) Existing building structure with a lot of unknown characteristics; 2) Dealing with tenants on-site; 3) Difficult construction site layout for logistics and material handling; 4) Highly specialized tasks and trades, i.e., removal of asbestos, etc. Kemmer (2018) reviewed the literature and points out that the traditional project management approach is insufficient in renovation and argues that lean management is superior. He argues that the traditional approach has a too-narrow focus on transformations, whereas lean expands to cover both transformations, flow, and value.

In the International Group for Lean Construction (IGLC), renovation projects and lean has mainly been investigated by Koskela, Kemmer, and Vrijhoef. Kemmer and Koskela (2012) started with an extensive literature review which revealed that the management of renovation works had not been appropriately addressed in prior research. They concluded that studies on practices applied to the management of this complex renovation system are scarce. Saurin et al. (2013) is exactly such a study of the Last Planner System (LPS) (Ballard 2000) implemented in renovation. The study was framed around construction as complex socio-technical systems, and they developed six guidelines for improved management which they tested on a renovation project. The conclusion was that the renovation project would have benefitted from having LPS implemented in addition to the six guidelines. However, they point out that LPS as a single tool is not sufficient for renovation. It needs to be supplemented with more training, leadership, and a better understanding of the complex socio-technical system. Kemmer and Koskela (2014) continued exploring renovation production systems with the aim to identify influential factors affecting planning and control effectiveness and the identification of the current managerial practices. They concluded that the most challenging characteristic of renovation is that works are carried out in an occupied building. Therefore, maintaining effective and constant communication with tenants is an essential competence for the contractor. Kemmer et al. (2016) continued the work of integrating LPS and renovation production systems. They found that regarding the benefits of utilizing LPS, there is a potential for reducing the disruptions on-site and compressing retrofit lead time. Improvements in communication and coordination were also noted as a result of the LPS adoption. In terms of implementation issues, the need to adapt the basic elements of LPS to suit the renovation context and get support from top management before start on site was identified as vital factors for successful application.

In continuation of the previous research on lean and renovation, this paper aims to report a case study where different lean tools helped improve flow and productivity and secured that the project was handed over to the client before schedule.

METHODS

The content of this paper is based on a case study. A single-case research approach was chosen. A case study allows for researching a single phenomenon in-depth but limits the ability to generalize the results beyond the single case study (Yin 2017). Nonetheless, this approach was perceived as valid for this topic.

The case selection criterion was that it should represent a typical renovation case, both in regards to the contractor's project portfolio but also with regard to the industry.

The primary data was quantitative data collected through Work Sampling (WS). Secondary data was unstructured and unrecorded qualitative information, observations, and reflections collected by the authors. The purpose was to enrich the quantitative data.

However, these secondary data cannot be repeated as the secondary data collection unfolded in an informal and unstructured approach. WS is a quantitative method for assessing the efficiency of the workforce through observations. Observers walk around the construction site every hour and note the type of work carried out each time a craftsman is observed. This is categorized into seven predefined categories, where the first is Direct Work (DW), also called producing. Three categories fall into In-Direct Work, namely transporting, preparing, and talking. Finally, three categories of Waste Work, walking, waiting, and gone. WS data were collected four times during the construction period, cf. figure 2. Each data collection included five days of observations from production start in the early morning until production stopped in the afternoon. Research assistants were thoroughly instructed and supervised during the WS data collection. The moving average of each category was continually analyzed to ensure stability in the data, cf. figure 3, 4, and 5.

THE RENOVATION CASE

The case is Fruehøj, a department in the Danish social housing company Fruehøjgaard. Fruehøj consists of 350 housing units established between the years 1953-1957. Windows was changed in the year 1987, and all apartments got new kitchens in the year 1992. The department consists of 19 blocks, all three stories high and with basement, cf. figure 1. A unit is a 2, 3, or 4-bedroom apartment from 53m^2 to 98m^2. All units are in one level only and include a small balcony. Besides, all units have a small storage room in the basement.

Figure 1. Picture of the housing department, showing its 19 blocks, three stories high.
Source: SDFE skråfoto (left), and Fruehøj.dk (right).

In the year 2013, the housing company initiated the process of an extensive renovation of all units. The construction period was scheduled from mid-2017 to early 2021. The Danish contractor Enemærke and Petersen was awarded the general contract after a public tender. The size of the contract was approximately USD 40 mill. It was a deep renovation where all units got a new kitchen, bathroom, facades, balcony, and completely new installations. All blocks got a new roof, improved insulation, and restored basements. Elevators were installed for 90 of the units. And several units were merged into larger units, resulting in 311 units after the renovation. In conclusion, it was a very extensive renovation, where units got upgraded to the current standard.

Figure 2 shows a milestone schedule of the project, including timestamps of productivity data collection on-site.

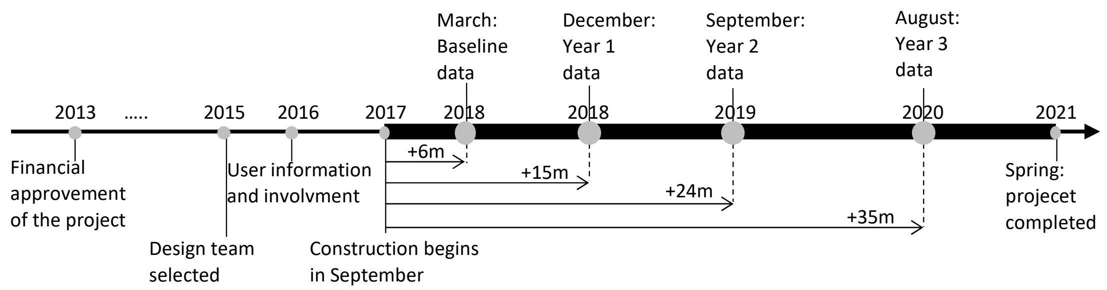

Figure 2. Milestone schedule and timestamps (months) for productivity collection.

The Fruehøj case is considered a 'normal' renovation case. It is a typical case for the contractor and is similar to many of the contractor's other renovation projects. In general, it is important that the case can be considered general so that learnings can be transferred to other renovation cases. Besides, the productivity data must be collected at the time of 'normal' production to ensure generalizability. Therefore, no data collection can be done within the first months of construction or if unique conditions arise, like holiday breaks, rough weather, delivery problems, etc.

WORK DESCRIPTION

Each block is renovated, following this overall description of process and work:

1. Tenants are relocated temporarily.
2. Demolition of all non-structural elements indoor and outdoor.
3. Establishing new elevator shafts and additional steel reinforcements.
4. The façade and roof are changed.
5. Masonry works are conducted. New internal walls & closing off old openings.
6. Installations and electrical work, including new wiring, new pipes, new heating, new ventilation, new bathroom, and new kitchen installations.
7. Carpenter internal works, in the form of walls, ceilings, etc.
8. Masonry works in bathrooms, including titles, sink, toilets, etc.
9. Plastering and paintwork.
10. Flooring in all rooms and installation of new kitchens.
11. Completion, correction, and approval by the client.
12. Tenants move back and work moves on to the next block.

LEAN ELEMENTS IMPLEMENTED

The baseline data collection in spring 2018 was conducted under 'normal' production. At that time, the contractor only used their traditional project management method and had not implemented any lean production or planning methods. The baseline was deliberated delayed until six months after the first on-site activity to ensure that all facilities were up and running and to ensure that all initial learnings and start-up complications were due.

After the baseline data, the project management decided that actions were needed to improve flow and productivity on the site. Step-wise, the following lean methods were implemented on the project by the site management facilitated by the contractors' process support function. The progress was monitored in collaboration with researchers.

Last Planner System (LPS)

In mid-2018 (after the baseline data collection), LPS was partially implemented on the site. The project already had a master schedule. The process schedule was not implemented; instead, the master scheduled fed the making-ready planning process implemented with an eight-week lookahead. Site management ensured the seven flows and facilitated the weekly planning meetings, where foremen of each trade participated in planning next week's work. No systematic follow-up was implemented, and Percent-Planned-Completed (PPC) was not applied. The site management's implementation and facilitation of the LPS system were carried out solely without support from the contractor's central lean and process support division. It was exclusively the project and site managers who implemented and trained superintendents and subcontractors. At year 1 data collection, LPS was still running well, and as the result section shows, a clear improvement in project performance was observed from the baseline to the year 1 data collection. It was later observed that the LPS method was gradually de-implemented. At year 2, only a weekly coordination meeting between superintendents was left. The contractor no longer applied the making ready process, including the seven flows, nor did they make coordinated and valid weekly work plans any longer.

Daily huddles

During the summer of 2018, the contractor also implemented short daily huddles on the site and weekly whiteboard meetings to identify critical tasks and solve emerging and critical production issues. The weekly whiteboard meetings continued through the construction time, whereas the daily huddles only lasted for around half a year. When the site management removed attention from these daily meetings, superintendents and craftsmen soon began to not conduction daily huddles any longer.

Location-Based Scheduling

In the spring of 2019, the contractor decided to award a full-time process facilitator to the project. Immediately after that, the process manager started implementing Location-Based Scheduling (LBS) (Seppanen and Kenley 2009). LBS soon became the dominant scheduling and production update tool and continued to be so until the project was completed. It also transformed the weekly meeting, where the process manager was now in charge and navigated through next week's tasks and locations, inspired by the LPS weekly work plan, however, based on a flow-line diagram. Thus meetings were information and coordination meetings, whereas the LPS weekly meetings intended to be Last Planner commitments. In addition, the process manager weekly updated the master plan based on a 12-week lookahead.

Visible site management

In addition to the well-known lean planning methods above, the contract began in 2019 to focus on the site manager's role on many of their project. The contractor identified that the site manager often tends to be busy in the site office with phone calls, emails, budgets, and spreadsheets instead of assisting the production with fast answers. Therefore, they started implementing visible site management as a concept on several projects, including this one. The purpose was to ensure that the site manager spends more time on-site and less time online! It was quickly realized that, especially during the morning start-up, it had a large effect on the productivity when site managers were accessible out on the site.

Process facilitation

As written, the contractor decided to add dedicated process facilitation support to the case during the spring of 2019. At that time, the project was behind schedule and above budget. The process facilitation came from the contractor's central lean and process support division and consisted of one full-time facilitator working on the site. His primary responsibility was to facilitate LBS implementation and train subcontractors, superintendents, and workers in this method.

RESULTS

The baseline data, cf. figure 3 and table 1, were collected during normal operation and when no lean methods were implemented and 6 months after construction started.

Table 1: Work Sampling data collected as the baseline.

		Direct Work		Indirect Work			Waste Work	
$\bar{p}$	(%)	26.0%		44.4%			29.6%	
n		7,777		13,257			8,850	
		Producing	Talking	Preparing	Transport	Walking	Waiting	Gone
$\bar{p}$	(%)	26.0%	20.9%	15.7%	7.7%	6.3%	6.7%	16.6%

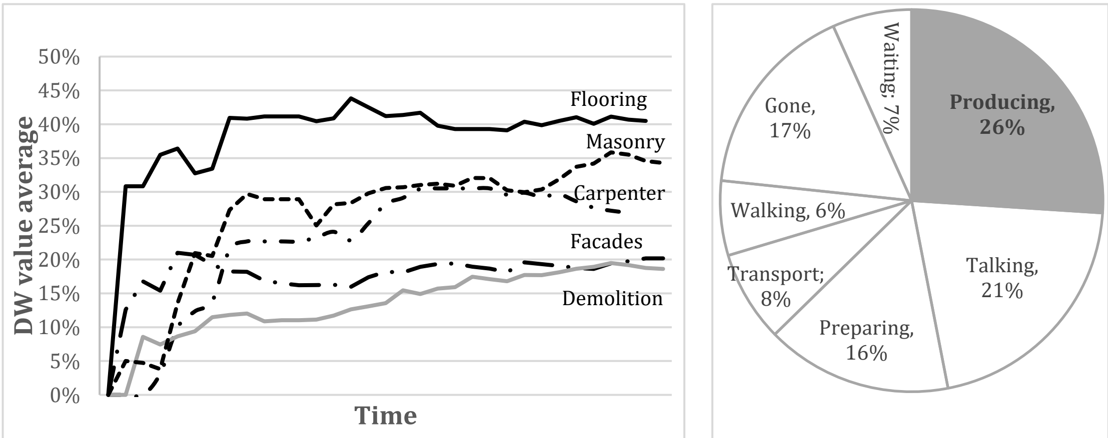

Figure 3. Baseline. Left side: DW Stabilization curves for each trade observed. Right side: Work Sampling Pie chart (n=24,884).

15 months after production started on-site, the year 1 data was collected, cf. figure 4 and table 2. Since the baseline data, the project did implement LPS and Daily huddles meetings, which, however quite fast, was not used more.

Table 2: Work Sampling data collected as of year 1.

		Direct Work		Indirect Work			Waste Work	
$\bar{p}$	(%)	34.0%		40.2%			25.8%	
n		1,534		1,813			1,160	
		Producing	Talking	Preparing	Transport	Walking	Waiting	Gone
$\bar{p}$	(%)	34.0%	11.0%	20.2%	9.1%	10.5%	3.6%	11.7%

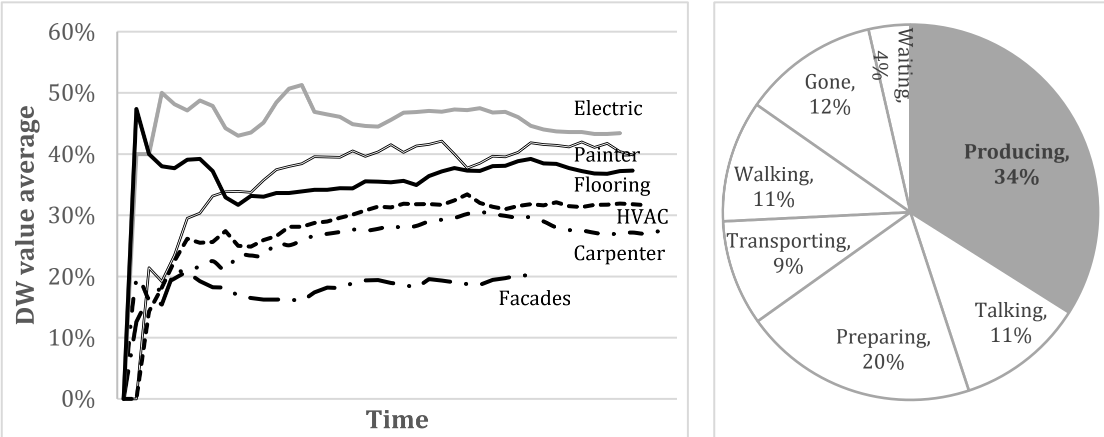

Figure 4. Year 1 data. Left side: DW Stabilization curves for each trade observed. Right side: Work Sampling Pie chart (n=4,507).

24 months after production started on-site, the year 2 data was collected, cf. figure 5 and table 3. Since the year 1 data, the project did implement LBS and the principles of visible site management. Moreover, the site began to have full-time process facilitation support.

Table 3: Work Sampling data collected as of year 2.

		Direct Work		Indirect Work			Waste Work	
$\bar{p}$	(%)	35.1%		38.4%			26.5%	
n		664		725			502	
		Producing	Talking	Preparing	Transport	Walking	Waiting	Gone
$\bar{p}$	(%)	35.1%	10.5%	15.5%	12.4%	11.8%	3.7%	11.0%

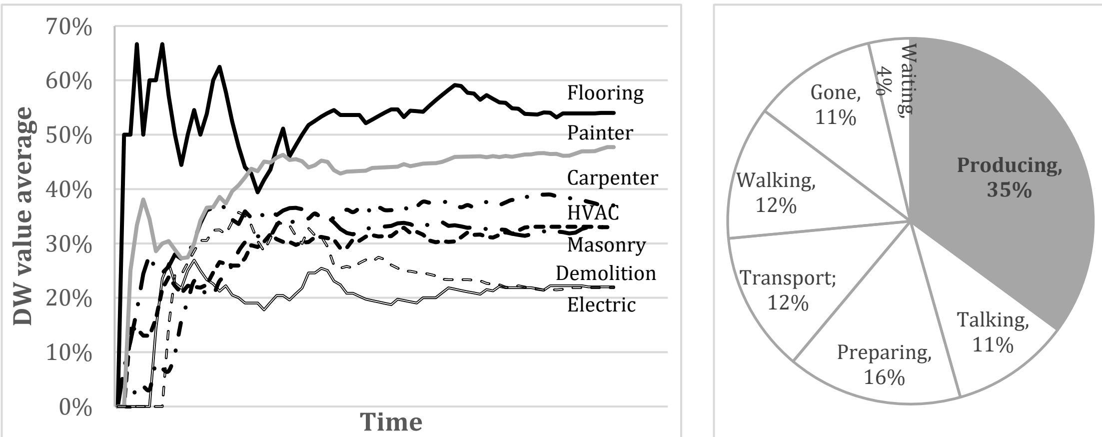

Figure 5. Year 2 data. Left side: DW Stabilization curves for each trade observed. Right side: Work Sampling Pie chart (n=1,891).

35 months after production started on-site, the year 3 data was collected. Since the year 2 data, the project did continue the work to improve the flow, mainly through LBS. The project continued to receive process facilitation support. At the year 3 data collection, no data for each trade was collected. Instead, figure 6 shows the DW distribution during an

average day. The following Work Sampling data were collected during 5 days, cf. figure 6 and table 4.

Table 4: Work Sampling data collected as of year 3.

		Direct Work		Indirect Work			Waste Work	
$\bar{p}$	(%)	39.6%		30.6%			29.8%	
n		565		436			424	
		Producing	Talking	Preparing	Transport	Walking	Waiting	Gone
$\bar{p}$	(%)	39.6%	8.8%	13.4%	8.4%	14.0%	4.2%	11.5%

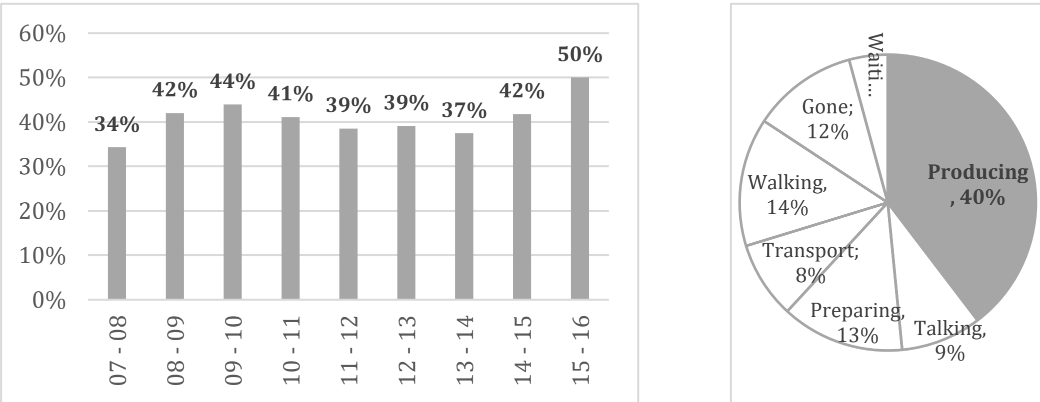

Figure 6. Year 3 data. Left side: average DW values during a workday. Right side: Work Sampling Pie chart (n=1,425).

DISCUSSION & CONCLUSION

A significant increase in productive time was observed in the WS studies from the baseline (no lean implementation) to year three (several lean tools implemented). At year three, the workforce spends more time on value-adding activities, which effectively also mean that the productivity was increased respectively. DW is improved with 54% from 26% to 40%, cf. figure 7. This is a significant improvement.

Improving productivity by 50% ensures that tasks are conducted at a faster speed, thus the project will be either completed faster or with fewer resources. Both were the situation for the case, as the project was handed over to the client one month before the planned deadline, and the project was able to reduce the on-site labor force by 25%.

Improved on the case is, in particular, talking, which more than halved, showing that planning and coordination improved, leaving fewer issues to be clarified. The credit for this is mainly the implementation of LPS and LBS in combination. Waiting and Gone have also been reduced. Waiting time is reduced by 43% as an effect of improved flow. In housing renovation, many of the units are similar; thus, the work is repetitive, and it then is important for us as a contractor to get the right takt. The project struggled heavily to get the right takt until the summer of 2019 when location-based scheduling was fully implemented.

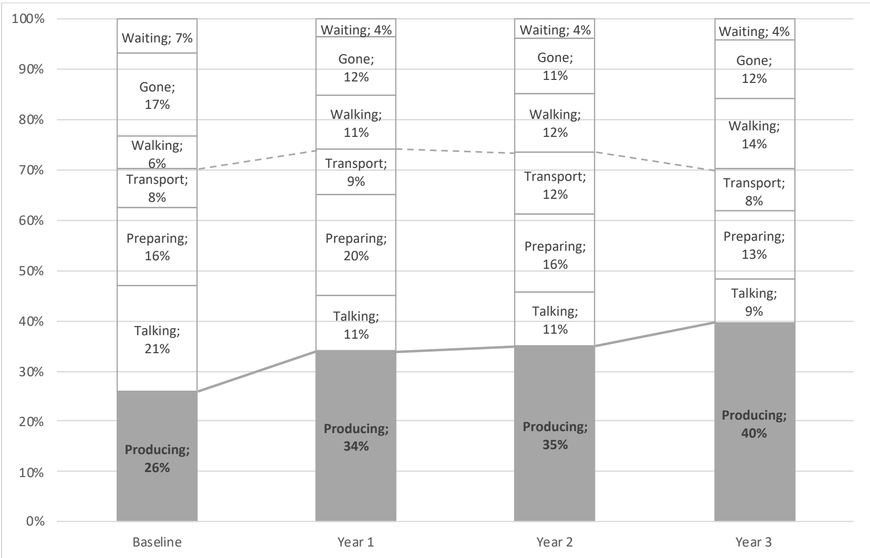

Figure 7. Overview of Work Sampling data over 3 years of the project lifetime.

The logistics were an increasing issue during the project. As work progressed, the construction site layout became less and less effective, as especially the distances from worksite to material storage, equipment containers, and cars, and to site offices and service pavilions increased. Only smaller adjustments were possible due to the layout of existing buildings and the infrastructure of the neighborhood. Overall, movement (walking and transporting) increased 71% from the baseline to year 2, and then slightly decreased during the last year, however still up 57% compared to the baseline. This clearly illustrates one of the renovation characteristics: the problem with the existing building's fixed position, making an optimal site layout troublesome. Future research in lean renovation could focus on how to overcome the challenges these renovation characteristics develop.

During the effort to improve flow and productivity, a number of the renovation production system behaviors reported by Neve et al. (2020) were identified in this case also. Firstly, 'case variance': The different trades performed with high variance also over time, cf. figure 3, 4, and 5. Secondly, 'starts and stops': this case showed issues with too much gone time, especially around agreed breaks, which often was too long. Thirdly, 'high performance and high stabilization': As productivity improved on the case, a more stable production flow with less variance was observed. Not only was the performance higher, but also the variance was lower. This is an important lean observation and perhaps the most relevant learning from this research. Nonetheless, more research on understanding renovation production systems and how to optimize these are still needed. Keeping in mind the large amount of renovation anticipated in Europe as well as Worldwide to encounter the green transition of the built environment.

It was clear that the project struggled to implement lean tools and sustain the change, as some elements gradually de-implemented once management focus moved away again. As explained in the Lean elements implemented section, the LPS system was only partially implemented, however still successful in improving performance (23,5%) from baseline to year one data collection. Even though LPS was gradually de-implemented after year one, the performance did not decrease similarly as the year two performance shows, cf. figure 7. The secondary data cannot explain this behavior. Lean implementation challenges and partial lean implementation (Wandahl 2014) are widely researched. The lean community would benefit from future research on sustaining and instituting change and investigating why lean implementation is sometimes unsuccessful.

In conclusion, this paper demonstrates how flow and productivity can be improved on a single renovation project by implementing different lean tools. Findings are aligned with other research on improving renovation processes (Wandahl and Skovbogaard 2017) and adds to the body of knowledge regarding how lean construction can be applied in renovation projects in particular. Overall, the productivity improved by 54% from the baseline (6 months into the project) to the completion (3 years).

REFERENCES

Ballard, G. (2000). "The Last Planner System of Production Control (Ph.D. Thesis)." University of Birmingham.

Bertelsen, S. (2003). "Complexity - A New Way of Understanding Construction." *Proc., 11th Annual Conference of the International Group for Lean Construction*Virginia, USA.

Kemmer, S. (2018). "Development of a Method for Construction Management in Refurbishment Projects." PhD, The University of Huddersfield.

Kemmer, S., Biotto, C., Chaves, F., Koskela, L., and Fazenda, P. T. (2016). "Implementing Last Planner in the Context of Social Housing Retrofit." *Proc., 24th Annual Conference of the International Group for Lean Construction*Boston, Massachusetts, USA.

Kemmer, S., and Koskela, L. (2012). "Developing a Lean Model for Production Management of Refurbishment Projects." *Proc., 20th Annual Conference of the International Group for Lean Construction*San Diego, California, USA.

Kemmer, S., and Koskela, L. (2014). "Understanding Production Management of Refurbishment Projects of a Housing Association – an Exploratory Case Study." *Proc., 22nd Annual Conference of the International Group for Lean Construction*Oslo, Norway, 651-662.

Neve, H. H., and Wandahl, S. (2018). "Towards Identifying Making-Do as Lead Waste in Refurbishment Projects." *Proc., 26th Annual Conference of the International Group for Lean Construction*Chennai, India, 1354-1364.

Neve, H. H., Wandahl, S., Lindhard, S., Teizer, J., and Lerche, J. (2020). "Learning to see value-adding and non-value-adding work time in renovation production systems." *Production Planning and Control*.

Saurin, T. A., Rooke, J., Koskela, L., and Kemmer, S. (2013). "Guidelines for the Management of Complex Socio Technical Systems." *Proc., 21th Annual Conference of the International Group for Lean Construction*Fortaleza, Brazil, 13-22.

Seppanen, O., and Kenley, R. (2009). *Location-Based Management for Construction*.

Tzortzopoulos, P., Kagioglou, M., and Koskela, L. (2020). *Lean Construction – Core Concepts and New Frontiers*, Routledge, London and New York.

Wandahl, S. (2014). "Lean Construction with or without Lean – Challenges of Implementing Lean Construction." *Proc., 22nd Annual Conference of the International Group for Lean Construction*Oslo, Norway, 97-108.

Wandahl, S., and Skovbogaard, J. (2017). "Towards Improving Productivity on Refurbishment Projects." *33rd Annual ARCOM Conference*, Cambridge.

Bataglin, F.S., Viana, D.D., Coelho, R.V., Tommelein, I.D., and Formoso, C.T. (2021). "Buffer types and methods of deployment in construction." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 849–858, doi.org/10.24928/2021/0171, online at iglc.net.

BUFFER TYPES AND METHODS OF DEPLOYMENT IN CONSTRUCTION

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ABSTRACT

Flow is a key concept in Lean Production and is particularly important in construction. Due to the complexity of projects, in part due to managerial practices adopted, much variability exists in construction resource flows. Production system design can be used to eliminate at least some unwanted variability and then reduce the impact of remaining variability by using buffers in order to improve such flows. Accordingly, planners may add buffers of certain sizes in certain locations into the system, or use more systematic, adaptive, data-driven methods. With this in mind, the authors initiated a systematic literature review (SLR) on buffers in construction. The paper contributes to knowledge by defining the term 'buffer' and providing a characterization of buffer types and methods of deployment. Despite advances in understanding and method development, no one method stands out. The methods as described fall short of being able to both proactively determine buffer sizes and locations in the production system to suitably accommodate anticipated needs, and also reactively adjust them in light of system design changes. The use of SLR as the research methodology has well-known limitations, but the findings were revealing, and follow-on research will cast a wider net for relevant literature.

KEYWORDS

Buffer, slack, contingency, flow, variability.

INTRODUCTION

The concept of flow plays a key role in Lean Production, changing the way production traditionally is understood. Lean production systems are designed ideally to transform inputs into outputs while striving for instant delivery, minimizing resource use, as well as maximizing value, thus enabling customers to better accomplish their purposes (Ballard et al. 2001). Flow is particularly important in construction as construction pertains to complex, one-of-a-kind products and is undertaken usually at the delivery point by a series of repeating but variable activities in multiple locations within a multi-skilled ad-hoc team (Kenley 2005). This makes the Lean ideal particularly difficult to achieve.

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Shingo (1989) defines production flow as a network of processes (flow of material or product in time and space) and operations (flow of workers and equipment in time and space). Ballard (2000) states that a requirement for good production flow is reliability, i.e., the necessary resources must be available at the right time to have a stable and predictable production system. The term resource refers to “a useful or valuable possession or quality that a person or organization has, for example, money, time, or skills” (Cambridge Dictionary 2021). In construction, resources are what is needed to execute a task, i.e., materials, information, workers, equipment and tools, space, time, and money.

Due to the peculiarities of construction projects and planning and control practices adopted, much variability exists in resource flows, and the probability of missing inputs is therefore considerable (Koskela 2000). Here, variability refers to “the quality of non-uniformity of a class of entities” (Hopp and Spearman 2011 p. 265). This can take on many forms, including process time variability and flow variability. Process variability stems from work procedure variations, setups, random outages, and quality problems. The related concept, process capability, refers to the characterization of such variability in the output of a process (or operation) under normal operating conditions and possibly adjusted for each project context by means of a probability distribution (Tommelein 2020). Hopp and Spearman further define that flow variability is created by the way work is released into the system or moved from one location to the next. Their key point is that the reduction of variability improves flow, yielding better results in production system performance. One way to reduce variability is to judiciously use buffers.

Production system design (PSD) is concerned with the development of operation and process design in alignment with product design, the structure of supply chains, and the allocation of resources (Ballard et al. 2001). It is an initial planning task that involves decisions that play an important role in the implementation of core Lean concepts, such as pull production, batch size, takt time (Schramm et al. 2006). PSD can be used to eliminate unwanted variability and reduce the negative impacts of the remaining variability by using buffers (Lee et al. 2006, Russell et al. 2015, Tommelein 2020).

So what are buffers and why use them? The term buffer is defined as a means to isolate operations subcycles from immediate interaction, i.e., to make them loosely linked (Howell et al. 1993). Buffers are resource cushions that can shield production from variability and thus help achieve desired outcomes (Alves and Tommelein 2004, Lee et al. 2006, Russell et al. 2015, Poshdar et al. 2018). Buffers make it possible to isolate a production process from its environment and also from the processes depending on it (González et al. 2011). Buffers are said to be redundancies that allow structural arrangement for the systems to accommodate variability (Miranda et al. 2007). However, in our view buffering does not mean that resources are necessarily redundant, e.g., standby capacity is related to the concept of underloading (i.e., intentionally scheduling resources to not be 100% utilized) in Takt Planning (TP) (Tommelein 2020) and helps to achieve reliability in systems subject to variability, i.e., most systems in the real world.

Terms related to buffer, are contingency and slack. The term contingency refers to a kind of buffer with time and money being the resources of concern. Contingency can cover possible time-cost-estimating errors and acts as a cushion against predictable as well as unforeseen risks (Barraza 2011).

The term slack generally appears to be given a broader meaning than buffer, with buffers being a kind of slack (Formoso et al. 2021, Saurin et al. 2021). Slack is more strategic in nature and of concern at the organizational level, whereas buffers tend to be more operational in nature and of concern at the project level. Slack is present when extra resources are available to allow an organization to adapt, change, and protect critical processes from internal pressures for adjustment or to external pressures for change in policy (Bourgeois 1981, Lawson 2002). One way of adapting is to use a buffer to insulate the organization's technical core from environmental changes (Moreno et al. 2009).

Buffers can serve as countermeasures to address production system performance concerns (Spear and Bowen 1999) and are then considered to be of value instead of waste. However, buffers that are not carefully sized and located can be wasteful and have negative impacts on the system, such as causing long lead times, inflating work-in-process (WIP), and increasing non-value-adding activities (e.g., multiple handling of materials) (Howell and Ballard 1995). Likewise, oversized inventory buffers that are a consequence of the traditional idea that resources (workers and equipment) should be always kept busy (i.e., maximizing their utilization) even when the performed tasks are not immediately needed are also wasteful.

A common practice in construction is to add time buffers to a project schedule using a deterministic approach, not considering the dynamic nature of projects, e.g., Poshdar et al. (2018) mentioned the practice of simply adding a fixed percentage of the expected duration to each activity in a project network. This percentage may be decided according to the personal judgment and experience of project managers, "a trial-and-error process with dubious results" (González et al. 2011 p. 715). An alternative to using deterministic approaches is to use systematic, adaptive, data-driven methods, based on probabilistic mathematical models to define buffers and adjust them in real-time as needed.

The aim of our research is to categorize buffering methods used in construction as presented in the literature. We are not aware of literature that does this but think that a categorization can help in choosing which methods to use, alone or in combination, and under what circumstances. The research question addressed is: What buffer types of buffers and methods of deployment have been used for buffer management? This paper reports on the results of the first stage of this research, consisting of conducting an exploratory literature review. It is the start of an iterative process (Lavallee et al. 2014).

RESEARCH METHODOLOGY

The research is based on a systematic literature review (SLR), which is a means of identifying, evaluating, and interpreting documents relevant to a specific research question (Kitchenham 2004, Lavallee et al. 2014). The use of SLR as the methodology has well-known limitations, but the findings were nevertheless revealing, and follow-on research will cast a wider net for additional documents.

The SLR used four databases: (1) Science Direct, (2) American Society of Civil Engineers (ASCE), (3) Taylor & Francis Online, and (4) International Group of Lean Construction (IGLC). The choice of these databases was admittedly somewhat arbitrary, but a starting point was needed for the review. The search used the terms {"buffer" OR "contingency" OR "slack"} (in the title, abstract, and keywords) AND "planning" AND "control" AND "management" AND "construction project" (anywhere in the paper). The first three were chosen because they appear to be used interchangeably; the others were used to limit the scope of the search in this first stage of exploration.

A challenge in conducting this review is the use of certain terminology. Planning and control refer respectively to proactive (preventing anticipated disturbances as early as they are foreseeable) and reactive methods (incrementally repairing the plan in response to internal and external events that cause deviation from the plan, after Miranda et al. (2007), although planning is loosely used for both. Different authors use the term buffer with different meanings or fail to define the term altogether. This challenge was addressed during the review (see earlier definitions of buffer, etc.).

The authors accessed the databases between August 10 and 13, 2020, and identified 336 papers[6]. Figure 1 illustrates the selection process steps. Use of these search criteria meant that certain papers were not found and consequently were not included in the review, although they might have been relevant (incl. several of our own papers that are relevant). Similarly, some papers found were judged to not suit the topic of interest and consequently were not included (e.g., papers in the domain of ecology).

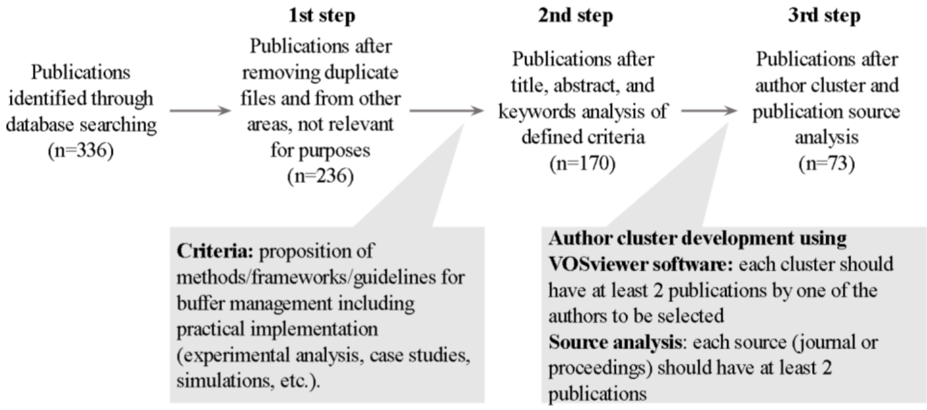

Figure 1: Steps of the systematic literature review

Assuming that authors (incl. teachers and students) may develop not one but several papers along a similar line of thought, we organized the papers by author cluster. The simultaneous review by cluster of multiple papers using related models and paradigms helped us gain better understanding of the authors' work. As a result of the overlapping between author clusters and source distribution analysis, 73 papers were selected for analysis. These formed 19 clusters (Figure 2). For brevity of this IGLC paper, limited to 10 pages, we report only the analysis of clusters with at least 3 papers and at least 3 authors per cluster (circled in Figure 2), which represent approximately 64% of all papers identified in the SLR.

Methods of buffer deployment were classified as proactive or reactive. They were also categorized according to different planning levels, considering the planning horizons adopted in the Last Planner® System (LPS) (Ballard and Tommelein 2021): (1) long-term: set milestones to be achieved during the execution of the project, (2) medium-term: identify and remove constraints by ensuring that necessary resources are made available, and (3) short-term: define and commit to work assignments that drive the production process.

RESEARCH FINDINGS

BIBLIOMETRIC INFORMATION

The 73 papers appeared in 11 different journals and conference proceedings with 75% of those being published over the last 15 years (since 2005), but some going as far back as 1994. The largest number of papers (44 in total) appeared in the Annual Conference of IGLC, and the next largest number (16) appeared in the ASCE Journal of Construction

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Engineering and Management. The paper's first authors were mostly from the United States (27 papers), Brazil (7), Chile (6), and New Zealand (6).

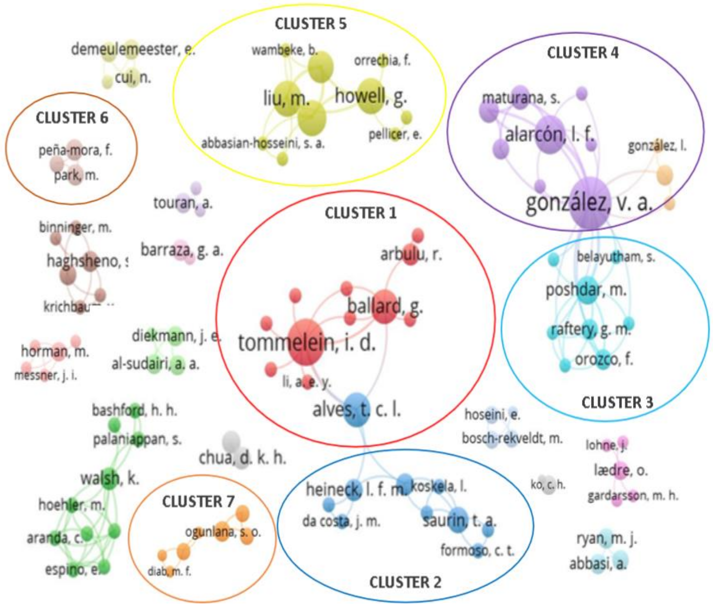

Figure 2: Network and clusters visualization

Authors from different clusters usually favored the use of one search term (either "buffer", "contingency", or "slack") over the other two, e.g., some authors who emphasized time and cost buffers used the term "contingency." Only the authors from Cluster 2 used the term "slack." They acknowledged that in Lean Construction the term "buffer" is more commonly used yet they preferred using "slack" because of its broader meaning. The IGLC papers by Formoso et al. (2021) and Saurin et al. (2021) discuss the concept of slack in greater depth and offer examples.

BUFFERING METHODS OF DEPLOYMENT

Buffering methods of deployment are identified based on the authors' cluster definition (numbers shown in Figure 3). Each of these is related to buffer types (space, capacity, information, time, inventory, and financial) based on the type of resource (space, workers, equipment/tools, material, information, time, and money). A sample of papers from these clusters is described next.

Frandson and Tommelein (2016) (Cluster 1) studied the use of TP for interior construction. The purpose is to create flow on a construction site based on a takt for each construction phase or process, i.e., each trade must complete their work in each assigned zone within the defined takt time. This method uses capacity buffers (underloading the resource) to balance the workflow. TP may be classified as a proactive method used for collaborative PSD, expanding on the commitment mechanism of the LPS.

Do et al. (2014) (Cluster 1) explored Target Value Design (TVD) as a method for controlling project cost overruns. Designing to a target cost is a product development practice that converts cost into a design criterion, rather than treat it as a design outcome. TVD projects, in contrast to other projects, require less contingency (financial buffer in this case) to cover a certain amount of uncertainty in the project because the project contingency gets pooled instead of being held individually by each participant.

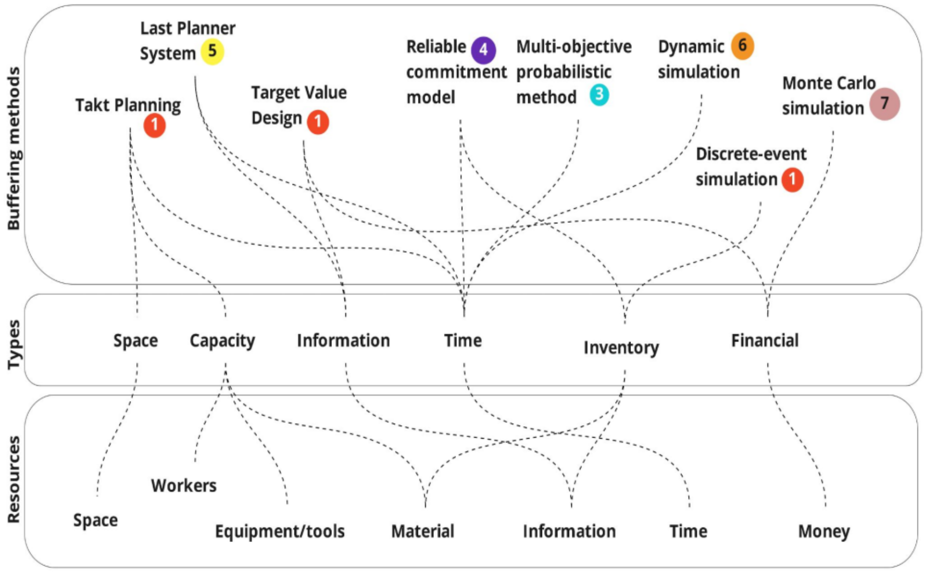

Figure 3: Buffering methods, types, and related resources

Alves and Tommelein (2004) (Cluster 1) used discrete-event simulation to mimic the behavior of the sheet-metal duct supply chain and how the choice of inventory buffers between activities impacts the system. The simulation revealed that if supply chain participants need large inventories between activities, lead times and WIP increase and the system's throughput decreases, a relationship described by Little's Law (Little 2011). Some contractors are sacrificing lead times and inventory levels for improvements in the reliability of their systems using buffers. The larger the buffer size, the longer it takes for the production batch to be assembled and released to the next activity, losing some advantages of the pull system. In this case, the supply chain loses its capacity to quickly respond to variations in demand. This amplifies the importance of first reducing the variation related to activities so that buffers can be reduced, and the system can be more effective. The simulation model offers a proactive approach because it allows understanding the system performance and prevents obstacles related to variability in this complex supply chain (incl. processes and operations), influencing all hierarchical levels of decision-making.

Poshdar et al. (2018) (Cluster 3) proposed using a multi-objective probabilistic-based time buffer allocation method (MPBAL) that was developed based on a mathematical solution to analyze construction project networks. They created models of variability at the activity level based on the information provided by project personnel and combined them into an integrated model that represents the probable time performance at the project level. Buffers are represented by the duration of the activities over their original expected duration. The project completion time, the project total cost, planning reliability, and schedule stability are the four criteria adopted to formulate the multi-objective problem of buffer allocation. MPBAL iteratively extends the duration of project activities by one unit of time buffer (e.g., 1 day) and quantifies their impact on the four criteria mentioned. The MPBAL method provided a range of options for the possible buffer allocation scenarios acting as a long-term proactive approach that gives decision-makers freedom to implement their preference in the final solution.

González et al. (2011) (Cluster 4) proposed a method for managing WIP buffers in repetitive projects, based on the reliable commitment model (RCM). RCM uses site information and planning reliability indicators that result in improved project performance, such as labor productivity and process progress. It provides a proactive approach for managing inventory buffers on construction projects at the operational level and demonstrates how WIP buffer size influences process capacity, resource use, and time delays. RCM aims to produce buffered work plans at the short-term level (weekly) using data from previous weeks to provide feedback into the system.

Russell et al. (2015) (Cluster 5) empirically demonstrated the effectiveness of the LPS in reducing time buffers and increasing Percent Plan Complete (PPC). Their findings demonstrate that the LPS exemplifies an effective planning strategy for construction managers to improve project performance and help them understand what drives the need for buffers in schedules, allowing efforts to strategically address areas of concern. Collection of time buffer, productivity, and PPC data demonstrated the effects of collaborative planning compared with traditional planning methods.

Lee et al. (2006) (Cluster 6) proposed a dynamic simulation-based buffering strategy to generate a construction plan, focusing on the detrimental impacts of errors and changes when concurrent design and construction are applied to a project. To absorb delays, this method places time buffers at the start of an activity, rather than at the end as a contingency buffer would. This time allows the performer of the activity to handle ill-defined tasks by using a pre-checking or make-ready process to capture and correct predecessors' hidden errors (i.e., errors that have not been identified through the quality management process) and latent changes (i.e., changes that have not been identified through the scope management process nor approved through the claim and change management process). Thus, the method supports proactive behavior at the level of long- and medium-term planning.

Panthi et al. (2009) (Cluster 7) focused on approaches to handle risks through the allocation of cost contingencies (financial buffers) on infrastructure projects such as highways, hydropower plants, and petroleum pipelines. Their method is divided into three steps: risk identification, risk assessment, and response. They quantified the effects of these risks by determining the probability and severity using the Analytical Hierarchy Process, and then in the response step, used Monte Carlo simulation to determine contingency. Theirs is a proactive approach because it was applied to allocate cost contingency for projects.

DISCUSSION

A variety of buffer types and methods of deployment were identified. Proactive methods are used during the planning process to anticipate possible problems and help to make decisions: methods focused on planning and control (Cluster 1); probabilistic and statistical models (Clusters 3 and 4); and tools such as simulations (Clusters 1, 6, and 7). Reactive methods use an outcomes analysis to determine a response based on how the results impacted the system performance (Cluster 5). Results from production system performance analysis, if reliable and consistent, may be used to generate data and provide feedback into the system, acting as inputs for proactive methods.

The scope for buffer allocation may be segmented into: (1) process (e.g., TP, LPS) vs. (2) operation (e.g., underloading with capacity), following Shingo's (1989) definition, and depending on the level of decision-making.

Based on the level of the planning system considered, buffer types can vary. Lee et al. (2006) (Cluster 6) added time buffers to the master schedule, whereas Alves and Tommelein (2004) (Cluster 1) added inventory buffers to the production schedule where details on resource allocation are visible. Also, some studies focused on a specific type of buffer, e.g., by Clusters 3 and 4 when probabilistic and statistical models are used. Others are more wide-ranging to allow decision-makers to choose what type of buffer they will prioritize, e.g., by Cluster 2 that focuses on design slack.

Saurin et al. (2013) (Cluster 2) illustrated the applicability of a set of guidelines for the management of complex socio-technical systems. One guideline suggested using design slack to reduce structural complexity and absorb the effects of unanticipated variability, which is a result of emerging events.

The concept of slack overlaps with the concept of buffer, but it has broader applicability. Cluster 2 authors recognized that in complex socio-technical systems, the concept of buffer is insufficient to deal with all possible types of variability. The evidence collected on a refurbishment project indicated that the master plan did not have any slack, regardless of its level of detail. According to the contractor's planner, a reason for no slack was the fact the client determined the handover dates, and there was little or no room for negotiating those dates. The planner also mentioned using, in some projects, a target plan that establishes a final handover date a few weeks before the date in the master plan. The target plan has best-case assumptions, and it creates a buffer to absorb delays that may yet happen. Whether or not the master plan has designed-in slack, it is worth noting that effects of unanticipated variability (e.g., schedule delays) can be dealt with not only by working longer hours and weekends but also by process and operation improvement (relying on human creativity) all of which are forms of slack capacity.

Fireman et al. (2018) (Cluster 2) investigated the role of slack in standardized work, assuming that it can be used to absorb variability from different sources. Standardized work is a type of action-oriented approach that sets a basis for continuous improvement and considers basic elements such as takt time, cycle time, WIP, and work sequence. Slack resources such as time, capacity, safety stocks, and also multifunctional team formation, cross-training, and the creation of help chains can enhance a project team's ability to deal with variability.

CONCLUSIONS

This paper provided an overview of buffering methods. The analysis of methods revealed that it appears to be impossible to define an absolute number for sizing buffers or to fix their location. The need for buffers is context-dependent and their use must be adapted to the nature of the system they pertain to. Construction projects are dynamic and buffering approaches must be able to adapt to changes in the system. A planner must understand the nature and functions in the system to decide where to invoke these functions' insights: in planning by adopting proactive methods or in reacting to circumstances. The deliberate use of buffers is important: if buffers are not well-managed they be wasteful instead of being of value by serving as a countermeasure to the manifestation of variability. Understanding sources of variability and removing unwanted variability must be done before adding buffers to reduce the impact of remaining variability in production systems.

Some studies proposed methods applicable to certain types of projects, nevertheless, for any type of project, the first step toward using buffers in construction management is to raise context awareness and answer questions such as: Are buffers needed, why?, What type of resources will be used as buffers?, and What type of methods of deployment will be used? Some methods are more complex to understand than others and consequently demand that users have prior knowledge of certain topics, e.g., mathematical modeling or simulation software. Such knowledge will affect which method users choose.

We note that existing buffering methods can serve as alternatives to deterministic approaches traditionally used to define buffers in construction. Despite the advances in new method development (e.g., advances in mathematical modeling and simulation), further work is necessary to create more adaptive systems that allow for real-time decision-making and can respond when the need to use buffers arises. Having started with a SLR to come to explore existing literature on buffer management in construction, follow-on research will certainly broaden the search for related literature.

ACKNOWLEDGMENTS

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REFERENCES

Alves, T. and Tommelein, I.D. 2004. “Simulation of buffering and batching practices in the interface detailing-fabrication-installation of HVAC ductwork.” *Proc. 12th Ann. Conf. Int. Group for Lean Constr.*, Helsingør, Denmark, 1-13.

Ballard, G., Koskela, L., Howell, G., and Zabelle, T. 2001. “Production system design in construction” *Proc. 9th Ann. Conf. Int. Group for Lean Constr.*, Singapore, 1-15.

Ballard, G. and Tommelein, I.D. 2021. *2020 Benchmark of the Last Planner® System*. Project Production Systems Laboratory, Univ. of California, Berkeley, CA, March.

Barraza, G. 2011. “Probabilistic estimation and allocation of project time contingency.” *J. Constr. Engin. Manage.*, 137(4), 259-265.

Bourgeois III, L.J. 1981. “On the measurement of organizational slack.” *Academy of Management Review*, 6(1), 29-39.

Cambridge Dictionary 2021. https://dictionary.cambridge.org/us (accessed March 2021).

Do, D., Chen, C., Ballard, G., and Tommelein, I.D. 2014. “Target Value Design as a method for controlling project cost overruns.” *Proc. 22nd Ann. Conf. Int. Group for Lean Constr.*, Oslo, Norway, 171-181.

Fireman, M.C.T., Saurin, T.A., and Formoso, C.T. 2018. “The role of slack in standardized work in construction: an exploratory study.” *Proc. 26th Ann. Conf. Int. Group for Lean Constr.*, Chennai, India, 1313-1322.

Formoso, C.T. et al. 2021. “Slack in construction - Part 1: Core concepts.” *Proc. 29th Ann. Conf. Int. Group for Lean Constr.*, Lima, Peru, forthcoming.

Frandson, A. and Tommelein, I.D. 2016. “Takt time planning of interiors on a precast hospital project.” *Proc. 24th Ann. Conf. Int. Group for Lean Constr.*, Boston, Mass., USA, 143-152.

González, V.A., Alarcón, L.F., Maturana, S., and Bustamante, J.A. 2011. “Site management of work-in-process buffers to enhance project performance using the reliable commitment model: case study.” *J. Constr. Engin. Manage.*, 137(9), 707-715.

Hopp, W. and Spearman, M. 2011. *Factory Physics*. 3rd ed., Waveland Press, Illinois.

Howell, G. and Ballard, G. 1995. “Factors affecting project success in the piping function.” *Proc. 3rd Workshop on Lean Construction*, Albuquerque, USA, 161-185.

Howell, G., Laufer, A., and Ballard, G. 1993. “Interaction between subcycles: One key to improved methods.” *J. Constr. Eng. Manage.*, 119(4), 714-728.

Kenley, R. 2005. "Dispelling the complexity myth: Founding lean construction on location-based planning." *Proc. 13th Ann. Conf. Int. Group for Lean Constr.*, Sydney, Australia, 245-251.

Kitchenham, B. 2004. *Procedures for performing systematic reviews.* Technical Report, Keele Univ., Keele, Staffs, UK, 28 pp.

Koskela, L. 2000. *An exploration towards a production theory and its application to construction*. VTT Technical Research Centre of Finland.

Lavallee, M., Robillard, P., and Mirsalari, R. 2014. "Performing systematic literature reviews with novices: An iterative approach." *IEEE Trans. on Educ.*, 57(3) 175-181.

Lawson, M. 2002. "In praise of slack: time is of the essence." *Academy of Management Perspectives*, 15(3), 125-135.

Lee, S., Peña-Mora, F., and Park, M. 2006. "Reliability and stability buffering approach: focusing on the issues of errors and changes in concurrent design and construction projects." *J. Constr. Engin. Manage.*, 132(5), 452-464.

Little, J. 2011. "Little's Law as viewed on its 50th anniversary." *Operations Research*, 59(3), 536-549.

Miranda, A.N., Costa, J.M., and Heineck, L. 2007. "Assessing the effects of structural differences on action, reaction and conformation in construction." *Proc. 15th Ann. Conf. Int. Group for Lean Constr.*, East Lansing, Mich., USA, 380-389.

Moreno, A, Fernandez, L., and Montes, F. 2009. "The moderating effect of slack resources on the relation between quality management and organisational learning." *Int. J. of Prod. Research*, 47(19), 5501-5523.

Panthi, K., Ahmed, S., and Ogunlana, S. 2009. "Contingency estimation for construction projects through risk analysis." *Int. J. of Constr. Educ. and Research*, 5(2), 79-94.

Poshdar, M., González, V.A., Raftery, G.M., Orozco, F., and Cabrera-Guerrero, G.G. 2018. "A multi-objective probabilistic-based method to determine optimum allocation of time buffer in construction schedules." *Autom. in Constr.*, 92(1), 46-58.

Russell, M.M., Liu, M., Howell, G., and Hsiang, S.M. 2015. "Case studies of the allocation and reduction of time buffer through use of the Last Planner System." *J. Constr. Engin. Manage.*, 141(2), 04014068.

Saurin, T., Rooke, J., Koskela, L., and Kemmer, S. 2013. "Guidelines for the management of complex socio-technical systems: An exploratory study of a refurbishment project." *Proc. 21st Ann. Conf. Int. Group for Lean Constr.*, Fortaleza, Brazil, 915-924.

Saurin, T.A. et al. (2021). "Slack in construction - Part 2: Practical applications." *Proc. 29th Ann. Conf. Int. Group for Lean Constr.*, Lima, Peru, forthcoming.

Schramm, F K., Rodrigues, A.A. and Formoso, C.T. 2006. "The role of production system design in the management of complex projects." *Proc. 14th Ann. Conf. Int. Group for Lean Constr.*, Santiago, Chile, 227-239.

Shingo, S. 1989. *A study of the Toyota production system from an industrial engineering viewpoint*. Cambridge, Mass.: Productivity Press.

Spear, S. and Bowen, H. 1999. "Decoding the DNA of the Toyota Production System." *Harvard Business Review*, 77(5), 96-106.

Tommelein, I.D. 2020. "Takting the Parade of Trades: Use of capacity buffers to gain workflow reliability." *Proc. 28th Ann. Conf. Int. Group for Lean Constr.*, Berkeley, Calif., USA, 421-432.

Ramirez-Valenzuela, A., Gamarra-Diaz G. G. and Erazo-Rondinel, A. (2021). "Proposal Model for the Management of Construction Based on Flows – A Complex Adaptative System." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 859–869, doi.org/10.24928/2021/0205, online at iglc.net.

PROPOSAL MODEL FOR THE MANAGEMENT OF CONSTRUCTION BASED ON FLOWS – A COMPLEX ADAPTIVE SYSTEM

André Ramírez-Valenzuela[1], Gilberto G. Gamarra-Díaz[2], and Andrews A. Erazo-Rondinel[3]

ABSTRACT

Project management models understand construction as an ordered and simple phenomenon without considering its complexity, dynamism, and high variability. Also, they are models adapted from other sectors such as manufacturing and information technology (IT). This research aims to be a new trend for developing management models, typical of construction, from complexity. The following points are considered, as a first step, to this new trend of holistic construction management: 1. Generate and manage flows, which are the main components for the production in construction—beginning to understand each flow, its importance, and its properties; and 2. Manage complexity in construction projects by understanding and promoting the production system as a Complex Adaptive System (CAS) that requires organizations of action and learning as an Operational Excellence Organization. The proposed model offers a holistic analysis of the system considering flow management as a basis. It relates the project management approaches proposed by Bertelsen and Koskela (2005), the Value – Flow – Operation (VFO) model proposed by Bertelsen (2017), and the seven preconditions of Koskela (2000), except for external conditions by which these are a threat of flow, but do not flow in the proposed model.

KEYWORDS

Complexity, flow integration, value, management, complex adaptive system (CAS).

INTRODUCTION

The construction sector is one of the engines of the economy and a significant generator of employment. Civil works such as hospitals and schools solve the needs of the towns.

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Internally, construction projects have unreliable schedules, additional costs generated by a low initial engineering or design study, continuous variations in scope, and little concern for the maintenance or post-construction stage. All the above is reflected in works with long, backward times, cost overruns, and a short time of useful life, generating dissatisfaction in the client and final user.

Accepting that construction is a complex, dynamic and non-linear phenomenon shows new management approaches that allow obtaining the desired results (Bertelsen 2003a; Bertelsen 2003b). Own management for the construction from a complexity perspective can be the solution with action and learning organizations. The paper aims to open a holistic management research field under construction and encourage developing new management models typical of this sector, considering its characteristics. Four objectives are defined: (1) Analyze the complex nature of construction. (2) Integrate existing flows in construction. (3) Analyze the importance of flow management in construction. (4) Analyze the management of people in construction.

METHODOLOGY

This research begins by presenting the models' evolution that seeks to describe the production system under construction. If someone wants to manage a project, they must first understand how the production system works. The models presented have not received the necessary importance or have not been understood in their entirety, this being the main point that hinders the project management under construction. Next, complexity and the construction of a complex system are described—an overview of its nature. The evolution of project management is explained before presenting the model for the management of construction based on flows, as an initial proposal of holistic construction management from a complexity perspective. Finally, the Complex Adaptive System (CAS) concept is presented to manage complexity from an action and learning organization, such as an Operational Excellence Organization. We are increasingly convinced that an organization that manages people and knowledge manages complexity.

PRODUCTION CONSTRUCTION SYSTEM

"The production system under construction is a set of operatively interrelated parts, dynamic, of which it is important to consider its global behaviour" (Ramirez 2014, p.28-29). Representing this system has been a complete challenge as an essential step to carry out an adequate study and analysis of it. Some authors, seeking to explain the nature of the production system, proposed models that evolved.

DUAL MODEL

Traditionally, construction has been seen and modelled as a series of conversion activities; the products (outputs) result from the transformation of raw materials (inputs). The main concern was to make conversions increasingly efficient (Koskela 1992). Based on the lean production philosophy, this thought was criticized by himself and proposes identifying and eliminating non-conversion activities in construction and establishing a dual model where non-conversion activities or flow activities must be eliminated or reduced to the maximum (Kraemer et al. 2007).

TRANSFORMATION – VALUE – FLOW (TFV) MODEL

From the dual model, flows received more importance. Flows are generated in the interaction of the production system's components. However, the transformation (T) and the flows (F) are differentiated, and the value (V) is spoken of; these three are seen independently. Subsequently, Koskela (2000) proposes the TFV model, grouping these three aspects or sub-theories of production, (T) as added value, (F) as non-conversion activities, and (V) under the concept of reflecting and satisfying the needs of customer or end-user.

FLOW NETWORK MODEL

For Shingo, flow is a chain of events related by a sequence to achieve a goal, and the production system is a network of process and operations flows. "*Processes are flows of objects, represent the progress of a product along a production line and operations are a temporal and spatial human flow that consistently focuses on the worker*" (Shingo 1988, p.4-5).

In construction, the process can be understood as the project's evolution and operations as the workers' work or equipment (Kalsaas and Bølviken 2010).

VALUE – FLOW – OPERATION (VFO) MODEL

Koskela et al. (2007) propose a new development of TFV theory, orienting it with the vision of Shingo (1988) in its flow network model, arguing that to manage construction. The three sub-theories of the TFV model must be considered and integrated: (T) Transformation, work-oriented (flow of subjects or operations), observing the interaction of labor and machinery with the materials, and workflow. (F) Flow, oriented to spatial and temporal movements of materials and information exchange; and (V) Generation of Value. Oriented to look at the process of designing and manufacturing products to satisfy the customer's needs (flow of objects or processes), see Figure 1.

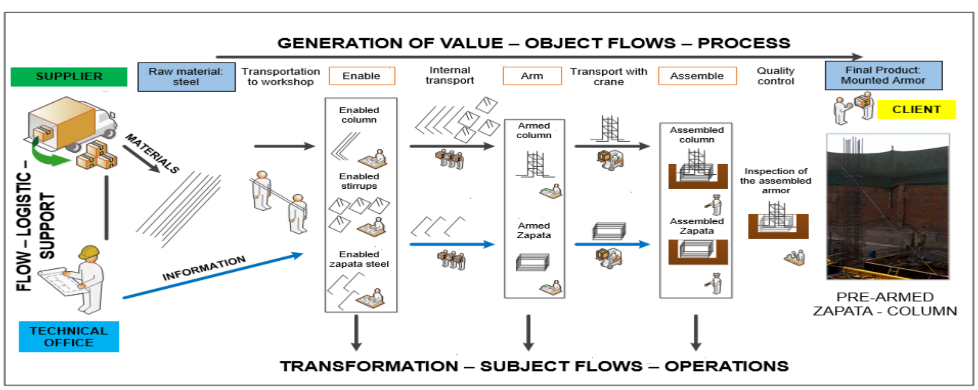

Figure 1: Vision of the Value – Flow – Operation (VFO) production model: Case Pre-armed Steel in Zapata-Column (Adapted from Ramirez, 2014)

This new development substantially improved the TFV theory, which differentiates transformation and value mainly. It was not called VFO until the publication of the article "Transformation-Flow-Value as a Strategic Tool in Project Production" by Bertelsen, and Bonke (2011), where they mentioned that value is the main objective of managing flows and executing operations (Value – Flow – Operation). Later Bertelsen (2017) already uses the name VFO in his book "The Unruly Project."

COMPLEXITY

COMPLEXITY IN CONSTRUCTION

The construction is a complex, dynamic and non-linear system, often on the edge of chaos where chaos "refers to a restricted set of phenomena that evolve in predictable unpredictable ways" (Bertelsen 2003a, p.3-4). It is complex from the product and the nature of the design process, which generates problems by not having agreed solutions, where it is not even clear that the customer want to get to the end, which leads to defining the conditions of satisfaction in parallel with the solutions (Bertelsen 2003a; Bertelsen and Emmitt 2005; Macomber and Howell 2003; Mossman 2017).

The dynamic nature is observed in the uncertainty present in the flows, affecting the execution of tasks (Bertelsen 2017; Hamzeh et al. 2016; Bertelsen et al. 2006) and the participants in the project's materialization due to its temporary nature.

While non-linearity reflects the unpredictable, the plans carried out represent a very idealized linear image of what should be executed, predictably, not considering the interdependence of the operations to be executed (Bertelsen 2003a; Koskela 2000; Koskela 2004; Hamzeh et al. 2016).

PERSPECTIVES OF COMPLEXITY IN CONSTRUCTION

Bertelsen (2003a) suggests analyzing the complexity of construction from three perspectives: 1. The complex and dynamic construction project. The management must give flows prime importance to ensure that the tasks have everything necessary to be executed (Bertelsen et al. 2006, Gamarra 2018); 2. The construction industry, fragmented "by increasingly common subcontracting practices, where the economic issue often prevails, not taking into account the complexity it generates, often reflecting problems of planning and control in projects" and, 3—the social aspects people should give importance. The project's success will depend on the cooperation, communication, and commitment that develops in it (Gamarra 2018).

PROJECT MANAGEMENT IN CONSTRUCTION

Koskela and Howell (2002) show that traditional construction management follows the Project Management Institute's good practices (PMI) based on the conversion model, presenting significant deficiencies from its theoretical base. Therefore, they propose new approaches based on the TFV model, see Table 1.

Table 1: Construction Project Management Approaches (Adapted from Table 1 and 3 in Koskela and Howell 2002)

Production model		Conversion model (PMI)	Model TFV (Koskela and Howell (2002).
Management	**Planning**	Operational planning.	Planification and organization.
	Execution	Order - execution.	Bidirectional communication.
	Control	Standard performance.	Identify errors. Proposal for improvement and learning.

The management proposed presents new and broader approaches, leaving aside the old view of construction, which can be organized, planned, and managed in a predictable way (Bertelsen 2003a), but still does not manage the construction in its nature.

PROJECT MANAGEMENT IN CONSTRUCTION WITH A COMPLEXITY APPROACH

Bertelsen and Koskela (2005), from the approaches to project management proposed by Koskela and Howell (2002), based on their experiences and the perspectives of the complexity of construction presented by Bertelsen (2003a), propose to manage construction projects under the following complexity approaches:

MANAGEMENT AS FLOW AND VALUE GENERATION

One of the first steps to properly manage a project is to identify the client's value proposition. Many, this being considered a problem "without solution" reflected, for example, in constant changes of design (Gamarra 2018). Studies by Drevland and Tillmann (2018) and Erikshammar et al. (2010) examine the value. At the same time, Bertelsen and Emmitt (2005) study the client as a complex system.

On the other hand, the flow management must be done from the beginning so that when reaching the operational level (figure 4), there are no disorder, ignorance, and problems that prevent the execution of tasks on their scheduled dates (Bertelsen and Koskela 2005, Gamarra 2018, Hamzeh et al. 2016, Koskela 2004, Kraemer et al. 2007).

MANAGEMENT AS TEAM BUILDING

The dynamism present in the construction is reflected in the temporary and transitory nature of the people. They mixed different cultures, thoughts, opinions, and others., which often were not taken into account despite the significant influence in the workplace. Establishing a spirit of teamwork where cooperation, collaboration, communication, and trust among all people prevail strengthens the way to achieve the project's objectives (Bertelsen and Koskela 2005, Gamarra 2018, Plenert 2018, Mossman 2017).

MANAGEMENT AS LANGUAGE/ACTION PERSPECTIVE

The erroneous thought of considering that the execution of work will be carried out by the simple fact of issuing an order often leads not obtaining the desired result. Moreover, if people want to be sure that this happens, people must control it exhaustively (Gamarra 2018, Koskela and Howell 2002).

This approach must follow the execution model based on the flow of commitments, which arises from the Theory of Linguistic Action, to guarantee a greater probability of compliance (Gamarra 2018, Macomber and Howell 2003, Mossman 2017).

MANAGEMENT AS SERVICES PROVISION

For management to add value to the production process, it must ensure that tasks are ready for execution (Hamzeh et al., 2016, Koskela 2004). It is necessary to ensure all the preconditions identified by Koskela (2000) that must be the primary function of management as a service provider, see figures 2,3, and 4.

MANAGEMENT AS AN ORGANIZATION

The organization's definitive objective must be to increase the people's reliability to delegate responsibilities. Before the occurrence of problems, these are solved by employing coordination at all levels. It is recommended to work with the Last Planner System (LPS) developed by Ballard (2000) but with the vision of Mossman (2017) and the management of commitments by Gamarra (2018).

MANAGEMENT AS SELF-ORGANIZATION

Can management, in certain aspects, generate more problems than it solves? (Bertelsen 2003a) *"This leads to a new understanding where any worker should have the freedom to self-organize to execute the work. In the short term, the idea is to obtain optimal results by making the minimum possible control"* (Gamarra 2018, p.44).

PROPOSAL FOR A FLOW BASED CONSTRUCTION MANAGEMENT MODEL

The proposed management model takes into account the management of flows. The complexity approaches for the management of construction projects described by Bertelsen and Koskela (2005), the VFO model proposed by Bertelsen (2017); and the seven preconditions de Koskela (2000), except for external conditions because they are a threat of flow, but not a flow in the proposed model.

DESCRIPTION OF THE COMPONENTS OF THE MODEL

- ***Project team***: Represent all project stakeholders for the materialization of the project.
- ***Client:*** Represents the value of the final product.
- ***Suppliers:*** Represents the external team that provides materials, equipment, and tools.
- ***Crews:*** Represents the operational part of the project team (workers).
- ***Value Flow or Process:*** Represents the processes to be executed to obtain the product and be able to satisfy the client's value proposition. The evolution of the product.

- ***Subject Flow or Operations:*** Represents the work of the operative part. It is where the interaction of labor and machinery with materials is generated, the workflow.
- ***Supply Flow:*** Represents the flow of resources for the execution of the project.
- ***Information Flow:*** Represents the transmission of information, at all levels, from the value proposition to the client for decisión making in the project.
- ***Layout Flow:*** Represents the distribution of space in the project, changing as the project's execution is carried out.
- ***Cost Flow:*** Represents the client's competence around the project's cash flow.

DESCRIPTION OF THE FLOW-BASED MANAGEMENT MODEL

The management model is explored in 3 levels: strategic, tactical, and operational.

At the strategic level seeks, in advance, to manage the flows for the execution of the products or final deliverables (for example, in the finishing phase of a multi-family building project, products can be basements, departments, common areas, facade), defined by the project team based on the client's value proposition.

The client's value proposition leads to identifying the value flow (for example, related to the product department: kitchen, bedroom, bathroom, living room, and others). The progress of these (until reaching the final product) is what represents the operations or workflow (for example, for the finished kitchen: pre-finished paint, floor and wall veneer, furniture, electrical appliance, granite countertops, sanitary appliances, windows, doors, and others)

At this level, the value flow is the critical flow (Bertelsen et al. 2006), the most important, and is fed by the others. It is necessary to decide how these will be executed to define the operations (for example, everything changes if you choose to prefabricate). Also, it is essential to approve and validate the design (Gamarra 2018) and develop dates of compliance or milestones of the support flows, information, supply, layout, and cost. For example, it is closing dates with suppliers and subcontractors, associated payments, information required with specific dates, distribution of the project layout over time, cash flow, and others (See Figure 2).

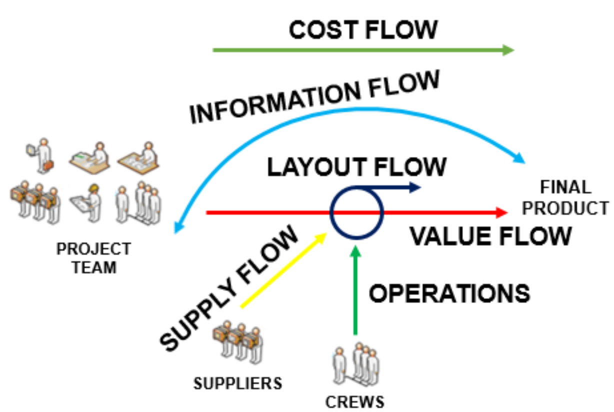

Figure 2: Flow management at a strategic level

At the tactical level, the subject flow is the critical flow (See Figure 3). At this level, flow management seeks to ensure that new support flows meet the workflow requirements. To do this, the person responsible for the task must know everything about the operations. Before executing the task, the person responsible should identify preconditions, defined by Koskela (2000), related to the tasks and ensure that preconditions are ready to execute (Gamarra 2018).

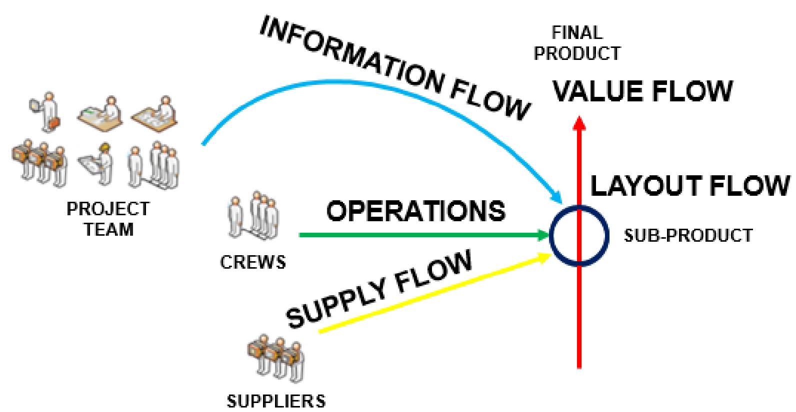

Figure 3: Flow management at the tactical level

Finally, the tasks would be ready to be executed (Hamzeh et al., 2016). Since the flows at the higher levels were already managed, it would only suffice to verify the preconditions for each task (Gamarra 2018).

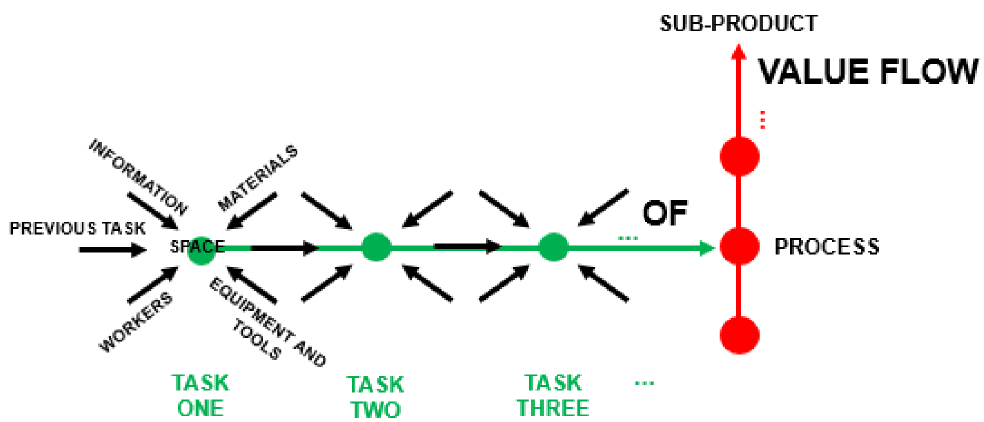

Figure 4: Flow management at the operational level

ORGANIZATION FOR THE MANAGEMENT OF CONSTRUCTION BASED ON FLOWS

COMPLEX ADAPTIVE SYSTEM (CAS)

Getting out of control is a characteristic of complex systems, but adaptability is also part of their nature. These systems can stabilize on their own.

"This can be seen as an important characteristic in the management perspective, since once the system has been established in a stable situation, it will probably remain there for a long time, which will encourage cooperation and, therefore, efficiency" (Bertelsen and Koskela 2005, p.7)

So, why not see the production system under construction as a Complex Adaptive System (CAS)? Authors believe that the desired stability can be achieved by developing an Operational Excellence Organization.

OPERATIONAL EXCELLENCE (OPEX)

Operational Excellence (OPEX) is the relationship between an organization's results and behavior based on principles. It is the consequence of ideal behavior, based on principles, to build a lasting excellence culture (Plenert 2018). The maturity of an organization concerning its learning, evolution, and sustainability (Shingo 1988).

The first challenge will be for the organization to define its basic principles. All those who are part of the organization must recognize these principles. Each person is expected to understand and commit to a culture that reflects behavior based on principles. These will be carried out sequentially, with continuous learning, and in an adaptative way, for which it will be necessary that everything developed is part of knowledge management.

DISCUSSION AND CONCLUSIONS

The proposed model offers the possibility of a holistic analysis of the production system under construction, considering flow management as a basis.

Although the Transformation – Flow – Value (TFV) model offers a good representation of the production system, this model focuses on the workflow and the flow of subjects for Shingo (1988). It does not achieve to cover an integral view of the system. By contrast, a flow model represents it better. The definition of flow as a "chain of events" offers the possibility of holistic analysis. An excellent initial proposal and little disclosed was the Value – Flow – Operation (VFO) model. This research proposes representing the preconditions of Koskela (2000) as flows in three different levels and prioritizing the location for each task characterized by the layout flow. Construction's nature must be managed based on the production location (Kenkey and Seppänen 2010).

The importance of the flows lies in being the main components of production under construction. Therefore, it is necessary to generate and manage flows and identify their role within the system and current events' chains. On the other hand, it is considered appropriate to change the paradigm of identifying constraints by the risk management of the flow at all levels, again see figures 2, 3, and 4. A first attempt to manage risk focuses on paying particular attention to the enemies of the flow: Mura, Muri, and Muda.

An integral vision of the production system allows us to observe that it covers the project, industry, social aspect, people, and interrelation established in an organization. The perspectives and approaches of complexity open a new panorama in construction management, showing the people's importance and influence.

This research proposes to manage complexity by understanding and promoting the production system as a Complex Adaptive System (CAS), where Operational Excellence (OPEX) is the main engine to create culture and organizations of action.

RECOMMENDATIONS AND FUTURE RESEARCH LINES

The authors recommend carrying out future investigations of each of the flows described in the proposal of the management model. All are equally important, but concerning which flow the project team wants to optimize, following the publication of Bertelsen et al. (2006), the team should consider this a critical flow within the model and perform the respective study.

On the other hand, the management based on flows is compatible with the Location-Based Management System (LBMS) because it requires the location for its graphic demonstration (Kenkey and Seppänen 2010). Authors consider that the flow line diagram is the value flow map for construction.

Finally, future research should aim for Operational Excellence (OPEX). The authors recommend following Shingo's ideas transmitted in Plenert (2018).

REFERENCES

Bertelsen, S. (2003a)."Complexity-Construction in a new Perspective". *Proceedings of the 11th annual conference, International Group for Lean Construction*, Blacksburg, Virginia, U.S.A., July, 2003.

Bertelsen, S. (2003b). "Construction as a Complex System". *Proceedings of the 11th annual conference, International Group for Lean Construction*, Blacksburg, Virginia, U.S.A., July, 2003.

Bertelsen, S. (2017). *The Unruly Project*. USA: Sven Bertelsen aps, pp. 13-81.

Bertelsen, S. and Emmitt, S. (2005). "The client as a Complex System". *Proceedings of the 13th annual conference, International Group for Lean Construction*, Sydney, Australia, July, 2005.

Bertelsen, S. and Koskela, L. (2005): "Approaches to Managing Complexity in Construction Project Production". *Becon: 1st International Conference on Built Environment Complexity*, Reino Unido.

Berltesen, S., Koskela, L., Henrich, G. and Rooke, J. (2006). "Critical Flow - Towards a Construction Flow Theory". *Proceedings of the 14th , International Group for Lean Construction*, Santiago, Chile.

Drevland, F. and Tillmann, P. (2018). "Value for Whom?". *Proceedings of the 26th annual conference,International Group for Lean Construction*, Chennai, India, July, 2018.

Erikshammar, J., Björnfot, A., Gardelli, V. (2018). "The Ambiguity of value". *Proceedings of the 26th annual conference,International Group for Lean Construction*, Chennai, India, July, 2018.

Gamarra, G. (2018). *Gestión de Compromisos de Subcontratistas para el Levantamiento de Restricciones en Procesos Incidentes de Acabados en Proyectos de Edificaciones Civiles. [Management of Subcontractors Commitments for Removing Constraints in Processes Incidents of Finishings in Projects of Civil Buildings]* BSc. National University of Engineering, Perú, pp.29, 44, 73-92.Available at: http://cybertesis.uni.edu.pe/handle/uni/15744.

Hamzeh, F., Zankoul E. and El Sakka, F. (2016). "Removing Constraints to Make Tasks Ready in Weekly Work Planning". *Creative Construction Conference,* Budapest, Hungary.

Kalsas B.T. and Bølviken T. (2010). "The Flow of Work In Construction: A Conceptual Discussion". *Proceedings of the 26th annual conference,International Group for Lean Construction*, Chennai, India, July, 2018.

Kenley, R. and Seppänen, O. (2010). *Location-based Management for Construction: Planning, Scheduling and Control.* London and New York: Spon Press, pp. 387-408.

Koskela, L. (1992). *Application of the New Production Philosophy to Construction*. CIFE Technical Report #72, Stanford University, Finlandia, pp.11-16.

Koskela, L. (2000). *An Exploration Towards a Production Theory and its Application to Construction.* PhD Diss, University of Technology, VTT Building Technology, Espoo, Finland, pp. 87-106.

Koskela, L. (2004). "Making do - The Eighth Category of Waste". *Proceedings of the 12th annual conference,International Group for Lean Construction*, Helsingør, Denmark.

Koskela, L. and Howell, G. (2002). *The underlying theory of project management is obsolete*. Project Management Institute, USA.

Koskela, L., Rooke, J., Bertelsen, S., and Henrich, G. (2007). "The TFV Theory of Production: New Developments". *Proceedings of the 15 th annual conference, International Group of Lean Construction*, East Lansing, Michigan, USA, July, 2007.

Kraemer, K., Koskela, L. and Kagioglou, M. (2007). "How Construction Flows Have Been Understood in Lean Construction". *Proceedings of 4th International Research Symposium (SCRI)*, University of Salford, UK.

Macomber, H. and Howell, G. (2003). "Linguistic Action: Contributing to the Theory of Lean Construction". *Proceedings of the 11th annual conference, International Group for Lean Construction*, Blacksburg, Virginia, U.S.A., July, 2003.

Mossman, A. (2017). *Last Planner®: 5+1 Crucial & Collaborative Conversations for Predictable Design & Construction Delivery*. The Change Business Ltd, pp.13-30.

Plenert, G. (2018). *Discover Excellence - An Overview of the Shingo Model and Its Guiding Principles.*Boca Raton, FL:Taylor & Francis Group, CRC Press, pp.27-54.

Ramirez, R. (2014). *Metodología para la Mejora Continua (Shingo) del Sistema de Construcción con Prefabricados de Concreto. [Methodology for the Continuos Improvement (Shingo) of the Construction System with Prefabricated Concrete]*. BSc. National University of Engineering, Perú, pp. 27, 95-111. Available at: http://cybertesis.uni.edu.pe/handle/uni/4398.

Shingo, S. (1988) *Non-Stock Production: The Shingo System of Continuous Improvement*. Cambridge, USA: Productivity Press,pp.4-5, 84-90.

Espinoza, L. R., Brioso, X. and Herrera, R. F. (2021). "Applying CBA to decide the best excavation method: scenario during the COVID-19 pandemic" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 870–879, doi.org/10.24928/2021/0209, online at iglc.net.

APPLYING CBA TO DECIDE THE BEST EXCAVATION METHOD: SCENARIO DURING THE COVID-19 PANDEMIC

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ABSTRACT

On January 30 of 2020, The World Health Organization declared the pandemic crisis as the first public emergency with international importance. Because of this, many building projects were paralyzed since then and the building industry experienced changes that have brought the inclusion of new tools to achieve the objectives of the projects. The purpose of the present paper is to present the application of Choosing By Advantages (CBA) methodology to select the best alternative in the material removal system in the execution of basements in a project that was paralyzed by the health emergency COVID-19. CBA is a lean tool used to make decisions with clarity and transparency and in this case is used to consider the constraints of COVID-19 protocol to guide in decisions making. This methodology was applied to a case study for a building project in the basement construction phase that restarts its activities in the excavations. For that, an expert panel was formed to analyze and decide the best alternative solution. Finally, the selected alternative was implemented on-site, validating the methodology. It is concluded that CBA is an excellent tool to transparently document the selection process of the removal system. Additionally, this methodology allows including activities regarding the COVID-19 protocol, without affecting the project's productivity.

KEYWORDS

Lean construction, Choosing by Advantages (CBA), decision-making, excavations, COVID-19.

INTRODUCTION

In March 2020, the coronavirus pandemic reached all the nations worldwide; it was declared a global pandemic by the World Health Organization (2020). This fact disrupted and put risk industries in the entire world, including the construction industry (Ogunnusi et al. 2021; Alsharef et al. 2021). Given this fact, building projects were paralyzed in the middle of the execution process, affecting the time, costs, and resources. This problem leads to building companies making important decisions in order to recover the initially planned term. On the other hand, in the construction industry, decision-making at any stage of the project is of utmost importance to increase value (Juan et al. 2017). However,

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traditionally, the decision-making of an alternative is carried out empirically, based first on the experience of expert judgment, second on the analysis of the budget available for said activity, and finally on the search for an alternative that meets the above and the customer's preference.

Choosing By Advantages (CBA) is a tool that helps decision-making based on relevant facts (Arroyo et al. 2013). CBA is used to make multiple decisions in the building project life cycle (Brioso et al. 2019); however, there are still no publications that explain its use during the COVID-19 pandemic in the excavation phase. The use of CBA during the pandemic is relevant, since it is part of a solution to the variability in the execution period, being that during the pandemic this problem worsens. This application guides on how to anticipate complex and unlikely situations in the future, such as the COVID-19 pandemic. The purpose of this work is to introduce the method CBA for decision-making of the best alternative in surplus material removal systems in basement construction and applying it to a real case study during the pandemic. With this application it is possible to document and formalize relevant data of the material removal system, making a decision based on important criteria for the context in which the project is located. In this case study, the effects of the pandemic could be positive as well as negative. Positive, because it was necessary to use alternatives of novel methods to avoid the virus spreading (Afkhamiaghd and Elwakil 2020). These alternative methods consider factors such as productivity, interferences with other areas, installation time, facility of installation, occupation area.

LITERATURE REVIEW

CHOOSING BY ADVANTAGES (CBA)

CBA was initially developed by Jim Suhr. CBA is a form of multi-criteria decision analysis (MCDA), although it was found to be superior to other MCDA methods (Suhr 1999). CBA encourages the use of correct data by basing decisions on anchor questions, relevant facts, and significance of the differences between the advantages of the alternatives (Suhr 1999). When implementing the CBA method, the steps are followed:

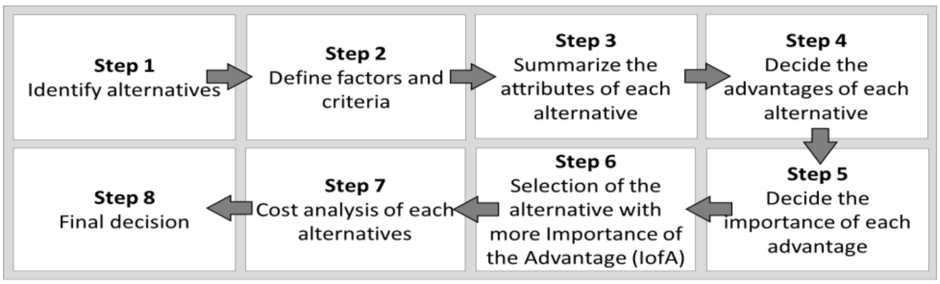

Figure 1. Steps to CBA method (Arroyo et al. 2013; Brioso et al. 2019).

CBA employs the following vocabulary: (1) alternative: a possible option; (2) criterion: a mandatory decision rule or desired guideline; (3) attribute: a feature or quality of a particular alternative; (4) advantage: a benefit-conferring difference between two and only two attributes; (5) factor: an "umbrella" concept, which includes the other concepts in the process; and (6) importance of an advantage: a degree of importance is assigned to each advantage for purposes of comparison. (Suhr 1999; Parrish and Tommelein 2009). CBA makes the decision-making process more transparent and provides a starting point for future work when faced with similar decisions. This makes it possible that the knowledge captured in the CBA table can be useful in the future. (Parrish and Tommelein 2009).

Some studies compare CBA with other methods. Arroyo et al. (2012) explored the characteristics that make a method viable and those that disqualify it, the authors compared and contrasted value-based methods versus CBA, and finally concluded that CBA produces fewer conflicting questions than other choice methods. The same author presented a case study comparing the use of Weighting Rating and Calculating (WRC) versus CBA in selecting a structural system for a residential building on a campus in Palo Alto, California. The case study found that the same decision resulted from both methods, but CBA helped create transparency and generate consensus on the rationale for the decision (Arroyo et al. 2014)

Other studies explored CBA to select an alternative. Parrish and Tommelein (2009) explored the use of CBA to select a design for steel reinforcement in a beam-column joint, this study showed that the values of the team members can conflict, without However, including all perspectives in the CBA table enriches the decision-making process. Martinez et al. (2016) used the CBA to choose the best formwork system, since traditionally they are selected based on the individual experience of the contractors. Karakhan et al. (2016) used CBA to make safety design decisions. Suarez et al. (2020) used CBA to compare 5D BIM models (integrated quantities, costs and schedules), flow lines (Location Based Management System scheduling system and CPM models (3D and 4D).

While other studies integrated CBA with other methods. Chauhan et al. (2019) applied CBA together with cost-benefit analysis to define a process for measuring the impact of prefabrication. Perez and Arroyo (2019) focused on analysing the environmental public policy design process using the CBA decision system integrated with the Design Structure Matrix (DSM) to make complex decisions. Brioso and Calderón-Hernández (2019) in a study aimed to improve the Scoring system with the elements of CBA and describe a teaching strategy applied in a Civil Engineering school. In conclusion, the authors recommended the inclusion of elements of the CBA in the general framework of the Scoring system, to create greater transparency and reduce the time to reach a consensus. The same author Brioso et al. (2019) integrated IVR with CBA in the selection of a fall protection system, with the aim of increasing transparency. On the other hand, Schöttle et al. (2019) use CBA to empower people in an organization and include them in the decision-making process, the author found evidence that CBA promotes inclusion to overcome groupthink and promotes psychological safety.

CBA BENEFITS

Among the benefits that CBA provides are the following: (1) It Generates transparency in the decision-making process and allows explicit consideration of multiple alternatives based on various impact factors (Parrish and Tommelein 2009; Arroyo et al. 2012; Chauhan et al. 2019; Arroyo et al. 2014). (2) It helps generate consensus based on the decision and promotes continuous learning (Parrish and Tommelein 2009; Arroyo et al 2012; Chauhan et al. 2019; Arroyo et al. 2014). (3) It helps to document information on why and on what basis decisions are made, so that they can be reviewed at a later time or in a future project (Parrish and Tommelein 2009). (4) It includes all perspectives of those involved, allowing multidisciplinary participation (Parrish and Tommelein 2009; Abraham et al. 2013; Karakhan et al. 2016). (5) CBA unlike other methods of decision analysis produces fewer questions conflicting, and allows the project team to discuss based on what they really value (Arroyo et al. 2012). (6) CBA Enables early participation and collaboration among stakeholders (Arroyo et al. 2012; Karakhan et al. 2016). (7) CBA deliver value to stakeholders and to the same time reducing uncertainty in the decision-making process, which will reduce the amount of waste generated incorrect decisions (Arroyo et al. 2012). (8) CBA Promotes stakeholder inclusion and promotes psychological safety (Schöttle et al. 2019). (9) It generates a social process in which the debate, argumentation and rhetoric played a role in the final resolution (Martinez et al. 2016). (10) CBA Helps decision makers to represent the context of their case, leading them to select the alternative that best suited the characteristics of their project (Martinez et al. 2016). (11) CBA generates an effective analysis and comparison of alternatives (Suarez et al. 2020). (12) Witch CBA the results of alternatives are easy to analyse, identifying the advantages, the factors in which is the difference and offer clearness to the criteria (Cortes et al. 2017).

COVID-19 PROTOCOL

In Peru, the COVID-19 protocol for building works was promulgated on May 8, 2020 (MCVS 2020). It likewise adopts actions indicated in the ministerial resolution of the Ministry of Health in Peru (MINSA 2020). Through this document is disseminating actions required to start or restart building projects. The protocol contains obligations stipulated. 1) Prepare a plan for the surveillance of the prevention and control of COVID-19. 2) Demand the mandatory use of masks. 3) Carry out a discard evaluation of all people at the entrance and exit of the work (control temperature and pulse oximetry). 4) Subscribe to the COVID-19 symptomatology file for anyone who returns to work. 5) Install information panels with basic recommendations; maintain a safety distance of 1.5m during the stay in work, disinfect with periodicity every environment, and restrict the meetings that generate crowds, providing a space for dining room with a reduced capacity may be in shifts. Likewise, establish areas destined for previous control, topic, changing rooms, lavatories, among other actions described in the protocol. All these actions to face COVID-19 modify the work production systems in building companies.

RESEARCH METHOD

This research adopted a CBA tabular method model, that consists of 8 steps for its implementation. The case study protocol is show in Figure 2:

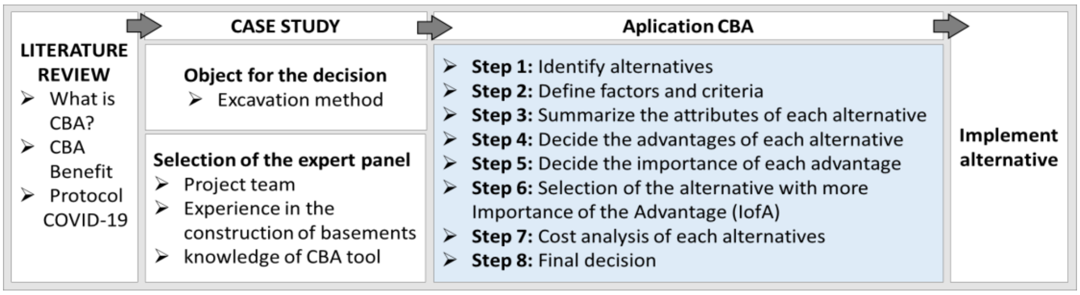

Figure 2. The case study protocol

CASE STUDY

The case study is a building project destined for offices located in Lima-Peru. It involves constructing nine basements, destined for parking lots and warehouses, and once floors destined for offices. This project is characterized by its deep excavation of up to 30.55 m, with a land area of 1,487.65 m^2. This project involves the construction of 350 panels of anchored walls. The duration of this activity is approximately nine months.

The project was paralyzed at the beginning of the excavations (on March 15, 2020). The national state of emergency was declared due to the serious circumstances that affected and continue affecting life as a result of the COVID-19 outbreak (PCM 2020). Under these circumstances, as part of the building project restart, the building company used the Last Planner System (LPS) where collaborative planning was carried out with the team in order to redraft activities in this phase. In this context, it the necessary to choose an adequate method to remove material in the deepest basements excavations not to harm the project deadline. Regarding eliminating the first seven basements, the ramp conformation was used, and a platform with two backhoes, which work satisfactorily (Guio and Cayllahua 2019). For the seventh, eighth, and ninth basements, the best alternative had to be decided, this being the object of this study. To decide the best alternative in advance, it was decided to apply the Lean Construction CBA tool. For this, the perspectives of the expert group were integrated, based on scenarios and early collaboration (Parrish and Tommelein 2009; Arroyo et al. 2013).

RESULTS AND DISCUSSIONS

OBJECT FOR THE DECISION

In the construction of conventional buildings, there are 4 main phases in its construction stage: (1) substructure (includes basements), (2) superstructure, (3) wet and dry finishes, next to the facilities and finally (4) exterior works and furniture installation. Each of these phases has takt-time planning, so taking advantage of some of these phases is crucial for the project in terms of time. One of the phases with the possibility of gaining an advantage is the substructure phase, especially in the material removal activity when choosing an effective removal system. It's so the advantage that has been taken in this phase is directly proportional to the fulfillment of the final project deadline.

In this case study, will be analyzed the material removal from the sixth to the ninth basement, in view of this activity is a bottleneck that blocks the substructure phase's takt-time, impairing the fulfilment of the drilling and the concreting of anchored walls. The origin of this bottleneck has two reasons. Firstly, the little space in the land area, since the zones designated for temporary areas grew to give space for areas such as topical, dining room, sinks and dressing rooms with the 1.5m distance, spaces planned as part of the Plan of the prevention and control of COVID-19. And secondly, the set of materials to be removed is supported in an area that needs to continue with the planning.

SELECTION OF THE EXPERT PANEL

The criteria for the selection of the panel of experts, first is that they are part of the project team. The expert team was constituted by the project manager, field engineer, safety engineer, and costs engineer. Second that the group of experts have experience in these building types (edifications with several basements and floors). And finally that they have some knowledge of the CBA tool. This last criterion is met since the project team previously received training on the philosophy and tools Lean from the company.

APLICATION CBA

Step 1: Identify Alternatives

The expert panel identified three alternatives. 1) Removal by conveyor belt anchored in walls (Figure 4.A). 2) Conveyor belt without anchoring in walls (Figure 4.B). 3) The vertical lifting system (Figure 4.C). For this building project, the expert's panel determined that the minimum material to be removed should be 400 m^3 per day to ensure the advance of the scheduled takt-time of the anchored walls.

Figure 4: Alternatives to remove material for the seven, eight and nine basements.

Step 2: Define factors and criteria

Factors and criteria were defined by the group of specialists. Thanks to the know-how of the Company, ten factors were recommended (1) Productivity, (2) Interferences with other areas, (3) Installation time, (4) Facility of installation, (5) Occupation area, (6) the number of workers, (7) equipment necessary for the movement of earth, and (8) transport of surplus material, (9) the safety factor and (10) the environmental impact factor for noise and dust. The last four factors are very important in order to comply with the COVID-19 protocol, in view that it allows maintaining the distancing of 1.5 m. The last five-factor were not considered in the CBA matrix because the factors and criteria were similar for the three alternatives (Table 1).

Table 1. Matrix factor and Criteria vs Plan of the prevention and control of COVID-19

Factor and Criteria and Protocol COVID-19 (x)	
(1) Productivity: Capable of removing material in a number equal to or greater than 500 m3 / day, to achieve the established term.	
(2) Interferences with other areas: That when removing material, it does not interfere with the execution of other planned activities, such as drilling or construction of anchored walls.	x
(3) Installation time: Short installation time, so as not to have to paralyze the project, or at least not to interfere with the execution of other activities.	x
(4) Facility of installation: Without needing excess machinery and workers	x
(5) Occupation area: A system is sought that occupies a small area, to avoid interference in the execution of other activities	x

Step 3: Summarize the attributes of each alternatives

In this step, the expert panel summarized the attributes of each alternative based on the specifications of the contractors that provide the removal of surplus material service and with the knowledge and experience of previous projects of the expert panel (see Table 2).

Step 4: Decide advantages of each alternative

In this step, based on the established criteria, the expert panel identifies the most advantageous alternatives. Table 2 shows a summary of the three alternatives advantages.

Step 5: Decide the importance of each advantages

In this step, the expert panel collaboratively assigned a level of importance for each advantage. A scale from 1 to 100 was used, giving the value of 100 to the most important advantage and giving lower values to others. Where the supreme advantage is the (5)

Occupancy area with an IofA of 100, secondly the (2) Interference with other areas and the (3) Installation time with an IofA of 75, and as a third advantage is the (1) Productivity and (4) Facility of installation with an IofA of 50. Once the importances have been assigned to each advantage, the total importance of each alternative is calculated, in such a way that it is easy to compare the alternatives (Table 2).

Step 6: Selection of the alternative with more Importance of the Advantage (IofA)
In this step, indicators such as importance level are considered in the making-decision. Table 2 shows the CBA analysis with three alternatives solutions to remove the surplus material from basement seven to basement nine. In this step, the importance score of each alternative is summed. It is likely to have tie alternatives due to closing scores, such as the alternative 2 and 3 with scores 295 and 305, respectively.

Table 2: CBA Analysis.

Solution alternatives for the removal of material from basement seven to basement nine				
Factor	**Criterion**	**ALTERNATIVE 1:** Conveyor belt anchored in walls	**ALTERNATIVE 2:** Conveyor belt without anchoring in walls + bucket crane	**ALTERNATIVE 3:** vertical lifting system
Productivity	Higher productivity is better	Attribute: 500 m^3/day	Attribute : 500 m^3/day	Attribute : 600m^3/day
		Advantage: 0	Advantage: 0	Advantage: 100 m^3
		Importance : 0	Importance : 0	Importance : 50
interferences with others areas	Less interference is better	Attribute: It hampers many tasks	Attribute: It hampers a little some task	Attribute: It almost does not hamper tasks
		Advantage: 0	Advantage: It interferes a bit more than alternative C	Advantage: It is the one that least interferes
		Importance: 0	Importance: 70	Importance:75
Installation time	Less time is better	Attribute: 14 days	Attribute: 5 days	Attribute: 5 days
		Advantage: 0	Advantage: 9 days	Advantage: 9 days
		Importance: 0	Importance: 75	Importance: 75
Facility of installation	Higher facility is better	Attribute: this alternative uses overlaps that make installation difficult	Attribute: average difficulty	Attribute: average difficulty
		Advantage a: 0	Advantage: the least difficult	Advantage: the least difficult
		Importance: 0	Importance: 50	Importance:50
Occupation area	Less area is better	Attribute: It occupies a considerable area	Attribute: occupies little area	Attribute: occupies little area
		Advantage: 0	Advantage: it allows more area available for work	Advantage: it allows more area available for work
		Importance: 0	Importance: 100	Importance: 100
Score IofA		**0**	**295**	**305**

The experts' panel excluded the alternative one, even if it had a low cost since it presented an IofA of zero. The experts' team concluded that it would present a high probability of non-compliance with the deadline and the COVID-19 protocol. On the other hand, it was observed that alternative 2 obtained a 295 IofA, and alternative 3 obtained 305. The difference between these two alternatives was 3.38%. The expert panel considered it as a tie since the difference was considered very small for the method used. Thus, the cost factor will determine the winning alternative.

Step 7: Cost analysis of each alternatives

A comparative graph of the IofA and the costs of the three alternatives is shown in Figure 5. The cost of each alternative includes the service of rental and maintenance of equipment, payment to workers, earthworks, and transportation of excess material to remove and insurance against accident.

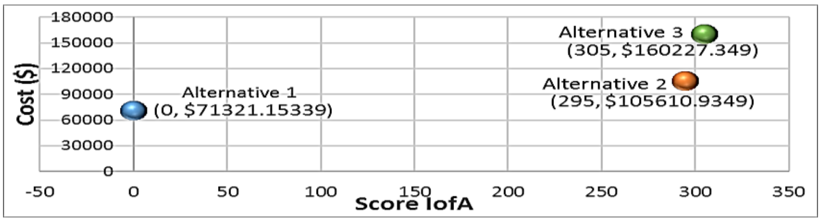

Figure 5. Alternative Costs.

Step 8: Final Decision

The expert panel determined that alternative 2 was the winner since alternative 3 was 51.7% higher in cost, and it was only 3.38% lower in the score obtained in IofA. The first alternative has 30% less cost, but this was excluded due to the probability of not comply the COVID-19 protocol and the deadline. CBA allowed that the expert team to select the alternative not necessarily the cheapest, but complied with expected performance. CBA helped to exclude one of the alternatives with low cost, but with a high likelihood to not comply with the deadline and the COVID-19 protocol.

IMPLEMENT ALTERNATIVE

After choosing the alternative, a test was made to observe its performance. Thus, it was observed that the operation of the belt had a cycle time of 1'15"64. It was also verified that the bucket crane efficiently removed large stones that could not be moved through the belt. In general, the task to remove exceeded 400 m3 per day, so it was always ahead of the other tasks, so it was not a bottleneck in this phase. Figure 6.A and 6.B show the conveyor belt operation, which is not anchored in walls. Figure 6.C shows the bucket crane removal work simultaneously. The panel of experts concluded that if there is no pandemic, they would also use the winning alternative (alternative 2). Since this alternative takes up less space than alternative 1, and allows activities to be carried out in parallel without interruption. In addition, as one of the benefits Parrish and Tommelein (2009) allude, in this study, with the application of CBA it was possible to document and formalize relevant data of the material removal system, making a decision based on important criteria for the context in which the project is located. As well as, speed up the decision-making process.

Figure 6. Operation of the conveyor belt and bucket crane.

CONCLUSIONS

The main findings of this study were: First, to evidence applying the Choosing by Advantages (CBA) successfully. Second, the evidence that the COVID-19 protocol compliance did not impact the productivity of the project. A practical contribution is the information and important data of the alternatives to choose the best removal system according to the conditions of the project. Given that, this type of construction with several levels of basements has been being carried out with increasing popularity in the city of Lima, which is why it is considered a systematic process. Some of the benefits of CBA that were evidenced are: Allows document and formalize relevant data, making decisions based on important criteria, speed up the decision-making process, allow decide for an alternative that meets with expected performance. The application of CBA presented no barriers since the panel of experts knew the method and it was a collaborative decision. Which differentiates it from other studies, where there are barriers such as resistance to change (Bayhan et al. 2019). Some limitations of the investigation were: First, the application was carried out in a single case study, in a particular company, under unique characteristics, so generalization should be avoided. Second, the factors considered as part of the CBA application are associated with productivity, safety, and compliance with the prevention plan against COVID-19, without considering factors associated with environmental sustainability.

REFERENCES

Afkhamiaghd, A. M., and Elwakil, E. (2020). “Preliminary modeling of Coronavirus (COVID-19) spread in construction industry.” *Journal of emergency management* (Weston, Mass.), 18(7), 9-17.

Alsharef, A., Banerjee, S., Uddin, S. M., Albert, A., and Jaselskis, E. (2021). “Early Impacts of the COVID-19 Pandemic on the United States Construction Industry.” *International journal of environmental research and public health*, 18(4), 1559.

Arroyo, P., Tommelein, I., & Ballard, G. (2012). “Deciding a Sustainable Alternative by Choosing by Advantages. In the AEC industry.” *20th Annual Conference of the International Group for Lean Construction*, San Diego, CA. 41-50.

Arroyo, P., Tommelein, I. D. and Ballard, G. (2013). “Using Choosing by Advantages to Select Tile From a Global Sustainable Perspective.” *21th Annual Conference of the International Group for Lean Construction*. Fortaleza, Brazil. 309-318.

Arroyo, P., Tommelein, I. D., & Ballard, G. (2014). “Comparing weighting rating and calculating vs. choosing by advantages to make design choices.” *22nd Annu. Conf. Int. Gr. Lean Constr*. Vol. 1, No. 510, 1-12.

Bayhan, H. G., Demirkesen, S., & Jayamanne, E. (2019). “Enablers and barriers of lean implementation in construction projects“. *IOP Conference Series: Materials Science and Engineering* (Vol. 471, No. 2, p. 022002). IOP Publishing.

Brioso, X., Murguia, D., and Urbina, A. (2017). “Comparing three scheduling methods using BIM models in the Last Planner System.” *Organization, technology & management in construction: an international journal*, 9(1), 1604-1614.

Brioso X., Calderon-Hernandez C., Irizarry J., and Paes D. (2019). “Using Immersive Virtual Reality to Improve Choosing by Advantages System for the Selection of Fall Protection Measures.” *Comput. Civ. Eng. 2019 Vis*. Inf. Model. Simul. - Sel. Pap. from ASCE Int. Conf. Comput. Civ. Eng. 2019, no. June. 146–153, 2019.

Brioso, X., and Calderón-Hernández, C. (2019). "Improving the Scoring System with the Choosing by Advantages (CBA) elements to evaluate Construction-Flows using BIM and Lean Construction". *Advances in Building Education*, 3(2), 9-34.

Chauhan, K., Peltokorpi, A., Lavikka, R., and Seppänen, O. (2019). "Deciding between prefabrication and on-site construction: a choosing-by-advantage approach." *27th Annual Conference of the International Group for Lean Construction*. 749-758.

Guio S. J., and Cayllahua H. D. (2019). "Análisis de los métodos de eliminación de material para construcción de sótanos en Proyectos que presentan suelo granular en Lima Metropolitana." *Research projects*. Faculty of engineering, Peruvian University of Applied Sciences, Lima, Peru. (in Spanish).

Juan, R., Jose P., Jose D. and Laura G. (2017). "Choosing by advantages; benefits analysis and implementation in a case study, Colombia." *Proc. 26th Annual Conference of the International. Group for Lean Construction*, Chennai, India. 636–646.

Karakhan, A., Gambatese, J., and Rajendran, S. (2016). "Application of Choosing By Advantages Decision-Making System to Select Fall-Protection Measures." *24th Ann. Conf. of the Int'l. Group for Lean Construction*, Boston, MA, USA, sect.11. 33–42.

Martinez, E., Tommelein, I., & Alvear, A. (2016). "Formwork system selection using choosing by advantages." *In Construction Research Congress 2016* (pp. 1700-1709).

Ministerio de Salud (MINSA). (2020). Resolución Ministerial N° 448-2020-MINSA. Lineamientos para la vigilancia, prevención y control de la salud por exposición al SARS-CoV-2. Diario Oficial El Peruano, Lima, Peru. (in Spanish).

Ministerio de Vivienda, Construcción y Saneamiento (MVCS). (2020). Resolución Ministerial Nº 087-2020-VIVIENDA. Protocolo sanitario del sector vivienda, construcción y saneamiento para el inicio gradual e incremental de las actividades en la reanudación de actividades. Diario Oficial El Peruano, Lima, Peru. (in Spanish).

Perez, C. and Arroyo, P. (2019). "Designing Municipal Waste Management Programs Using Choosing by Advantages and Design Structure Matrix." *27th Annual Conference of the International. Group for Lean Construction*, Pasquire C. and Hamzeh F.R. Dublin, Ireland. 1345-1368.

Presidencia del Consejo de Ministros (PCM). (2020). Decreto Supremo Nº 044-2020-PCM. Decreto Supremo que declara Estado de Emergencia Nacional por las graves circunstancias que afectan la vida de la Nación a consecuencia del brote del COVID-19. Diario Oficial El Peruano, Lima, Peru. (in Spanish).

Ogunnusi, M., Hamma-Adama, M., Salman, H., and Kouider, T. (2020). "COVID-19 pandemic: the effects and prospects in the construction industry. International journal of real estate studies.", 14(Special Issue 2).

Parrish, K. and Tommelein, I. D. (2009), "Making Design Decisions Using Choosing by Advantages." *17th Annual Conference of the International Group for Lean Construction*. Taipei, Taiwan, 15-17 Jul 2009.

Suarez, J. C., Zapata, J., and Brioso, X. 2020. "Using 5D Models and CBA for Planning the Foundations and Concrete Structure Stages of a Complex Office Building." *28th Annual Conference of the International Group for Lean Construction.* Berkeley, California, USA.

Suhr. J. (1999). "The choosing by advantages decision making system, Quorum." *Greenwood Publishing Group*.

World Health Organization. (2020). "WHO characterizes COVID-19 as a pandemic." World Health Organization.

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Safety, Quality, and Green Lean

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Lima, M. I. S. C., Melo, R. R. S., and Costa, D. B. (2021). "Contribution of UAS monitoring to Safety Planning and Control." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 883–892, doi.org/10.24928/2021/0138, online at iglc.net.

CONTRIBUTION OF UAS MONITORING TO SAFETY PLANNING AND CONTROL

Mahara I. S. C. Lima[1], Roseneia R. S. Melo[2], and Dayana B. Costa[3]

ABSTRACT

Among the technologies used for safety management at construction sites, Unmanned Aerial System (UAS) stands out due to its ability to capture images and videos of large areas, reduce data collection and processing times, and improve risk identification at the jobsite. Despite the advances in safety monitoring using UAS, there is still a gap regarding the effective use of information provided by this technology for assisting Safety Planning and Control (SPC). This study proposes a set of practices to incorporate the information collected from a UAS safety monitoring system into SPC routines. The research strategy used was the Design Science Research (DSR), and preliminary implementation of the artifact occurred during 14 weeks in a residential construction project. The evaluation involved establishing a set of constructs and variables such as transparency, collaboration, and utility to analyze the contributions of the practices proposed. As preliminary contributions, results show that the visual display implementation significantly impacted the sharing of safety information, the awareness of safety conditions, and the promotion of new learnings for workers. Moreover, the practices implemented provided foreman participation in decision-making related to safety and construction site organization and housekeeping.

KEYWORDS

Safety management, safety inspection, unmanned aerial systems (UAS), construction site, digital technologies.

INTRODUCTION

The dynamism of workflows at construction sites makes safety management challenging through the conventional methods, which are time-consuming and prone to errors (Guo et al., 2017). Some of the challenges encountered are related to large construction sites (Irizarry et al., 2012), the sharing of large amounts of information, and the lack of practice in transforming the information gathered into performance indicators (Zhang et al., 2016). In addition to those limitations, the lack of adequate technological support hampers effective decision-making at construction sites.

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The literature shows that digital technologies improve performance and make processes more straightforward and productive (Guo et al., 2017). However, Simpson et al. (2019) noted the need to implement the technologies with management practices. Their contribution is not limited to digitalize processes but to solve real problems in the construction industry.

Among the digital technologies used for safety management on construction sites, Unmanned Aerial Systems (UAS) have attracted attention. The main positive characteristics of UAS are their ability to capture images and videos of large areas, reducing data collection and processing time, and facilitating the identification of risk situations (Irizarry et al., 2012; Melo and Costa, 2019).

According to Melo and Costa (2019), UAS monitoring supports activities workflow, enables the identification of safety and production trade-offs, and anticipates risk situations faced by workers, as well as interferences between processes. For these authors, the information provided by UAS could enhance SPC; however, an effective response is related to the team's skills to make it promptly. Martinez et al. (2020) proposed a method for safety planning and monitoring using UAS in which visual information (photos and 3D models) generated by UAS were used to identify and assess hazards. According to these authors, the pictures and 3D models allowed identifying more hazards than in the traditional method, besides improving managers' perceptions concerning risk assessment. Both studies performed weekly safety monitoring; however, none of them proposed learning mechanisms or practices to support the continuous improvement of safety planning, such as tools for follow-up action plans regarding the nonconformities identified on-field. Based on that, there is a gap regarding the effective use of information provided by UAS for safety management.

Despite the advances in safety monitoring using UAS, few studies, such as Melo and Costa (2019) and Martinez et al. (2020), have explored UAS monitoring to assist Safety Planning and Control (SPC). Therefore, this paper suggests a set of managerial practices and indicators to incorporate the information provided by UAS monitoring into SPC. A computerized safety inspection system, called Smart Inspecs System, is used for data processing, analysis, and storage.

BACKGROUND

According to Saurin and Formoso (2008), an effective risk assessment consists of four stages. First, the risks to which workers are exposed must be identified and evaluated. In response, the management teams must define measures to control the hazards and monitor their implementation. During the monitoring, performance measurement must be carried out, and actions must be implemented, providing feedback to the previous stages of the management cycle.

Regarding practices to enhance SPC, Coble and Elliot (2000) say that the identification and evaluation of risks must be performed by the production and safety teams, taking into account the work packages scheduled, the workforce's capabilities, and the participation of frontline workers. Jiang et al. (2014) highlighted that the communication between managers and workers about safety issues is essential to improve safety awareness and knowledge. The adoption of visual tools improves communication efficiency, ensures transparency, and increases employee motivation and self-management (Galsworth, 2017). The compliance with mandatory regulations and internal procedures must be evaluated through safety inspections (Kjellén and Albrechtsen, 2017), generating safety indicators. Thus, to achieve continuous improvement in safety performance measurement, there is a need to assess whether planned objectives are getting reached, identify target areas for improvement, propose proactive measures, and evaluate their effectiveness (Lingard et al., 2019).

RESEARCH METHOD

This study adopted the Design Science Research (DSR) approach (Vaishnavi and Kuechler, 2015). The practical problem is how to effectively use the information provided by UAS monitoring to improve the safety planning and control processes. The research was conducted according to the following steps: awareness, suggestion, implementation and evaluation, and conclusion. This paper focuses on the first cycle of the implementation and evaluation steps (see Figure 1).

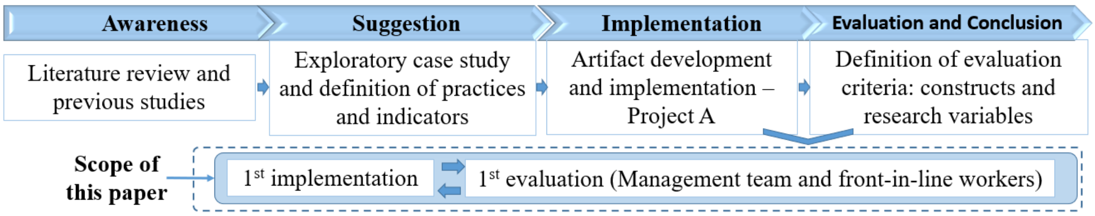


Figure 1: Research design

IMPLEMENTATION OF PRACTICES AND INDICATORS PROPOSED

The **implementation stage** initially occurred during 14 weeks in Project A, a residential condominium consisting of three 20-story buildings and a garage building (5 floors). During the study, the construction phases were the residential towers' foundation and the garage building's precast concrete structure.

Based on the awareness and suggestion stages, the artifact proposed and implemented consists of a **set of practices and indicators to incorporate the UAS safety monitoring using the Smart Inspecs System into the SPC process** at two levels (weekly and monthly), as shown in Figure 2.

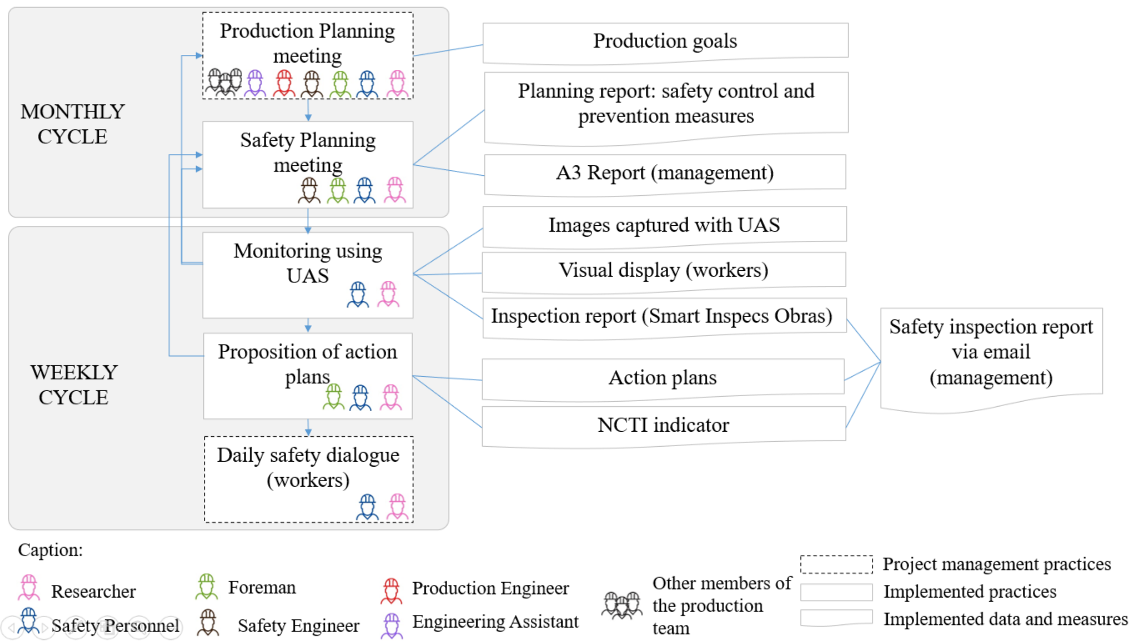


Figure 2: Workflow to use the information provided by UAS monitoring into SPC.

In Project A, monthly Production Planning meetings are held to present and discuss production goals. The study proposed the implementation of Safety Planning meetings to establish preventive and control measures for the planned work packages. These meetings involve Safety personnel, Safety Engineering, and Foreman. A **Safety Planning report** containing the decisions and planned actions established at the meeting is shared with managers via email. The **safety monitoring using UAS** was carried out weekly using the DJI Phantom 4 and the Smart Inspecs System.

The Smart Inspecs System is a computerized safety inspection system that uses UAS to monitor safety conditions on-site and a web system to automate the inspection process [9]. The UAS safety checklist has 241 items divided into 21 categories, such as organization and housekeeping, storage of materials, construction site signaling, stairs and ramps, collective protective equipment, and earthwork and foundation. The pilot (principal author) performed the inspections, supported by an observer (assistant researcher) and the project safety personnel who participated in eight from 14 assessments. Figure 3 presents the safety inspection protocol used and Table 1 shows the Flight log data collected during the 14 inspections performed in Project A.

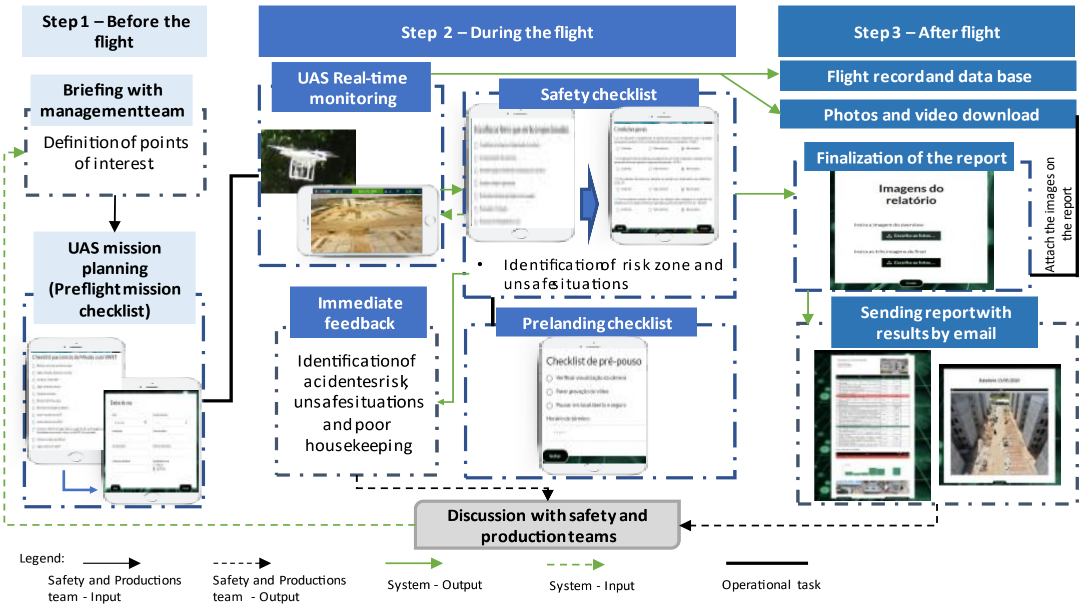


Figure 3: Safety inspection protocol using Smart Inspecs Systems (adapted from Melo, 2020)

Table 1: Visual assets data collected in Project A

Number of Inspections	Number of Images	The average flight distance (m)	Maximum height (m)	Total Flight time (h)	Average Flight time (h)
14	477	867	75	03:59:34	00:17:06

The output of the inspections using the Smart Inspecs System is composed of an **inspection report** which contains a safety checklist assessment, images collected with UAS, and the safety compliance indicator (i.e., the ratio of the sum of compliant items and the sum of items checked). At the end of the inspection, a feedback meeting is performed involving safety personnel and Foreman to propose an **action plan** for each nonconformity identified on the assessments.

The action plans analysis is carried out through the **Nonconformity Treatment Indicator (NCTI)**, calculated as the ratio between the sum of planned corrective actions and the sum of the executed corrective actions. The **safety inspection report**, the NCTI, and the action plans are delivered via email to the management team. The inspection results are communicated to workers via **visual display** and during the **daily safety dialogue**. The visual display is updated on a weekly and monthly basis, as presented in Figure 4.

Figure 4: Visual display

The information collected during the weekly cycle is used to support the SPC for the following month. The communication of monthly results to the management team is done using an A3 report containing (a) the graph of the evolution of the Safety Compliance Indicator, (b) the Nonconformity Treatment Indicator per week, (c) the classification of the nonconformities per categories, and (d) the recurrences of non-conformities. An example of the A3 report is presented in Figure 5 (Result Section). Finally, the information is used to support monthly Safety Planning meetings.

Evaluation of the Practices and Indicators Implemented

The **evaluation phase** involved analyzing the contribution of the practices and indicators implemented into the SPC routines through a set of constructs and variables (Table 2). Those constructs and variables were defined based on the literature review and previous studies carried out by the research group. The primary sources of evidence used for this evaluation were: (a) participant observations during the 14 weeks, (b) document analysis (safety planning report, A3 report, production planning spreadsheet, safety inspection report, emails, action plans spreadsheet), (c) images collected with UAS, and (d) semi-structured interviews, as detailed as follows.

The first round of interviews to collect the managers' perception of the implementation of the artifact proposed in Project A was carried out with five members of the management team composed by Production Engineer, Assistant Engineer, Foreman, Safety Engineer, and Safety Personnel (n=5). The questionnaire used in the interviews had eight closed-ended questions with subheadings using a Likert Scale with five-level impact and four complementary open-ended questions. Additional data collection involved the use of a questionnaire to collect the workers' perception. A total of 22 workers were interviewed (n=22 workers) about the understanding of safety conditions information (transparency) and use of the information provided by UAS to improve safety conditions (utility). This questionnaire had two closed-ended questions with subheadings using the same Likert Scale described above and four complementary open-ended questions.

Table 2: Constructs and Variables (Research evaluation criteria)

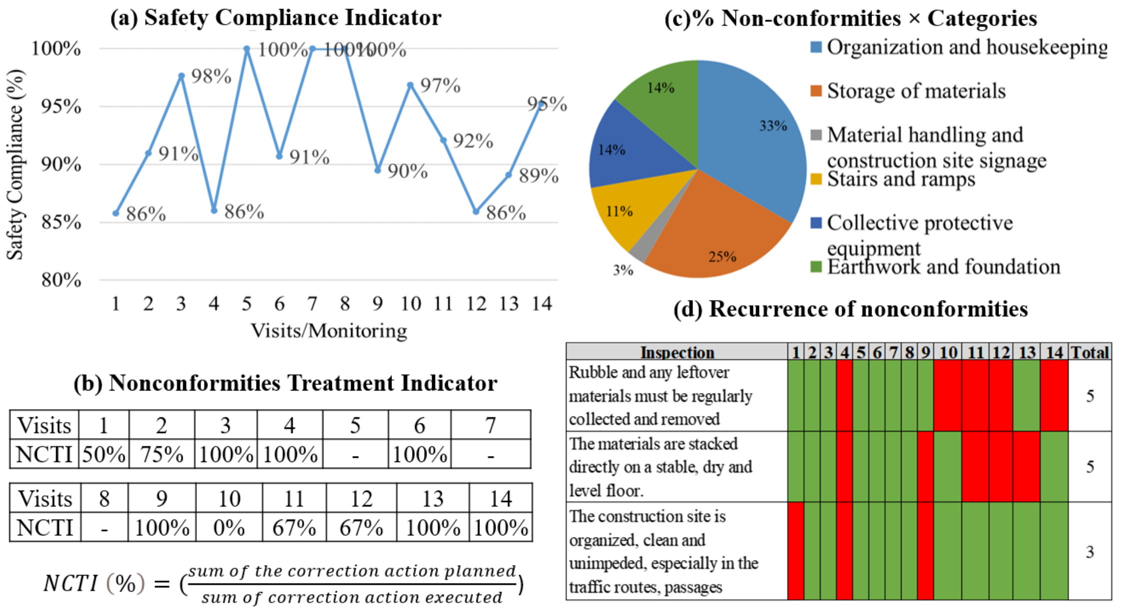
Constructs	Variables
Collaboration	Sharing information related to SPC between safety and production teams. Interaction between the production and safety teams to improve decision-making.
Transparency	Contribution for a better understanding of safety conditions information. Identification of risks and conditions not previously considered in the SPC.
Utility	Use of the information provided by UAS to plan preventive and corrective measures. Use of the information provided by UAS for planning the acquisition of resources. Use of the information provided by UAS to anticipate and eliminate safety constraints. Use of the information provided by UAS to improve safety conditions. Identification of factors that influence safety performance.

RESULTS AND DISCUSSION

This section presents the results obtained during the implementation and evaluation stages.

Safety Performance Based on the Practices Implemented

Figure 5 shows the A3 report with the results of the 14 weeks of implementation in Project A.



Visits	1	2	3	4	5	6	7
NCTI	50%	75%	100%	100%	-	100%	-

Visits	8	9	10	11	12	13	14
NCTI	-	100%	0%	67%	67%	100%	100%

$$NCTI\ (\%) = \left(\frac{sum\ of\ the\ correction\ action\ planned}{sum\ of\ correction\ action\ executed}\right)$$

Inspection	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Rubble and any leftover materials must be regularly collected and removed															5
The materials are stacked directly on a stable, dry and level floor.															5
The construction site is organized, clean and unimpeded, especially in the traffic routes, passages															3

Figure 5: A3 Report - Safety performance Project A

In Project A, during the 14 inspections carried out, there were 36 nonconformities associated with 18 safety requirements, which corresponds to two notifications per assessment. These 36 nonconformities are distributed into six categories (see Figure 5), such as organization and housekeeping (33%), material storage (25%), and collective protective equipment (14%).

Results show that five action plans had performance (NCTI) below the average (78%), and the time taken to carry out the corrective actions was 1 to 3 weeks. The main difficulties faced on the implementation of correction actions were the layout planning failure, equipment unavailability, lack of technical experience with the construction process adopted and, the lack of prioritization to correct situations with low accident risk.

Additionally, during the implementation, the management team made efforts to improve site organization and housekeeping. However, regarding the production pressure, the safety team argues that the production goals are overly aggressive, making it difficult to propose any action.

EVALUATION OF THE ARTIFACT

Table 3 describes the management team's perception, including the Production Engineer, Assistant Engineer, Foreman, Safety Engineer, and Safety Personnel regarding the evaluation of collaboration and transparency constructs.

Table 2: Management team's perception about collaboration and transparency (n=5)

CONSTRUCTS	COLLABORATION					TRANSPARENCY				
Variables	Sharing information related to SPC between safety and production teams					Understanding information about safety conditions				
Data and measures	**Very low**	**Low**	**Indifferent**	**High**	**Very High**	**Very low**	**Low**	**Indifferent**	**High**	**Very High**
Safety inspection report				100%					40%	60%
Images collected with UAS				60%	40%				40%	60%
NTCI				80%	20%				40%	60%
Visual display			20%	40%	40%				40%	60%
A3 report			20%	60%	20%				80%	20%
Variables	Interaction of the production and safety teams for improving decision-making					Identification of risks and conditions not previously considered in the SPC				
Practices	**Very low**	**Low**	**Indifferent**	**High**	**Very High**	**Very low**	**Low**	**Indifferent**	**High**	**Very High**
Safety planning meetings			40%	40%	20%		20%		40%	40%
Action plan meeting			20%	80%					60%	40%

Regarding the collaboration, most interviewees considered that the data and measures adopted have a high to a very high level of efficiency in sharing safety information. They highlighted the relevance of the images collected with UAS and the visual display to improve communication, as Galsworth (2017) indicated. The participants indicated that the data and measures delivered are objective and easy to understand, in addition to providing better visualization of the project's failures.

The interaction between the production and Safety teams was mainly promoted by the safety meetings and action plans. According to the interviewees, the research contributed to the collaboration between the teams and increase the Foreman's participation on the decision-making process. The Foreman reported that "before the safety meetings, I only received the plans of how things need to be performed. Along the study I began to participate in the discussions and my opinion was considered". However, for the Production Engineer, Foreman, and Safety Engineer, the practices impact in improving the interaction between teams was "indifferent" or "low" because the participation of the production team was centralized in the Foreman. They consider that it is necessary to involve the entire production team. Thus, there is a need for better alignment between the production and safety meetings, so everyone involved can participate.

About the **transparency,** the five members of the management team highlighted a better understanding of the safety conditions due to the aerial images captured by UAS. Respondents noted that the aerial images allow them to view the site as a whole and identify situations that are not perceived on a daily basis. According to the respondents, the data and measures had a high to very high contribution to the understanding of safety conditions.

Regarding the variable understanding information about safety conditions, most of the workers interviewed, a total of 22 workers, reported a high level of understanding about the information presented on the visual display. However, 18% of the interviewees faced difficulties in the understanding of the graph about safety compliance indicators, and 9% had problems understanding the good practices.

Table 4 presents the management team's perception of the utility of data and measures and practices to improve the SPC process. The results show that the main contribution concerning the utility of the practices proposed was in their ability to anticipate and eliminate safety constraints. According to the interviewees, the safety planning meetings and the definition of action plans allowed identifying challenges in resource acquisition and the elaboration of effective planning with a focus on safety. The images collected with UAS contributed to planning resources acquisition, including production supplies, such as concrete blocks. These results are similar to those achieved by Melo and Costa et al. (2019), which identified the potential use of the products generated by the monitoring with UAS to determine the trade-off between safety and production and support safety planning. The safety inspection report and the images collected with UAS had a high impact on the planning of corrective and preventive measures, supporting the immediate decision-making.

Table 3: Management team's perception regarding utility (n=5)

CONSTRUCT	**UTILITY**									
Variable	Use of the information provided by UAS for planning preventive and corrective measures					Use of the information provided by UAS for planning resources acquisition				
Data and Measures	**Very low**	**Low**	**Indifferent**	**High**	**Very High**	**Very low**	**Low**	**Indifferent**	**High**	**Very High**
Safety inspection report		20%	20%	20%	40%				60%	40%
Images collected with UAV			20%	20%	60%				60%	40%
NCTI			20%	60%	20%		20%	20%	40%	20%
Visual display			40%	40%	20%		20%	20%	60%	
A3 report			40%	60%			20%	20%	40%	20%
Variables	Use of the information provided by UAS to anticipate and eliminate safety constraints					Identification of influencing factors for safety performance				
Practices	**Very low**	**Low**	**Indifferent**	**High**	**Very High**	**Very low**	**Low**	**Indifferent**	**High**	**Very High**
Safety planning meetings		20%			80%			60%		40%
Action plan meeting		20%			80%			20%	40%	40%

For the management team, the main benefits of the implementation were (a) the increased productivity of the safety team, (b) the better analysis of site conditions through the images collected with UAS, and (c) the improvement of the response time due to the speed of inspection and feedback.

Regarding the **use of information provided by UAS to improve safety conditions**, 77% of the workers' interviewed (n=22) noted a very high impact on the safety conditions. They highlighted improvements in the organization and housekeeping aspects, adequate waste disposal, and construction site signalling. According to 86% of the workers, the construction management team has promoted discussions about the nonconformities identified in the inspections with UAS, especially in the daily safety dialogues.

The main difficulty is related to the incorporation of the practices into safety routines due to the overwork and prioritization of production goals by managers. As further opportunities, the respondents noted the need for an indicator that emphasizes the recurrence of nonconformities and more engagement of the production team in discussions and UAS inspections.

On the following implementation, the recurring nonconformities will be included in the email sent with the safety inspection report (weekly) and in the A3 report (monthly). Moreover, the A3 report and the safety planning report will be printed and exhibited in the engineering and foreman rooms. To enhance the indicators' use, the production engineer can use the ITNC indicator to evaluate the team commitment to put the planned actions in practice, understand the difficulties they face, and contribute to taking the activities on time. Production and safety planning must be integrated and developed in a way that involves all stakeholders, achieving a greater interaction between teams in the data analysis and SPC decision-making. Besides the researcher's efforts to incorporate the monitoring using UAS into SPC, it is essential the management commitment to align the safety and production plans and use the information provided by UAS monitoring to make the SPC process more efficient.

CONCLUSION

This paper presents the proposition and implementation of practices and indicators to incorporate the information generated by UAS monitoring into SPC. The results obtained in Project A show that the Smart Inspecs System and the practices implemented have the potential to contribute to the development of safety skills since they improve visual management through the visual display, images collected with UAS, and A3 report. These data and measures proved to be helpful to enhance safety training and workers' risk awareness, as evidenced by the management team and workers' perception.

Additionally, the proposed practices supported a better discussion between safety and production teams, promoting more consistent safety planning meetings and anticipating and eliminating safety constraints, such as resource acquisition. Despite the advances, the management team argues that the interaction between safety and production teams in the SPC processes remains inefficient with minor production teams' involvement. As a suggestion, there is a need to encourage the discussion of safety results with the entire production and safety teams.

As the main limitation, it should be highlighted the impossibility to inspect safety requirements within buildings. In addition, the practices and indicators were implemented only in Project A, which stands out the need to apply them in others types of construction sites with more structured safety management systems. As future research, this paper indicates the need to investigate how to use the information provided by UAS to improve SPC in the medium and long term, as well as use the information to increase the engagement and participation of workers in safety practices.

REFERENCES

Galsworth, G. (2017). *Visual Workplace - Visual Thinking*. CRC Press, New York, EUA.

Guo, B., Scheepbouwer, E., Yiu, T. W., and Gonzalez, V. (2018). "Overview and analysis of digital technologies for construction safety management." *Proc. of the 41th Australasian Universities Building Education Association Conference,* Melbourne.

Irizarry, J., Gheisari, M., and Walker, B. N. (2012). "Usability assessment of drone technology as safety inspection tools." *Electronic Journal of Information Technology in Construction,* p. 194–212.

Jaafar, M., Arifin, K., Aiyub, K., Razman, M., Ishak, M., and Samsurijan, M. (2017). "Occupational safety and health management in the construction industry: a review". *International Journal of Occupational Safety and Ergonomics*, 24 (4), p. 493-506.

Khosravi, Y., Asilian-Mahabadi, H., Hajizadeh, E., Hassanzadeh-Rangi, N., Bastani, H., and Behzadan, A. (2014). "Factors Influencing Unsafe Behaviors and Accidents on Construction Sites: a review". *International Journal of Occupational Safety and Ergonomics,* 20 (1), p. 111-125.

Lingard, H., Zhang, R., Pirzadeh, P., and Blismas, N. (2019). *Understanding and Applying Health and Safety Metrics*. In: Lingard, H., and Wakefield, R. Integrating Work Health and Safety into Construction Project Management. Wiley, Hoboken, p. 143-171.

Martinez, J. G., Gheisari, M., and Alarcón, L. F. 2020, "UAV Integration in Current Construction Safety Planning and Monitoring Processes: Case Study of a High-Rise Building Construction Project in Chile." *Journal of Management in Engineering*, 36 (3), 05020005.

Melo, R. R. S. and Costa, D. B. (2019). "Integrating resilience engineering and UAS technology into construction safety planning and control". *Engineering, Construction and Architectural Management*, 26 (11), p. 2705-2722.

Saurin, T. A., and Formoso, C.T. (2008). "Guidelines for considering construction safety requirements in the design process". *Proc. of the 14th* CIB W99 International Conference, Gainesville, p. 115-129.

Vaishnavi, V., and Kuechler, W. (2015). *Design Science Research Methods and Patterns - Innovating Information and Communication Technology*. CRC Press, New York, EUA.

Gordon, E., Rawlinson, K., Eldamnhoury, E., Marosszeky, M., and Dean, R. (2021). "The Impact of Implementing a System Approach to Quality: A General Contractor Case Study." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 893–902, doi.org/10.24928/2021/0193, online at iglc.net.

THE IMPACT OF IMPLEMENTING A SYSTEM APPROACH TO QUALITY: A GENERAL CONTRACTOR CASE STUDY

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ABSTRACT

This paper introduces a novel General Contractor approach to quality management called the Systems Approach to Quality **(SAQ),** which shares the Behavior-Based Quality (**BBQ**) concern for individual initiative and responsibility, and Quality Function Deployment **(QFD)** principles. Building on that previous work, this paper investigates the quantitative and cultural impacts of implementing a company's SAQ approach in its construction projects across the U.S. To do so, the authors examine lagging indicators of various performance areas including cost, schedule, quality, safety, and changes for a group of projects that implemented the SAQ approach and compare them to another group of projects that did not. The hypothesis under investigation is that SAQ implementation in projects improves performance across a range of critical indicators. Furthermore, the study compares project culture in projects where SAQ was implemented to those where it was not using Quinn's Competing Values Framework (**CVF**). The early results from this work indicate that the implementation of an approach such as SAQ leads to significant financial and non-cost benefits including improved collaboration.

KEYWORDS

Action learning, complexity, process, waste, collaboration, trust, system approach, quality function deployment (QFD), performance metrics, quinn competing values.

INTRODUCTION

Rework is a substantial risk in the construction industry due to its significant repercussions on other critical aspects of construction performance such as schedule, cost, quality, profitability, and safety (Love et al. 2016). Love et al. (2020) define construction rework as "wasteful and non-value-adding activity in correcting efforts and fixing defects resulting in variation in the scope of work." According to the Construction Industry

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Institute (CII), direct costs in the US caused by rework average 5% of total construction costs (CII 2005). In Australia, Marosszeky and Thomas (2002) reported a detailed study that costed 3500 rework items on $60 million of construction across four projects and found it to be 6.5% of construction cost. In addition, Love (2002) indicated that, on average, rework contributes up to 52% of the total growth of incurred costs and can increase schedule overruns by 22%. Based on the CII study, considering that $1.75 trillion was spent on construction in the US in 2017, almost $87 billion was wasted on rework.

The industry's longstanding view of rework causation mainly focuses on individual behavior, adopting the traditional "blame the perpetrator" approach (Bertelsen 2003). In this view, the cause of rework is fully explained by individuals' bad judgments, inaccurate assessments, or violations. This approach assumes that management systems are inherently sound, linear, and only the unreliability of individuals creates rework. However, organizations are non-linear interconnected sub-systems that encompass various levels of complexity. Saurin et al. (2013) describes a complex system as a system that has: (1) large number of dynamically interacting elements; (2) wide diversity of elements; (3) unanticipated variability; and (4) resilience. While an individual's unreliability can partially contribute to errors, it is a symptom of a deeper problem within the system that stems from multiple causes and dynamic complexity. It is impossible to separate systematic management of the workplace and the behavior of an individual within a system. Dekker (2017) shows that a more accurate explanation for errors can be found by finding how an individual's actions and behaviors made sense at the time given the circumstances within their environment. From this view of causation, an employee's behavior alone cannot be blamed for a quality failure. Viewing quality through a complex-system perspective, and accounting for environmental pressures, unruly technology, and social processes within an organization leads to a more robust and plausible understanding of quality management.

This means that the responsibility for quality performance within complex systems rests with the management system as well as the behavior of employees within it. This dynamic between management system factors that influence an individual's behavior and how the individual responds can also be described as team culture. The SAQ systems approach described in this paper recognizes the system complexity within which employees operate through trade-offs; it builds from available knowledge to identify Distinguishing Features of Work (DFOW), understands stakeholders' critical requirements; aligns expectations prior to starting work and tracks measurable criteria as the work is delivered. In addition, it recognizes that promoting healthy behavioral practices can improve overall quality performance within an organization. This includes upfront, honest conversations amongst team members and with different stakeholders to create psychological safety that encourages questioning and discussion.

A SYSTEM APPROACH TO QUALITY

In a 2018 paper (Spencley et al. 2018), the approach to quality management developed by a major US builder was described as a Behavior Based Quality (BBQ) approach. That paper referenced the similarity of elements of the company's BBQ approach to Quality Function Deployment (QFD). In hindsight, the authors believe the label is not accurate, that it should be seen as a systems approach.

The approach was described as recognizing upstream requirements, information packaging, mindsets, behaviors, practices, and information gaps that result in quality issues and unpredictable results downstream in the production process. It is a method in which client, design team, and construction stakeholders share their expectations, knowledge, experience and agree on Distinguishing Features of Work (DFOW), Measurable Acceptance Criteria (MAC) for each work package, resulting in better project outcomes. It was argued that quality management must require accountable project stakeholders from the owner's team, design team, GC's team, and Trade partners' teams to explore, discuss, and eventually agree on the requirements that are to be met, rather than simply checking quality to ensure compliance. It was argued that quality management should focus on the role of individuals' behaviors and demonstrate an understanding of people's roles throughout the project lifecycle from pursuit through closeout: what do stakeholders (those providing the deliverable, the supplier and those receiving the deliverable, the customers) want, know, and believe should be done. t is crucial to acknowledge that individuals operate within an ever-changing complex system, and to improve quality performance, systems-focused adaptive approaches need to be implemented.

QFD is a powerful systems-approach that interprets the design requirements of the client into terms that trade contractors understand. This process is used to translate users' needs into critical product characteristics and specific measurable criteria that can be incorporated early in the design stage (Alarcon and Mardones 1998). A QFD system can be realized through (1) ensuring consistency between customer requirements and product's measurable criteria, (2) converting consumer's demands into major quality assurance milestones or "Points of Release" throughout the project lifecycle, (3) ensuring consistency between the design phase and construction work, and (4) optimizing the integration of consumer's perceptions and other aspects that can affect project outcomes (Gargione 1999).

SAQ Development and Characteristics

In this paper, the same approach is reinterpreted as a Systems Approach to Quality **(SAQ),** recognizing that the approach is much more than a behavior-based approach. Rodney Spencley, the architect of the SAQ approach, came into a senior quality leadership role after successfully implementing a behavior-based safety (BBS) approach within the company. He ensured that the importance of individual responsibility (for safety outcomes) was incorporated into the company's approach to quality. Although developed independently of QFD, the SAQ approach has similar characteristics to QFD. Saurin et al. (2013) identified six guidelines for the management of complex socio-technical systems like construction including: (1) giving visibility to processes and outcomes; (2) encouraging diversity of perspectives when making decisions; (3) anticipating and monitoring the impact of small changes; (4) Understanding the gap between prescription and practice; (5) and creating an environment that supports resilience. To this extent, SAQ emerged as an organic response to customer-initiated quality challenges facing the business, while at the same time it recognized the complex nature of projects.

This homegrown SAQ also recognizes the importance of having healthy individual behaviors including open lines of communications, measurable collaboration, and psychological safety, which is synergetic with SAQ. Spencley et al. 2018 describes how the model is based on 1)- unifying language and perspectives among different stakeholders; 2)- understanding expectations and best work practices; and 3)- developing objective measurable acceptance criteria for the end product and the processes and deliverables to achieve the end product. Table 1 summarizes the characteristics and workflows of the model that was further developed after coaching hundreds of different projects from 1M to 5B across the U.S. over many decades. Each project was experiencing different variations of stakeholder engagement, stakeholder availability and capability, supply chain variability and site working conditions. These experiences reflect Bertelsen (2003) conclusion “that construction is indeed a complex, nonlinear and dynamic phenomenon, which often exists on the edge of chaos.” Knowing that every project experience unpredictability and different levels of variability, these characteristics and workflows were developed to help clarify and prioritize what teams should focus on to set themselves up for the greatest likelihood of reliable outcomes.

Table 1: GC Systems Approach to Quality

Principle	Implementation
Build from Knowledge & Information	Project teams start with the project information and a working understanding of what others have learned and identified as Distinguishing Features of Work (DFOW). DFOW are those features of a product and the processes necessary to create it, that require increased attention to achieve the intended result.
Points of Release	Project teams also identify key Points of Release (POR) in the project life cycle. A POR can be a project milestone, importantly it reflects that work will be released to the next phase. This is a critical gate in the workflow. Work should be assessed as ready for release before it is masked by new work.
Understand Expectations (DFOW)	The entire project team and supply chain must understand the vision of no surprises and predictable outcomes. Engaging the team starts with the First Planners and understanding their DFOW. First Planners are those project stakeholders accountable for delivering the project goals. Based on the project POR, there is a process to engage team members in understanding the organizational and personal commitments needed to achieve this vision. As new stakeholders: the owner; end-user designers; fabricators; builder; trade partners; Authority Having Jurisdiction (AHJ) and other decision makers accountable for project results on-board, they are engaged in this process.
Align Teams to Measurable Acceptance Criteria (MAC)	The process of aligning the team Measurable Acceptance Criteria (MAC) involves accountable stakeholders communicating and aligning on expectations for the POR. Numerous deliverables and workflows provide information for each POR. For each phase of the project, stakeholders firstly identify DFOW and risk specific to key deliverables and secondly, define MAC and clear commitments to achieve them. Visual controls show whether conversations are happening in the right time frame, with the right stakeholders and result in the documented MAC.
Evaluate Delivered Product	At the identified POR, deliverables are evaluated against the agreed to MAC. When work does not meet the MAC, those involved in the work investigate the breakdowns in the work process through cause-mapping. Leaders develop a strategy to mitigate the situation.
Building the project knowledge base	Now understanding the breakdowns in the work processes, the team reflects on what they have learned, records it in the form of lessons, and shares their learning within the project as well as their organizations.

THE IMPACT OF SAQ ON PROJECT SUCCESS

This study aimed to evaluate the effect of implementing the SAQ approach on performance in relation to cost, schedule, safety, quality, and change. The scope of the study involved a quantitative assessment of the performance of a group of projects that implemented SAQ (Intervention Group) and compared their outcomes to a similar group of projects that did not (Control Group). The goal was to identify if projects that adopted the SAQ approach had any advantages. All the projects were completed in the past 5 years. The specific quantitative performance areas and metrics were selected to be consistent with data availability and the company's internal critical success factors. Table (2) lists the investigated performance areas and the corresponding performance metrics and units of measurement.

The two sample groups were designed to be similar and to be representative of the company's business in terms of project type and geographic reach. Data was collected from 22 projects, 60% were GMP, and 40% were lump sum, 36% of the projects were advanced technology, 27% were higher education, 18% were commercial, 9% were healthcare, and 9% other. The combined, total dollar amount of construction work for the studied projects was around \$3.5 billion, with an average cost of around \$162 million per project. The sample groups were similar in total value. Table 2 shows the various performance metrics that were studied and their units of measurements.

Table 2: Performance Metrics and Unit of Measure

Area	Metric	Formula	Unit of Measure
Cost	Cost Growth	$\frac{Actual\ Cost - Intial\ (Anticipated) Cost}{Intial\ Cost}$	Percentage of the total cost
	Fee Gain	$\frac{Fee\ Erosion + Fee\ Gain + Nonreimbusrables}{Contract\ Fee (Current - Appraoved\ Fee\ for\ changes)}$	Percentage of total fee
Schedule	Schedule Growth from Mobilization	$\frac{SC\ at\ Trend\ (Actual) - SC\ at\ Mbilization}{Actual\ SC - Actual\ Mobilization}$	Percentage of the total duration
	Change percent duration	$\frac{Ave. Potential\ Change\ Items\ (PCI) Processing\ Time}{Actual\ Construction\ Duration}$	Percentage of total duration
Change Manage-ment	Value of Percent Changes	$\frac{Total\ Value\ of\ Change\ Orders}{Actual\ Contract\ Cost\ (Revised)}$	Percentage of the total cost
Safety	Incidents per \$100M	$\frac{Number\ of\ Incidents}{\$100M}$	Number per million dollars
Quality	Value of reported Claims	$\frac{Order\ of\ Magnitude\ of\ Reported\ Claims}{Total\ Contract\ Cost}$	Percentage of the total cost

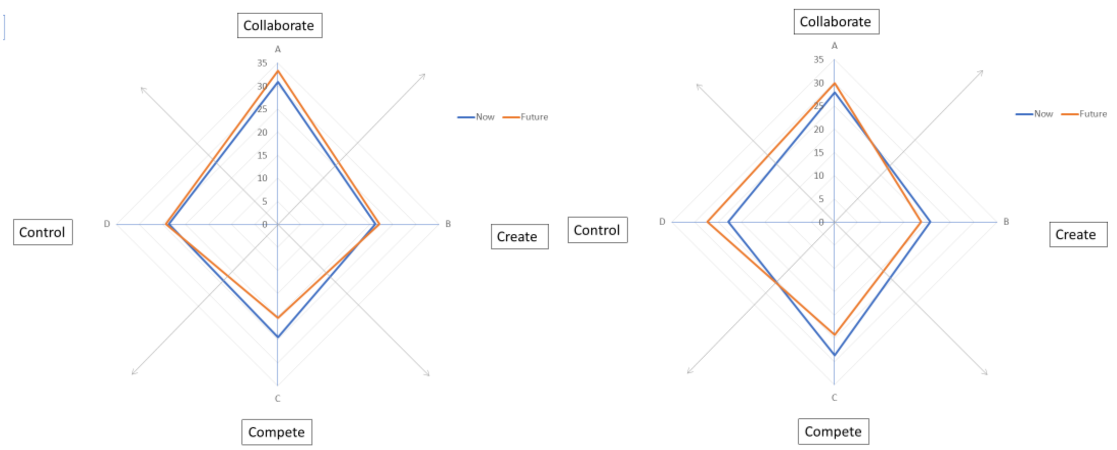
The comparison also involved an assessment of project culture using Quinn's Competing Values Framework (CVF) for both groups. The assessment of project culture was important as the SAQ approach had been designed to change team culture towards one of collaboration in terms of behaviors and information sharing. The CVF is designed to assess and characterize the cultural orientation of a team or company (Cameron and Quinn 2011). The CVF is based on the hypothesis that the culture of every organization can be characterized in terms of four basic orientations, pairs of which are in tension with each other. On one axis the tension is between collaborate (clan) and compete (market) behaviors, while on the other the tension is between control (hierarchy) and create (adhocracy). The characteristics of teams on the collaborate-compete axis are relatively easily understood in terms of teamwork, trust, openness, and flexibility. But, on the control-create axis, the characteristics in tension are less obvious. The control bias reflects a belief that processes can be codified, learned, and simply need to be repeated, whereas the create bias reflects a belief that teams operate in more complex and variable environments where they also need the ability to agilely solve unexpected problems.

CVF has been tested on thousands of organizations and has been found to provide a robust scientific approach, it also leads to recommendations for how to improve individual and organizational performance (Cameron and Quinn 2011). The assessment is based on a representative set of team members answering questions in relation to six aspects of organizational culture: dominant characteristics, organizational leadership, management of employees, organizational glue, strategic emphases, and criteria of success. Respondents select from four descriptors in relation to each aspect by dividing 100 points between the four alternatives provided. The selection is made to describe the existing status as well as a desired future state if greater success were to be achieved. The framework provides a basis for gaining an improved understanding of the basic elements of culture and provides some insight into how the culture can be changed.

ANALYSIS

CULTURAL STUDY

The research team distributed surveys to three key members of each of the project's teams involved in both groups of projects. Twenty-two valid responses were collected from the Intervention Group and 18 valid responses were collected from Control Group. Invalid responses were rejected, also, several key team members who had been involved in projects had left the company and could not be contacted. Going forward, it was proposed to survey project teams during the project lifecycle. Figure 1 shows the cultural biases of the project teams for Intervention and Control projects during the project and the culture shift they would like to see to improve outcomes. The data was also aggregated according to the roles of the respondent (i.e., Superintendents, Project Managers (**PM**), Project Engineers (**PE**). This allowed the researchers to identify the different cultural perceptions of team members in different roles on projects.



Intervention Gorup Control Group

Figure 1: Assessment of Projects' Teams Culture Shift

On the Collaborate-Compete axis, Intervention Group teams perceived their culture to be significantly skewed toward collaboration relative to Control Group teams. Both groups wanted slightly more collaboration in the future than at the present.

On the Control-Create axis, Control Group respondents perceived that they have a higher level of control relative to create and perceived the need for a further increase in control in the future at the expense of create. Intervention Group respondents perceived a balance between control and create and did not see a need to change that balance.

Control Group PMs perceived site culture to be more competitive than do Intervention Group PEs who perceived it to be significantly more collaborative. This may be due to the nature of the PM's job and their accountability for meeting cost and schedule constraints while PEs see much more collaboration because they are coordinating meetings with different stakeholders to work through construction issues. In the future, the Intervention Group PMs wanted to significantly decrease competition, and to see an increase in creation on projects.

QUANTITATIVE STUDY

To identify the impact of SAQ on key performance areas (i.e., cost, schedule, safety, change management, quality management) a comparison of Intervention Group and Control Group projects was conducted based on these metrics. Table 3 summarizes the comparison across the 2 groups of projects.

Table 3: Performance Metrics Medians

Performance Area	**Performance Metric**	**Median**	
		Intervention group	**Control group**
Cost	Cost Growth	5%	9%
	Fee Gain	4%	-35%
Schedule	Schedule Growth at Mobilization	11%	18%
Change Management	Change Percent Duration	14%	18%
	Value of Percent Changes	5%	13%
Safety	Incidents per $100M	1.5	1.9
Quality	Value of Claims as a Percentage of Contract Cost	0.14%	0.87%

Cost Performance

The researchers examined the cost performance of both groups of projects using two metrics: Cost Growth and Fee Gain. Both metrics show very significantly improved and more predictable performance when SAQ is implemented.

Schedule Performance

The researchers examined the schedule performance of both groups of projects using Schedule Growth from Mobilization, which is the difference between the substantial completion date forecasted at mobilization and the actual substantial completion date achieved. This metric indicates the effectiveness of schedule management during construction, and it was found that Intervention Group projects had significantly less Schedule Growth.

Change Management Performance

Change Management Performance was examined by measuring two metrics: Change Percent Duration and the Value of Percent Changes. Both metrics indicate that Intervention Group projects performed significantly better as the extent of change was substantially lower and more predictable.

Quality Performance through Evaluation of Claims

To evaluate whether project teams could manage expectations with predictable results, the cost of claims reported by each group was reviewed. These costs included uninsured and insured property damage claims during the project and construction defect claims during the project and after the project. Construction defect latent claims can be reported up to 10 years after project completion. These claim costs do not represent all the rework costs incurred in a project, only the claim costs reported to the GC’s internal risk group. Teams can also manage property damage and construction defect claims within the project budget and without reporting claims to the risk teams. These two factors help to explain why the cost of claims on these projects is significantly lower than industry standards. Of the two groups, Control Group projects had a higher reported amount of cost associated with the claims.

Safety Performance

No significant difference was observed in overall safety performance between the Intervention and Control Groups projects. What became obvious in the analysis was that a small number of projects (fewer than 20%) had a disproportionate impact on the overall safety results. Closer examination revealed that on projects that were run by “recently recruited” project team leaders, poorer safety outcomes were achieved.

DISCUSSION AND CONCLUSION

Performance data was collected from 22 projects about cost, schedule, safety, quality, and changes. The projects were divided into two comparable groups, those that implemented SAQ and those that did not (the Control Group). Projects that implemented SAQ generally performed significantly better against a range of cost, schedule, and quality outcome metrics and had outcomes more consistent with the goals.

Across all standard project performance measures, the SAQ projects share two distinct advantages. First, results were more predictable as the performance outcomes were more closely aligned with the project targets. Second, SAQ projects have significantly improved results in all the dimensions that were assessed, higher profitability, better cost predictability, and improved schedule achievement.

Overall, wherever SAQ was deployed, trade partners and internal stakeholders were encouraged to have more and earlier conversations to facilitate planning, and to engage more closely to build a more collaborative project culture. There was also a focus on developing clearer contract language to describe customer objectives. SAQ appears to have facilitated better design with earlier stakeholder engagement to improve the outcomes of risk management plans by eliminating subsequent changes.

In addition, Quinn’s CVF model was used to measure the cultural orientation of the two groups of projects. The study of culture was limited to three participants from each project, and even this was not achieved on some. People in three key roles were surveyed, PMs, PEs and Superintendents, and the assessments of participants in each group were aggregated.

The culture on projects where SAQ had been implemented was perceived to be more collaborative, less competitive, and more creative. Interestingly, on projects that did not deploy SAQ, it was perceived that they needed more control while in the projects that did deploy SAQ, respondents felt they had sufficient control. This observation reflects the reality, that the projects that deployed SAQ had better control as indicated by all measures.

It was observed that people in different roles have different perceptions of culture, as this is influenced by their responsibilities and work practices. This confirmed the expectation that a larger team of respondents is needed to achieve a reliable view of cultural orientation on any one project.

A significant difference was observed between the perceptions of culture on the collaborate-compete axis between Intervention Group PMs and PEs. It is postulated that this is most likely be due to the difference in the roles of the respondents. Nevertheless, this is considered to be a significant difference that is worthy of further research.

Finally, there was no significant difference in the safety performance of the 2 groups, though the overall rate for each group was disproportionately influenced by a small number of projects that had high to very high incident rates.

This work is a first step in the assessment of these critical correlations and shows the way forward towards improved project culture and outcomes. This includes (1) studying the impact of SAQ on outcomes across a company's different business units; and (2) understanding the factors that improve leadership engagement and operational adoption of SAQ. To facilitate this, the authors recommend: (a) implementing Quinn Survey throughout project's milestones; (b) performing cause-mapping to identify successful best practices and the upstream impacts; and (c) connecting findings back to how project teams operationalized the SAQ framework to better support underperforming business units. Further investigation is planned to study the impact of project delivery type, contract type, and leadership style and experience with repeat customers, and staffing on implementing SAQ.

LIMITATIONS

This study reports an early-stage investigation of the impact of SAQ on project outcomes. The number of projects included in this study is relatively small (22 projects), and future research is proposed to validate this study's findings and to better understand the impact of SAQ on project performance. While the results indicate a compelling case for implementing SAQ systems such as this in construction, it is important to recognize this study's limitations. It was not possible to characterize the projects in terms of many significant and important parameters such as team leadership, team experience, client culture and experience, contract type and maturity of SAQ implementation.

REFERENCES

Alarcon, L. F., and Mardones, D. A. (1998). "Improving the Design-Construction Interface."

Bertelsen, S. (2003). "Complexity – Construction in a New Perspective." *International Group of Lean Construction*, 12.

Cameron, K. S., and Quinn, R. E. (2011). "The competing values culture assessment: A Tool from the Competing Values Product Line." *Wiley*, (March), 1–14.

Gargione, L. A. (1999). “Using Quality Function Deployment (Qfd) in the Design Phase of an Apartment Construction Project.” *7th Annual Conference of the International Group for Lean Construction*, (55), 357–368.

Love, P. E. D. (2002). “Influence of Project Type and Procurement Method on Rework Costs in Building Construction Projects.” *Journal of Construction Engineering and Management*, 128(1), 18–29.

Love, P. E. D., Matthews, J., and Fang, W. (2020). “Rework in Construction: A Focus on Error and Violation.” *Journal of Construction Engineering and Management*, 146(9), 06020001.

Love, P. E. D., Teo, P., Morrison, J., and Grove, M. (2016). “Quality and Safety in Construction: Creating a No-Harm Environment.” *Journal of Construction Engineering and Management*, 142(8), 05016006.

Marosszeky, M., and Thomas, R. (2002). “Quality management tools for lean production-moving from enforcement to empowerment.” *10th Annual Conference - International Group for Lean Construction (IGLC-10)*, 61(2), 1–13.

Saurin, T. A., Rooke, J., Koskela, L., and Kemmer, S. (2013). “Guidelines for the management of complex socio-technical systems: An exploratory study of a refurbishment project.” *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*, 915–924.

Slosharek B., Dlouhy J., Schneider-Marin P., and Lang W. (2021). "Takting the sustainability of construction processes: An environmental assessment method" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 903–912, doi.org/10.24928/2021/0198, online at iglc.net.

TAKTING THE SUSTAINABILITY OF CONSTRUCTION PROCESSES: AN ENVIRONMENTAL ASSESSMENT METHOD

Benjamin Slosharek[1], Janosch Dlouhy[2], Patricia Schneider-Marin[3] and Werner Lang[4]

ABSTRACT

The building sector is key to achieving global sustainability targets due to its significant resource consumption, associated emissions, and waste generation. Life cycle assessment (LCA) evaluates the environmental quality of buildings to identify improvement possibilities. However, current research activities limit their focus on a few life cycle phases, while the construction phase receives none to little attention. At the heart of the problem lies the lack of information about on-site processes and the lack of tools to evaluate the environmental quality of construction processes. The authors developed a conceptual framework to assess this aspect using an interdisciplinary approach. The proposed solution is based on two main methods, namely LCA and Takt Planning (TP). Based on literature research we identified the main categories for environmentally relevant in- and outputs of construction processes. This allows a structured, standardized, and scalable assessment of each single process step from an environmental perspective We anticipate this method to be a starting point for a holistic sustainability approach for construction process assessment. Further development of this framework aims to broaden the current environmental evaluation in the building sector and to improve both, the construction process and the building product from an environmental point of view.

KEYWORDS

Sustainability, takt planning (TP), life cycle assessment (LCA), lean construction (LC), process, theory.

INTRODUCTION

The construction industry can be held responsible for 36% of the global energy consumption and 39% of the global emissions (IEA 2019). In addition, more than 50% of total waste generation in Germany can be linked to the construction sector (UBA 2019). Due to this, the research issue of energy and resource efficient buildings becomes more and more important. Throughout the last two decades, the majority of research of

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sustainable and green buildings targeted the operational phase, i.e., optimizing and reducing the energy consumption and the related emissions. As the operational phase of the building constitutes only one part of the whole building life cycle, the consistent reduction of these emissions is not expedient for a holistic sustainable approach. Energy and emissions caused by the manufacturing of the building materials, the construction stage, and the deconstruction of a building are rarely seen in the sustainability assessment (Takano et al., 2014). Dependent on the energy standard of the building and the duration of the operational phase the shares of the embodied energy gain in importance compared to the energy consumption during the operational phase. Therefore a holistic approach to the sustainability assessment of a building should include all life cycle stages of a construction project (Wiik et al., 2017).

Decisions affecting the environmental quality of buildings mostly disregard the construction process, consisting of transportation (phase A4 per BS EN 15978) and the construction/installation (phase A5). There are hardly any valid data sets for the phase of construction (A5) as well as the deconstruction phase (C1) due to the infrequent consideration and the lack of understanding of the construction and deconstruction processes (Gantner et al., 2015). The individual character of each construction project and uncertainties in future scenarios lead to the presumption, that an analysis procedure based on standardized process sequences is difficult to realize (Wiik et al., 2017). Decoding the construction site is perceived as too burdensome, especially considering the overall benefits (Torres, 2014). This leads to the exclusion of the construction phase from environmental assessments, because transparency with regard to construction processes is too hard to achieve. At the same time, the impact of these phases is assumed to be lower compared to other life cycle phases.

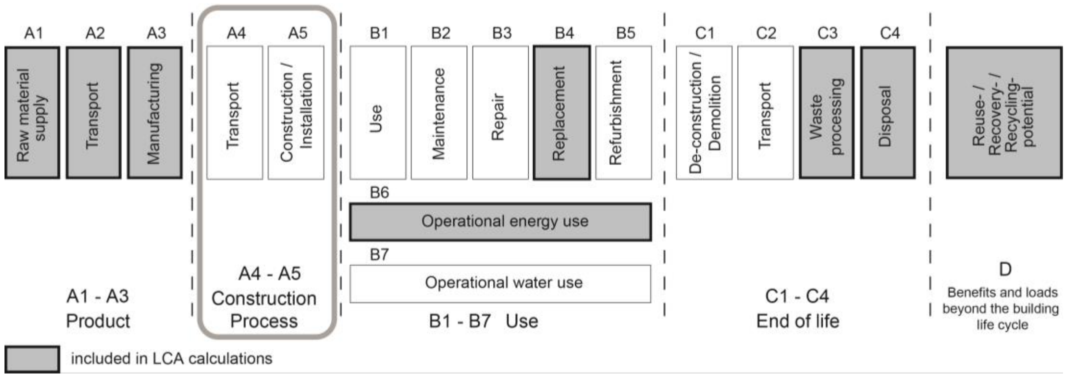

Figure 1: Life cycle phases of a building (BS EN 15978)

Lean Construction (LC) aims to maximize customer value by minimizing waste in the construction process (GLCI, 2019). In order to analyze waste in processes, the value chain has to be as transparent as possible. The LC approach can therefore provide a transparent and stable foundation for environmental assessments of the process sequences. As a method of LC, Takt Planning and Takt Control (TPTC) pursues to define standardized and harmonized process sequences and thereby to ensure the flow and stability of the ongoing work steps during the construction process (Dlouhy et. al., 2016).

With the process sequences, LC and TPTC thus offer a transparent basis for quantifying the different dimensions of an individual work step on the construction site. The idea of the proposed framework is to link these process elements with environmental parameters and thus to make the process sequences accessible from an environmental point of view. There are existing methods that quantify the environmental impact of a process. Faulkner and Badurdeen (2014) developed a similar approach for manufacturing, called *sustainable value stream mapping*. Within the construction sector, such an assessment of environmental sustainability can rarely be found in recent research activities (Fu et al., 2015; Rosenbaum et. al., 2014), as the adaptation of production methods in this sector is still in its early stages.

THEORETICAL BACKGROUND

LEAN CONSTRUCTION AND SUSTAINABILITY

LC focuses primarily on increasing productivity and thus predominantly on economic parameters. The individual steps within a process, which are essential for delivering value, are deciphered, and the flow efficiency and productivity can be increased.

LC therefore takes a process-oriented view when considering the life cycle phases of the building: The process and not the product is the main focus of these studies (Ballard et al., 2007). LC follows the approach of eliminating any waste in processes during a building's life cycle (Ballard et al., 2007). Resources in this context represent only means that are needed for a process to take place. Thus, according to LC, waste of financial resources, human resources, materials or time should be prevented (Koskela, 1992).

The sustainable building approach, on the other hand, is based on the tripartite nature of sustainability in terms of environmental, economic, and social matters. For example, the triple bottom line divides the broad subject area into three basic domains: the (1) social domain, the (2) environmental domain, and the (3) economic domain (Elkington, 2013) Another variation of the division sees the economic system as a subsystem of the social system, which in turn is a subsystem of the environmental system (Cato, 2009, p. 37). Following this approach, the concept of green building extends the classic paradigm of management between quality, time, and cost to include global factors such as reduction of resource depletion, reduction of emissions, and protection of natural land areas (Huovila and Koskela, 1998)

Depending on how and in what form LC is used in a construction project, the effects on overall sustainability can vary (Nahmens and Ikuma, 2012). The avoidance of waste can be identified as the most frequently cited commonality between the two philosophies based on several research reports (Carvajal-Arango et al., 2019). The dimensions of waste are defined differently. While sustainable buildings aim to minimize unnecessary emissions and resource waste in the form of material and energy consumption (Kibert, 2016), LC focuses on economic factors.

SYNERGIES IN PRACTICAL APPLICATION

Carvajal-Arango et al. (2019) conducted a literature review to investigate the relationships between LC and sustainability with regard to the construction phase of a building. The authors analyzed different LC methods and their impact on the overall sustainability of building construction. The authors found that the most common reasons for implementing LC could be attributed to economic motivation, whereas, positive effects on the environmental impact of the construction phase emerged as well. Demanding a holistic assessment, the authors advocate a standardized sustainability assessment method for the construction phase of LC projects additionally to existing economic indicators.

Fu et al. (2015) show how LC methodologies, in terms of process optimization, can help to improve sustainability during the construction phase . The authors analyzed individual processes on the construction site and compared several process variants based on environmental impacts. By using the LCA method the authors accurately allocate the environmental impacts to the respective input categories of the process: energy, transportation, machinery, and materials are identified as the main categories which can cause environmental impacts. The researchers use greenhouse gas emissions to quantify these impacts. Emissions, especially from materials and machine use, could be reduced by such a process analysis. At the same time, however, improvements were also shown on an economic basis: time and money were saved, working conditions were improved, and potential safety risks for employees were reduced. The authors recommend a stronger link between LC and LCA, especially if both can be carried out on the basis of standardized processes.

CONCEPTUAL FRAMEWORK FOR SUSTAINABILITY ASSESSMENT OF CONSTRUCTION PROCESSES

METHODOLOGY

The development of the framework follows two perspectives: the process perspective of the LC approach and the perspective of sustainability in the sense of the environmental impact of the process steps. The aim of this framework is to visualize and assess the environmental impacts caused by construction processes by integrating the environmental dimension into the TP method.

Figure 2: Example sequence with application of the resource categories to the work steps for dry wall construction.

For the process-related view, the method of TPTC is used, in which the process steps of the construction site are arranged into work packages and harmonized “wagons” (Dlouhy et al., 2016). The standardization of the process sequences makes the individual work steps scalable (Haghsheno et al., 2016). For the environmental evaluation of each process step, the input-output life cycle assessment (LCA) method is used. In this assessment, the expenditures (inputs) and the resulting impacts (outputs) of a process or a product are examined and analyzed in detail in terms of environmental sustainability. The combination of the two fields of research should ease a quantification of the environmental impact caused by the process steps.

LCA applied in construction usually considers building parts composed of building elements (König et al. 2009) consisting of material layers. This subdivision is necessary for the assessment of potential environmental impacts, since only at the material level one can assign the characteristic values for environmental impacts via databases. For example, a drywall without any installation should be divided into the material-layers (1) frame, (2) insulation, (3) planking, and (4) paint for an assessment. The process view follows a different approach: the construction process analysis focuses on the work packages of the trades, which is why the drywall is classified by the perspective of the trades: Position (1) to (3) are provided by the drywall construction trade and position (4) is provided by the painting work trade.

Assessing the environmental impacts of construction processes requires the combination of the material/product perspective with the process perspective. In order to achieve this, the construction process must be defined to such an extent that materials and products can be clearly assigned. In this case, the proposed environmental process analysis considers the work packages of the respective trades with their individual steps. In Figure 2 the work packages (Number 2 and 5) and process steps (2a-2c; 5a-c) necessary for a drywall construction are highlighted within a sample sequence. This subdivision can logically be related to the TPTC method, as the individual work steps are systematically broken down as following: TP follows the 3-level model with the macro, norm and micro level. The micro level is the most detailed level of a construction process and contains information on each individual process step (Dlouhy et al., 2016). According to the logic of the framework, environmental parameters are assigned to each step of the construction process as a basis for environmental impact calculation. This procedure follows a bottom-up approach: The smallest unit of a system is analysed to draw general conclusions for the whole.

Table 1: Categories for assessing the environmental impacts of construction sites, BS EN 15978

Phase A4 - Transport	Phase A5 - Assembly on Site
Material Transports, Gate to Site	Assembly of building components
Transport of Construction Equipment to Site	Installation of building materials, auxiliary materials included
Material losses during transportation	Air conditioning of site or material storage
Optional: Transport of workers to site	

RESOURCE CATEGORIES: ENVIRONMENTALLY RELEVANT INPUTS OF CONSTRUCTION PROCESSES

Following the LCA method, relevant inputs and outputs have to be defined for each individual step of the process. The activities on the construction site consume time, energy, material, labor and financial resources in order to create value, i.e., the building itself. For the calculation of environmental parameters it is necessary to define inputs and outputs, which are linked to environmental sustainability. Previous studies targeting environmental assessments of building sites used differing approaches:

Kellenberger and Althaus (2009) mainly consider the necessary auxiliary materials for the construction of a building component. Takano et al. (2014) list transportation and logistics expenses as a main driver of potential environmental impacts during the construction of buildings. Wiik et al. (2017) consider a relatively broad system boundary of the construction phase and link the main environmental impacts to usage of construction machinery, on-site electricity consumption, transportation, and the general installation of materials. Fu et al. (2015) identify in their case study project four main causes or emissions: energy, materials, machinery, and transportation. Thus, the categories of (1) material, (2) machinery, and (3) transportation can in general be derived from these research reports. Similar breakdowns can be found in the international standard for environmental assessment approaches. DIN EN 15978:2012-10 (2012) as shown in Table 1.

In summary, the first main element of the proposed framework is deduced from the research reports: The *resource categories*. These are represented by (1) materials, (2) machinery, and (3) transportation. Based on these subdivisions, it should be possible to define the main expenses from an environmental perspective for a process step. These categories can be seen as the environmentally relevant inputs of a single process. The framework should offer the possibility to link exact values to each process step, e.g. for material quantity, construction machine hours, or transport distances.

IMPACT CATEGORIES: ENVIRONMENTALLY RELEVANT OUTPUTS OF CONSTRUCTION PROCESSES

All process steps have differentiated amounts of environmental impacts due to the respective types of expenditure. These are divided into different impact categories for the environmental impact assessment step of LCA. The focus of the framework is on the construction sector, for which GWP (global warming potential) and AP (acidification potential) are deemed the most relevant impact indicators (Ismaeel, 2018). Additionally, the PENRT (total use of nonrenewable primary energy resources) and the amount and type of material waste are included in the environmental assessment framework of the process steps. In summary, the categories (1) PENRT, (2) GWP and AP, and (3) Waste represent the second core element of the framework: the impact categories. From an environmental point of view, they represent the relevant outputs of the process apart from the building component itself. In strict LCA methodology, primary energy is accounted for as input and therefore as part of the resource categories. Similarly, in LCA, waste is considered an output category. However, within the developed framework, PENRT and waste are treated as an assessment index for the construction process steps and are thus considered impact categories.

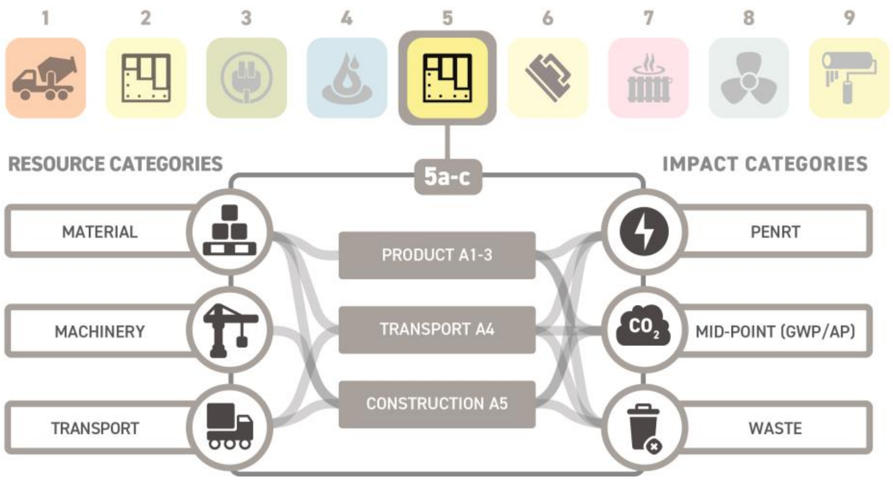

Figure 3: framework for the environmental assessment of construction processes with in- and outputs

To summarize, as shown in Figure 3, the three resource categories represent the relevant expenditures from an environmental perspective, which are necessary for the process to take place and create the added value. The impact categories, on the other hand, provide information about the environmentally relevant impacts of a process step.

RESULTS AND POTENTIAL OF THE FRAMEWORK

Provided that the framework is successfully implemented in the TPTC, the construction processes can be analyzed in different ways simultaneously, as shown in Figure 4. It seems reasonable to differentiate the calculated results of the framework into the product view and process view, as described by Ballard et al. (2007).

Table 2: Exemplary results of the framework application to the work package 5

Description	Resource Category	Life cycle Phase	Impact Category GWP [kg-CO2e]	Product / Process View
Plasterboard and insulation	Material	A1-3	7.37	Product
Trasportation Gate to Site (Plasterboard and Insulation)	Transport	A4	0.43	Process
Filler (Auxillary material)	Material	A5	0.21	Process
Materiallosses due to cuts (Plasterboard and Insulation)	Material	A5	1.47	Process
Usage of table saw and cordless screwdriver	Machinery	A5	0.84	Process

Table 2 shows results for the application of the method to the drywall process shown in figure 3, divided by the process and product view. Accordingly, the product view refers to phase A1-3 where the ideal amount of material within the final product is being assessed. The process view complements these considerations with environmentally relevant impacts during phases A4-5, which, as explained in the introduction, are currently rarely mapped. The results show 7.37 kg-CO_2e for the impacts of the product view, which is equivalent to 71% of the impacts of the work package, whereas 2.95 kg-CO_2e or 29% are related to the process view. Based on the developed framework each impact can be related to the life cycle phases, the source of the impact, and whether it is related to the product or process view. The exemplary results refer to 1m² of drywall construction.

Figure 4: Analysis options when applying the framework to Takt Planning

As a holistic approach, the method of TPTC within LC offers several potentials for synergies with the developed framework. TPTC is based on the approach of generic process sequences and maps the construction project based on recurring takt areas with identical work packages within the taktplan (Binninger et al., 2017) This method of process sequences enables the scalability of the processes (Haghsheno et al., 2016) and therefore the scalability of environmental impacts calculated with the framework.

Furthermore, based on the taktplan, not only the spatial and thus qualitative, but also the temporal dimension of the process can be related to its environmental impacts. The environmental factors can be used as a performance indicator alongside economic factors to evaluate the construction progress during an ongoing project.

DISCUSSION

The approach of combining LCA and TP to analyze the environmental sustainability of construction processes is considered a useful and detailed methodology. It can be used to map material and energy flows, transport expenditures, and emissions or resource depletion from a processual point of view.

The framework extends the current focus of the LC philosophy, which currently aims for high productivity and high quality (Kaiser, 2013; GLCI e.V., 2019). Considering environmental and process quality at the same time can be beneficial and obstructive at the same time. On the one hand, this adds a new dimension to the existing analysis of processes and generates more insights into the overall performance of the process. On the other hand, when improving the process, environmental and economical goals can be in conflict. Therefore one has to prioritize one dimension regarding possible trade-offs.

Potential limitations in the framework can also be identified. The resource categories convey a clear structure but can be too general for the assessment of every single process step. Thus a relevant set of subcategories of the resource categories should be defined by further research. Furthermore, not every source of environmental impact can be linked to a single process step, like site facilities or lifting equipment. Accordingly, the results of the framework so far are limited to resource categories that can be linked to a single work package directly. Finally, the applicability to construction projects without TPTC is limited because there are no standardized sequences to assess. This might be overcome by the assessment of multiple TPTC projects with the proposed method when sound knowledge about the main processes on every construction site can then be derived and applied to projects without TPTC. All of the mentioned limitations can have a significant impact to the scalability of the method and need to be addressed by studies in the future.

Generally speaking, the extension of current environmental analyses with a process view requires a change in thinking: Alongside the materials and the quantification of *what* the building consists of, one clearly needs transparency to understand the process and *how* the building is constructed. Both product and process assessment should be quantified separately and in detail. Otherwise, comparability to other scientific studies suffers since standardized construction processes or work packages of single trades have rarely been taken into account for environmental evaluations so far.

CONCLUSION

Climate change is the greatest global challenge in the foreseeable future. As one of the main greenhouse gas emitters worldwide, the construction sector has a responsibility to find solutions. The environmental waste during construction is neither surveyed nor evaluated. Due to continuous optimization of the operational phase, the consideration of the Product (A1-3) and Construction Process (A4-5) phases according to BS EN 15978 become increasingly relevant for a holistic sustainability assessment. The framework presented in this paper enables analysis and visualization of emissions and environmentally relevant waste of construction processes. This is possible due to TP, even without expert knowledge about LCA. Results are determined at the point of value creation, the work process, utilizing the impact categories. Optimization can thus take place directly and measurably. A consideration of the environmental waste on building sites, without the LC approach of TP, appears very complex and error-prone. The transfer of construction processes into a construction production using TP shows its scalable and data-driven capabilities, especially when assessing environmental quality through the described framework.

Furthermore, the use of digital tools and databases for emissions, waste, and traditional TP parameters should allow for better applicability of more and more complex data structures when assessing the processes in practice. The authors see an opportunity for a holistic and integral perspective in the planning of construction processes as well as in the selection of construction products through the proposed environmental assessment of takted processes. The possibility to evaluate and compare the environmental efficiency of building processes, building materials, and the overall building construction has the potential to lead to new conclusions and thus novel solutions.

REFERENCES

Ballard, G., Tommelein, I., Koskela, L., and Howell, G. (2007). “Lean construction tools and techniques.” *Design and Construction*, Routledge, 251–279.

Binninger, M., Dlouhy, J., and Haghsheno, S. (2017). “Technical Takt Planning and Takt Control in Construction.” *Proc. 25th Ann. Conf. of the IGLC*.

Carvajal-Arango, D., Bahamón-Jaramillo, S., Aristizábal-Monsalve, P., Vásquez-Hernández, A., and Botero, L. F. B. (2019). “Relationships between lean and sustainable construction: Positive impacts of lean practices over sustainability during construction phase.” *Journal of Cleaner Production*, Elsevier, 234, 1322–1337.

Cato, M. S. (2009). *Green Economics: An Introduction to Theory, Policy and Practice*. Earthscan.

Chastas, P., Theodosiou, T., and Bikas, D. (2016). “Embodied energy in residential buildings-towards the nearly zero energy building: A literature review.” *Building and Environment*, Elsevier, 105, 267–282.

BS EN 15978:2011. (2011). Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method. Standard, BSI, London.

Dlouhy, J., Binninger, M., Oprach, S., and Haghsheno, S. (2016). “Three-level method of Takt Planning and Takt control–A new approach for designing production systems in construction.” *Proc. 24th Ann. Conf. of the IGLC*.

Elkington, J. (2013). “Enter the Triple Bottom Line.” *The Triple Bottom Line*, Routledge, 23–38.

Faulkner, W., and Badurdeen, F. (2014). “Sustainable Value Stream Mapping (Sus-VSM): methodology to visualize and assess manufacturing sustainability performance.” *Journal of cleaner production*, Elsevier, 85, 8–18.

Fu, F., Sun, J., and Pasquire, C. (2015). “Carbon emission assessment for steel structure based on lean construction process.” *Journal of Intelligent & Robotic Systems*, Springer, 79(3–4), 401–416.

Gantner, J., Wittstock, B., and Lenz, K. (2015). *EeBGuide Guidance Document Part B: Buildings. Operational guidance for life cycle assessment studies of the Energy Efficient Building Initiative*. Fraunhofer Verlag.
GLCI e.V. (2019). *Lean Construction - Begriffe und Methoden*. German Lean Construction Institute – GLCI e. V. c/o KIT Institut für Technologie und Management im Baubetrieb.
Haghsheno, S., Binninger, M., Dlouhy, J., and Sterlike, S. (2016). "History and Theoretical Foundations of Takt Planning and Takt Control." *Proc. 24th Ann. Conf. of the IGLC*.
Huovila, P., and Koskela, L. (1998). "Contribution of the Principles of Lean Construction to Meet the Challenges of Sustainable Development." *6th Ann. Conf. of the IGLC*.
IEA. (2019). Global Status Report for Buildings and Construction 2019 – Analysis - IEA. International Energy Agency.
Ismaeel, W. S. (2018). "Midpoint and endpoint impact categories in Green building rating systems." *Journal of Cleaner Production*, Elsevier, 182, 783–793.
Junnila, S., Horvath, A., and Guggemos, A. A. (2006). "Life-cycle assessment of office buildings in Europe and the United States." *Journal of Infrastructure systems*, ASCE, 12(1), 10–17.
Kaiser, J. (2013). *Lean Process Management in der operativen Bauabwicklung*. Institut für Baubetrieb.
Kellenberger, D., and Althaus, H.-J. (2009). "Relevance of simplifications in LCA of building components." *Building and Environment*, Elsevier.
Kibert, C. J. (2007). "The next generation of sustainable construction." *Building Research & Information*, Taylor & Francis, 35(6), 595–601.
Klöpffer, W., and Grahl, B. (2014). *Life cycle assessment (LCA): a guide to best practice*. WILEY-VCH Verlag.
König, H., Kohler, N., Kreißig, J., and Lützkendorf, T. (2009). *Lebenszyklusanalyse in der Gebäudeplanung*. Detail Green Books, DeGruyter, Berlin.
Koskela, L. (1992). *Application of the new production philosophy to construction*. Stanford University Stanford.
Koskela, L. (2006). "Foundations of concurrent engineering." *Concurrent Engineering in Construction Projects*, Routledge, 26–43.
Nahmens, I., and Ikuma, L. H. (2012). "Effects of lean construction on sustainability of modular homebuilding." *Journal of Architectural Engineering*, ASCE, 18(2)
Rosenbaum, S., Toledo, M., and Gonzalez, V. (2014). "Improving Environmental and Production Performance in Construction Projects Using Value-Stream Mapping: Case Study." *Journal of Construction Engineering and Management*, 140
Takano, A., Pittau, F., Hafner, A., Ott, S., Hughes, M., and De Angelis, E. (2014). "Greenhouse gas emission from construction stage of wooden buildings." *International Wood Products Journal*, Taylor & Francis, 5(4), 217–223.
Torres, N. (2014). "Study of sustainability opportunities during construction." PhD Thesis, University of Texas, Austin.
UBA. (2019). "Abfallaufkommen | Umweltbundesamt." Umweltbundesamt.
Wiik, M. R. K., Sørensen, \AAse Lekang, Selvig, E., Cervenka, Z., Fufa, S. M., and Andresen, I. (2017). "ZEB Pilot Campus Evenstad. Administration and educational building. As-built report." *ZEB Project report*, SINTEF akademisk forlag.

Arroyo, P., and Gomez, S. (2021). “Building Quality Builders: Lessons Learned from a Companywide Training on Behavior-Based Quality.” *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 913–922, doi.org/10.24928/2021/0201, online at iglc.net.

BUILDING QUALITY BUILDERS: LESSONS LEARNED FROM A COMPANYWIDE TRAINING ON BEHAVIOR-BASED QUALITY

Paz Arroyo[1] and Sulyn Gomez[2]

ABSTRACT

This paper describes the process of designing, testing, and adjusting a virtual workshop called Building Quality Builders (BQB) to train a general contractor’s employees on a Behavior-Based Quality (BBQ) approach with the purpose of increase implementation and reduce re-work. The paper summarizes a two-year journey that started in March 2019 and ramped up in 2020 due to the increased use of virtual training caused by Covid-19 pandemic. This paper describes the continuous improvement process and the lessons learned along the way. Lessons learned from developing and implementing this training are 1) BQB workshop main purpose to help participants improve the delivery of quality has been achieved by including a commitment to action from participants who took the workshop, 2) BQB format and content can be constantly improved if feedback from participants is being used for continuous improvement, and 3) BQB workshop is highly recommended by participants who took it, the recommendation extends to everyone in the company due to the benefits participants identified from BQB.

KEYWORDS

Behavior-based quality (BBQ), virtual workshops, quality.

INTRODUCTION

During 2019 – 2020, DPR Quality Group developed a virtual workshop called Building Quality Builders (BQB) to lead DPR teams through activities to prepare them with skills and resources to align and strategize on their quality implementation plan. The workshop was developed with the main intent of helping participants to create an action plan for the team to implement DPR’s Behavior-Based Quality (BBQ) approach (Spencley et al. 2018, Gomez et al. 2019, and Gomez et al. 2020). The workshop helps participants to identify Distinguishing Features (DF) from all stakeholders’ perspectives, to manage DF’s timely, to agree on Measurable Acceptance Criteria (MAC) before the scope of work is handed off, and to communicate MAC to the field to have clarity on the work to do and ultimately avoid surprises (e.g., defects, rework, owner’s dissatisfaction). The workshop provides tools that teams need to be more successful at identifying risks and be more proactive in the alignment of stakeholders’ expectations to meet stakeholders’ expectations.

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The paper summarizes a two-year journey that started in March 2019, and it accelerated in 2020 given DPR's corporate decisions to deal with Covid -19 pandemic challenges. This workshop responded to 1) the need to improve quality management at the project level, 2) avoid rework and 3) an increased acceptance for virtual workshops. During Covid-19, with many teams working remotely, a larger number of teams were willing to join the workshop virtually. Up to date, 253 have taken the workshop in a total of 26 rounds. Participant's roles vary, including superintendents, project managers (PMs), and project engineers (PEs) including teams in all US Regions, Europe, and India.

Throughout conducting the workshops, we learned:

1. How to engage diverse teams ,
2. how to change the quality mindset from quality is something that happens after I do the work towards a proactive behavioral approach for quality, and
3. how to foster actions for implementing what was learned after taking the workshop.

For developing this workshop, we identified some of the behaviors that we want teams to display and created tools to support teams when having to lead difficult conversations to align expectations with owners, architects, and trade partners.

In this paper, we will share our journey to create the workshop, our struggles, the changes we implemented, and the results. We believe this process is not only useful for practical resons, but can also be a contribution to research for the lean construction community. In any lean implementation, spreading an idea or a program throughout a large organization is a challenge, especially in a company were top-down orders are not an option, instead the workshop aim to inspire and motivate teams so they want to achieve quality results. In this case, we worked to increase the practice of understanding and aligning expectations with all stakeholders, which is central to DPR's BBQ quality approach and for DPR's quality framework, based on Build with Passion, Clarity and Knowledge.

Several papers have studied teaching lean practices, such as lean leadership training (Hackler et al. 2018), teaching choosing by advantages (Arroyo et al. 2019), teaching lean construction (Tsao et al. 2013 and Nofera et al. 2015). However, due to the novelty of the BBQ approach, no publications on how to train people on the topic have been developed. This paper closes that gap. The paper describes the experience of designing a companywide virtual workshop to shift the quality mindset from build and check it to proactively align expectations to avoid rework, and describes the findings of having conducted the training with multiple teams. The paper also discusses the struggles, changes, and results to get more engagement and implementations. Finally, we discuss struggles and present recommendations for escalating the BQB workshop.

METHODOLOGY

The methodology to develop and test the workshop followed Design Science Research (Hevner, 2007), where the artifact was the BQB workshop. DSR aims to test an Applied Science/Engineering (AS/E) to produce a scientific methodology (artifact) for construction projects, which are phenomena that vary according to time, contexts, and application conditions (Hevner, 2007). Design Science Research (DSR) is useful to evaluate evidence of learning and gain knowledge to inform best practices (Van Aken 2004).

In order to test the success of the BQB workshop several measures were used, such as 1) the number of participants that graduated from the program and its distribution by role and by region, 2) the commitment to implement DPR's BBQ from the participants and actual implementation verified on a follow up session, and 3) the participant's post-evaluation of the workshop through a survey providing feedback on the workshop's, content, format, and impact.

BQB DEVELOPMENT AND ADJUSTMENTS

The authors of this paper developed the first Building Quality Builders (BQB) pilot workshop with the support of DPR's Learning and Development team. This workshop was inspired by the company's BBQ approach. The pilot included 8 sessions, 1 session per week, with topics ranging from why a quality approach focused on behavior was needed to the leadership's role in implementing this approach and the relevance of language in quality. Figure 1 shows the evolution of the first 6 rounds (each round represents one group that took the workshop).

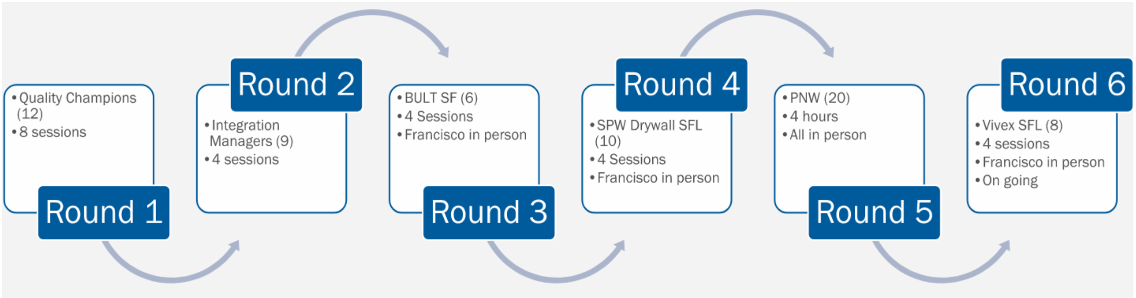

Figure 1: BQB Format Variation Changes

The pilot of BQB followed the flipped classroom approach, where all the learning material is available for participants before every meeting with the facilitator. The workshop material consisted of short videos, mostly DPR's internal videos of discussions held on a quality summit and a few project implementation stories, reading materials (Including Spencley et al. 2018), and live discussions with the facilitator(s) and supplemental resources. BQB pilot session was facilitated by the first author and the second author played the role of a participant along with other people. After each round the BQB workshop was adjusted based on the post-evaluation survey, and plus deltas given during the workshops.

Challenges found in launching and conducting the pilot, and the actions taken to address these challenges are:

- Commitment to an 8-week training was difficult for some participants, especially for the ones working on project sites whose schedule was highly variable. This helped to change the 8-week program to a 4-week program keeping the flipped classroom approach.
- Ideas and theory needed to be translated into more tangible examples. This helped to insert examples of projects that have implemented certain pieces of the BBQ process, how they did it, and what they achieved through this so that the workshop participants can visualize the implementation of the process in real cases.
- Some reading materials were too theoretical or extensive for some of the participants. This helped realized the struggle of people in projects to keep up with

readings and we replace these for videos that included similar messages that the readings intended to deliver.

- Some videos were too long. With the support of Learning and Development team some videos were edited aiming for shorter times so participants can watch them in small batches to accommodate their schedule.

Round 2 of BQB was tested with Integration Managers, who are in charge of supporting project teams set up best in class practices and help them choose the right tools. Some of the challenges highlighted after this round were:

- How to to escalate best in class practices across a variety of projects, including small renovations and large projects. Even when some project stories were added, the feedback was to develop more implementation examples from a variety of project types, especially for small projects.
- More clarity was needed on where was appropriate to identify DF, when to start implementing, and how to engage with external stakeholders. This led to looking for more case studies and develop more videos.

In parallel with BQB training, the authors kept learning from project implementation stories. Gomez et al. (2019) described a case study where the concept of BBQ was applied to the delivery of the component of architectural shear walls for a large project. This implementation highlighted areas for improvement in the delivery of quality components such as the need to:

- Make quality a responsibility of every individual and not just the project's quality champion or quality manager.
- Increase the awareness of DPR's quality approach focus on behaviors.
- Highlight best builders' behaviors by providing real case examples where BBQ was implemented.
- Create a quality implementation plan at the project level that engages every participant who has a stake in the delivery of specific quality components or services.

Round 3 was tested with a Business Unit Team that lead operations in South Florida. The team gave the following feedback:

- The team valued the materials, but the workshop had to be more action-oriented. This led to rethink all the prework questions to motivate participants to think about how they will implement BBQ on their projects or groups and to arrange all materials so the last session finished with an action plan.
- Better management of when this information is presented to teams. This lead to identify the project on the SE where new rounds will be tested, aiming for the early stages of the projects.
- Some videos were still long, and some had audio issues, specially wen it was a presentation recorded in a computer. This led to hire a videographer and make more professional videos capturing project stories.

Round 4 was tested on a self-perform team focused on Drywall. For this round, some shorter videos on drywall were added and most reading materials were only provided as additional materials, but not mandatory pre-work. The feedback was that the workshop was very helpful, but some members would have preferred an in-person session.

Round 5 was compressed and develop in-person in 4 hours, some videos were sent as pre-work, but not all participants. Local quality champions presented stories and some role-play exercises were developed. The feedback of the session was positive; however, it was not possible to use all the materials. The conclusion was that keeping the flip classroom approach and the 4-week meetings was more valuable for participants.

Round 6 was presented to a project team in the early stages, one of the facilitators was on site and the other connected remotely. The team was excited about implementing this approach and the timing of the content was appropriate. Also, in round 6 we added a follow-up session 1 month after the last session to check on the team implementation.

From rounds 7 to 26 the format was the same as in round 6. We keep including new videos as they were developed for the pre-work, the new videos focused on interviewing teams and telling their perspectives on implementation, some project teams also included owners on the video stories. In addition, some of the sessions were offered to anyone in a region regardless of role, this helped tested the content on people working on small projects where having the whole team in the training at the same time was not practical. Also coordinating the right timing for teams has proven to be challenging. So, we offered a session for teams and open to anyone on a Business Unit or region.

INTRODUCING PSYCHOLOGICAL SAFETY INTO CONVERSATIONS ABOUT QUALITY

The construct of psychological safety has been linked to teams' learning behaviors and better team performance in multiple industries ranging from manufacturing to product development (Edmondson 2012, Edmondson 2018). In construction, as in other industries, learning is fundamental to keep improving and mitigating or eliminating issues that impact the quality, safety, and overall delivery of value (evidencing by rework, accidents, delays, cost overruns, and loss of trust). Gomez et al. (2020) introduced arguments that link psychological safety with the specific impact it can have on quality in construction projects. In summary, psychological safety is needed to raise questions or concerns about quality, and to lead conversations for aligning expectations with several Stakeholders.

BQB rounds 19 and 20 were used to introduced psychological safety into the conversations surrounding the delivery of quality components. This introduction to psychological safety included four steps: 1) presenting the definition of psychological safety, 2) highlighting its role in delivering quality, 3) discussing how psychologically safe participants feel on project teams with different project stakeholders, and 4) conducting an on-hands exercise where participants can observe and experience aspects of psychological safety.

The first and second steps of introducing psychological safety into the workshop consisted on conversations where participants described first their understanding of psychological safety and then the facilitators introduced the concept to the group together and discussed its relevance for delivering quality components. The third step aimed to grasp an overview of how psychologically safe participants feel when they work in construction projects and interact with multiple stakeholder groups, particularly with people from their own company itself (i.e., general contractor employees), owners, architects, and other subcontractors/trade partners. Figure shows an example of the BQB 20 participants' responses to the question "how psychologically safe do you feel with these stakeholder groups?" The last and fourth step consisted of an exercise where participants were put in a certain scenario where they are asked to say "No" when they receive a request. In the scenarios given for the exercise, participants are paired with another participant whose role can be seen as being a position of a higher or lesser power (i.e., an owner or a subcontractor respectively).

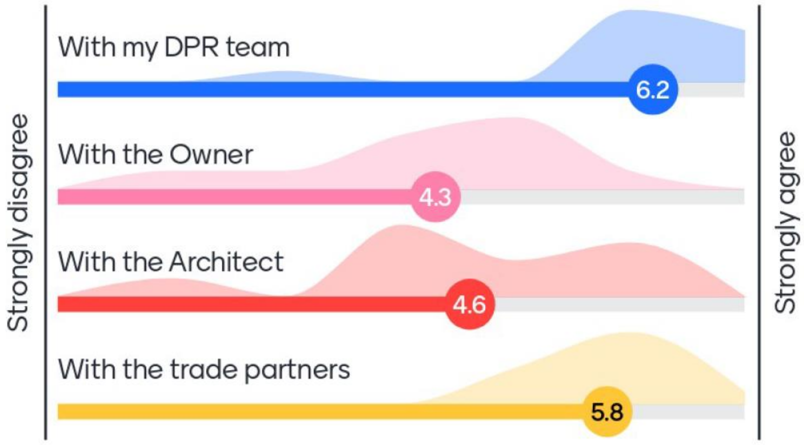

Figure 2: Participants Feeling of Psychological Safety with Different Stakeholders Groups from the Perspective of the General Contractor in BQB Round 20

Exercise on Assertions (Facts) and Assessments (Stories)

Gomez (2020) described the importance of the Language Action Perspective (LAP) theory in delivering quality components. LAP describes the different speech acts that can be part of a conversation. Among those speech acts, the assertions (also known as facts) and assessments (also known as stories) are fundamental for avoiding misunderstanding and confusion around quality expectations.

Round 19 and 20 also introduced an exercise where participants were asked to describe a picture of an architectural shear wall and a stairs mock-up. In their descriptions, they were challenged to differentiate whether what they have included in their list to describe the component was indeed an assertion (a fact that cannot be neglected e.g., the measure of the wall provided in the picture), or an assessment (an assessment that can be subject to interpretation). Round 23- 26 we kept the exercise on identifying facts and stories using the wall and stair examples.

BQB Current Format

The current format of BQB is based on a 4-week course plus a follow-up session a month after the latest session. BQB is facilitated internally by DPR Quality Leaders.

BQB continues to follow the Flipped Classroom approach. The course consists of short videos of DPR teams presenting their implementation stories now using a variety of project types, including small and large projects, different core markets, and also different perspectives based on roles. The class now also provides a summary of quality tools (A3 templates for DF, QIP templates, etc.). The applied learning activities described above (i.e., exercise on facts and stories) are also part of the live discussions with the facilitator(s). Participants are asked to dedicate 2 hours per week, totaling around 8 hours across 4 consecutive weeks, consisting of 1-hour of pre-work (watching short videos, reading short documents, and answering 5 questions) and 1-hour team call where participants engage in a safe and productive conversation. In addition, participants are asked to go to a 1-hour follow-up session that allows everyone to share what has been working and what needs to change.

The BQB workshop current agenda includes:

- Session 1 -Why a Behavioral Approach to Quality?
- Session 2 -Quality Language and Leadership
- Session 3 -How to Apply the DPR Quality Approach? (videos and materials include pursuit, pre-construction, construction, and post-construction examples)
- Session 4 -Action Plan
- Follow up – 4 weeks after session 4.

RESULTS

This section presents the results from the workshop in terms of feedback received from participants and examples of implementation where re-work was avoided.

PARTICIPANTS

Over the 26 BQB rounds, 253 participants have graduated. Participants have been mostly joining from the North West (NW) region, which includes DPR offices in San Francisco, Redwood City, Sacramento, San Jose, and Seattle. This is mainly due to stronger leadership support from the NW region. Other regions where participants have voluntarily enrolled in the training are South West (SW), South East (SE), North East (NE), Central, Europe, and India (Figure 3).

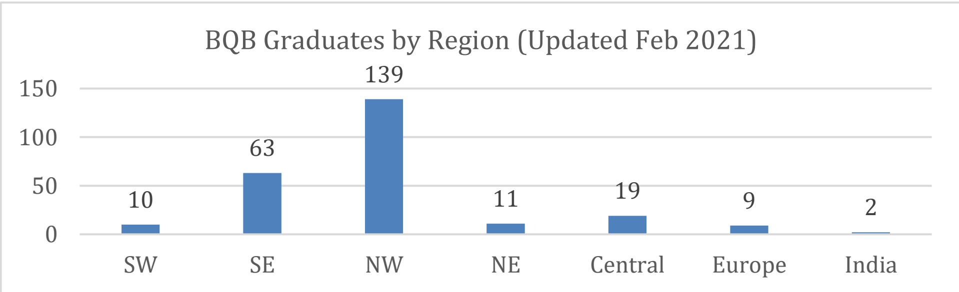

Figure 3: Number of BQB Participants by Region

Figure 4 shows BQB Participants by role. A variety of roles have participated in the training, with superintendents being the biggest group, followed by PMs and PEs.

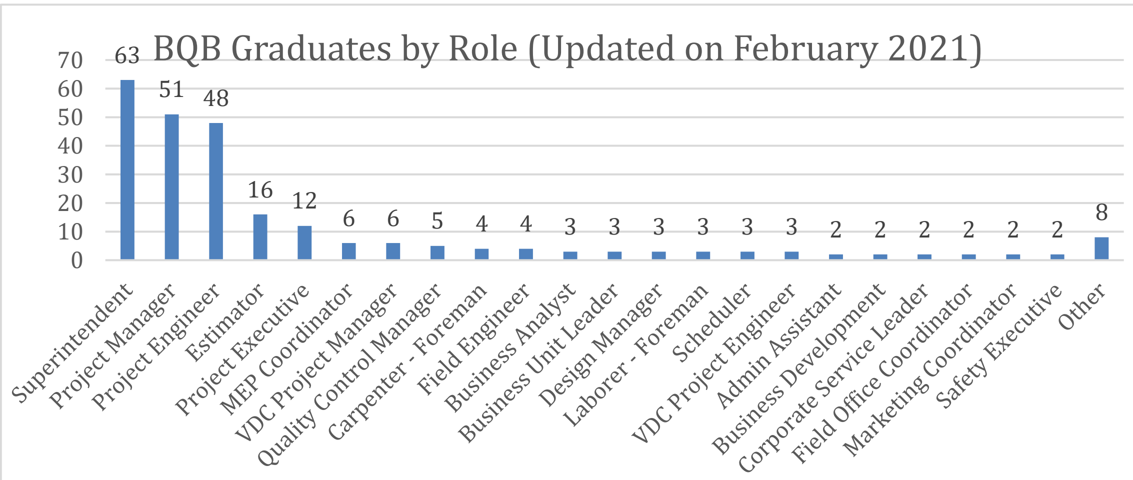

Figure 4: Number of BQB Participants by Role

Commitment to Action

In the last session of the training, participants are asked to develop an action plan in which they explain what they plan to do to implement what they have learned through the training. Table 1 shows an example of commitments made on BQB round 24 for a project team in the NE building a hospital project. A follow-up session was scheduled 1 month after the last BQB session, participants performed all committed actions.

Table 1: BQB Group 24 Strategic Action Items

	Strategic Action	Responsible
1	Create DFOW log	Project Manager (PM)
2	Creating Visuals for Stairs	Project Engineer) & PM
3	Taking the visuals and making sure they are part of Foreman meetings and post them on the field in the areas.	Superintendent
4	Provide support in the process, be engaged in quality conversations. Provide input on problem areas.	Precon
5	Ensure Quality approach gets implemented in next projects. GMP. Planting seed in proposals.	Project Executive

An A3 visual was developed for the Distinguishing Features of the stairs (Figure 5). The team collaborated with the project architect and owner to dive deeper into the construction details and found out some items were not clear, so they developed alignment and described MAC for them. The team was happy that all these details were sorted beforehand and agreed with the architect and owner, so all rework is avoided on this scope of work.

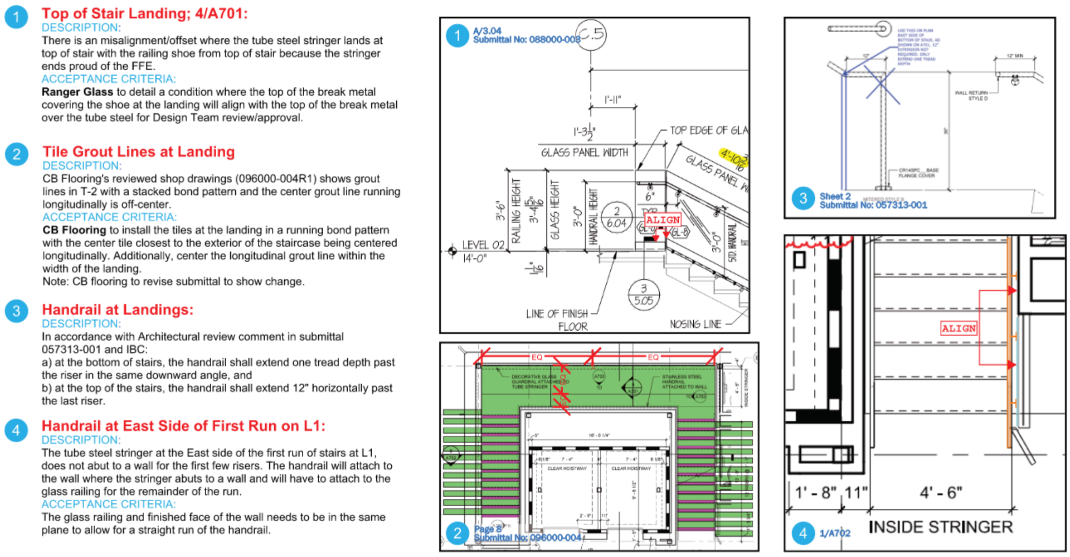

Figure 5: Example of Visual explanation of Distinguishing Features for a Stair.

Participants Feedback

Feedback from participants was collected in a voluntary post-evaluation survey (48 respondents out of 253 participants). This section summarizes the results of BQB groups from 1 to 20. Participants were asked whether they would recommend the training to others at the company. Results show that 98% (47 out of 48) of the participants would recommend this program to their co-workers. When participants were asked who should go through the training the answers point out to PEs, Superintendents, PMs, PXs, Pre-construction, and BULT, many said everyone in the company.

In addition, participants' testimonials emphasized the benefit of the training and how it would change their behaviors moving forward when asked about their takeaways and future actions:

> "The class significantly changed my view of quality and how awesome no rework can be, by being on the top of our game. I completely believe that anyone executing work should go through this training" – DPR Superintendent

> "I am going to ask more questions, earlier to ensure that the "Unknown" is turned into the "Known" – Integration Manager

> "The class reinforced to me the reality that we are a service industry. Most of our competition can build. We set ourselves apart when we have a process for capturing what's important to our clients and we deliver consistently. I think DFOW is a game-changer." - SPW Drywall Team Member

> "When engaging the client, I will continue the conversation of what is important to them and how we incorporate quality." – Business Development

> "DFOW aren't just applicable to the finished product but processes. Maintaining some type of consistency office-wide can help reinforce making our quality program and DFOW a habit." – Project Engineer

> "It (Quality) represents an opportunity for DPR to drive higher Gross Margins. We need to create a common language that gives context to Quality as a value position." – Business Unit Leader Team Member

CONCLUSIONS

This paper described the lessons learned through the development and teaching of BQB, a virtual workshop for training employees working in the construction industry on the BBQ approach towards quality. Following the DSR method, the workshop has followed a continuous improvement cycle of testing and refinement. The paper explains the different changes made to the pre-work, format to deliver the content, and discussion exercises. These changes were progressively made considering feedback from the post-evaluation survey that participant gave regarding the format and content of the workshop.

Each addition to the workshop responded to specific needs. For example, the addition to include discussions around psychological safety into the workshop aimed to cover the gap of helping participants in the workshop understand how psychological safety can impact their work of delivering quality. Similarly, the addition to include an exercise on language action perspective basics to differentiate assessment versus assertions aimed to increase clarity on the way workshop participants express their expectations and understand other people's expectations properly. Another example is the addition to focus on getting commitment to action. Participants were asked to develop an action plan for how they could implement what was learned in the workshop sessions to the work they do.

Participants who took the workshop highly recommend taking this workshop to their peers, business unit leaders, and some recommended everyone in the company taking it. Their testimonials showed different areas where they observed the workshop being helpful to them in meeting quality expectations. The BQB workshop has helped participants understand ways for how to better deliver quality in any time of work they do.

ACKNOWLEDGMENTS

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REFERENCES

Arroyo, P., Christensen, R., Schöttle, A. & Long, D. (2019). "Lessons Learned on Teaching Choosing by Advantages" In:, Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC). Dublin, Ireland, 3-5 Jul 2019. pp 405-416.

Van Aken, J.E. (2004). "Management Research Based on the Paradigm of the Design Sciences: The Quest for Field-Tested and Grounded Technological Rules." Journal of Management Studies, 41(2), 219–246.

Gomez, S. , Huynh, R. , Arroyo, P. , Ballard, G. , Tommelein, I. & Tillmann, P. (2019). "Changing Behaviors Upstream to Achieve Expected Outcomes" In:, Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC). Dublin, Ireland, 3-5 Jul 2019. pp 13-24.

Gomez, S. , Ballard, G. , Arroyo, P. , Hackler, C. , Spencley, R. & Tommelein, I. D. (2020), "Lean, Psychological Safety, and Behavior-Based Quality: A Focus on People and Value Delivery" In:, Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC). Berkeley, California, USA, 6-10 Jul 2020. pp 97-108

Edmondson, A.C. (2012). Teaming: How Organizations Learn, Innovate, and Compete in the Knowledge Economy. John Wiley & Sons

Spencley, R. , Pfeffer, G. , Gordon, E. , Hain, F. , Reed, D. & Marosszeky, M. (2018) "Behavior-Based Quality, Case Study of Closing the Knowing-Doing Gap" In:, 26th Annual Conference of the International Group for Lean Construction. Chennai, India, 18-20 Jul 2018. pp 1170-1181.

Hackler, C. , Byse, E. , Alves, T. C. L. & Reed, D. (2018), "Lean Leadership Training: Lessons From a Learner-Centered Analysis" In:, 26th Annual Conference of the International Group for Lean Construction. Chennai, India, 18-20 Jul 2018. pp 484-494.

Tsao, C. C. , Azambuja, M. , Hamzeh, F. R. , Menches, C. & Rybkowski, Z. K. (2013). "Teaching Lean Construction Perspectives on Theory and Practice" In:, Formoso, C. T. & Tzortzopoulos, P., 21th Annual Conference of the International Group for Lean Construction. Fortaleza, Brazil, 31-2 Aug 2013. pp 977-986.

Nofera, W. , Abdelhamid, T. S. & Lahouti, A. (2015), "Teaching Lean Construction for University Student(S)" In:, Seppänen, O., González, V. A. & Arroyo, P., 23rd Annual Conference of the International Group for Lean Construction. Perth, Australia, 29-31 Jul 2015. pp 424-433.

Veran-Leigh, D. and Brioso, X. (2021). "Implementation of lean construction as a solution for the COVID-19 impacts in residential construction projects in Lima, Peru" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 923–932, doi.org/10.24928/2021/0215, online at iglc.net.

IMPLEMENTATION OF LEAN CONSTRUCTION AS A SOLUTION FOR THE COVID-19 IMPACTS IN RESIDENTIAL CONSTRUCTION PROJECTS IN LIMA, PERU

Daniel Verán-Leigh[1] and Xavier Brioso[2]

ABSTRACT

At the beginning of 2020, a virus discovered in the province of Wuhan in China identified as SARS- COV-2, denominated COVID-19, began to spread globally, being identified by the World Health Organization (WHO) as a pandemic on March 13 since the epidemic has spread to several countries in all the continents and affects a large number of people (WHO 2020). In Peru the entry of COVID-19 caused the Peruvian government to take different options to control its spread such as mandatory quarantines and lockdowns. In front of this scenario, the Architecture Engineering and Construction (AEC) sector had to reinvent itself since it is a sector where work depends on a significant amount of personnel (IPE 2020). Furthermore, the level of industrialization in Peru is significantly lower compared with industrialized countries, generating that the consumption of labor is greater as well as the cost of the project, searching for new solutions to improve productivity. Moreover, considering the new sanitary measures for COVID-19 including new health protocols, controls, and improvement of working sanitary standards. Therefore, the main purpose of the present paper is to present a planning proposal for a system that integrates the Lean tools and the COVID-19 protocol for armed concrete buildings in Peru and present the preliminary results of its modification on the production system, design of work schedules, planning meetings, among other aspects of the construction system.

KEYWORDS

COVID-19, lean construction, Last Planner® System, construction system.

INTRODUCTION

The construction industry production has grown just 1% per year over the past 2 decades and is reflected in the lagging productivity, combined skilled labor shortages, and unpredictable materials cost, leads to low projects performance, over budget, and times of execution more than planned (McKinsey & Company 2020).

Related to the construction sector in Peru, affected by the COVID-19 pandemic, reduced its productivity by 15.6% during 2020 (La Republica 2019, Veran-Leigh et al. 2019). Nevertheless, it is considered to increase to 17.4% in 2021 and 4% in 2022

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according to the Central Reserve Bank of Peru (El Peruano 2020). In response to the high expectations of recovery in the construction sector in the next years, the use of different construction methods and philosophies such as Lean Construction (LC), have been implemented to enhance construction systems, with the main goal of improving competitiveness and performance (Alarcon 1997, Ghio 2001, Cho and Ballard 2011).

Furthermore, the pandemic has highlighted the importance of the physical proximity and level of human interactions across occupations, including the construction sector. Considering this one as an on-site field job, the use of remote work does not work efficiently and is unproductive for the sector, considering the face-to-face construction works and constant communication within the project for each of the specialties involved (McKinsey & Company 2021). Is in this scenario where the implementation of new construction systems, technology and procedures using the new sanitary protocols for the control of the workforce become a must in every construction project that requires a significant amount of manpower to carry out day-to-day jobs (Fischer et al. 2017, McKinsey & Company 2020).

According to the Peruvian scenario, the story starts at the end of May 2020 when the Peruvian state established the beginning of the fourth phase of reactivation with the opening of economic activities related to construction, transport, mining, among others (MINSA 2020). This restart of construction activities was first linked to the preparation of a COVID-19 protocol by each construction company, then once the projects restarted, problems such as COVID-19 tests, contagion control, the amount of available trained workforce, among others problems, became recurrent (MVCS 2020). To control them and improve the procedures, the implementation of the Lean Construction Philosophy (LCP), became a possible solution to continue the processes and be able to move the project forward. Therefore, the main purpose of the present work is to present a planning proposal for a system that integrates the Lean tools and the COVID-19 protocol for armed concrete buildings in Peru and present the preliminary results of its application in a building project.

COVID-19 PROTOCOLS IN THE CONSTRUCTION SECTOR

The construction sector globally had to implement new security and COVID-19 control protocols. The similarity that occurs in first world countries such as the United States of America (USA) as well as in Latin American countries such as Peru, Chile, and Colombia, was the implementation of security protocols, entry of personnel, control of exposure risk levels, standard operating procedures, reduction of staff, implementation of teleworking and teleconferences to reduce as much as possible the approachement between workers, among other variables (BID 2020, United States Department of Labor 2020).

The cessation of works at the national level from the beginning of the pandemic until thereactivation of phase 4 in June 2020. Starts with the presentation of the COVID-19 Resumption plan to the Peruvian Ministry of Health (MINSA), where the following information was presented: a descriptive report of the project, current state of the work stations, modifications in the health protocols to comply with the new COVID-19 Protocol, work fronts (sectorizations), amount of personnel by work areas, disinfection and collective biosafety protection, the staff distribution and comorbidity screening. This information was presented and aligned with the ministerial Resolution 448-2020 in June 2020 (MINSA 2020) and the newest document presented in February 2021 (MINSA 2021).

LEAN CONSTRUCTION, LAST PLANNER® SYSTEM AND SAFETY MANAGEMENT

LC is a way to design a production system to minimize waste of materials, time and effort to generate the maximum possible amount of value. Additionally, the lean tools have the next benefits: organize the project system, work areas, productivity, reduce waste, increase added value, improve occupational health, among other benefits. (Howell et al. 2017). LC contains five main principles used to gain maximum benefit from the system: specify a value for the customer, identify value stream, make value flow without interruptions, let the customer pull value from the producer and pursue perfection (Bertelsen & Koskela 2004). Furthermore, safety management is considered as one of the chronic problems in construction and LC can contribute to this area by the standardization and systematized production that leads to better safety in the project by having less material in the work area, have the workplace orderly and clean, less confusion in a systematized workflow and fewer disturbances (Koskela 1992). There are several tools and techniques used in LC, such as Last Planner® System (LPS), first-run studies, 5S, fail-safe for quality and Safety and Takt time planning (Koskela et al. 2002, Porwal et al. 2010).

On the one hand, LPS, considered as a collaborative, commitment-based planning system that integrates should-can-will-did planning (Seed 2020). Moreover, the LPS includes the planning cycle divided in four different levels; the master schedule, the phase schedule, look ahead planning (LAP) and the weekly work plan (WWP). The LPS is focused on the reduction of uncertainty and variability in a project workflow, including the management tools of Plan Percent Complete (PPC) to measure the system performance defined according to Ballard et al. (2007a) as "the number of completions divided by the number of assignments for a given week" and the Cause of Non-Compliance (CNC) that can be obtained by performing a root cause analysis to identify the source of action or event chain to learn how repeated failures can be prevented (Ballard 2000, Orihuela 2011, Kassab 2020). Furthermore, contracts with subcontractors and stakeholders are key drivers for participation and attendance in Pull Planning (PP) sessions (Murguia et al. 2016).

On the other hand, the lean safety management system is based on creating an environment in a workplace where there is employee motivation and reliable management. All the different levels of an organization need to put forth their best efforts on a day-to-day basis and work together toward achieving improved performance and reducing waste. 5S (Sort, set in order, Sweep, Standardize, Sustain) is one of the most effective tools of LC because it is the basis for an effective Lean Implementation (Anvari et al. 2011). Moreover, 5S is a method for the cleanup and organization of the workplace and it has been developed in Japanese just-in-time manufacturing and has been used in the implementation of the construction sector. Furthermore, the 5S process is a structured program to systematically achieve total organization, neatness, cleanliness, standardization and discipline in the workplace (Lein et al. 2014).

In addition, the LPS recommends: (1) producing collaborative planning including the participation of support areas, like safety and health, (2) identifying and enforcing the adequate anticipation of the constraints, among others (Brioso 2011). Additionally, a case study shows that several tools from LC are related to some of the more common practices implemented even now in the Safety Management System (Antillon et al. 2011).

RESEARCH METHOD

Based on the information presented before, the following method of integration on site of the use of lean tools was proposed in conjunction with the new preventive measures of the COVID-19 protocol in Peru. The case of analysis of the impact of the COVID-19 in the construction work will be a project of 18 floors, 4 basements, and common areas of residential housing in Lima, Peru.

Firstly, the COVID-19 implementation plan at work is divided in 5 parts: the modification of changing rooms according to the new distancing and physical separation protocols, relocation of the dining room and common areas, installation of disinfection points at the entrance of the project and in common areas near the changing rooms, expansion of bathrooms and general disinfection of work biweekly (see Figure 1).

The implementation of LC, in the security and production areas, was modified due to the implementation of the COVID-19 protocols. Initially, the use of 5S for the COVID-19 context was presented as a solution for the reorganization of the common areas of the workers. On the other hand, the production system for the design of the flows, the Takt Time Planning (TTP) also known in Peru as a train of activities, like other location-based planning methods, schedules the use of construction workspace along with the time (Pons & Perez 2019, Singh et al. 2020) was used in the project in the Pre pandemic context and now is modified by the COVID-19 protocols. New restrictions were presented compared to before COVID-19 including: reduction of the sectorization due to the fulfillment of the number of personnel for the type of construction, problems related to the supply of materials by suppliers affected by problems of importing materials, and the increase in the time of the entry of personnel in a staggered and controlled manner due to the protocols of the COVID-19 surveillance plan.

To control the advancement of personnel, before the pandemic there was a sectorization by workgroups for different work items: steel installation, formwork work and concrete pouring. These crews have throughput and a daily work lot. The project had been using the Last Planner® System before the start of the pandemic including the analysis of the cause of non-compliance and analysis of restrictions. Because of the COVID-19 pandemic, the maximum number of people per m^2 that could be in the sectors was calculated and the areas of each sector were reduced by 20% to reduce the number of personnel per work zone. With the new health protocols, productivity was modified and there were different restrictions and causes of non-compliance.

ANALYSIS OF RESULTS

After the implementation, the on-site work was restarted. These had modifications such as the entry of medical personnel into the project due to the new regulations and the number of personnel, taking rapid COVID-19 tests for the detection of IGG and IgM antibodies or serological tests, COVID-19 training talks (see Figure 1), and restarting work on pouring concrete in the tower. This restart came hand in hand with problems such as sources of contagion, public transport strikes, cessation of metropolitan transportation services, among other factors (El Comercio 2020).

The MINSA approved the use of rapid tests and that workers were only allowed to enter to work if they had tested with negative IGG and IGM results. The problem with this criterion was that it limited enough personal entry to work since there were records of up to 33% of positives in personnel who went on to do a COVID-19 test since most of them having IGG (who presented antibodies) could not enter until coming out on the negative test. Likewise, comorbidity medical examinations were carried out, affecting the number of personnel on-site because those with comorbidities such as hypertension, obesity, diabetes, or those over 60 years of age could not work on the projects, making it difficult to find skilled labor.

The modifications related to the safety in the construction security system apart from the COVID-19 implementation presented the following differences compared to the previous security system including: reduction of capacity in the dining and changing rooms, the use of personal chemical barriers (Alcohol) and more disinfection points. Related to sustainability and safety, minimize the use of disposable bottles and disposable containers to control the entry of personal meals. The prohibition of not leaving organic residues on-site, the order in the use of cleaning areas based on cleaning shifts, and tool washing points.

The solutions that were implemented on-site to be able to maintain production were several, these include the installation of a temporary ladder in the rear area to reduce the flow of personnel, avoiding having a single transit point. In this way, the probability of contagion was significantly reduced, considering that the work was in the hull stage with the beginning of finishes (masonry) and there were more than 100 people on site (see Figure 1).

Figure 1: Location of the second access ladder to reduce the flow of work personnel, Disinfection common areas and COVID-19 diary training

Moreover, related to the tower production, according to the TTP method, LPS and COVID-19 protocol the sectors were reduced from 4 to 5. To control the performance of labor as can be seen in Figure 2, sectorization reduced the advance by 20% in productivity, but the performance of the personnel and the control of the COVID-19 advance could be maintained, complying with the minimum distance of the personnel.

Columns and Plates	
Productivity index	Total (m^3/day)
4 Sectors	13.55
5 Sectors	10.84
Percentage	20%

Slab and Beam	
Productivity index	Total (m^3/day)
4 Sectors	37,50
5 Sectors	40,84
Percentage	20%

Total	
Productivity index	Total (m^3/day)
4 Sectors	37,50
5 Sectors	40,84
Percentage	20%

Figure 2: Initial and final sectorization of the project in the helmet stage, with 4 and 5 sectors according to the COVID-19 scenario

On-site control of progress and personnel was done by the use of LC tools such as LAP, PP, Gemba walk, among others. In figure 3 is presented the use of LPS. Furthermore, we have seen that the implementation of LPS before and after the pandemic obtain positive results in the organization, planification and control of the project. Integrating the COVID protocols were detected new restrictions in the execution of the projects as a sanitary safety control, sectorization, efficient workspace distribution and useful work area. In addition, the planning and control tools included COVID-19 measures. For example, the meetings were held with all COVID-19 control protocols, virtual meetings with contractors were implemented to have the only and necessary direct contacts. Daily health awareness talks were held to staff and the entry of staff and contractor companies was stricter according to the new COVID-19 guidelines.

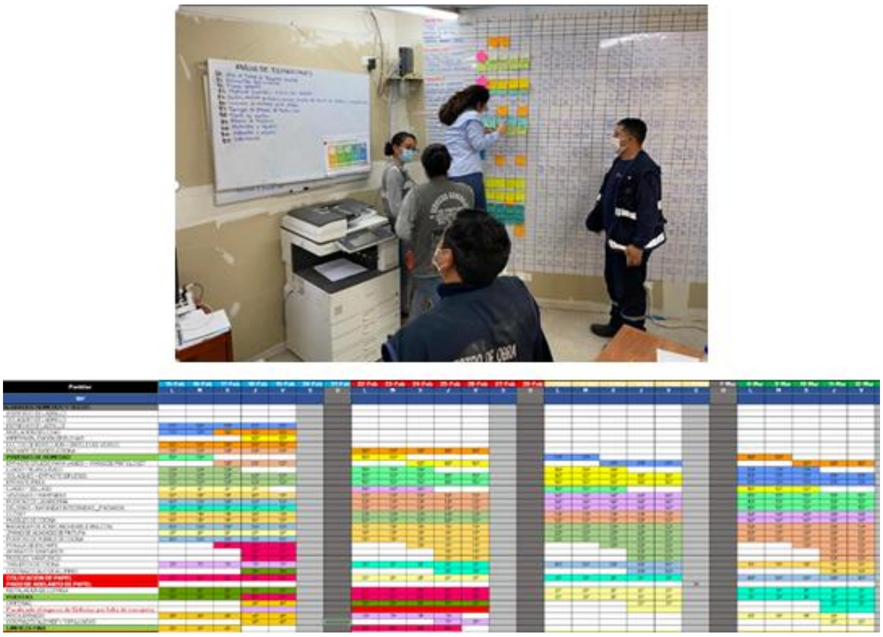

Figure 3: Implementation of Look ahead planning in the week-control and the planification of 4 weeks ahead.

The PP activity, phase planning, was carried out differently from that implemented in previous stages such as hull and excavation. Each person had their materials (post-its, markers, mandatory disinfection alcohol, among others). It was accomplished by working in open and ventilated offices with compliance with the use of the COVID-19 Personal Protect Equipment (PPES). In this way it was possible to have the work planning, taking into account the experience of the foremen, the team coordination and identifying the material and personnel constraints for each item. Figure 5 is presented ahead. Furthermore, the use of Gemba Walk, a technique used to observe and understand how work is being performed (Dalton 2019), was applied with the entire engineering staff, the superintendence area and the project manager of the real estate agency. To make a team tour, among all the interested parties, to be able to review the work area at the time of the work, resolve doubts about details, progress, be informed of all of the flow of activities and incidents of the work, among other benefits that together in the field could be appreciated.

Figure 5: Pull Planning on-site with the project team

To date, the civil construction stage of the project has ended and the finishing stage of the project has been completed. The following analysis is presented using the LCP of CNC and PPC of the studied project. In the analysis presented in Figures 6 and 7, the following can be seen. The PPC during the pandemic was lower compared to the pre-pandemic PPC (4-5%). In addition, the CNC was greater in the Post-Pandemic stage compared to the previous one due to the insert of the external causes related to the COVID-19. For the Control of the PPC and the CNC was used the software POWER BI of Microsoft (Aspin 2016). Moreover, in the analysis of the results of the implementation of the COVID-19 protocols, stakeholders concluded that the implementation of lean tools such as PP and WWP served to comply with the COVID-19 protocols. Given that in these meetings served for planning and coordinate the work, solutions, provisions and regulations of all the personnel, so that everyone agrees, maintains the same rules and thus complies with the protocols correctly.

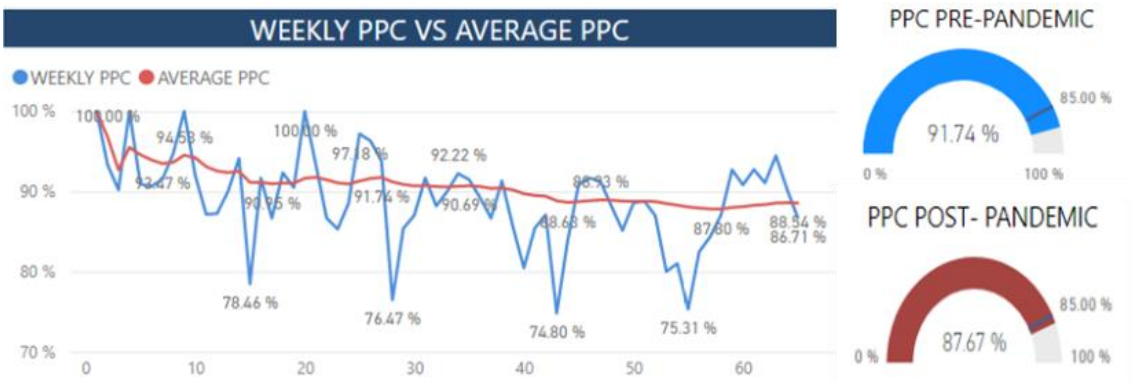

Figure 6: Plan Percent Complete in the residential studied project.

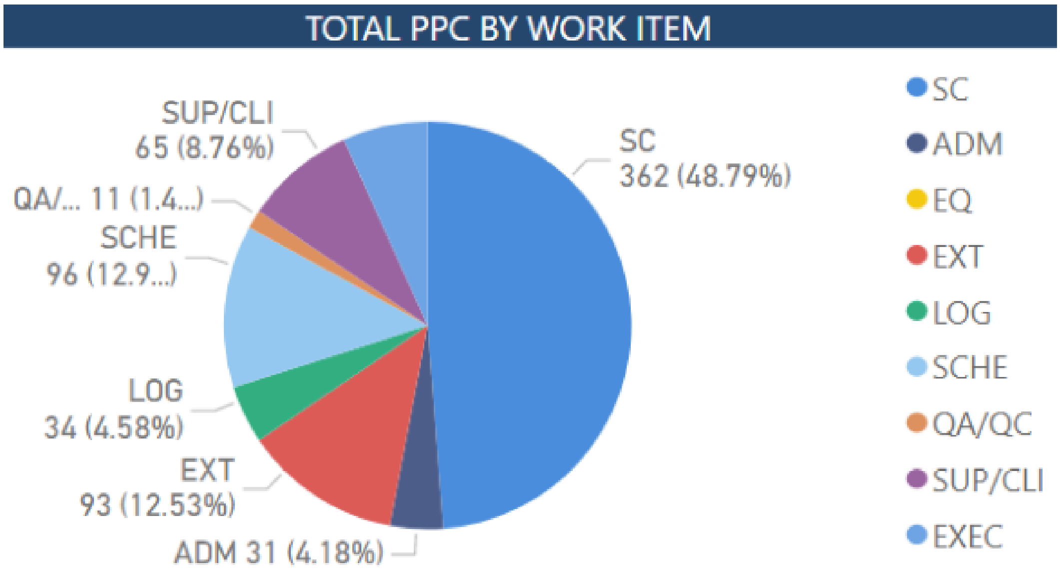

Figure 7: Cause of non-compliance in the residential studied project

However, it is important to mention that the stages in which COVID-19 appeared are different. On the one hand, the Pre COVID-19 scenario was in the structural period, where the participation of interested parties is lower compared to the architectural stage where the number of people, companies, and restraints is greater, which was directly linked to the CNC. Likewise, it is important to emphasize that to date, almost 12.53% of CNC were generated by external causes (COVID-19) due to: number of infected, personnel with medical rest, difficulty in finding trained personnel, delay in the dispatch of materials from abroad (mainly from China), among other factors. In addition, it is important to consider that the use of PPC and the CNC helped us to be able to identify problems in advance, to be able to solve them and identify the restraints raised and avoid stopping the workflow. Besides, the use of the LCP served to maintain communication between staff to be able to map the infected staff, restraints, and emergency work plans.

CONCLUSIONS

We can conclude that the impact of COVID-19 in the construction sector was significant during 2020 and at the beginning of 2021, largely modifying security controls, work priorities, construction processes, and control methodologies. On the one hand, it eliminated several companies that did not comply with the appropriate security standards, secure protocols, are informal, among others. Nevertheless, on the other hand, it is important to consider that, COVID-19 was an accelerator of the sector in the face of productivity and the implementation of technologies in the sector, driven by social distancing and the need to find new processes. Also, the implementation of new philosophies such as LC for the control, planning, and execution of work turned out to be a successful option to be able to maintain productivity in the residential studied project, complying to date with the deadline, cost, safety, and quality required in the project.

REFERENCES

Alarcón, L. (1997). "Lean construction". CRC Press.

Antillon, E. I., Alarcon, L. F., Hallowell, M. R. & Molenaar, K. R. 2011, "A Research Synthesis on the Interface Between Lean Construction and Safety Management" In: Rooke, J. & Dave, B., 19th Annual Conference of the International Group for Lean Construction. Lima, Peru, 13-15 Jul 2011.

Anvari, A., Zulkifli, N., Yusuff, R. M. (2011). Evaluation of approaches to safety in lean manufacturing and safety management systems and clarification of the relationship between them. World Applied Sciences Journal, 15(1), 19-26.

Aspin, A. (2016). Pro Power BI Desktop. Apress.

Banco Interamericano de Desarrollo (BID). (2020). El impacto de la crisis del coronavirus en el sector de la construcción pública.

Bertelsen, S., & Koskela, L. (2004, August). Construction beyond lean: a new understanding of construction management. In Proceedings of the 12 th annual conference in the International Group for Lean Construction.

Brioso, X. (2011), 'Applying Lean Construction to Loss Control ' In: Rooke, J. & Dave, B., 19th Annual Conference of the International Group for Lean Construction. Lima, Peru, 13-15 Jul 2011.

Cho, S., & Ballard, G. (2011). Last Planner and Integrated Project Delivery. Lean Construction Journal.

Dalton, J. (2019). Gemba walks. In Great Big Agile (pp. 173-174). Apress, Berkeley, CA.

Diario La República. (2019). La productividad de la construcción es solo del 20%.

El Peruano (2020). Sector construcción se recupera y prevén un avance significativo el 2021. Revista: El Peruano, Lima, Perú.

El Comercio (2020). Paro de transportistas: el minuto a minuto de la suspensión del transporte público que afecta a Lima y el Callao. Revista: El Comercio, Lima, Perú.

Fischer, M., Ashcraft, H. W., Reed, D., & Khanzode, A. (2017). Integrating project delivery. John Wiley & Sons.

Ghio Castillo, Virgilio. "Productividad en obras de construcción; Diagnóstico, crítica y propuesta". Lima: Fondo editorial PUCP. 2001.

Instituto Peruano de Economía (IPE). (2020). Señales de un sector en construcción.

Glenn Ballard. "The last planner system of production control". [Tesis doctoral]. Birmingham: Universidad de Birmingham, Facultad de Ingeniería. 2000.

Howell, G., Ballard, G., & Demirkesen, S. (2017, July). Why lean projects are safer. In Proceedings of the 25th Annual Conference of the International Group for Lean Construction, Heraklion, Greece (pp. 4-12).

Kassab, O. A., Young, B. K., & Lædre, O. (2020). Implementation of Last Planner® System in an infrastructure project.

Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2002). The foundations of lean construction. Design and construction: Building in value, 291, 211-226.

Koskela, L. (1992). Application of the new production philosophy to construction (Vol. 72). Stanford: Stanford university.
Leino, A., Heinonen, R., & Kiurula, M. (2014). Improving safety performance through 5s program. In Proc 22nd Ann Conf of the Int'l Group for Lean Construction.
McKinsey Global Institute (2021). The Future of work after COVID-19.
McKinsey & Company (2020). Rise of the platform era: The next chapter in construction technology.
McKinsey & Company (2020). The next normal in construction.
Ministerio de Salud (MINSA). (2020). Resolución Ministerial N° 448-2020/MINSA Lineamientos para la vigilancia, prevención y control de la salud por exposición al SARS-CoV-2.
Ministerio de Salud (MINSA). (2021). Resolución Ministerial N° 972-2020/MINSA Lineamientos para la vigilancia, prevención y control de la salud por exposición al SARS-CoV-2.
Ministerio de Vivienda, Construcción y Saneamiento (MVCS). (2020). Resolución Ministerial Nº 087-2020 Protocolo Sanitario Sectorial (07 de mayo de 2020).
Murguía, D., Brioso, X. & Pimentel, A. 2016, 'Applying Lean Techniques to Improve Performance in the Finishing Phase of a Residential Building' In:, 24th Annual Conference of the International Group for Lean Construction. Boston, Massachusetts, USA, 20-22 Jul 2016.
Orihuela, Pablo y Ulloa, Karen. "La planificación de las obras y el sistema last planner". Boletín N° 12, Corporación aceros Arequipa, julio. 2011.
Pons Achell, J. F., Rubio Pérez, I. (2019). Lean Construction y la planificación colaborativa. Metodología del Last Planner® System.
Porwal, V., Fernandez-Solis, J., Lavy, S., and Rybkowski, Z. 2010. "Last planner system implementation challenges" Proc. 18th Annual Conf. Int. Group for Lean Constr., Technion, Haifa, Israel, 548-556.
Seed. W.R. (2000) "Don't Conform, Transform! A Guide to Better Project Outcomes, Narrated by a Pioneering Leader" Lean Construction Institute.
Singh, V. V., Tommelein, I. D., & Bardaweel, L. (2020). Visual tool for workload leveling using the work density method for takt planning. In Proceedings of the 28th Annual Conference of the International Group for Lean Construction (IGLC28), Berkeley, CA. doi (Vol. 10, No. 2020, p. 0061).
United States Department of Labor (2020). COVID-19 - Control and Prevention - Construction Work.
Verán-Leigh, D., Larrea-Gallegos, G., & Vázquez-Rowe, I. (2019). Environmental impacts of a highly congested section of the Pan-American highway in Peru using life cycle assessment. The International Journal of Life Cycle Assessment, 24(8), 1496-1514.
World Health Organization. (2020). Coronavirus disease (COVID-19).

SUPPLY CHAIN MANAGEMENT AND OFF-SITE CONSTRUCTION

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Berroir, F., Guernaccini, P., Boje, C., and Maatar, O. (2021). "Reducing construction logistics costs and embodied carbon with CCC and kitting: A case study" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 935–944, doi.org/10.24928/2021/0120, online at iglc.net.

REDUCING CONSTRUCTION LOGISTICS COSTS AND EMBODIED CARBON WITH CCC AND KITTING: A CASE STUDY

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ABSTRACT

Supply chain management was originally proposed to improve construction sites performances, nonetheless this simultaneously presents a potential solution for reducing the carbon footprint of the construction sector. Therefore, both environmental and cost impacts must be considered in order to raise the sector's awareness and foster change towards more sustainable practices. The purpose of this research is to evaluate the applicability of such a model for the supply chain by implementing Just-in-Time deliveries using kitting and a Construction Consolidation Centre managed by a Third-Party Logistics operator on a real-life construction project. Data was collected on actual tasks durations, time losses for site's workers and deliveries, and used as input to estimate the corresponding values with a traditional logistics and to model impact on both direct and indirect costs for comparison and discussion. Findings indicate that this new logistics paradigm can lead to productivity improvements and overall reduction in transportation needs. These have an implicit positive impact on both the environment and cost savings, which are calculated and discussed. Based on these results, it is argued that the adoption of this model contributes to a lean-green deal by demonstrating the positive impact of Lean Construction techniques towards better supply chain integration.

KEYWORDS

Supply chain management (SCM), sustainability, action research, CCC, kitting.

INTRODUCTION

From a supply chain perspective, a construction project can be viewed as an assembly process that requires several types of materials or components to be put together. As a result, activities such as the purchasing of materials and services from suppliers and subcontractors represent between 60 and 80% of the gross work done in construction projects, which consequently have an important impact on project performance (Eleskar 2020). Applying adequate logistics methods is still a major challenge as these are often poorly mastered or sometimes even consciously neglected when it comes to cutting costs.

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Instead of investing in order to properly manage and optimize material flows in early stages, it appears often easier to place responsibility on subcontractors and just let workers and site managers make do (Mossman 2008; Lafhaj and Dakhli 2018). These adversarial behaviours are even strengthened by the silo nature of the construction industry and results in wastes and time losses, notably due to repeated moving of materials (Vrijhoef and Koskela 2000; Mossman 2008; Tetik 2020).

From an environmental perspective, the construction sector is considered as one of the most polluting industries, accounting for approximately 50% of greenhouse gas production in the UK (Dadhich 2015), and a significant cause of traffic congestion in urban areas. It is estimated that building materials can make up to 30% of the tons carried across cities in growing urban areas (Dablanc 2009). Accordingly, improving construction material flows is not only about productivity and profits for the stakeholders of the built environment, but also a global environmental, health and well-being issue.

In order to tackle the above challenges, this research is set to demonstrate the applicability of innovative construction supply chain management based on Just-in-Time principles using a Construction Consolidation Centre (CCC) and a Third Third-Party Logistics (TPL) model in a Luxembourg. The potential benefits of this approach are investigated through a case study on a real-life construction site. More specifically, this article investigates how consolidated logistics can lead to both economic and environmental improvements. This is achieved by estimating: (1) the cost breakdown, return on investment and potential for profit sharing, and (2) the embodied carbon and congestion reduction. Additional benefits regarding resilience in pandemic times, Lean Construction maturity and digitalisation will be discussed as well as the current limits and barriers identified towards a fully interoperable and integrated Construction Supply Chain.

BACKGROUND

Supply Chain Management (SCM) was proposed as an answer to the productivity issues observed in construction (Vrijhoef and Koskela 2000). Based on manufacturing techniques, researchers advocated for a transfer of activities from the site to the supply chain (mentioned as “role 3”) and an integrated management of the supply chain and the construction site (mentioned as “role 4”). Practical solutions were developed in the literature including Just-In-Time deliveries, packaging, Kanban and logistic centres (Arbulu and Ballard 2004; Hamzeh et. Al 2007).

By adopting and implementing the proposed SCM model, several studies demonstrated its benefits. Elvfing (2010) described successful practices implemented by a Finnish contractor using a logistics centre to manage make-to-order and large make-to-stock items and reported productivity gains of 20%, while also indicating that the productivity increase exceeded the additional cost related to the warehouse. Mossman 2008 reported several key figures of test projects using the London Construction Consolidation Centre, such as the building rate which sits at 60% ahead of the industry benchmark, the building cost at 80% of industry benchmark, while achieving a 73% reduction in CO_2 emissions. Despite these significant improvements, the construction industry lacks initiative to replicate and eventually generalise this paradigm across several contexts. This lack of initiative suggests a need for economical evidences acknowledged by surveys (Lafhaj and Dakhli 2018). More recent studies have been carried out with a focus on estimating additional transportation reductions (Samuelsson 2014) and on-site labour productivity improvements (Tetik 2020) while also advocating for more in depth analysis of direct and indirect costs.

According to Eleskar 2020, there is a new and under-investigated phenomenon in the construction industry, which is referred to as Third-Party Logistics (TPL), where specialised actors take over all or parts of the logistics management as part of specialised and project specific construction logistics arrangements. These lead to productivity improvements, cost savings and increased utilisation of site assets, however, the lack of knowledge on internal costs for logistics and the fear for unrealistic fees are barriers for a wider diffusion of the model. Although some studies provide empirical data on the costs of the TPL approach (Janné 2020), these are insufficient to be able to discern if the extra costs were offset by the benefits incurred.

In order to foster transition towards more sustainability at an urban scale, there is a need to bring more awareness on the issues concerning construction logistics, as well as a need for deeper collaboration (Morel 2020). Accordingly, this paper aims to demonstrate feasibility of TPL integrating kitting and CCC services in new context, and to provide a deeper understanding of the costs and benefits breakdown for general contractor and subcontractors and of the conditions for embodied carbon reductions.

METHODOLOGY

This research describes a case study analysis conducted during the implementation of the first CCC experiment using a TPL operator and Kitting in Luxembourg as part of a collaborative research with a General Contractor (GC). The TPL agreement included all direct logistics costs and needed to be compared with traditional logistics costs. In addition, indirect costs had to be investigated for both cases. According to Josephson (2003), Non-Value-Adding activities can be identified, categorized (when/who/how) and discussed in order to estimate and tackle over costs. This approach was chosen since the logistics costs may be borne by distributors, subcontractors or main contractor and can have many indirect impacts. As, no other project available at the time of the experimentation presented enough similarities to perform a comparative analysis, data on NVA activities and delivery scenarios for both traditional and new logistics were collected on the same site and discussed in group with contractors and subcontractor. Accordingly, following methodology was applied in order to set up a commonly agreed model of costs and carbon footprint related to logistics:

1. Initial model of cost breakdown and Key Performance Indicators (KPI) definition according to state of the art;
2. Data collection on site: All kits deliveries and consumption (giving start and end dates of corresponding tasks) were monitored in a custom web-platform prototype;
3. Estimation of the delivery scenarios with a traditional model on a bi-weekly basis based on actual needs and constraints performed by GC project managers;
4. Non-value adding time measurement on a sample of traditionally managed tasks;
5. Validation of the estimates from the previous step with subcontractors and calculation of corresponding KPI (including carbon footprint, see Table 1);
6. Adapted cost breakdown for the actual case based on accounting data from the General Contractor and indirect costs (see Table 2);
7. Adapted cost estimation for the fictional "without CCC" case based on a reviewed model (see Table 2).

Table 1: Main KPI measured and their corresponding data collection method

KPI	Metrics	Data collection and calculation methods
Planning Reliability	Saved days	For each task (involved in CCC) actual task durations have been measured and compared to site schedule forecasts
Productivity	Time spent on Non value adding activities	Time measurement on Non Value adding activities on tasks with kitting and on comparable tasks on the same site without CCC.
Transport efficiency	Number of deliveries Filling rates % of satisfying deliveries	With CCC: actual data from the web-platform (including trip from supplier to CCC and from CCC to site) Without CCC: delivery constraints on site, subcontractors' delivery habits and actual needs have been collected to estimate a corresponding number of deliveries
Costs		*See detailed model of cost (table 2)*
Sustainability	Embodied Carbon	Calculated using geographical information and number of transports (with CCC: actual, without CCC: estimated)

Table 2: Direct and indirect cost breakdown (for General Contractor and subcontractors)

	With CCC (actual case)	Without CCC (simulated case)
Direct costs	(A1) Actual costs observed and billed including warehouse and storage costs at CCC, TPL labour costs for picking and packing material in CCC, transportation (trucks, driver…), dispatching of kits at workplaces and TPL margins. (Paid by GC) (A2) Transportation costs from suppliers to the CCC calculated based on actual deliveries. (Paid by SC)	(A1) Simulation of direct logistics costs if the same material for the same site had been managed by the subcontractors without kitting. This includes transport from supplier to the site and handling on site. Calculations are based on simulated delivery scenarios and samples of time measurements for similar task and products on the same site (for instance, pipes and external doors were managed by same subcontractors but with traditional logistics, and thus could be used as control sample) (Paid by SC)
Indirect costs	(B1) Management cost including software fee and manager time on purchasing and on-site inventory.	
	(B1) The actual times spent were directly measured along the project	(B1) Average times per order of similar tasks and products on the site, multiplied by the number of orders and deliveries estimated. (Paid by both GC and SC)
	(B2) Lifting equipment costs, based on detailed site accounting per subcontractor and avoided congestion-based utilisation rates of the lifts on site. These costs may also concern subcontractors out of the tasks using the CCC (Paid by SC)	
	(B3) Overall days saved on planning and their value in terms of manpower (paid by SC) and overall site costs (Paid by GC)	
	(B4) Productivity losses (excluding direct handling cost listed in direct costs above). This includes moving and waiting times of site crews. These costs differ from B3 as they will impact crew size instead of task duration and were obtained through comparison of time measurements on a sample of tasks with and without kitting (Paid by SC)	

(Note: figures A1, B1, B2, B3, B4 are mentioned to improve readability of figure 3)

CASE STUDY

DESCRIPTION

This case study focuses on the construction of a 58m tower in Luxembourg by the company CLE (General Contractor). The overall project budget of €35M was planned for a 14-floor, 138-apartment building block with a total surface area of 22,000 m^2. Several constraints were identified: (1) location - a recently built dense urban area, (2) site access - very limited, (3) storage capacity on site - very low, (4) schedule - tight and (5) each apartment being finished according to individual buyer choices. Due to high prices per square meter and high demand, this context is representative of current country's market. Constraints (1-4) are considered usual suspects within the context of TPL approaches (Eleskar 2020) that drove the General Contractor to investigate SCM. Constraints (1-3) led the GC to consider testing a self-operated warehouse. Kitting was proposed as solution to constraint (4). Constraint (5) was considered as the most challenging since site managers believed kitting to manage only standardized material demands. Consequently, being able to develop the right tools and demonstrate the applicability of kitting in this context were supposed to facilitate replication to more repetitive and less variable contexts. A preliminary study eliminated the self-operated option and a CCC was organized with a TPL operator accordingly. It enabled materials to be stored, repacked and dispatched in each apartment according to site needs. Specific types were chosen for experimentation: HVAC, bathtubs/showers, tile/parquets flooring, sanitary equipment and joineries (based on subcontractor's willingness to experiment new logistics). A web-based platform was specifically set up in order to define and track material kits for each planning task. Last Planner System (already implemented at earlier stages of the project) was used to collaboratively manage deliveries. Deliveries and data collection started in November 2019 and finished in July 2020.

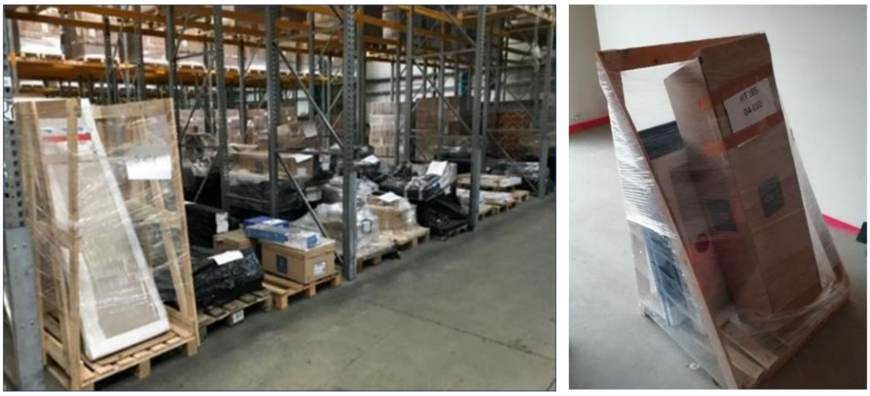

Figure 1 Example of kits at the CCC and after dispatch at the workspace

RESULTS

Productivity and planning reliability

According to Table 1, for each task using kitting and CCC, the actual task durations were measured and compared to initial planning duration estimated by the subcontractor before application of the new logistic system. The results are presented in Figure 2. Some task durations have been impacted by an identified external factor and thus excluded from the study (hashed boxes on the figure). The tiles tasks particularly were impacted by a repeated lack of labour as acknowledged by stakeholders on site. Apart from these cases, a total of 74 days was saved representing a 15% of total duration of the considered tasks.

Floor	Ventilation			Bath/shower			Tiles			Sanitary equipment			Interior Doors		
	Planning	Reality	saved days	Planning	Reality	saved days	Planning	Reality	saved days	Planning	Reality	saved days	Planning	Reality	saved days
2nd Floor	10	12	-2	15	3	12	15			9	10	-1	5	5	0
3rd Floor	10	6	4	10	6	4	15			9	7	2	5	5	0
4th Floor	10	5	5	10	6	4	17			9	5	4	5	Workforce	
5th Floor	10	6	4	10	6	4	17			8	7	1	5	3	2
6th Floor	10	9	1	10	9	1	15	Insufficient Workforce		8	9	-1	5	no data (Covid)	
7th Floor	10	9	1	10	8	2	15			8	9	-1	5	2	3
8th Floor	10	Workforce		10	5	5	14			8	7	1	5	5	0
9th Floor	10	7	3	10	Delay due to other Task (Tiles)		15			8	8	0	5	2	3
10th Floor	9	8	1	9			15			8	5	3	5	2	3
11th Floor	9	6	3	10			15			8	no data (Covid)		5	2	3
12th Floor	10	plans delayed		10			9			8			5	plans delayed	
13 Floor (duplex)	No Initial planning duration available														
Total saved days			20			32			0			8			14

Figure 2 Gaps between planned and actual durations for tasks using kitting

Although the above results are coherent with similar cases within literature (Mossman 2008; Elving 2010; Tetik 2020), the difference may also be a result of an overestimation (consciously or not) of task durations and other positive factors may also have contributed.

To account for this, only tasks that 1° were on the critical path according to weekly planning and 2° were confirmed by site crews to have been impacted by kitting were kept for the calculation of overall saved days costs (B3). Moreover, the quantitative analysis was also complemented with surveys to both general contractor's team members and subcontractors (workers and supervisors). 6 out of 7 site managers expressed a light or very significant improvement in planning reliability and transparency. Similarly, 91% of workers and supervisors declared that a considerable time saving had been reached by using a CCC. The reliability of the delivery process was also directly monitored by collecting the remarks of rejected deliveries on the web-platform. In the case of the CCC, 98.5% of deliveries were performed on site as planned and at the desired time. The remaining 1.5% were mainly due to upstream errors detected and reported soon enough by the operator to mitigate their impact on-site.

Total cumulated costs

Demonstrating the economic impact of the implementation of the CCC is a complex task. While the invoiced costs related to CCC are known explicitly, they replace traditional costs that are usually confidential and difficult to measure by nature because of the specificity of each construction project. The results announced below are therefore hypothetical. The overall costs measured and calculated are presented in Figure 3 according to the model of costs presented Table 2. An unexpected cost is mentioned in the "with CCC" section and describes the impact of the costs related to the Covid-19 crisis, which overlapped with the case study time span. This is since some storage costs continued to be billed during the shutdown of production due to the lockdown in April 2020. These costs have been integrated in the final model for actual costs. However, the impact of the pandemic on estimated cost with a traditional logistic scheme could not be modelled. Overall, the estimates show a 9.5% increase in direct logistic costs (and 15% if Covid costs are considered). This is coherent with the state of the art as TPL (Eleskar 2020) or kitting (Tetik 2020) adds additional billed services such as warehouse costs or preparation costs. Direct costs, although "visible one", account for a minority share of the overall costs according to the estimations. The total calculated impact of logistics accounted for ~13.3% of the turnover of the lots considered. Thanks to kitting and TPL, this figure was decreased by up to 39%, down to 8.1%. This would mean a potential 2.4%

(without considering planning indirect impacts on planning B3) to 5.2% (with B3) margin increase for the specific lots/types of objects with kitting.

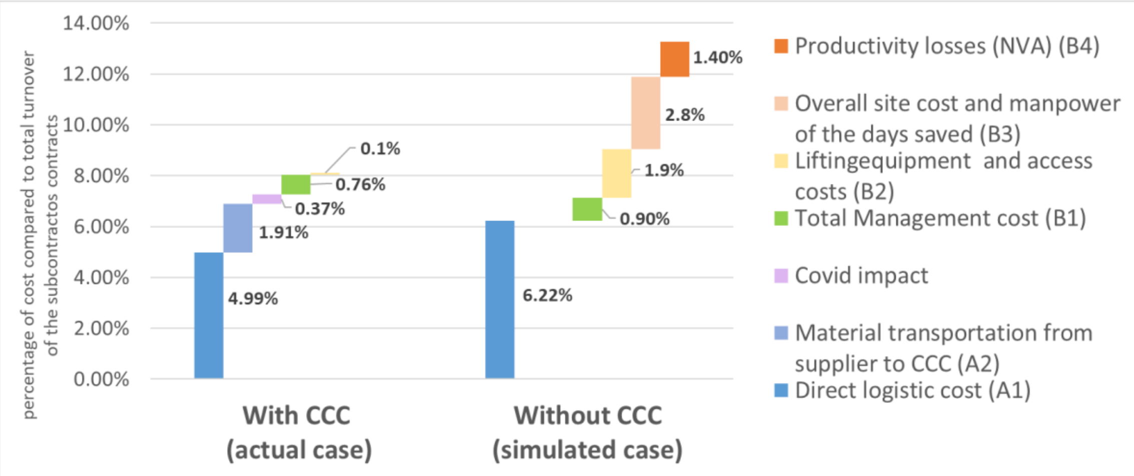

Figure 3 Overall costs breakdown in percentage of the total turnover of the lots studied

The TPL approach has also caused a shift in the distribution of costs between project stakeholders. If the GC paid the totality of the TPL agreement, the total costs related to logistics for the GC would increase from 1.9% with the traditional model to 6.1% of the considered tasks turnover, whereas the corresponding cost for subcontractors would decrease from 11.4% to 1.9%.

Transport, congestion and carbon footprint

With 138 apartments on 12 floors, it was estimated that 144 deliveries (for 744 pallets) would have been performed without CCC. This estimation has been established considering the constraints observed such as storage area, delivery rate, availability of the lift, available workforce and usual transportation mean used by subcontractors or by their supplier on a weekly basis.

The data management platform set up for the project offered the possibility to collect the totality of delivery vehicles' contents and track the resulting filling rates. As a result, 49 deliveries were made to the construction site and 96 deliveries were made from the supplier to the CCC. This means an overall reduction in transport arriving on site by 66%.

Filling rates measured exceed 80% on average, except during the month of April which was strongly impacted by disturbances due to the Covid-19 sanitary crisis and certain special contexts (notably during holiday periods).

Knowing locations of the CCC and suppliers/subcontractors' facilities and each usual transportation means, it was possible to calculate the carbon footprint of deliveries with the consolidated logistics method, for both scenarios according to EN 16258 (2012). These estimates show an overall 46% reduction in carbon emissions for transports compared to traditional logistics (see Figure 4).

Task	With CCC	Without CCC	Impact
Ventilation	10.12	10.4	-2.69%
Bath/Shower	0.61	0.8	-23.75 %
Sanitary equipment	0.64	0.6	+6.7%
Tiles	3.79	1.9	+99.5%
Doors	10.91	34.2	-0.68
Total (in T of CO2)	**26**	**48**	**- 46 %**

Figure 4 – Total CO2 emissions in tons for transports

DISCUSSION

Impact on project management and Lean construction maturity

Beyond a flat reduction of management costs (B1), the measures reveal a change in the site's management practices. Contingency management, reception of delivery vehicles and inventory tasks were normalised over the week and mostly replaced by anticipation tasks. This was considered as a driver for better collaboration on site, while also offering a clear framework for recently hired managers to get more responsibilities and skills. This improvement in collaboration was also confirmed by qualitative feedbacks from subcontractors about the use of Last Planner System (LPS). Although kitting and TPL could have been managed without the LPS, the collaborative framework of LPS facilitated the gathering of the actual material needs and constraints. On the other hand, having a reliable and constantly updated view of material status enabled to start weekly meeting with a trusted workable backlog. These findings are further arguments in favour of the development of a holistic Lean Construction approach.

TPL viability and gain sharing

In order to validate the TPL choice, a GC self-operated warehouse scenario was modelled under the same hypothesis. It concluded that direct logistic costs (A1) would have been double compared to actual case with TPL. In comparison with TPL, self-operated centralised logistic requires existing facilities and a higher volume of activities in order to be relevant and applicable in the considered context.

With TPL, a potential 5% overall margin gain was estimated, but this gain must be shared between stakeholders to ensure its applicability. Indeed, the TPL model as implemented in this study was driven and financed by the General Contractor, but it appears to mostly benefit the subcontractors. In the context of this project, a total 3.6% price cut was negotiated between stakeholders, which covered 72% of the costs of TPL.

According the results of this case study, a contribution of approximately 5% from the turnover would cover all the direct costs endorsed by the General Contractor while maintaining a 4.4% margin increase for the subcontractors.

Covid-19 and co-activity reduction

Covid-19 negatively impacted the costs results of the case study because of unexpected storage costs. However, qualitative feedbacks also indicate some potential advantages of kitting and CCC to deal with similar unexpected situations. This is acknowledged by planning reliability measures indicating that with the workflow being streamlined, kitting reduced co-activity. Additionally, the CCC worked as a buffer for materials during the lockdown. This may be one of the reasons why the site had nearly fully recovered its normal productivity rates in May (which according to the GC was not the case in most of its other projects) suggesting that CCC could improve the sector's resilience.

LIMITATIONS AND FUTURE RESEARCH

This research was limited to one pilot case study in order to test feasibility in a new context and to perform an in-depth analysis of costs and impacts on site of the new logistics model. Productivity and planning gains were particularly hard to assess as other factors may have contributed to improved performance. More studies are needed to confirm the model of cost proposed and to validate the authors' findings. Two key points of interest are highlighted by this study.

CCC AND KITTING SUSTAINABILITY ASSESSMENT

The findings of this study indicate that CCC and kitting can be used as an efficient strategy in order to reduce embodied carbon. However, Figure 5 shows discrepancies on the carbon emissions reduction achieved in the study. For example, the model was not relevant for some suppliers that were located closer to the site. This shows that under certain circumstances the model might not be optimal. Defining these conditions and being able to integrate them into projected simulations would enable better sustainability and better estimations of the impacts. In addition, kitting enabled better productivity on site through better resource efficiency (mainly of workers and lifting capacity) that might also have a positive environmental impact, but these impacts still must be assessed.

DIGITAL TWIN FOR INTEGRATED SUPPLY CHAIN MANAGEMENT

The new logistics organisation implied a transfer of responsibility and hence an extended knowledge of the products to be delivered as well as full traceability of the materials condition. To achieve this, an online platform had been set up that enabled to define custom kits for each task and manage event or relevant status. This information system appeared to be a key factor to a successful implementation. However, most information had to be entered manually and was in a format that could not allow further use of the data. Therefore, data should be structured, interoperable and dynamic in a way that it allows collaboration and transfer along the supply chain and support decision-making. As a solution, the emerging research on Digital Twin (Boje et al. 2020) and application of Products Data Templates (ISO 23386 and EN ISO 23387) appear as key research topics.

CONCLUSION

This paper investigated the potential for innovative Supply Chain Management based on Lean Management techniques to be an economically relevant paradigm that can help reduce the carbon footprint of the sector. The pilot project in Luxembourg successfully implemented Just-In-Time logistics using kitting and a Construction Consolidation Centre managed by a Third-Party Logistics operator. Despite the fact that the empirical results were limited in scope, they confirm both the economic and environmental improvements due to these methods by enabling at the same time up to 39% reduction of logistics related costs - that would mean a 5% potential margin increase for the considered tasks, and a 46% reduction of carbon emissions. These findings are preliminary as this project was the first of its kind in the country and some other factors may have interfered and should be further investigated (especially regarding the impact on planning). Additional improvements through new services such as reverse logistics and multi-site deliveries should also be considered and tested. The study emphasizes three potential barriers that need to be addressed. Firstly, the model of costs developed through the project estimated that logistics and material handling would have accounted for at least 13% of the turnovers of the lots if managed in a traditional way. More data on the implications of these costs are necessary to raise sector’s awareness and interest in newer methods. Secondly, the environmental impacts must be further studied to ensure case-by-case improvements. Lastly, the kitting required detailed information about planning and actual material status and constraints that should be addressed through collaborative practices on site and digitally supported integration of the supply chain.

REFERENCES

Arbulu, R., and Ballard, G. (2004). "Lean Supply Systems in Construction"*12th Annual Conference of the International Group for Lean Construction.* Helsingør, Denmark, pp 1-13.

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y. (2020). "Towards a semantic Construction Digital Twin: Directions for future research" *Automation in Construction*, 114, 103179.

Dablanc, L., (2009). "Freight transport for development toolkit: urban freight" (No. 57971). The World Bank, 1818 H Street NW, Washington, DC 20433.

Dadhich, P., Genovese, A., Kumar, N., and Acquaye, A. (2015). "Developing sustainable supply chains in the UK construction industry: A case study", *International Journal of Production Economics* Vol. 164, pp. 271-284.

Dakhli, Z., and Lafhaj, Z. (2018). "Considering Materials Management in Construction: An Exploratory Study." *Logistics*. 2(1):7. doi.org/10.3390/logistics2010007.

Ekeskär, A., and Rudberg, M. (2020). "Third-party logistics in construction: perspectives from suppliers and transport service providers." Production Planning & Control, 0(0), 1–16. doi.org/10.1080/09537287.2020.1837932.

Elfving, J. A. , Ballard, G. and Talvitie, U. (2010). "Standardizing Logistics at the Corporate Level Towards Lean Logistics in Construction" *18th Annual Conf. of the International Group for Lean Construction*. Haifa, Israel, 14-16 Jul 2010. pp 222-231.

Hamzeh, F. R. , Tommelein, I. D. , Ballard, G. and Kaminsky, P. M. (2007). "Logistics Centers to Support Project-Based Production in the Construction Industry" *15th Annual Conference of the International Group for Lean Construction.* East Lansing, Michigan, USA, 18-20 Jul 2007. pp 181-191.

Josephson, P. & Saukkoriipi, L. (2003). "Non Value-Adding Activities in Building Projects: A Preliminary Categorization" *11th Annual Conference of the International Group for Lean Construction.* Virginia, USA.

Janné, M., and Rudberg, M. (2020). "Effects of employing third-party logistics arrangements in construction projects." Production Planning & Control, 0(0), 1–13. doi.org/10.1080/09537287.2020.1821925.

Mossman, A. (2008) "More than materials: managing what's needed to create value in construction." *2nd European Conference on Construction Logistics – ECCL*, Dortmund, May 08.

Samuelsson, S., and Ahmetasevic, M. (2014). "Management of construction logistics in Stockholm: Identifying ways of improvement for construction logistics within the inner city of Stockholm" (Dissertation). Retrieved from http://uu.diva-portal.org/smash/record.jsf?pid=diva2%3A733476&dswid=-4129.

Tetik, M., Peltokorpi, A., Seppänen, O., Leväniemi, M., and Holmström, J. (2021). "Kitting Logistics Solution for Improving On-Site Work Performance in Construction Projects." Journal of Construction Engineering and Management, 147(1), 05020020.

Vrijhoef R. and Koskela L. (2000). "The four roles of supply chain management in construction", *European Journal of Purchasing & Supply Management*, Vol 6, pp. 169-178.

Van Dijkhuizen, M.J., Vrijhoef, R., and Bakker, H.L.M. (2021). "A conceptual model to determine the impact of off-site construction on labour productivity." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 945–954, doi.org/10.24928/2021/0121, online at iglc.net.

A CONCEPTUAL MODEL TO DETERMINE THE IMPACT OF OFF-SITE CONSTRUCTION ON LABOUR PRODUCTIVITY

Martin J. van Dijkhuizen[1], Ruben Vrijhoef[2], and Hans L.M. Bakker[3]

ABSTRACT

Despite the efforts of governments and firms, the construction industry is trailing other industries in labour productivity. Construction companies are interested in increasing their labour productivity, particularly when demand grows and construction firms cope with labour shortages. Off-site construction has proved to be a favourable policy to increase labour productivity. However, a complete understanding of the factors affecting construction labour productivity is lacking, and it is unclear which factors are influenced by off-site construction. This study developed a conceptual model describing how 15 factors influence the construction process and make a difference in labour productivity between off-site and on-site construction. The conceptual model shows that all 15 factors affect labour productivity in three ways: through direct effects, indirect effects and causal loops. The model is a starting point for further research to determine the impact of off-site construction on labour productivity.

KEYWORDS

Labour productivity, construction process, off-site construction, modelling.

INTRODUCTION

Productivity is an important indicator of the efficiency of an industry, company, or project. Productivity represents the relationship between the created output (e.g., number of products) and the input needed (e.g., capital, materials, labour). Companies with high productivity have advantages because they can deliver more output using as much input as their competitors do.

Productivity can be expressed in several ways, depending on which inputs are considered, such as capital, labour, energy, plant and equipment, materials, services, and overhead. Labour productivity indicates how much output is generated per work hour; it will increase by producing more with the same number of hours worked. Traditionally, production in construction is primarily dependent on human effort and performance. Jarkas and Bitar (2012) concluded that labour costs comprise 30% to 50% of the overall

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project costs. Therefore, Construction Labour Productivity (CLP) has a significant effect on project expenses and can influence the profitability of construction firms. However, despite the efforts of governments and firms, the construction industry is trailing other industries in labour productivity (Abdel-Wahab & Vogl 2011, Stehrer et al. 2019). Construction companies are interested in how they can increase their CLP, particularly at a time when demand grows and construction firms cope with labour shortages (Bertram et al. 2019).

Vrijhoef and Van Dijkhuizen (2020) have introduced an action research approach for improving professional practice. In this approach, companies that aim for a higher CLP identify the factors that influence CLP. After that, they design an intervention for improvement. Companies can identify factors by considering the construction process as a flow that converts inputs into outputs with a minimum of waste, as shown in Drewin's (1982) conceptual model for labour productivity (Figure 1). Internal factors and external factors will influence this process. All factors affecting the conversion will influence its efficiency (i.e., CLP). An intervention can be designed based on proven policies that increase CLP, for instance, off-site construction. Vrijhoef (2016) has shown that prefabricated roofs in housing renovation projects can improve CLP. Accordingly, Eastman and Sacks (Eastman and Sacks 2008) hint at the advantages of off-site construction. They have demonstrated that CLP in off-site sectors, such as curtain wall construction, structural steel construction, and precast concrete fabrication, is about 43% higher than in on-site construction sectors.

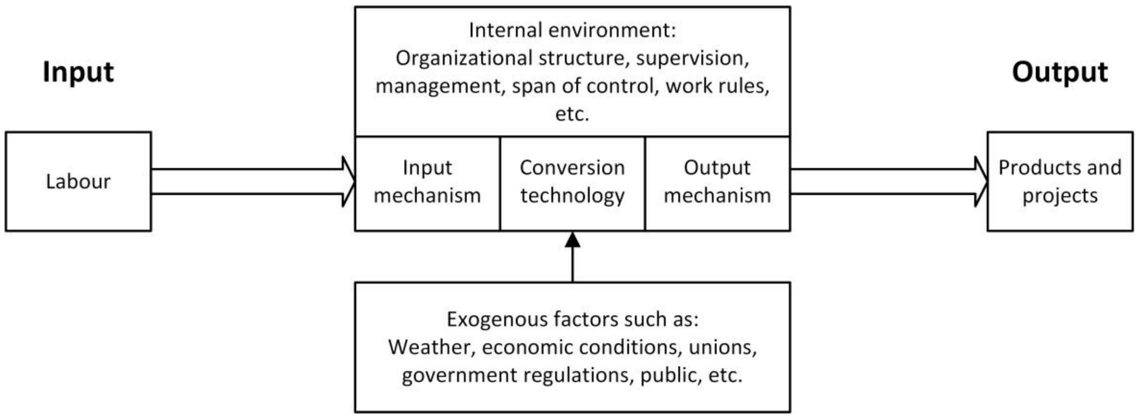

Figure 1: Conceptual model for Construction Productivity (Drewin 1982)

This paper is part of research that compares the impact on CLP of off-site and on-site construction for building projects. The study endeavours to contribute by filling two gaps found in the literature. First, it completes Drewin's model. Thomas and Sakarcan (1994) have studied the model and have noted that it does not include all potential variables that may exist. For instance, Chan et al. (2001) have concluded that literature made little mention of how the differences in the workers' abilities account for differences in productivity levels. A complete conceptual model for construction productivity can strengthen practitioners' insight into factors that can improve CLP. Completing the conceptual model is the first goal of this study.

Second, the mechanisms are unknown how off-site construction policies influence construction labour productivity. Off-site construction has many deemed advantages, such as reduced rework and less site congestion (Durdyev and Ismail 2019). However, it is unknown how these advantages influence CLP. Therefore, the second goal of this study is to develop a conceptual model to determine the impact of off-site construction on labour productivity.

METHOD

Literature yields two types of studies considering factors affecting CLP. First, studies that determine the influence of one or a few factors on CLP, for example, identifying the relationship between non-value-adding activities and productivity (Zhao and Chua 2003). Second, studies that list factors affecting CLP after surveying construction practitioners. A literature search on the second type resulted in 13 relevant studies (Table 1).

Table 1: Result of literature search

	Study	Focus	Context	Number of factors
1	Alinaitwe et al. (2007)	Project managers	Building projects	36
2	Chigara and Moyo (2014)	Consultants, contractors	Building projects	40
3	Dixit et al. (2017)	Labour, management	Construction industry	24
4	El-Gohary and Aziz (2014)	Client, consultants, contractors	Construction industry	30
5	Enshassi et al. (2007)	Contractors	Building projects	45
6	Fagbenle et al. (2011)	Labour, contractors	Construction industry	12
7	Hwang et al. (2017)	Developers, contractors, consultants	Green building projects	26
8	Jarkas and Bitar (2012)	Contractors	Building and civil engineering projects	45
9	Kaming et al. (1997)	Labour	Building projects	11
10	Kazaz and Ulubeyli (2007)	Managers, technical staff	Construction industry	18
11	Rivas et al. (2011)	Labour, midlevel management	Mining projects	15
12	Robles et al. (2014)	Companies related to construction	Construction industry	35
13	Zakeri et al. (1996)	Labour	Construction industry	13

The authors searched in five prominent journals concerning construction and project management: Construction Management and Economics, International Journal of Project Management, Journal of Construction Engineering and Management, Journal of Civil Engineering and Management, and Journal of Management in Engineering. The search string consisted of four main concepts (i.e., labour, productivity, construction, and factor) and their alternative spellings, synonyms, and alternatives within the timeframe 2009 – 2020. The authors selected the studies that list factors influencing CLP and give insight into relations between factors and CLP, enabling to draw the cause and effect relations.

For instance, Fagbenle et al. (2011) have concluded that participation in decision-making (cause) will affect motivation, and this will affect CLP (effect). The initial search includes the results of a limited number of journals and a limited time frame. However, the found articles refer to other relevant articles that were not in the initial search results. Therefore, those articles were added to the results. The authors used qualitative data analysis software to report factors influencing CLP and causal relations between them. Based on these articles, the model of Drewin (1982) was elaborated. After that, the authors searched in literature for advantages and disadvantages of off-site construction comparing to on-site construction. This search was combined with the model to create a new conceptual model that describes the impact of off-site construction on CLP.

RESULTS

FACTORS AFFECTING LABOUR PRODUCTIVITY

Based on the literature, the authors developed the model shown in Figure 2, in which four primary groups of factors can be distinguished. Those groups influence the efficiency of the construction process, and therefore CLP. Within each primary group and the construction process, the study identified several factors and sub-factors. Analyses of the relations between all factors and sub-factors resulted in a complicated cause and effect diagram with more than 90 variables (factors and sub-factors) and more than 100 causal links. Figure 2 summarises the causal links between the primary groups. For instance, the arrow heading from the group of external factors to the group of labour factors means that external factors and sub-factors will influence labour factors and sub-factors.

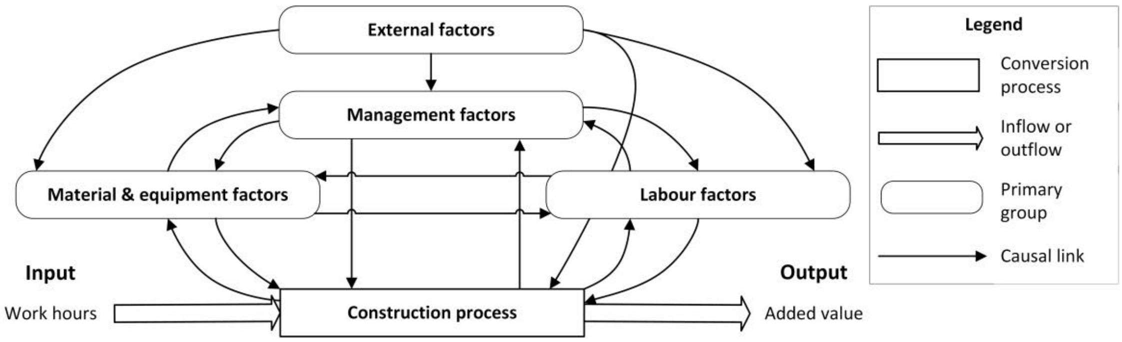

Figure 2: Conceptual model for factors influencing CLP

Table 2 shows the factors and sub-factors within the four primary groups and the construction process. The first group consists of factors that are not likely to be influenced by construction practitioners; however, this can be argued. For instance, government regulations are defined as an external factor. However, construction firms might influence this factor through a lobby.

Table 2: Factors and sub-factors affecting labour productivity

Factor	Sub-factors	Mentioned in studies[a]
	Primary group: External factors	
Client	On-time payment, quality demand, trust	1,4,5,11
Site characteristics	Limited working space, restricted access	8,10,12
Surroundings	Government regulations, weather, insecurity, power & water supply	1,3,4,5,6,7, 11,12,13
	Primary group: Management factors	
Ability of management	Communication, competence, motivation, presence	1,2,3,4,5,6,7, 8,9,11,12,13
Crew management	Incentives, work time policy, crew composition, treatment	1,2,3,4,5,6,7,8, 9,10,11,12,13
Design & engineering management	Change orders, quality of design & engineering, time needed for design & engineering	1,2,3,4,5,6,7, 8,9,11,12,13
Financial management	Financing possibilities, liquidity	1,2,3,4,5,7
Health & safety management	Safety measures, working climate	2,3,4,5,9,10, 11,12,13
Construction coordination	Research & development, facilitation, schedule change, contract type, timely interventions	1,2,3,4,5,6,7, 8,9,11,12,13
Supply chain management and logistics	Quality of transportation, storage, distribution	2,3,4,5,6,8, 9,11,12,13
Tool & equipment management	Maintenance policy, substitution policy	1,2,11,13
	Primary group: Labour factors	
Behaviour	Absenteeism, effort, turnover	1,2,3,4,5,6,7,8, 9,10,11,12,13
Characteristics & traits	Age, crew availability, crew size, fatigue, health, intelligence, values, personal circumstances, learning speed, confidence, integrity, loyalty	1,2,3,4,5,6,7,8, 9,10,11,12,13
Motivation	Satisfaction, distraction, sense of pride	2,5,7,8, 10,11,12
Skills	Flexibility, preparedness, communication, reaction time, resourcefulness, efficiency, experience, literacy, management skills	1,2,3,4,5,6,7, 8,9,11,12,13
	Primary group: Material & equipment factors	
Materials	Availability, congestion, quality of materials, sabotage, capacity of manufacturing industry	1,2,3,4,5,7,8, 9,11,12,13
Tools & equipment	Availability, quality of tools & equipment, site lay-out	1,2,3,4,5,6, 7,11,12,13
Construction process	Method, overcrowding, quality of work, quantity of work, rework, schedule pressure, waiting time	1,2,3,4,5,7,8, 9,11,12,13

[a] Following the numbering in Table 1

The second group contains management factors. Managers influence the construction process directly or indirectly through labour factors or material and equipment factors. They provide their subordinates with guidelines for making decisions, also called policies. The authors distinguish policies in seven different fields, but first of all, the chosen policy will only be effective with the presence and adequate ability of the managers. For instance, poor instructions cause low quality of work, and this can cause rework (Zakeri et al. 1996). All 13 studies refer to the manager's competence, education level, motivation, and communication skills as essential sub-factors.

To influence labour, managers can choose several policies. They influence labour motivation by financial incentives such as remuneration (Kazaz and Ulubeyli 2007) or non-financial incentives such as offering promotion opportunities, job security, and recognition (Rivas et al. 2011). Managers can influence the material and equipment factors by choosing the right supply chain management policy. Just-in-time delivery will prevent material buffers (Horman and Thomas 2005), but it can cause waiting time when not properly executed (Alinaitwe et al. 2007). Material buffers will prevent waiting time, but they can cause more time to spend on logistics (Dixit et al. 2017).

The third group includes labour-related factors such as motivation and absenteeism. Workers influence the conversion of input into output, but they also affect management and material and equipment factors. For instance, labour commitment determines the effectiveness of a management policy and the quality of equipment maintenance. The motivation of labourers is of significant influence because motivated labourers usually are enthusiastic, take the initiative, work hard and respond fast to instructions, making them more productive than demotivated or discouraged labourers (Jarkas and Bitar 2012). Some studies rate absenteeism as a top factor (Dixit et al. 2017, Kaming et al. 1997), while Chigara and Moyo (2014) see little influence. This difference can be explained by realising that managers will neglect absent workers as input if the absent workers do not get paid. In this case, absenteeism will not (directly) influence the output-input ratio.

The fourth group embodies factors concerning materials and equipment, such as their availability and quality. They influence the construction process directly or indirectly by affecting the effectiveness and efficiency of labour and management. Material, tools and equipment shortages cause workers' idle time (Alinaitwe et al. 2007). Causes of material shortages include on-site transportation difficulty, poor supply chain management (Kaming et al. 1997), incorporating not locally manufactured materials in design, and insufficient manufacturing industry capacity (Chigara and Moyo 2014). Causes of tools and equipment shortages include tools and equipment breakdown and expensive tool and equipment prices (Chigara and Moyo 2014).

Finally, the study distinguished several factors within the construction process. Quality of work (Dixit et al. 2017) and continuous changes and improvements of construction method (Fagbenle et al. 2011) will increase CLP, while overcrowding, rework (El-Gohary and Aziz 2014, Enshassi et al. 2007, Robles et al. 2014), and schedule pressure or work overload (Dixit et al. 2017) have a negative effect.

OFF-SITE CONSTRUCTION'S IMPACT ON CLP

Several studies describe the advantages and disadvantages of off-site construction. Within the advantages and disadvantages, the authors selected elements that match factors and sub-factors of Table 2. Those (sub-)factors might be responsible for the difference in CLP between off-site and on-site construction. Figure 3 represents an overview of the factors and sub-factors found.

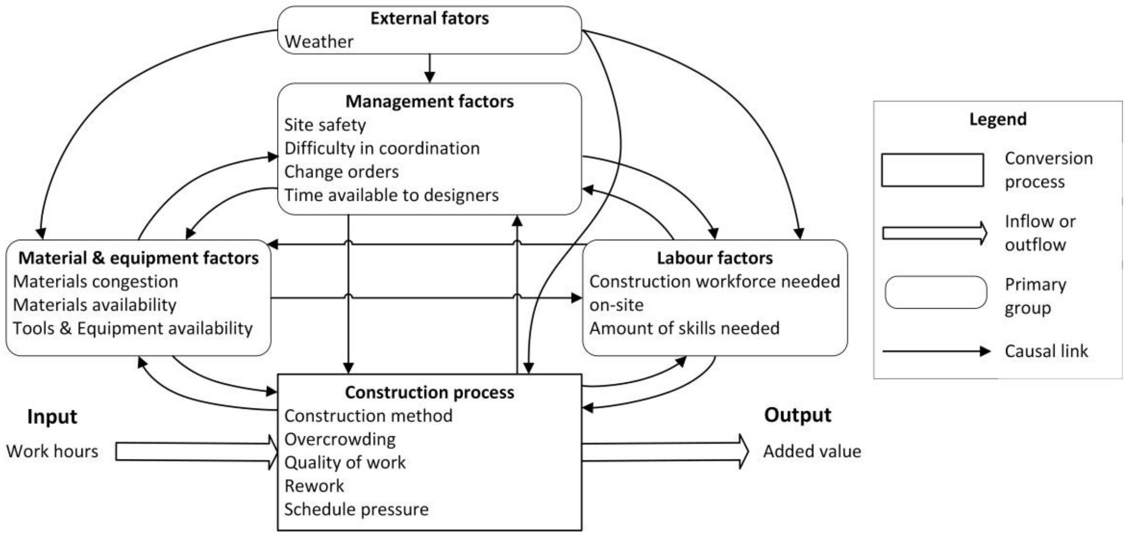

Figure 3: Conceptual model for determining the impact of off-site construction on labour productivity

Off-site construction in a factory hall is independent of weather (Antillón et al. 2014, Gibb and Isack 2003). This can affect the construction process directly because the loss of quality and time due to harsh weather can be avoided. It can also indirectly influence the construction process because weather conditions can damage building materials (Chauhan et al. 2019), decreasing material availability. Due to less time spent on site, the risk of weather-related accidents is also lower (Durdyev and Ismail 2019). Less time spent on site will limit absenteeism due to mishaps.

Within the group of management factors, two advantages occur with off-site construction. First, management can experience a decrease in coordination between sub-contractors and different trades (Antillón et al. 2014), allowing them to put more time into crew coordination. Second, factory-controlled fabrication improves construction safety performance on site (Durdyev and Ismail 2019). Antillón et al. (2014) and Chauhan et al. (2019) expect a higher safety of off-site construction due to reduced dangerous working conditions and less traffic. Off-site construction also has some disadvantages affecting CLP negatively. Off-site construction requires a more detailed design and more time for designers (Chauhan et al. 2019). In case of a tight schedule, this might influence the quality of design, drawings and specifications, influencing the quality of work. Off-site construction is also less flexible than on-site construction. Late customer changes are not possible (Chauhan et al. 2019). In the case of regular change orders, off-site construction is at a disadvantage compared to on-site production. In the worst case, production will have to stop, causing waiting time. Nevertheless, also without change orders, off-site production is less flexible. Off-site construction products such as precast concrete have to be ordered ahead of time. However, the construction process is very volatile, disallowing contractors to predict the quantities in advance accurately. The contractor might not install all requested precast elements, thus building up unneeded inventory on-site (Ballard et al. 2003).

The study found two advantages of off-site construction concerning labour factors. Durdyev and Ismail (2019) mention that less construction workforce is involved on-site, influencing CLP on-site. However, the off-site fabrication process needs more labour input. Therefore, no conclusion can be made if off-site construction needs more or less workforce and if this difference will cause less CLP. Also, the amount of skills needed for off-site construction is assumed to be less than constructing on-site (Durdyev and Ismail 2019). The number of skills can positively affect CLP because the production process will be less dependent on specialists. On the other hand, it can negatively affect CLP because workers' motivation might decrease when workers are not challenged.

A controlled factory environment can lower the risk of material congestion (Gibb and Isack 2003). Material congestion will compel labour to search for materials or move others to reach the materials needed. Off-site construction requires fewer materials, tools and equipment on-site (Durdyev and Ismail 2019), which may affect the availability.

The study distinguished five sub-factors within the construction process that will influence CLP in off-site construction. The construction methods accompanying off-site construction provide controlled work heights, tool weights, and environmental conditions (Chauhan et al. 2019). Fewer workers are needed on-site, which will prevent overcrowding (Durdyev and Ismail 2019). The quality of the work done is generally higher (Gibb and Isack 2003). High quality of work will decrease rework (Gibb and Isack 2003). Finally, off-site construction gives the opportunity to pre-plan the work, lowering the schedule pressure (Durdyev and Ismail 2019).

CONCLUSION

This paper focused on the factors affecting construction labour productivity and which are influenced by off-site construction. This study analysed 13 articles that list factors affecting construction labour productivity after surveying construction practitioners. The analysis resulted in a complicated cause and effect diagram. The study summarised the diagram into a conceptual model representing the relations between the construction process and four primary groups: external factors, management factors, labour factors, and material and equipment factors. Next, a literature search yielded the advantages and disadvantages of off-site construction. Fifteen of the advantages and disadvantages of off-site construction can affect labour productivity.

The conceptual model shows that all 15 factors affect labour productivity in three ways: through direct effects, indirect effects and causal loops. The factors affect labour productivity directly by influencing the efficiency of the construction process. On the other hand, the factors affect labour productivity indirectly through other factors. For instance, off-site construction in a factory hall protects materials from weather influences, keeping them intact and available. This prevents workers from waiting for materials, enabling them to continue the construction process. The model also shows that the factors and links can invoke causal loops. This can cause a reinforcing or balancing effect on productivity. For example, the limited skills needed for off-site construction can make the work less challenging. Unchallenging work can decrease workers' motivation which results in a lower quality of work. Low quality of work can demotivate the workers even more. Further research concerning off-site construction's impact on labour productivity will focus on the 15 factors. However, the indirect effects and causal loops compel researchers to consider the intermediate factors, such as labour motivation.

This model helps to understand the relations between factors in the primary groups, construction process, and labour productivity. Further research is needed to handle the study's limitations. First, this study is based on surveys concerning different project types in different countries. In future studies, construction practitioners can confirm, reject or add factors to ensure validity for specific projects under specific circumstances. Second, the conceptual model can be elaborated to give insight into the relations between factors within the primary groups and the construction process. Third, the qualitative model can be refined into a quantitative model. And fourth, the model can be tested with empirical data. For now, the conceptual model is a start to study the impact of off-site construction on construction labour productivity.

REFERENCES

Abdel-Wahab, M., and Vogl, B. (2011). ‘Trends of productivity growth in the construction industry across Europe, US and Japan’. *Construction Management and Economics*, 29(6), 635–644.

Alinaitwe, H. M., Mwakali, J. A., and Hansson, B. (2007). ‘Factors affecting the productivity of building craftsmen - studies of Uganda’. *Journal of Civil Engineering and Management*, 13(3).

Antillón, E. I., Morris, M. R., and Gregor, W. (2014). ‘A value-based cost-benefit analysis of prefabrication processes in the healthcare sector: A case study’. *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*, 995–1006.

Ballard, G., Harper, N., and Zabelle, T. (2003). ‘Learning to see work flow: An application of lean concepts to precast concrete fabrication’. *Engineering, Construction and Architectural Management*, 10(1), 6–14.

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., and Woetzel, J. (2019). *Modulair Construction: From projects to products*. McKinsey & Company.

Chan, P., Puybaraud, M. C., and Kaka, A. (2001). ‘Construction training: A linkage to productivity improvements’. *17th Annual ARCOM Conference, 5-7 September 2001*, A. Akintoye, ed., University of Salford. Association of Researchers in Construction Management, Salford, 143–55.

Chauhan, K., Peltokorpi, A., Lavikka, R., and Seppänen, O. (2019). ‘Deciding Between Prefabrication and On-Site Construction: A Choosing-by-Advantage Approach’. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, 749–758.

Chigara, B., and Moyo, T. (2014). ‘Factors Affecting Labor Productivity on Building Projects in Zimbabwe’. *International Journal of Architecture, Engineering and Construction*, 3(1).

Dixit, S., Mandal, S., Pandey, A., and Bansal, S. (2017). ‘A study of enabling factors affecting construction productivity: Indian scnerio.’ *International Journal of Civil Engineering and Technology*, 8(6), 741–758.

Drewin, F. J. (1982). *Construction productivity : measurement and improvement through work study*. Elsevier, New York.

Durdyev, S., and Ismail, S. (2019). ‘Offsite Manufacturing in the Construction Industry for Productivity Improvement’. *Engineering Management Journal*, 31(1), 35–46.

Eastman, C. M., and Sacks, R. (2008). ‘Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities’. *Journal of Construction Engineering and Management*, 134(7), 517–526.

El-Gohary, K. M., and Aziz, R. F. (2014). ‘Factors Influencing Construction Labor Productivity in Egypt’. *Journal of Management in Engineering*.

Enshassi, A., Mohamed, S., Mustafa, Z. A., and Mayer, P. E. (2007). ‘Factors affecting labour productivity in building projects in the Gaza strip’. *Journal of Civil Engineering and Management*.

Fagbenle, O. I., Ogunde, A. O., and Owolabi, J. D. (2011). 'Factor Affecting the Performance of Labour in Nigerian Construction Sites'. *Mediterranean journal of social sciences*, 2(2).

Gibb, A., and Isack, F. (2003). 'Re-engineering through pre-assembly: client expectations and drivers'. *Building Research & Information*, 31(2), 146–160.

Horman, M. J., and Thomas, H. R. (2005). 'Role of Inventory Buffers in Construction Labor Performance'. *Journal of Construction Engineering and Management*, 131(7), 834–843.

Hwang, B.-G., Zhu, L., and Ming, J. T. T. (2017). 'Factors Affecting Productivity in Green Building Construction Projects: The Case of Singapore'. *Journal of Management in Engineering*.

Jarkas, A. M., and Bitar, C. G. (2012). 'Factors Affecting Construction Labor Productivity in Kuwait'. *Journal of Construction Engineering and Management*.

Kaming, P. F., Olomolaiye, P. O., Holt, G. D., and Harris, F. C. (1997). 'Factors influencing craftsmen's productivity in Indonesia'. *International Journal of Project Management*, 15(1), 21–30.

Kazaz, A., and Ulubeyli, S. (2007). 'Drivers of productivity among construction workers: A study in a developing country'. *Building and Environment*, 42(5), 2132–2140.

Rivas, R. A., Borcherding, J. D., González, V., and Alarcón, L. F. (2011). 'Analysis of Factors Influencing Productivity Using Craftsmen Questionnaires: Case Study in a Chilean Construction Company'. *Journal of Construction Engineering and Management*.

Robles, G., Stifi, A., Ponz-Tienda, J. L., and Gentes, S. (2014). 'Labor productivity in the construction industry – Factors influencing the Spanish construction labor productivity.' *International Journal of Civil, Architectural, Structural and Construction Engineering*, 8(10), 999–1008.

Stehrer, R., Bykova, A., Jäger, K., Reiter, O., and Schwarzhappel, M. (2019). *Industry level growth and productivity data with special focus on intangible assets, wiiw Statistical Report No. 8.*

Thomas, H. R., and Sakarcan, A. S. (1994). 'Forecasting Labor Productivity Using Factor Model'. *Journal of Construction Engineering and Management*, 120(1), 228–239.

Vrijhoef, R. (2016). 'Effects of Lean Work Organization and Industrialization on Workflow and Productive Time in Housing Renovation Projects'. *24th Annual Conference of the International Group for Lean Construction*, Boston, MA.

Vrijhoef, R., and Van Dijkhuizen, M. (2020). 'Lean Toolbox Approach for Effective Preparation of Housing Refurbishment Projects Using Critical Success Factors'. *Proc. 28th Annual Conference of the International Group for Lean Construction (IGLC28)*, I. D. Tommelein and E. Daniel, eds., Berkeley, CA, 181–192.

Zakeri, M., Olomolaiye, P. O., Holt, G. D., and Harris, F. C. (1996). 'A survey of constraints on Iranian construction operatives' productivity'. *Construction Management and Economics*, 14(5), 417–426.

Zhao, Y., and Chua, D. K. H. (2003). 'Relationship Between Productivity and Non Value-Adding Activities'. *11th Annual Conference of the International Group for Lean Construction*, Singapore.

Marte Gómez, J.A., Daniel, E.I., Fang, Y., Oloke, D. and Gyoh, L. (2021). "Implementation of BIM and Lean construction in offsite housing construction: evidence from the UK" *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 955–964, doi.org/10.24928/2021/0122, online at iglc.net.

IMPLEMENTATION OF BIM AND LEAN CONSTRUCTION IN OFFSITE HOUSING CONSTRUCTION: EVIDENCE FROM THE UK

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ABSTRACT

The benefits of integrating Lean construction (LC) and Building Information Modelling (BIM) have been discussed in recent research studies. However, the effects of implementing these methodologies as an integrated approach in offsite housing construction (OSHC) processes have not been explored in the UK. This research aims at assessing the current situation of the implementation of BIM and LC in OSHC in the UK. A quantitative research method was adopted in the study and thirty-two questionnaire survey responses were received from professionals and practitioners of Lean, BIM and offsite methodologies in the UK construction industry. The study found that there is increasing use of LC and BIM in the development of OSHC projects in the UK. It further reveals that these two methodologies when appropriately implemented can bring several benefits. This study sheds light on the current status of implementation of BIM and LC in OSHC and the benefits of the implementation of both BIM and LC in OSHC processes in the UK.

KEYWORDS

Lean construction, building information modelling, offsite construction.

INTRODUCTION

The UK construction industry has expressed a growing interest in the improvement of essential areas of construction such as efficiency and production. Several aspects of performance enhancement approaches including offsite production, standardisation and supply chain partnerships have been addressed in reports such as the Offsite manufacture for construction report (UK parliament, 2018), the Farmer Review of the UK construction labour model (Farmer, 2016) and the Egan report (Egan, 1998). Nevertheless, the

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implementation of these performance improvement approaches has been hindered mostly due to complications that builders have encountered in appreciating the value these approaches may bring into their projects (Pasquire et al, 2004).

BIM is defined as a process for the creation and management of information of infrastructure, building or facility through its lifecycle (Eastman et al., 2008). This process results in the creation of the BIM, a digital representation of all the significant aspects of the building. BIM diverges from other design technologies in the way information is managed allowing an effective interchange of essential data between stakeholders throughout the project lifecycle and post-construction performance (Smith and Tardif, 2009). Lean construction (LC) is another performance enhancement approach that aims to improve the entire construction process in order to effectively satisfy the customer's needs (Bhatla and Leite 2012). LC focuses on reducing waste and increasing value which translates into quality and productivity improvement (Bernstein and Jones, 2013). The LC methodologies considered in this study include: Just-in-time, Visual management, Last Planner System, Target Value Design, Value Stream Mapping, 5S, Lean Project Delivery System, Process mapping, First run study, Mistake proofing, Takt time planning and Choosing by advantages.

LC and BIM have influenced considerably the AEC industry and despite being considered as distinct and independent, their principles seem to amalgamate in their intentions and ideals (Sacks et al., 2009). The synergies of BIM and LC have led the broadly fractured construction industry into a pathway of enhancing construction processes whilst increasing the value of a project towards the customer (Oskouie et al., 2012). Although the benefits of integrating BIM and LC have been discussed in recent studies (Sacks et al., 2009), the effects of integrating BIM and LC in offsite housing construction (OSHC) have not been explored in the UK.

This study aims to evaluate the current situation of the implementation of BIM and LC in OSHC. By identifying the actual status of the implementation of these methodologies, the results of this study would enable critical improvements on the benefits these methodologies bring into the UK construction industry. The research questions are as follows: What is the current status of implementation of BIM and LC in OSHC in the UK? What are the benefits of the implementation of the integrated BIM and LC in OSHC processes in the UK?

LITERATURE REVIEW

LEAN CONSTRUCTION AND OFFSITE CONSTRUCTION

Offsite construction (OSC) involves the process of manufacturing components, elements or modules in a controlled environment before their transportation and later installation in the construction site (Kolo et al., 2014). This allows the achievement of higher standards of quality, waste reduction, and increased productivity, therefore improving the overall efficiency of the process (Nanyam et al., 2017). Pan and Goodier (2012) state that OSC represents an effective alternative to traditional construction processes by improving life cycle environmental performance, productivity and predictability.

Abanda et al. (2017) identify the main types of offsite manufacturing as Volumetric, 3D factory-produced units that enclose usable space but are not part of the building structure; Sub-assembly systems, prefabricated sections of the building that would normally be produced on site; Modular systems, volumetric units preassembled in a factory controlled environment and together form the whole building; Panelised, factory-produced flat panel units assembled on site to produce the 3D structure; and Hybrid methods, a combination of both volumetric and panelised systems.

OSC has been promoted in recent literature with the objective of improving efficiency, quality and environmental performance of house construction, use and demolition (Pan and Goodier, 2012). The factory precision of prefabricated housing panels has been associated with a better insulation performance, improving occupant comfort and reducing household energy demands (Steinhardt and Manley, 2016). Additionally, as seen in table 1, OSC have several benefits when compared to traditional construction methods.

Notwithstanding the increasing interest of adopting OSC methods, the UK remains behind similar economies in the uptake of offsite methodologies (Steinhardt and Manley, 2016). This growing interest is mainly driven by a shortfall in housing supply, with some reports showing that the UK needs 345,000 new homes per year (Housing, Communities and Local Government Committee, 2019) and the increasing pressure from the government for the emulation of the manufacturing sector (Parliament, 2018).

LC is a moderately new approach that focuses on minimising activities that do not generate value for the project owner. In this context, these non-value adding activities are considered wastes (Tafazzoli et al, 2020). Variety has been considered as one of the main reasons that Lean production is not suitable for the construction industry (Yu et al., 2013). However, Yu et al. (2013) also add that this variety is the ground on which the Lean production system was based and the reason that Lean production is different from mass production ineffectiveness. As seen in table 1, LC provides several benefits for the AEC industry and essentially aims to work on constant improvement, strong user focus, value for money, waste elimination, high-quality management of projects and efficient supply chain (Office of Government Commerce, 2000).

Table 1: Benefits of BIM, LC and OSC

Benefits of BIM	Benefits of LC	Benefits of OSC
-Clash detection improves communication; models can be updated in real-time allowing the exchange of critical information throughout the project lifecycle (Banuelos Blanco and Chen, 2014). -Predesign analysis prevents time consuming redesign (Azhar, 2011). -Effective data management improves the efficiency of activities such as quantity surveying, procurement and material supply integration (Steel et al., 2012).	-Waste reduction and enhanced cooperative relationships (Green and May ,2005). -Increased process efficiency and labour productivity (Goh and Goh, 2019). -Improved quality and productivity through effective collaboration between stakeholders (Bernstein and Jones, 2013)	-Effective quality control in complying with quality standards (Blismas et al., 2006). -Preliminary costs are lower, less waste, less onsite damage and increase of economic value (Elnaas et al., 2014). -Less site disruption, removal of extensive operations off site, work can be carried out simultaneously offsite and onsite (Blismas et al., 2006). -Risk reduction and better safety due to carefully planned processes in a factory (Ajayi et al., 2019).

BIM AND OFFSITE CONSTRUCTION

According to Azhar (2011), over the past decade, BIM has added significant value to the construction sector and, as Aranda-Mena et al. (2009) state, has proven to be more than just a modelling tool by providing relevant benefits throughout the entire construction lifecycle, from design to occupancy and maintenance. The UK Government's BIM Level 2 mandate helped the construction industry to become a world leader in BIM adoption (Alwan et al., 2017). This mandate requires collaborative BIM level 2 models on all government-funded projects from 2016 onwards (Government, 2013).

Offsite manufacturing can be facilitated by BIM in several ways. It helps in the specification of material requirements which results in reducing over-ordering and minimise waste in the construction site (Abanda et al, 2017). BIM also allows the accurate representation of geometry, behaviour and properties of individual components that can facilitate their incorporation into modularised building elements made available digitally (Nawari, 2012). Notwithstanding these benefits, barriers such as limited interoperability and standardisation, lack of confidence in small organisations about their BIM skills and client's unawareness of BIM benefits are still hindering the adoption of BIM in the AEC industry. However, Abanda et al (2017) argue that BIM can enhance the existing benefits of OSC and can notably contribute to overcoming the barriers that are currently hindering the uptake of OSC. Although several studies have identified the benefits of BIM on conventional construction (Table 1), it can be argued that the impact of these benefits in OSC can be greater given that OSC has numerous benefits over traditional construction.

SYNERGIES BETWEEN BIM AND LEAN CONSTRUCTION FOR OFFSITE CONSTRUCTION

Despite the latent benefits of OSC and LC, there is a lack of design assessment tools that integrate both concepts to support designers and managers in evaluating the implications of efficient assembly processes (Gbadamosi et al., 2019). On the other hand, BIM enhances the early-stage decision- making through advanced data visualisation, clash detection, material quantity take-off, and others (Mahamadu et al., 2017).

Fundamentally, LC and BIM are different processes that separately have a significant impact on improving construction processes (Robey and Issa, 2015). Although the two approaches represent potential benefits when used together (Sacks et al., 2009), the authors suggest that further improvements can be achieved to further enhance the efficiency of both methodologies as an integrated approach. Additionally, a National Research Council (2009) study in the United States recommended five opportunities for significant advancement in construction productivity. These recommended opportunities included the use of OSC, the increased implementation of BIM, improvements in processes materials, equipment and information that have a direct relationship with LC principles. These recommendations fundamentally recognise the potential of BIM, Lean and OSC in improving and ensuring the efficiency and quality of the construction industry.

RESEARCH METHOD

As this study aims to collect data about the current implementation of BIM and LC in OSHC projects in the UK, a quantitative research approach was implemented with the use of a questionnaire survey as the main data collection tool. The study commenced by reviewing the literature available about the current status of the implementation of BIM, LC and OSC. The questionnaire survey was developed considering the results from the literature review and consists of two sections; the first section was designed to obtain relevant background information about the respondents such as occupation, years of experience and previous knowledge in BIM, LC and OSHC while the second section focuses on obtaining information regarding the practices and techniques of BIM, LC and OSC currently being implemented in the UK construction sector.

The questionnaire survey was hosted online from August to November 2020, using Google forms. Purposive sampling was used in selecting the research participants in order to ensure that only those with adequate knowledge of the subject participated in the study. The population of the study consisted of experienced OSC professionals with background and knowledge in BIM and LC in the UK. Considering the database of the UK Offsite Hub and Building and Design, the population of OSC practitioners in the UK is estimated to be approximately 228 organizations. With a confidence level of 90% and a margin of error of 8%, the ideal population sample was calculated to be seventy-three. Based on this, eighty survey links were sent out through email and social media platforms such as LinkedIn and Twitter across the four nations of the UK. However, after three months with several follow-up emails and reminders only 32 responses were received representing 44% of the ideal sample size. Although the number of responses obtained represents a valuable evidence, it should be recognized that this representative sample is fairly weak due to the low rate of responses received. Besides, the authors observed that the COVID-19 pandemic of 2020 partly impacted the number of responses received as people were unsettled to participate in the study. The data collected from the survey were analyzed using Microsoft Excel to obtain the graphics and tables.

RESULTS AND DISCUSSION

RESPONDENTS BACKGROUND INFORMATION

Most respondents are involved actively in the construction industry and have relevant roles in their organisations. Out of the 32 respondents of the survey, 25% identified themselves as Founder and CEO's of their organisation, which is the highest percentage of responses for the roles identified in the survey. The rest of the participants included construction managers, architects, project managers, quantity surveyors, engineers and offsite and LC consultants and lecturers.

IMPLEMENTATION OF BIM AND LEAN CONSTRUCTION IN OFFSITE HOUSING CONSTRUCTION IN THE UK

As this study aims to identify the status of the implementation of LC and BIM in OSHC, it was necessary to identify which methodologies have been or are currently being implemented by respondents in construction projects. As shown in figure 1, 40.63% of participants indicated to have implemented or are currently implementing BIM- LC and OSC methods in construction projects. According to the results, BIM is the preferred methodology in construction projects by 15.63% of respondents, while LC accounts for 12.50%.

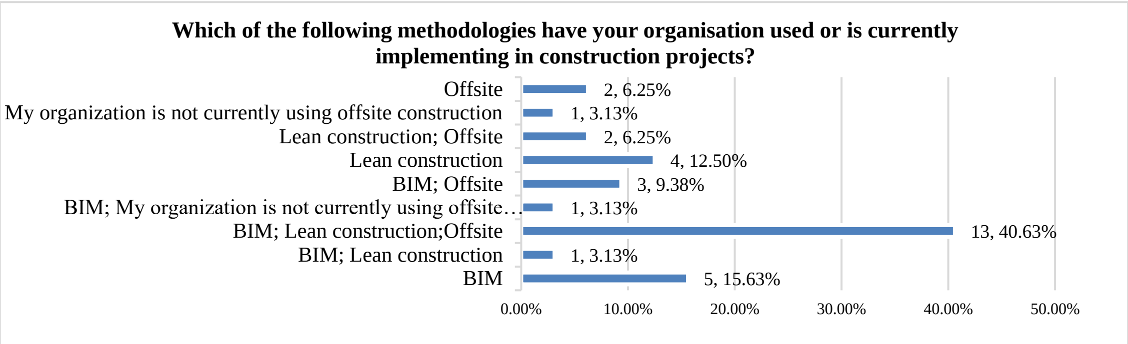

Figure 1-Methodologies implemented in offsite construction projects.

6.25% of respondents indicated that OSC is the only methodology being implemented their organisations. A further 9.38% of respondents indicated BIM and OSC as the main methods being implemented in construction projects while 6.25% identified LC and OSC as the methodologies of choice. These results suggest that an increasing number of organisations are currently implementing BIM and LC concepts into OSHC methods. However, the results also indicate that LC and BIM in construction projects are individually being implemented by 28.13% of respondents. In OSHC projects, (9.38%) indicated they are currently implementing only BIM while LC implementation accounts for 6.25%.

Analysing the results from the implementation of LC in OSC, 46.88% of respondents indicated to have been implementing LC in OSC projects from 1 to 5 years whereas those implementing LC in OSC for 5 to 10 years accounted for 21.88%. While 9.38%. stated to have been using LC in OSC from 10 to 15 years, 18.75% of respondents stated they have been implementing LC in OSC for longer than 15 years. A further 21.88% of participants indicated to have not implemented LC in OSC projects. These results correspond with the literature about an increasing LC implementation in OSC due to the benefits these two approaches can bring into construction projects (Gbadamosi et al, 2019). The increasing use of offsite in the UK in housing delivery could be due to the renewed government effort to close the housing shortage gap using OSC methods as recommended by the House of Commons housing committee (Housing, Communities and Local Government Committee, 2019).

As for the implementation of BIM in offsite, most respondents indicated they have been implementing BIM in offsite for 1-5 years (59.38%), followed by 25% of respondents who stated they have not implemented BIM in offsite. Also, 6.5% of respondents indicated to have been implementing BIM in offsite for 5-10 years and 10-15 years respectively.

According to the previous results, despite the lack of implementation of BIM in OSC projects, there is an increasing tendency in the implementation of BIM in OSC projects in the last few years which match with the literature about the impact of government regulations and acknowledgement of the benefits of BIM for construction projects (Alwan et al., 2017). As shown in figure 2, the most used OSC method being implemented is the Modular system with 62.50% of participants, whereas Volumetric is the second most implemented OSC method with 56.25%. These results match with the literature where the Modular system is highlighted as one of the most implemented OSC techniques in residential and hospitality buildings (Lawson et al, 2012) whilst Volumetric implementation has been increasing amongst UK housebuilders due to its several benefits in helping to tackle the ageing workforce and labour shortages (Booth, 2017).

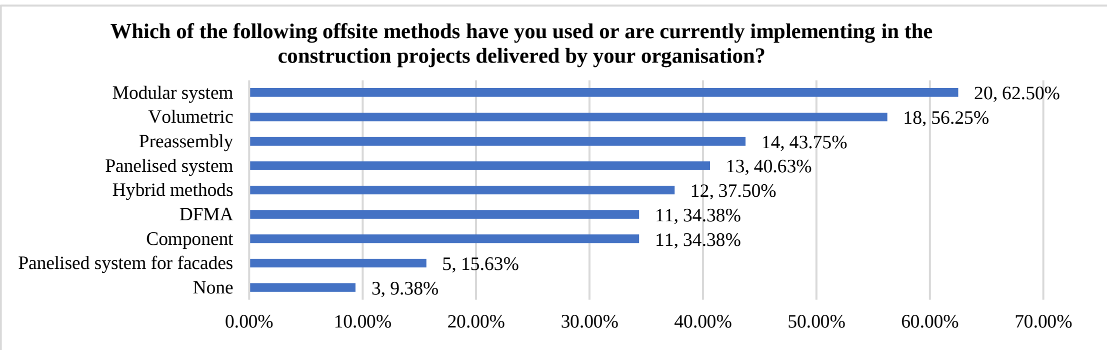

Figure 2-Offsite methods used in the delivery of construction projects.

As can be identified in figure 3, the questionnaire survey highlights the Lean concepts being implemented in offsite projects by participants. Just In Time (JIT) was chosen as the main Lean technique implemented in projects with 56.25% of participants. Followed by Visual Management (34.38%) and Last Planner (34.38%), Target Value Design (28.13%) and Value Stream Mapping (28.13%), 5S (25.00%) and Lean Project Delivery System (25.00%),. Process mapping (18.75%), First Run Study (15.63%), Mistake Proofing (15.63%) and Takt Time Planning (15.63%). 12.50% of participants indicated not having implementing any of these LC concepts while only 6.25% of participants chose Choosing by advantages as one of the techniques applied in their projects. These results clearly show that construction companies in the UK have embraced the philosophy of JIT, due to its numerous benefits in construction projects such as increased productivity and quality (Pheng and Shang, 2011).

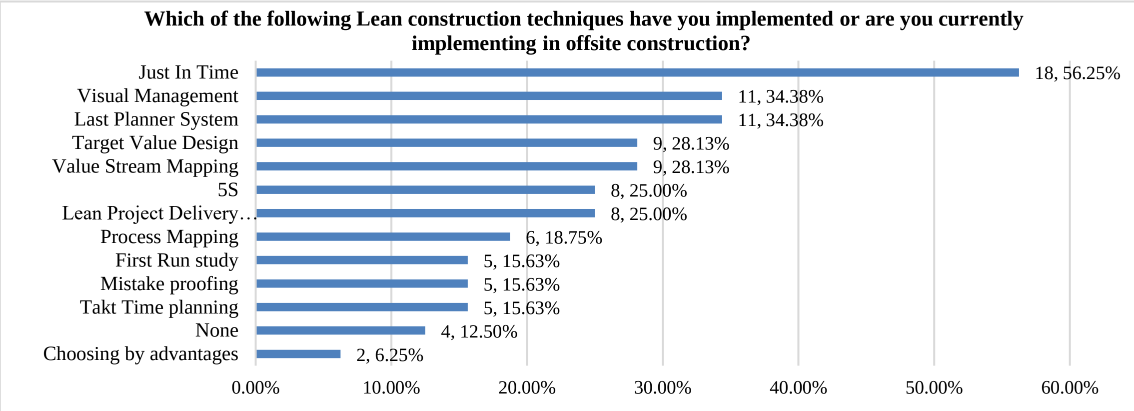

Figure 3-Lean techniques used in offsite projects.

Integration of Building Information Modelling and Lean Construction for Offsite Housing Construction

The integration of BIM and LC for Offsite projects was assessed by showing participants several benefits of offsite construction processes and asking them to identify the likelihood of these benefits to be achieved by the combination of these two approaches. As shown in figure 4, respondents considered that effective collaboration would be the main benefit of integrating LC and BIM with a weighted average of 4.6. Because the production process of off-site construction is fragmented, and OSC projects should involve close cooperation of multiple interdependent stakeholders, better quality control is a major challenge to promote OSC projects (Pablo and London, 2020). LC tools such as Kanban and huddle meetings can provide a new platform to increase value to BIM and improve construction site collaboration (Von Heyl and Demir, 2019).

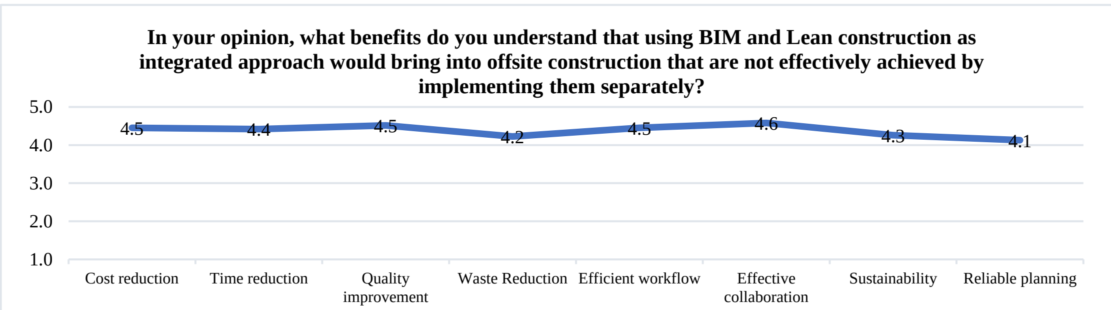

Figure 4-Benefits of integrated BIM-Lean for offsite projects.

Similarly, participants agreed that cost reduction, efficient workflow and quality improvement are three main benefits of integrating these two approaches for offsite with both obtaining a weighted average of 4.5. That is because BIM provides a digital platform through which participants can effectively share and manage information of the project, while LC practices solve the problem of enhancing the coordination of the stakeholders, and smooth the workflow by reducing waste and adding value (Zhang et al., 2018).

CONCLUSIONS AND FUTURE RESEARCH

This study was undertaken to evaluate the current practices and status of the implementation of BIM and LC in OSHC projects in the UK. The investigation reveals that the implementation of LC in OSC has been increasing considerably over the last 5 years, with techniques such as JIT, Visual management and Last Planner System amongst the most implemented in offsite projects particularly. The study established the most used offsite methods in the UK include modular, volumetric and preassembly. Similarly, the study shows that the use of BIM in the delivery of OSHC projects in the UK has seen an increase in the last five years. In term of the benefits of the implementation of LC and BIM in OSHC projects, this study revealed that these two methodologies when appropriately implemented can bring several benefits such as efficient collaboration and team integration, time reduction, cost reduction, quality improvements, efficient workflow, waste reduction and sustainability, customer's satisfaction, higher performance and risk reduction.

This study contributes to the current knowledge and future implementation of BIM and LC in OSHC projects. The evidence presented would enable project practitioners to understand the importance of the integration of BIM and LC in the delivery of OSHC project. Although the response is low due to COVID-19, this study shed light on the current status of implementation of BIM and LC in OSHC and the benefits of the implementation of both BIM and LC in OSHC processes in the UK. Additionally, the results of this study would enable further improvements on the implementation and synergies between these methodologies to effectively increase efficiency and quality in the AEC industry in the UK.

REFERENCES

Abanda, F. H., Tah, J. H. M., & Cheung, F. K. T. (2017). "BIM in off-site manufacturing for buildings." *J. Build. Eng.,* 14, 89–102.

Ajayi, S. O, Oyedele, L. O., Akinade, O. O, Bilal, M, Owolabi, H. A., Alaka, H. A., and Kadiri, K. O. (2016) "Reducing waste to landfill: A need for cultural change in the UK construction industry." *J. Build. Eng.,* 5, 185-193.

Alwan, Z., Jones, P., and Holgate, P. (2017). "Strategic sustainable development in the UK construction industry, through the framework for strategic sustainable development, using BIM." *J. Clean. Prod*., 140, 349–358.

Aranda-Mena, G., Crawford, J., Chevez, A., and Froese, T. (2009). "Building information modelling demystified: does it make business sense to adopt BIM?" *Int. J. Manag. Proj. Bus*., 2(3), 419–434.

Azhar, S. (2011). "Building Information Modelling (BIM): Trends, benefits, risks, and challenges for the AEC industry." *Leadersh. Manag. Eng*., 11(3), 241–252.

Banuelos Blanco, F.G. and Chen, H. (2014), "The implementation of building information modelling in the UK by the transport industry." *Procedia Soc Behav Sci.,*138, 510 -520.

Bernstein, H.M. and Jones, S.A. (2013). *Lean construction: Leveraging collaboration and advanced practices to increase project efficiency*. McGraw Hill Construction, Bedford, MA.

Bhatla, A., & Leite, F. (2012). "Integration framework of BIM with the last planner system." In *IGLC 2012 - 20th Conf. Int. Gr. Lean Constr.*

Blismas, N., Pasquire, C. and Gibb, A. (2006). "Benefit evaluation for off-site production in construction." *Constr. Manag. Econ.*, 24(2),121-130.

Booth, R. (2017) "UK housebuilders to prefabricate hundreds of homes in factories." https://www.theguardian.com/business/2017/dec/31/uk-housebuilders-factories-prefabricating-homes (Sep.15, 2020).

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2008). "BIM for the Construction Industry." In BIM Handbook (pp. 207–242).

Egan, J. (1998). *Rethinking Construction*. DETR, London.

Elnaas H., Gigado K. and Ashton P. (2014). "Factors and drivers effecting the decision of using off-site manufacturing (OSM) systems in house building industry." *J. Oper. Prod. Manag.*, 4(1), 51-58.

Farmer, M., (2016). "The farmer review of the UK construction labour model." Construction Leadership Council.

Gbadamosi, A. Q., Mahamadu, A. M., Oyedele, L. O., Akinade, O. O., Manu, P., Mahdjoubi, L., & Aigbavboa, C. (2019). "Offsite construction: Developing a BIM-Based optimizer for assembly." *J. Clean. Prod.*, 215, 1180–1190.

Goh, M. and Goh, Y. M. (2019). "Lean production theory-based simulation of modular construction processes." *Aut. in Const.* 101, 227–244.

Green, S. and May, S. (2005). "Lean construction: arenas of enactment, models of diffusion, and the meaning 'leanness." *Build. Res. Inf.*, 33(6), 498-511.

Housing, Communities and Local Government Committee (2019). "Modern methods of construction." Available at:https://publications.parliament.uk/pa/cm201719/cmselect/cmcomloc/1831/1831.pdf (Dec. 22,2019).

Kolo, S. J., Rahimian, F. P., & Goulding, J. S. (2014). "Offsite manufacturing construction: A big opportunity for housing delivery in Nigeria." *Procedia Eng.*, 85, 319–327.

Lawson, R. M., Ogden, R. G., & Bergin, R. (2012). "Application of Modular Construction in High-Rise Buildings." *J. Archit. Eng.*, 18(2), 148–154.

Machado, M., Underwood, J., & Fleming, A. (2017). "Implementing BIM to Streamline a Design, Manufacture, and Fitting Workflow." *Int. J. 3-D Inf. Model.*, 5(3), 31–46.

Mahamadu, A. M., Mahdjoubi, L., & Booth, C. A. (2017). "Critical BIM qualification criteria for construction pre-qualification and selection." *Archit. Eng. Des. Manag.*, 13(5), 326–343.

Manufactured Housing Research Alliance (2007). "Pilot Study: Applying Lean Principles to Factory Home Building. Technical Report." U.S. Department of Housing and Urban Development.

Nanyam, V. P. S. N., Sawhney, A., & Gupta, P. A. (2017). "Evaluating Offsite Technologies for Affordable Housing." *Procedia Eng.*, 196, 135–143.

Office of Government Commerce (2000). "Achieving Sustainability in Construction Procurement, by the Sustainability Action Group of the Government Construction Clients." Panel (GCCP), available at:

www.ogc.gov.uk/documents/Sustainability_in_Construction_ Procurement.pdf (Jul. 18, 2020).

Oskouie, P., Gerber, D. J., Alves, T., & Becerik-Gerber, B. (2012). "Extending the interaction of BIM and lean construction." In *IGLC 2012 - 20th Conf. Int. Gr. Lean Constr*., 1, (617), 111-120.

Pablo, Z., & London, K. A. (2020). "Stable relationality and dynamic innovation: two models of collaboration in SME-driven offsite manufacturing supply chains in housing construction." *Eng. Constr. Archit. Manag.*, 27(7),1553-1577.

Pan, W., & Goodier, C. (2012). "House-Building Business Models and Off-Site Construction Take-Up." *J. Archit. Eng.*, 18(2), 84–93.

Pasquire, C., Gibb, A., & Blismas, N. (2004). "Off-site Production: Evaluating the Drivers and Constraints." *12th Annu. Conf. Int. Gr. Lean Constr*., 655-662.

Pheng, L. S., & Shang, G. (2011). "The application of the Just-in-Time philosophy in the Chinese construction industry." *J. Constr. Dev. Ctries.*, 16(1), 91–111.

Robey, M. W., & Issa, R. R. A. (2015). "Implementation of Prefabrication and Modular Offsite Construction using BIM and Lean Construction Techniques." In *Modul. Offsite Constr. Summit Proceedings.*

Sacks, R., Dave, B. A., Koskela, L., & Owen, R. (2009). "Analysis framework for the interaction between lean construction and Building Information Modelling." In Proc. *IGLC17 17th Annu. Conf. Int. Gr. Lean Constr*.

Smith, D.K. and Tardif, M., (2009). *Building information modelling: a strategic implementation guide for architects, engineers, constructors, and real estate asset managers.* John Wiley & Sons. Hoboken, NJ.

Steel, J., Drogemuller, R. and Toth, B. (2012), "Model interoperability in building information modelling." *Softw. Sys.t Model*., 11(1), 99-109.

Steinhardt, Dale. A. and Manley, K. (2016) "Adoption of prefabricated housing–the role of country context." *Sustain. Cities Soc.*, 22,126–135.

Tafazzoli, M., Mousavi, E., & Kermanshachi, S. (2020). "Opportunities and challenges of green-lean: An integrated system for sustainable construction." *Sustain. (Switzerland).*, 12(11), 44–60.

UK parliament (2018) "Off-site manufacture for construction: Building for change" 2nd Report of Session 2017-19 - published 19 July 2018 - HL Paper 169.

Von Heyl, J. & Demir, S. (2019). "Digitizing Lean Construction With Building Information Modelling." In:, Proc. *27th Conf. Int. Gr. Lean Constr*., 843-852.

Zhang, X., Azhar, S., Nadeem, A., & Khalfan, M. (2018). "Using Building Information Modelling to achieve Lean principles by improving efficiency of work teams." *Int. J. Constr. Manag.*, 18(4), 293-300.

Kim, T. and Kim, Y. (2021). "Early Due Low Uncertainty (EDLU) For Improving Supply Chain Performance under Order Variability in Precast Concrete Production." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 965–973, doi.org/10.24928/2021/0128 , online at iglc.net.

EARLY DUE LOW UNCERTAINTY (EDLU)FOR IMPROVING SUPPLY CHAIN PERFORMANCE UNDER ORDER VARIABILITY IN PRECAST CONCRETE PRODUCTION

Taehoon Kim[1] and Yong-Woo Kim[2]

ABSTRACT

The AEC (architect, engineering, and construction) industry finds a trend that more projects are adopting a prefabrication for various reasons. In a context of prefabrication, reliable supply chain is one of critical factors for project success. One of prefabricated products being adopted in building construction is precast concrete. A precast conctete supplier needs to optimize his production schedule while meeting various demands from multiple customers (i.e., contractors on project site). Most suppliers rely on dispatching rule in their production scheduling. However, contractor's order variability makes an impact on a supplier's production schedule and the reliability of supply chain. The authors proposed a new dispatching rule (EDLU, early due low uncertainty)taking into account a contractor's order reliability, followed by simulation experiments. The study suggests that (1) order variability leads to variance of prefabricated product delivery; (2) EDLU is more effective than traditional dispatching rules when order variability increases; (3) a proposed dispatching rule of EDLU gives incentives to a contractor's reliable order by giving production priority to orders with low uncertainty.

KEYWORDS

Precast concrete, production schedule, dispatching rule, EDLU (early due low uncertainty), operational strategy.

INTRODUCTION

The AEC (architect, engineering, and construction) industry finds a trend that more projects are adopting a prefabrication for various reasons. A study carried out by Mc-Graw Hill Construction (2011) showed that nearly all construction stakeholders expect to utilize prefabrication in some of their projects. As a result, the effective management of prefabrication supply chain can make a considerably influence on the performances of construction projects. In a context of prefabrication, reliable supply chain is one of critical factors for project success.

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In projects using precast concrete structures (e.g., precast wall panels), precast concrete structures are manufactured off-site in a controlled environment, transported to the site, and lifted into place (Benjaoran et al. 2005). A precast conctete supplier needs to optimize his production schedule while meeting various demands from multiple customers (i.e., contractors on project site). Most suppliers do not have capital enough to invest advanved optimization scheduling tool to develop and update their production schedule. Accordingly, they rely on dispatching rule (i.e., the way to prioritize work orders) in their production scheduling to meet various demands (Kim et al. 2020).

However, contractor's order variability makes an impact on a supplier's production schedule and the reliability of supply chain. The authors proposed a new dispatching rule taking into account a contractor's order reliability, followed by simulation experiments. The authors finally proposes three operational strategies based on the simulation results.

PRECAST CONCTETE SCHEDULING AND ORDER RELIABILITY

PRECAST CONCRETE PRODUCTION SCHEDULE

Precast concrete production is a flow production system which consists of six processes: formwork assembling (m1), rebar and other all embedded parts installation (m2), concrete casting (m3), concrete curing (m4), formwork dismantling (m5), and PC product finishing (m6). The precast concrete production system can be classified into interruptabile production and uninterruptable production (Wang and Hu 2017). Among six processes, concrete curing (m4) is categorized as a parallel process because it doesn't need any external resources once concrete casting (m3) is complete (Kim et al 2020).

Literature on precast concrete production schedule is found. However, most studies have been carried out on precast conceret production scheduling without demand uncertainty considered. Dawood (1995) carried out the heuristic approach-based production schedule model for the precast concete. Benjaoran et al. (2005) suggested a production scheduling model using the genetic algorithm (GA) for bespoke precast concete with multiple molds. Yang et al. (2016) suggested the searching technique based on a multi-objective GA for evaluating the time and cost from production to assembly.

The authors also found that several studies carried out the scheduling problem for the precast concrete production under the uncertainty. Chan and Wee (2003) used GA to develop the heuristic approach based-schedule repair model to resolve schedule disturbance. However, they didn't include due date changes as uncertainty. Ko (2010) suggested the prnciples for schedule adjustment to cope with the demand variability. Ma et al. (2018) suggested an approach to optimize the rescheduling of multiple production lines for the PC to cope with production emergencies, but they didn't take count into the uncertainty of on-site schedule. Ho (2019) investigated the optimization using interprogramming under demand uncertainty and work station capacity of the supplier. Kim et al. (2020) proposed a simulation module for scheduling PC under due date changes, but they didn't focus on how the plan reliability can make an impact on supply chain performance.

ORDER RELIABILITY

A construction project schedule has some uncertainty that makes an impact on the activities related to installation of prefabricated products (Chan and Wee 2003). Planning reliability is directly related to the order of prefabricated products. Order variability (i.e., changes in delivery order) may come from (1) working out of optimum sequence", or (2) expediting or delaying the progress with pre-arranged sequence (Ballard and Arbulu 2004). Although order variability may also come from design changes, this study exclude this case because delivery orders are usually made only after shop drawings are approved. It is rare that product design changes after its shop drawing is approved.

The changes either in work sequence or in timing of the installers schedule frequently lead to changes in delivery order unless the installer has space enough to hold inventory. The changes in delivery order made by installers (i.e., contractors on site) disrupts the fabricator's production schedule, leading to additional costs and time. The delivery order changes (i.e. order variability) may occur before or during corresponding precast concrete production. If the delivery order changes prior to precast concrete production begins, the suppler should rearrange their production schedule. If the delivery order changes while precast concrete production in process, either the suppler or the contractor should hold the inventory unless the third party dealer who is in charge of logistics takes care of inventory.

A SUPPLIER'S PRODUCITON SCHEDULE AND DISPATCHING RULE

There are multiple areas to respond to such order variability to reduce the negative impact on supply chain performances (i.e., lead time and costs). They include improving a contractor's planning reliability through the Last Planner System, setting up a production layout so that the supplier's production schedule can be flexible enough to respond to order changes, or having a contractor purchase the supplier's production capacity rather than products. The study focuses only on the supplier's production scheduling with the following assumption:

- A contractor's order reliability is given
- A production layout does not change. (i.e., the production duration is given)
- A contractor does not have any strategic solution to change the contractual relationship.

Many construction fabricators have limited planning capacity not enough to develop a robust scheduling or schedule optimization responding to order variability (Kim et al. 2020). Instead of complex scheduling method such as optimization algorithm, many construction fabricators have used dispatching rules in practice because of their simplicity and intuitiveness. The following is the list of dispatching rules being commonly used by the manufacturers.

- The EDD (earliest due date) rule has been widely used for production scheduling problem because of its simplity and better performance than other rules (Chan and Hu 2002). The EDD rule chooses the next job having earliest due date from the queue. This rule focuses on satisfying job due dates.
- The SPT (shortest processing time) rule chooses the next job having the shortest processing times from the queue. This rule has been known to be one of the best to reduce work-in-process inventory because the rule minimize the time a job stays in the shop (Weng and Ren 2006).
- The CR(critical ratio) rule chooses the next job considering the available time divided by the total remaining process time of the job.

The existing rules didn't take into account the order uncertainty which may change due dates of orders. This study propose a new rule of EDLU (early due and low uncertainty) taking into account. The PC production schedule can be more flexible by responding to order variability (i.e, the due date changes occur before the production gets started). However, it is strenuous to adjust the PC production schedule if the orders' due date changes are notified after the production gets started. The authors propose to shift the risk of production disruption to the party who creates the order variability (i.e, contractor who frequently changes the delivery order). Therefore, it was required that order with high uncertainty of the due date is started late among orders with a similar priority.

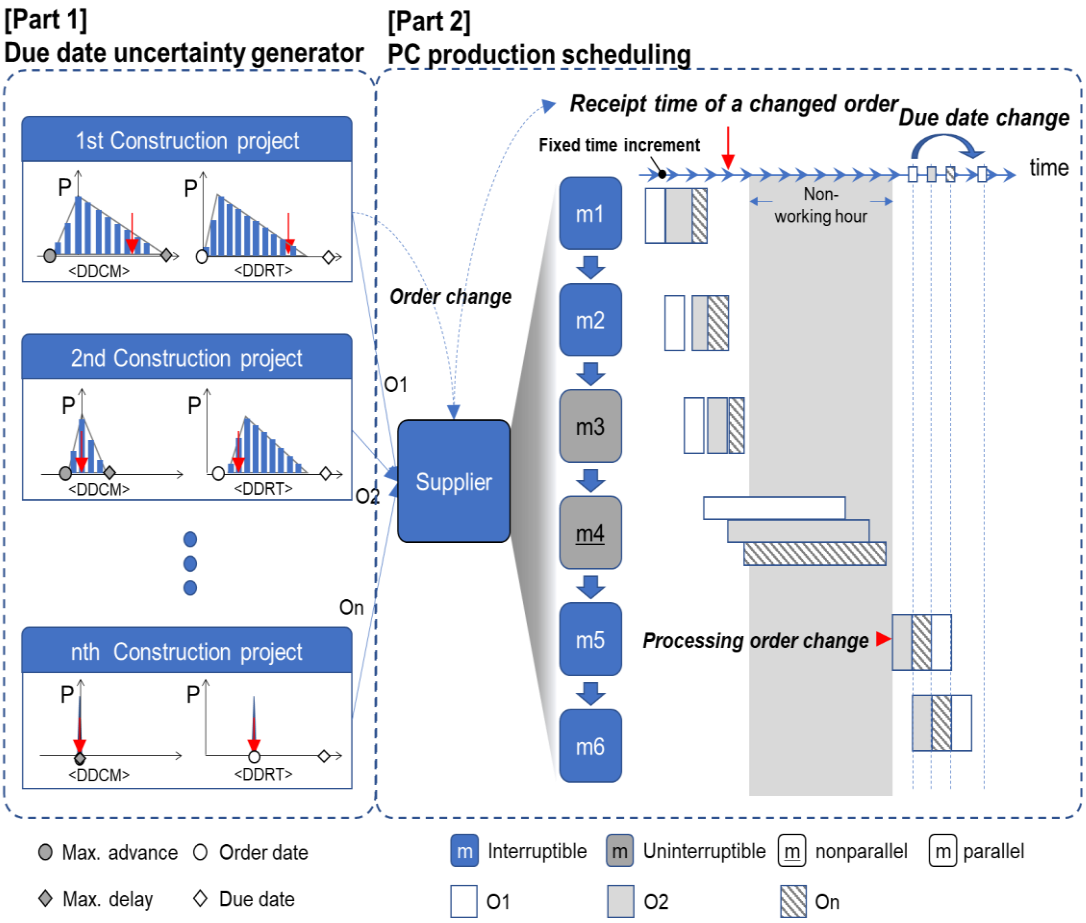
The proposed dispatching rule uses EDD as a baseline because EDD has been popularly applied for PCs production scheduling because it has better performance compared to other dispatching rules (Ho 2018). The proposed rule evaluates the due date and the contractor's order uncertainty when the order's due date is confirmed. The proposed one evaluates the due dates giving priority to the order with early due date in their production sequence. If multiple orders have the same due date, the proposed rule make the priority of orders having the higher uncertainty lower (Kim et al 2020).

SIMULATION EXPERIMENT

SIMULATION METHOD

Simulation experiments have been conducted to compare the performance of the proposed rule to existing rules such as EDD, SPT, and CR and verify the validity. For simulation experiments, the study set up several parameters such as the due date interval, due date tightness, due date uncertainty. In order to examine the effectiveness of reliability in supply lead time, the DPPSM (Dynamic Prefabricated Product Scheduling Model, Kim et al 2020), which has been developed for Precast Concrete Schedule Simulation, is adopted and simulated with the diverse cases.

The DPPSM uses a discrete-time simulation (DTS) method to model precast concrete production process. The DPPSM consists of two parts: (1) a due date uncertainty generator and (2) production scheduling system (Figure 1, Kim et al 2020). The due date uncertainty generator creates due date changes resulting from a predefined probability distribution function. The production scheduling system consists of a module of 'search and update' and 'priority evaluation.' If a priority rule is given, the module identifies a priority task. The DPPSM allows to reschedule the precast concrete production to cope with the due date changes.



P indicates possibility; m indicates machine; O indicates order; DDCM indicates due date change magnitude; and DDRT indicates changed due date receipt time.

Figure 1: DPPSM (Dynamic Prefabricated Product Scheduling Model, Kim et al 2020)

Simulation Experiments

Description of Scenarios

The simulation experiments in this study assumed several conditions as scenarios (Table 1). There were total fifteen orders. The all order dates were Day 1 and their due times were the end time on the due date. The receipt time about the changed due date was the start time on the due date. The original due date (ODD) classified into three types: order date (OD) + t. OD + t + a, OD + t + 2a. The variable t indicates the due date tightness level. The variable *a* is related to the gap day between two jobs' due dates and indicates the production load level.

Table 1. PCs Order Information in Simulation Experiments.

No.	Job	Product type	OD	ODD	Uncertainty	
					Min. Due date	Max. Due date
1	J1	P1	Day 1	OD + t	ODD -1	ODD + u
2		P2		OD + t	ODD -1	ODD + u
3		P3		OD + t + a	ODD -1	ODD + u
4		P5		OD + t + a	ODD -1	ODD + u
5		P7		OD + t +2a	ODD -1	ODD + u
6	J2	P2	Day 1	OD + t	ODD -1	ODD + u
7		P4		OD + t	ODD -1	ODD + u
8		P8		OD + t + a	ODD -1	ODD + u
9		P9		OD + t + a	ODD -1	ODD + u
10		P10		OD + t +2a	ODD -1	ODD + u
11	J3	P2	Day 1	OD + t	ODD -1	ODD + u
12		P4		OD + t	ODD -1	ODD + u
13		P6		OD + t + a	ODD -1	ODD + u
14		P8		OD + t + a	ODD -1	ODD + u
15		P10		OD + t +2a	ODD -1	ODD + u

In terms of uncertainty, all jobs had the same due dates variance. The maximum delay of and a maximum advance of All jobs were u and one days, respectively; The focus of this study placed the maximum delay because construction delays happens more frequently than early construction completion (Kim et al. 2020).

The processing time and mold type in this study are shown in Table 2 (Benjaoran et al 2005). This study assumed the quaitity of each mold type is two molds to consider resource constraint in the real PCs production situations. The simulation time advance step unit for DPPSM was set to 0.1 hour.

Table 2. Processing Time for Each Machine and Mold Type according to Product Type

Product type	Mold type	Processing time (h)					
		m1	m2	m3	m4	m5	m6
P1	A	2.0	1.6	2.4	12.0	2.5	1.0
P2	B	3.4	4.0	4.0	12.0	2.4	5.0
P3	A	0.8	1.0	1.2	12.0	0.8	0.1
P4	A	0.6	0.8	1.0	12.0	0.6	2.0
P5	C	3.0	3.6	2.4	12.0	2.4	3.0
P6	A	3.0	3.2	3.0	12.0	3.0	1.6
P7	C	1.3	0.9	2.4	12.0	1.9	1.8
P8	B	1.7	1.4	1.1	12.0	0.9	0.7
P9	A	2.2	1.8	1.2	12.0	2.3	0.7
P10	C	1.6	3.2	2.3	12.0	2.1	2.7

Note: m1, mold assembling; m2, reinforcement and placing of all embedded parts; m3, concrete casting; m4, concrete curing; m5, mold dismantling; m6, product finishing, The authors simulated a total of 18 scenarios. The daily working hours was assumed to ten hours.The variable u which means the due date uncertainty differed from one days to five days with two-day gap. The variable *t* which means the due date tightness differed from one day to three days with one-day gap, and the variable *a* which means production load level differd from one day to three days with a two-day gap.

Simulation Results

The authors showed the relative performance by calculating the increase in terms of total tardiness using each rule with compared to the proposed rule. As a result of simulating all scenarios, the average relative performance over the 300 replications are shown in Table 3. The scenarios were named as 'S*uta*'. For example, the S321 means a scenario with three of *u*, two of *t*, and one of *a*.

Table 3. Simulation Results of Dispatching Rules

Scenario	DPPSM	CR	EDD	SPT
S111	742.4 (0, 0%)	699.2 (-43.2, -5.8%)	723.8 (-18.5, -2.5%)	490.7 (-251.7, -33.9%)
S113	331.4 (0, 0%)	316.2 (-15.2, -4.6%)	330.2 (-1.2, -0.4%)	364.6 (33.2, 10%)
S121	365.0 (0, 0%)	407.1 (42.1, 11.5%)	384.1 (19.1, 5.2%)	311.5 (-53.5, -14.7%)
S123	131.2 (0, 0%)	138.1 (6.9, 5.3%)	132.4 (1.2, 0.9%)	232.9 (101.7, 77.5%)
S131	152.0 (0, 0%)	158.3 (6.3, 4.2%)	154.0 (2, 1.3%)	173.1 (21.1, 13.9%)
S133	31.4 (0, 0%)	39.4 (8.0, 25.5%)	32.3 (0.9, 3%)	136.0 (104.6, 333.2%)
S311	407.6 (0, 0%)	417.9 (10.4, 2.5%)	417.7 (10.1, 2.5%)	337.9 (-69.7, -17.1%)
S313	158.3 (0, 0%)	167.4 (9.1, 5.7%)	165.4 (7.1, 4.5%)	249.8 (91.4, 57.8%)
S321	178.4 (0, 0%)	190.4 (12.0, 6.7%)	182.6 (4.3, 2.4%)	190.3 (11.9, 6.7%)
S323	56.4 (0, 0%)	61.1 (4.6, 8.2%)	59.5 (3.1, 5.4%)	148.8 (92.4, 163.6%)
S331	51.2 (0, 0%)	60.5 (9.3, 18.2%)	52.1 (1.0, 1.9%)	101.4 (50.2, 98.1%)
S333	12.3 (0, 0%)	17.7 (5.4, 44.2%)	13.3 (1.0, 7.8%)	82.1 (69.8, 567.8%)
S511	218.1 (0, 0%)	232.2 (14.2, 6.5%)	226.8 (8.7, 4.0%)	226.7 (8.7, 4%)
S513	87.1 (0, 0%)	93.1 (6.0, 6.9%)	96.3 (9.2, 10.6%)	172.1 (85.0, 97.6%)
S521	88.2 (0, 0%)	103.1 (14.9, 16.9%)	94.1 (5.9, 6.7%)	128.4 (40.3, 45.7%)
S523	31.7 (0, 0%)	36.9 (5.2, 16.2%)	36 (4.2, 13.3%)	98.3 (66.6, 209.8%)
S531	25.5 (0, 0%)	27.2 (1.6, 6.3%)	26.2 (0.7, 2.7%)	62.2 (36.6, 143.4%)
S533	9.0 (0, 0%)	9.8 (0.8, 9.2%)	9.2 (0.2, 2.2%)	51.9 (42.9, 476.4%)

Two numbers in parentheses indicate increase and ratio compared to DPPSM. For example, two numbers in parentheses of CR in S111 were calculated by $-43.2 = 699.2 - 742.4$, $-5.8\% = -43.2 / 742.4$.

The DPPSM showed better performance in most of scenarios with three (u=1), five (u=3), and six (u=5). Also, the DPPSM made better performance as u increases compared to the other rules. In case of scenarios with tight due date such as S111 and S311, SPT was the best rule showing the lowest tardiness, which was as known (Weng and Ren 2006). These results show that the DPPSM tends to be superior to using the existing rules as the due date uncertainty increases.

DISCUSSIONS AND CONCLUSIONS

In this simulation experiments, the authors tested four different dispatching rules (or priority rules) in job shop scheduling for precast concrete production when there exists order variability by a contractor. In most cases where order variability, the simulation results suggest that a new priority rule of EDLU, which penalizes a job order by a contractor with low order reliability, shows better delivery performances in terms of the average lead time and its variance. In light of lean construction principles, the simulation results suggest the followings:

First, order variability leads to variance of prefabricated product delivery. The best way to reduce order variability is to improve a contractor's planning reliability. The lean construction literature has shown that the planning reliability makes an impact on project schedule and productivity of trades on sites. The simulation experiments suggest that the order variability makes a negative impact on the lead time and its variance of prefabricated products.

Second, EDLU is more effective than traditional dispatching rules when order variability increases. The paper proposes a new dispatching rule of EDLU. The proposed EDLU may help the precast concrete suppliers develop their job shop schedule when there is order variability.

This study supposed that the due date uncertainty has the uniform distribution. The authors will conduct the further study to verify the effectiveness of the proposed model with the distribution shape of the uncertainty obtained from real construction projects.

REFERENCES

Ballard, G. and Arbulu, R. (2004). "Making Prefabrication Lean", International Group of Lean Construction, Helsingor, Denmark.

Benjaoran, V., Dawood, N., and Hobbs, B. (2005). "Flowshop scheduling model for bespoke precast concrete production planning". *Construction Management and Economics*, 23(1), 93–105.

Chan, W. T. and Hu, H. (2002). "Production scheduling for precast plants using a flow shop sequencing model". *Journal of computing in civil engineering*, 16(3), 165–174.

Chan, W. T. and Wee, T. H. (2003). "A Multi-Heuristic GA for Schedule Repair in Precast Plant Production". *International Conference on Automated Planning and Scheduling, American Association for Artificial Intelligence*, Trento, Italy, June 9–13 (pp.236–245).

Dawood, N. N. (1995). "Scheduling in the precast concrete industry using the simulation modelling approach". *Building and Environment*, 30(2), 197–207.

Ho, C. (2019). Application of optimization to the production planning of construction prefabrication supply chains. Ph.D. Dissertation, College of Built Environment, University of Washington.

Kim, J. M., Zhou, Y. D., & Lee, D. H. (2017). "Priority scheduling to minimize the total tardiness for remanufacturing systems with flow-shop-type reprocessing lines". *The International Journal of Advanced Manufacturing Technology*, 91(9-12), 3697-3708.

Kim, T., Kim, Y., and Cho, H. (2020). "Dynamic production scheduling model under due date uncertainty in precast concrete construction", *Journal of Cleaner Production*, 257.

Ko, C. H. (2010). "Production control in precast fabrication: considering demand variability in production schedules". *Canadian Journal of Civil Engineering*, 38(2), 191–199.

Ma, Z., Yang, Z., Liu, S., and Wu, S. (2018). “Optimized rescheduling of multiple production lines for flowshop production of reinforced precast concrete components”. *Automation in Construction*, 95, 86-97.

McGraw Hill Construction. (2011). *Prefabrication and Modularization: Increasing productivity in the construction industry*. Smart Market Report, New York.

Wang, Z. and Hu, H. (2017). “Improved precast production–scheduling model considering the whole supply chain”. *Journal of computing in civil engineering*, 31(4), 04017013.

Weng, M. X. and Ren, H. (2006). “An efficient priority rule for scheduling job shops to minimize mean tardiness”. *IIE transactions*, 38(9), 789–795.

Yang, Z., Ma, Z. and Wu, S. (2016). “Optimized flowshop scheduling of multiple production lines for precast production”. *Automation in Construction*, 72, 321–329.

Atiq Ur Rehman, M., Chaabane, A., and Khan, S.A. (2021). "Review of Construction Supply Chain Optimization Papers for Performance Improvement." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 974–984, doi.org/10.24928/2021/0132, online at iglc.net.

REVIEW OF CONSTRUCTION SUPPLY CHAIN OPTIMIZATION PAPERS FOR PERFORMANCE IMPROVEMENT

Muhamamd Atiq Ur Rehman[1], Amin Chaabane[2], and Sharfuddin Ahmed Khan[3]

ABSTRACT

For many countries, improving the construction sector's productivity is becoming more critical for achieving a sustainable long-term competitive advantage. Moreover, the construction industry is increasingly considering digitization, automation, and Information and Communications Technology (ICT) to achieve this objective. Advanced analytics application in supply chain optimization plays a critical role in supporting enterprise performance optimization in many sectors.

Therefore, this research aims to provide researchers with an overview of the recent developments of optimization techniques on the construction supply chain (CSC) for maximizing performance or minimizing cost and highlight the current research gaps in the field. The systematic desk methodology has been used in this research.

The findings of this study shows that there is need of a framework that integrate all CSC processes for its overall optimization as very few studies incorporated design phase processes with procurement and execution phase processes in their optimization model.

KEYWORDS

Off-site construction, supply chain management, modular construction, optimization, Integration.

INTRODUCTION

Construction supply chain management (CSCM) comes with challenges such as lack of collaboration among construction project stakeholders, lack of knowledge transferring and sharing capabilities, lack of standardization and lack of process integration(Saini, Arif, & Kulonda, 2019) and its optimization for maximizing productivity and minimizing project cost is even greater complex and challenging because CSC involves multiple players and such as owner, designer, contractor, sub-contractor, and outsources labor and processes such as manufacturing ,warehousing , inventory ,transporation and execution at construction site.These stakeholders and processes are interdependent to each other at different levels of a project.

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In addition to this, the stakeholders' benefits and requirements are conflicting as well so it is intricate to achieve a win-win situation for every stakeholder in a construction project. Also, lack of engagement during project lifecycle results in over budget and longer duration for a construction project completion and due to these reasons small and medium-sized companies are way behind reaping optimized integration benefits involved in a construction project. (Bahadorestani, Naderpajouh, & Sadiq, 2020). Consequently, in order to optimize overall CSC of a project and avoiding any conflict , all the processes and their effects must be incorporated in a model developed for maximizing performance of a project.So there is need of a research that provide comprehensive overview of existing papers focused on application of optimization on CSC processes.

Therefore, in this study, an attempt has been made to review the CSCM optimization papers that incorporated major CSC processes in their model and identify research gaps for further improvement in this area.

LITERATURE REVIEW

There are few studies that reviewed CSCM papers but they were not related with optimization application. One review study was related to enablers in CSC (Q. Chen, Hall, Adey, & Haas, 2020) , one was related with decision making in CSC (Phuoc Luong Le, Elmughrabi, Dao, & Chaabane, 2020) and the other was done on the development of framework for SC planning consist of construction process critera(Thunberg, 2016).Furthermore ,one paper reviewed CSC papers in the context of industry 4.O (Dallasega, Rauch, & Linder, 2018) and one paper review is related with internet of things(Kumar & Shoghli, 2018) .Thus this study is going to be first of its kind that reviewed CSC optimization papers against SC processes.

To review the CSC optimization papers, a benchmark or refrence list of exhastuive SC processes was required to evaluate review papers against those processes.(Y. Liu, Dong, & Shen, 2020) and (Phuoc Luong Le et al., 2020) identified the CSC levels, phases and processes in a very comprehensive manner is presented in table 1. These processes is taken as benchmark and review of CSC optimization papers is carried out based on these processes in this study.

Table1: Phases and Processes in Construction Supply Chain Management

Collaboration Level								Execution level			
Design Phase			Procurement Phase					Construction Phase			
CSC Configuration	Modularity	Strategic Planning/ Risk Evaluation	Production/ Prefab components Planning	Supplier Selection	Purchasing Decision	Storage	Building Partnership	Transportation	Site Layout Planning	Controlling Information Flow and Other Delay Factors	Material Handling

- CSC Configuration (CC): To configure and allocate CSC factors, SC participants, material and information flows, strategies, and resources of the SC network.
- Modularity (M): To determine the modularity of a building under controlled conditions.
- Strategic Planning/ Risk Evaluation (SR): To identify, assess risks, raise mitigation and contingency strategies, and respond efficiently to recognized threats as they arise. Production/Prefab Components Planning (PP): To make and control the construction project's production plan and manufacturing processes.
- Supplier Selection (SS): To apply efficient methods for supplier evaluation & selection.
- Purchasing Decision (PD): To employ the efficient methods for material procurement.
- Storage(S): To figure out the most cost-effective warehousing of prefab components.
- Building Partnership (BP): To apply SCM in construction to achieve long-term and supportive partnerships among stakeholders to ensure project cost optimization
- Transportation (T): To establish and control the transportation system (Off & On-Site).
- Site Layout Planning (SLP): To improve the on-site construction performance by optimizing the arrangement of facilities.
- Controlling Information Flow and Other Delay Factors (CD): To control information and physical flows to avoid instability in construction execution.
- Material Handling (MH): To convey, elevate, position, transport, package, and store materials and facilities management.

RESEARCH METHOD

A systematic literature review has been carried out in this research. This approach is adopted from the papers (Seuring & Gold, 2012) and (Khan, Chaabane, & Dweiri, 2018), and it of papers (Mettler, Eurich, & Winter, 2014).

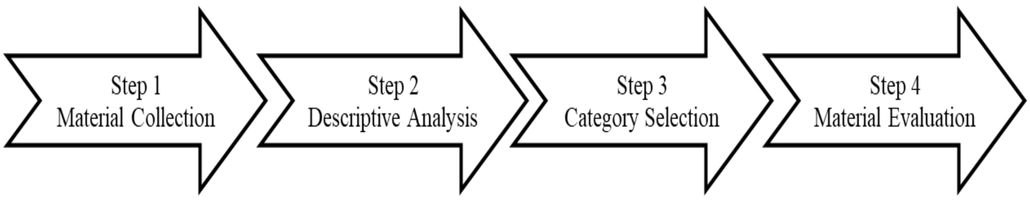


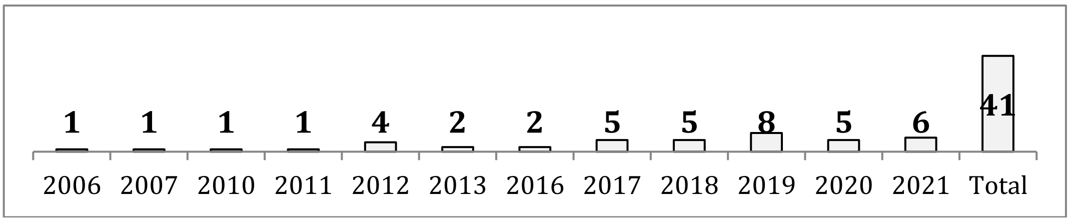
Figure1: Literature Review Method

- Step1: The Scopus database has been used in this research because it covers a superior number of journals and articles (Aghaei Chadegani et al., 2013). Unpublished work, non-reviewed papers, working papers, and book chapters are not considered in this study. The keyword search approach is used because it is the most common way of literature review in databases and library services (Seuring & Gold 2012). The different keywords and their combination results are shown in Table 2.

Table 2: Selected Keywords Combination Search Results

Keywords Combination	Search Results
Construction Supply Chain AND Optimization AND Logistics	99
Construction Supply Chain AND Optimization AND Material Planning	31
Construction Industry AND Optimization AND Supply Chain	146
Construction Industry OR Building AND Supply Chain	471
Building AND Optimization AND Supply Chain	536
Construction Supply Chain AND Modular AND Optimization	17
Building AND Optimization AND Logistics	291
Construction AND Supply Chain AND Optimization	516
Construction AND Supply Chain AND Improvement	522
Construction AND Logistics AND Optimization	726
Construction AND Logistics AND Improvement	506
Construction AND Material Planning AND Optimization	647
Construction AND Material Planning AND Improvement	591
Building AND Supply Chain AND Improvement	431

- Step2: After searching papers using different keywords combination, filtration of those papers was done through the criteria: If a paper studied or implement the application of optimization tools on construction supply chain processes as identified in this paper, that paper was selected. 41 papers were finalized after step 2, as shown in below graph 1.



Graph 1: Year Wise break up of Selected Papers

- Step3: Categorized them on the basis of optimization tools and CSC processes.
- Step4: Evaluation of selected papers was done by reading the article's abstract, methodology, and conclusion. Then, identify what and how many supply chain process factors are incorporated in a paper's mathematical model. This material evaluation process was based on all authors' academic judgment, and cross-reading was performed to eliminate the discrepancy in understanding among authors for material evaluation.
- Step5: An additional step is also taken, which is not a part of this approach. The optimization tools identified in the papers mentioned in table 3 are verified with the literature definition of the tools to ensure correct understanding of the tools concept.

RESULTS

In line with the first research objective of this study , analysis was done on the filtered papers against CSC processes and optimization tools as mentioned in table 3. As mentioned in Table 3, the MCDM tool is found to be the most used optimization technique. In CSC, out of 41 papers, 25 and 24 articles have focused on CSC's transportation and purchasing decision processes, followed by the storage process, which has been studied 21 times. At the same time, CSC configuration and strategic planning received the least attention from the authors as only six studies have focused on them. The process such as material handling, site layout planning, and supplier selection has been studied moderately.Following is the analysis of table 3 findings:

DESIGN PHASE

Collaboration level processes received the least attention relatively with the rest of the processes. Only 19 papers from 44 have focused at least on one of the management-level processes. Very limited numbers of papers were found that used mathematical tools to develop construction supply chain configuration and strategic management, so the application of mathematical tools is still not very mature or underexploited.

PROCUREMENT PHASE

Most of the studies on CSC have focused on planning-level processes. Thirty-six papers from 44 have contributed to at least one of the CSC procurement phase processes as mentioned in Table3. Multi-criteria decision-making tools have been applied successfully in mostly supplier selection problems. Operation research modeling such as linear, integer, or even mixed-integer linear programming models along with stochastic models has been used to tackle manufacturing planning, material ordering, and storage issues of construction material and prefabricated components.

CONSTRUCTION PHASE

32 papers have focused on at least any one of the processes of this phase. Hybrid models, simulation techniques, and multi-criteria decision-making have been applied to predict delays on construction sites and supply material transportation. Using mathematical models for optimizing transportation processes is very mature in other sectors and looks promising in other processes as well.

Authors	Optimization Tool	CC	ML	SR	PP	SS	PD	S	BP	T	SL	CD	MH
(Elimam & Dodin, 2013)	MILP				√	√	√	√		√			
(Alayet, Lehoux, & Lebel, 2018)	LP				√			√		√			
(Cengiz, Aytekin, Ozdemir, Kusan, & Cabuk, 2017)	MCDM					√			√				
(Q. Chen, García de Soto, & Adey, 2021)	NLP						√	√	√	√			
(W. W. Chen, Lei, Wang, Teng, & Liu, 2018)	MILP					√	√	√		√			√
(Costa, Granja, Fregola, Picchi, & Staudacher, 2019)	MCDM	√		√					√			√	
(Deng, Gan, Das, Cheng, & Anumba, 2019)	NLP					√	√	√	√	√	√		√
(Hemanth et al., 2017)	MCDM			√					√			√	
(Hsieh, 2016)	Hybrid Methods									√	√	√	
(P. Y. Hsu, Angeloudis, & Aurisicchio, 2018)	Two-stage Stochastic		√		√	√	√	√		√			
(P. Y. Hsu, Aurisicchio, & Angeloudis, 2017)	MILP		√		√	√	√	√	√	√			
(P.-Y. Hsu, Aurisicchio, & Angeloudis, 2019)	Hybrid Methods		√			√	√	√		√	√	√	
(JaŚkowski, Sobotka, & Czarnigowska, 2018)	MILP					√	√	√					
(Karabayir, Botsali, Kose, & Cevikcan, 2020)	MCDM					√							
(Kayhan, Cebi, & Kahraman, 2019)	MCDM			√		√	√						
(S. Kim, Chang, & Castro-Lacouture, 2020)	Simulation methods											√	
(T. Kim, Kim, & Cho, 2020)	Simulation methods			√	√					√	√	√	√
(Y. W. Kim, Han, Yi, & Chang, 2016)	Simulation methods	√			√		√	√		√			
(Komsiyah, Wongso, & Pratiwi, 2019)	MCDM					√			√				
(Kristy & Zagloel, 2020)	MCDM					√			√				
(Leontaris, Morales-Nápoles, Dewan, & Wolfert, 2019)	Simulation methods			√			√			√	√	√	√
(van der Beek, van Essen, Pruyn, Aardal, & Hopman, 2019)	MILP		√		√		√	√					
(J. Liu & Lu, 2017)	LP		√				√			√		√	√
(Yazdi, Fini, & Forsythe, 2020)	LP		√		√						√		
(Jing Liu & Lu, 2018)	Hybrid Methods		√	√	√		√			√		√	√
(Tserng, Yin, & Li, 2006)	Constraint Programming				√		√	√	√	√			
(Castro-Lacouture, Medaglia, & Skibniewski, 2007)	LP							√					
(Taghaddos, Hermann, AbouRizk, & Mohamed, 2010)	Simulation		√		√		√	√		√	√	√	√
(Pan, Lee, & Chen, 2011)	LP	√				√	√	√		√			
(Cadena, Ramos, Gómez, & Munoz, 2012)	MILP										√	√	√
(D. Liu, 2012)	Genetic Algorithm	√											
(Said & El-Rayes, 2012)	Genetic Algorithm						√	√		√	√		√
(Xanthopoulos, Aidonis, Vlachos, & Iakovou, 2012)	LP										√	√	√
(Said & El-Rayes, 2013)	Hybrid Methods	√					√	√	√	√	√	√	
(J. H. Chen, Yan, Tai, & Chang, 2017)	Linear Programming				√					√			
(Golkhoo & Moselhi, 2019)	Hybrid Methods						√	√		√		√	√
(Jaafar, Elbarkouky, & Kennedy, 2021)	MILP										√	√	√
(P. L. Le, Jarroudi, Dao, & Chaabane, 2021)	LP					√	√	√	√	√			
(Mirghaderi & Modiri, 2021)	Hybrid Methods	√			√		√	√		√			√
(Son, Duy, & Dat, 2021)	Hybrid Methods				√		√	√		√			
(Zhu, Dai, Liu, Xu, & Alwisy, 2021)	LP		√		√		√			√		√	√
Total papers / CSC Process		6	9	6	15	14	24	21	11	25	12	16	14

DISCUSSION

RESEARCH OPPORTUNITY (RO) 1

"Best Decision-Making Tool for Each Construction Supply Chain Process"

There are papers where operations research is applied to the construction supply chain process, and some papers even try to cover the whole aspect of the construction supply chain. However, there is still a lack of research that identifies the best decision-making tool for each supply chain aspect. For example, Fuzzy AHP is most recommended for supplier selection as identified from the literature review (Su, 2020) but it is not adequate for other processes such as demand prediction where stochastic models may work well. Therefore, research is needed to find the best decision-making tool for each supply chain construction process that can incorporate uncertainties and scenarios of that process.

RESEARCH OPPORTUNITY 2

"Framework for Optimizing Overall Construction Supply Chain"

There is a need for a framework to identify the best practice to optimize the overall construction supply chain. That framework will include phases and processes like mentioned in this research and the best tools for each process mentioned in research gap that framework will also identify how to integrate each process's best results to optimize the overall construction supply chain to produce the most effective results.(S.-Y. Kim & Nguyen, 2020) also identified factors that are barrier in effective CSC implementation , some barriers were lack of involvement in active participation from parties and lack of knowledge of applied SCM etc , so their study can be helpful for this research opportunity.

RESEARCH OPPORTUNITY 3

"Standardizing Supply Chain processes through Lean Construction."

Recent trend shows that researchers have recommended lean construction. The research can be done on standardizing construction supply chain processes. Lean management is about removing things that do not add value to the cause; that can be an operation or/an excess of anything such as cost, time utilized in executing any function. Therefore, standardization of construction supply chain processes through lean management tools such as Value Stream Mapping (VSM) can be a critical first step before optimizing or improving those processes.Similar opportunity was identified by (Dana Broft, 2020) where they proposed combine usage of SC and lean pricnicples for effective CSCM.

CONCLUSION

An attempt has been made in this research to identify and analyze the papers related to the application of optimization tools to maximize performance or minimize the cost of CSC. Forty-one papers were analyzed against 12 processes of CSC, and none of them were covering all the processes in their optimization model. Design-level processes are qualitative and not easy to incorporate them into the model. Still, their factors and effects can be incorporated in future optimization tools to comprehend all the processes and optimize CSC effectively. This is the major research opportunity identified in this research. However , to achieve this effectively, it is needed to identify the best decision-making tool for each process (RO 1) and then incorporate all the processes and their effects, especially design level qualitative processes, in a mathematical model (RO 2).

This research has some limitations. Indeed, only the Scopus database has been used to explore papers, so a web of science database could be added for future research. Finally, this research focuses only on CSC optimization.Therefore, doing the same research from different methodology/technique perspective could also be done in the future.

REFRENCES

Aghaei Chadegani, A., Salehi, H., Yunus, M., Farhadi, H., Fooladi, M., Farhadi, M., & Ale Ebrahim, N. (2013). A comparison between two main academic literature collections: Web of Science and Scopus databases. *Asian social science, 9*(5), 18-26.

Alayet, C., Lehoux, N., & Lebel, L. (2018). Logistics approaches assessment to better coordinate a forest products supply chain. *Journal of Forest Economics, 30*, 13-24.

Bahadorestani, A., Naderpajouh, N., & Sadiq, R. (2020). Planning for sustainable stakeholder engagement based on the assessment of conflicting interests in projects. *Journal of Cleaner Production, 242*, 118402.

Cadena, J. E., Ramos, M. A., Gómez, J. M., & Munoz, F. (2012). *Facility layout optimization detailed research through MILP and MINLP.* Paper presented at the Global Congress on Process Safety 2012 - Topical Conference at the 2012 AIChE Spring Meeting and 8th Global Congress on Process Safety.

Castro-Lacouture, D., Medaglia, A. L., & Skibniewski, M. (2007). Supply chain optimization tool for purchasing decisions in B2B construction marketplaces. *Automation in Construction, 16*(5), 569-575.

Cengiz, A. E., Aytekin, O., Ozdemir, I., Kusan, H., & Cabuk, A. (2017). *A Multi-criteria Decision Model for Construction Material Supplier Selection.* Paper presented at the Procedia Engineering.

Chen, J. H., Yan, S., Tai, H. W., & Chang, C. Y. (2017). Optimizing profit and logistics for precast concrete production. *Canadian Journal of Civil Engineering, 44*(6), 393-406.

Chen, Q., García de Soto, B., & Adey, B. T. (2021). Supplier-contractor coordination approach to managing demand fluctuations of ready-mix concrete. *Automation in Construction, 121*, 103423.

Chen, Q., Hall, D. M., Adey, B. T., & Haas, C. T. (2020). Identifying enablers for coordination across construction supply chain processes: a systematic literature review. *Engineering, Construction and Architectural Management*.

Chen, W. W., Lei, L., Wang, Z. W., Teng, M. F., & Liu, J. M. (2018). Coordinating supplier selection and project scheduling in resource-constrained construction supply chains. *International Journal of Production Research, 56*(19), 6512-6526.

Costa, F., Granja, A. D., Fregola, A., Picchi, F., & Staudacher, A. P. (2019). Understanding Relative Importance of Barriers to Improving the Customer-Supplier Relationship within Construction Supply Chains Using DEMATEL Technique. *Journal of Management in Engineering, 35*(3).

Dallasega, P., Rauch, E., & Linder, C. (2018). Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry, 99*, 205-225.

Dana Broft, R. (2020). Lean Supply Chain Management in Construction: Implementation at the ‘Lower Tiers’ of the Construction Supply Chain. *Successful Construction Supply Chain Management: Concepts and Case Studies*, 271-287.

Deng, Y., Gan, V. J. L., Das, M., Cheng, J. C. P., & Anumba, C. (2019). Integrating 4D BIM and GIS for Construction Supply Chain Management. *Journal of Construction Engineering and Management, 145*(4).

Elimam, A. A., & Dodin, B. (2013). Project scheduling in optimizing integrated supply chain operations. *European Journal of Operational Research, 224*(3), 530-541.

Golkhoo, F., & Moselhi, O. (2019). Optimized material management in construction using multi-layer perceptron. *Canadian Journal of Civil Engineering, 46*(10), 909-923.

Hemanth, G., Sidhartha, C., Jain, S., Saihanish, P., Rohit, V., & Ieee. (2017). *AHP analysis for using Cloud Computing in Supply Chain Management in the Construction Industry*.

Hsieh, F. S. (2016). *Location-aware workflow scheduling in supply chains based on multi-agent systems.* Paper presented at the TAAI 2015 - 2015 Conference on Technologies and Applications of Artificial Intelligence.

Hsu, P.-Y., Aurisicchio, M., & Angeloudis, P. (2019). Risk-averse supply chain for modular construction projects. *Automation in Construction, 106*, 102898.

Hsu, P. Y., Angeloudis, P., & Aurisicchio, M. (2018). Optimal logistics planning for modular construction using two-stage stochastic programming. *Automation in Construction, 94*, 47-61.

Hsu, P. Y., Aurisicchio, M., & Angeloudis, P. (2017). *Supply chain design for modular construction projects.* Paper presented at the IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction.

Jaafar, K., Elbarkouky, R., & Kennedy, J. (2021). Construction site layout optimization model considering cost and safety in a dynamic environment. *Asian Journal of Civil Engineering, 22*(2), 297-312.

Jaśkowski, P., Sobotka, A., & Czarnigowska, A. (2018). Decision model for planning material supply channels in construction. *Automation in Construction, 90*, 235-242.

Karabayir, A. N., Botsali, A. R., Kose, Y., & Cevikcan, E. (2020) Supplier selection in a construction company using fuzzy AHP and fuzzy TOPSIS. In*: Vol. 1029. Advances in Intelligent Systems and Computing* (pp. 481-487).

Kayhan, B. M., Cebi, S., & Kahraman, C. (2019). Determining and Prioritizing Main Factors of Supplier Reliability in Construction Industry. *Journal of Multiple-Valued Logic and Soft Computing, 32*(1-2), 111-134.

Khan, S. A., Chaabane, A., & Dweiri, F. T. (2018). Multi-criteria decision-making methods application in supply chain management: A systematic literature. *Multi-criteria methods and techniques applied to supply chain management, 1*.

Kim, S.-Y., & Nguyen, V. T. (2020). Supply chain management in construction: critical study of barriers to implementation. *International Journal of Construction Management*, 1-10.

Kim, S., Chang, S., & Castro-Lacouture, D. (2020). Dynamic Modeling for Analyzing Impacts of Skilled Labor Shortage on Construction Project Management. *Journal of Management in Engineering, 36*(1).

Kim, T., Kim, Y. W., & Cho, H. (2020). Dynamic production scheduling model under due date uncertainty in precast concrete construction. *Journal of Cleaner Production, 257*.

Kim, Y. W., Han, S. H., Yi, J. S., & Chang, S. W. (2016). Supply chain cost model for prefabricated building material based on time-driven activity-based costing. *Canadian Journal of Civil Engineering, 43*(4), 287-293.

Komsiyah, S., Wongso, R., & Pratiwi, S. W. (2019). *Applications of the fuzzy ELECTRE method for decision support systems of cement vendor selection.* Paper presented at the Procedia Computer Science.

Kristy, C. N., & Zagloel, T. Y. (2020). *An Integrated Analytical Hierarchy Process and Monte Carlo Method Approach for Supplier Selection in Construction's Supply Chain.* Paper presented at the ACM International Conference Proceeding Series.

Kumar, A., & Shoghli, O. (2018). *A review of IoT applications in supply chain optimization of construction materials.* Paper presented at the ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction.

Le, P. L., Elmughrabi, W., Dao, T.-M., & Chaabane, A. (2020). Present focuses and future directions of decision-making in construction supply chain management: a systematic review. *International Journal of Construction Management*, *20*(5), 490-509.

Le, P. L., Jarroudi, I., Dao, T. M., & Chaabane, A. (2021). Integrated construction supply chain: an optimal decision-making model with third-party logistics partnership. *Construction Management and Economics*, *39*(2), 133-155.

Leontaris, G., Morales-Nápoles, O., Dewan, A., & Wolfert, A. R. M. (2019). Decision support for offshore asset construction using expert judgments for supply disruptions risk. *Automation in Construction, 107*, 102903.

Liu, D. (2012). *The decision-making model of partnership portfolio on supply chain.* Paper presented at the 2012 IEEE International Conference on Mechatronics and Automation, ICMA 2012.

Liu, J., & Lu, M. (2017). *Optimization on supply-constrained module assembly process.* Paper presented at the IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction.

Liu, J., & Lu, M. (2018). Constraint Programming Approach to Optimizing Project Schedules under Material Logistics and Crew Availability Constraints. *Journal of Construction Engineering and Management*, *144*(7).

Liu, Y., Dong, J., & Shen, L. (2020). A Conceptual Development Framework for Prefabricated Construction Supply Chain Management: An Integrated Overview. *Sustainability*, *12*(5), 1878.

Mettler, T., Eurich, M., & Winter, R. (2014). On the use of experiments in design science research: a proposition of an evaluation framework. *Communications of the Association for Information Systems*, *34*(1), 10.

Mirghaderi, S. D., & Modiri, M. (2021). Application of meta-heuristic algorithm for multi-objective optimization of sustainable supply chain uncertainty. *Sadhana - Academy Proceedings in Engineering Sciences, 46*(1).

Pan, N. H., Lee, M. L., & Chen, S. Q. (2011). Construction material supply chain process analysis and optimization. *Journal of Civil Engineering and Management, 17*(3), 357-370.

Said, H., & El-Rayes, K. (2012). *Optimal material logistics planning in congested construction sites.* Paper presented at the Construction Research Congress 2012: Construction Challenges in a Flat World, Proceedings of the 2012 Construction Research Congress.

Said, H., & El-Rayes, K. (2013). *Automated system for multi-objective optimization of construction supply and site logistics.* Paper presented at the Proceedings, Annual Conference - Canadian Society for Civil Engineering.

Saini, M., Arif, M., & Kulonda, D. J. (2019). Challenges to transferring and sharing of tacit knowledge within a construction supply chain. *Construction Innovation*.

Seuring, S., & Gold, S. (2012). Conducting content-analysis based literature reviews in supply chain management. *Supply chain management: An international journal*.

Son, P. V. H., Duy, N. H. C., & Dat, P. T. (2021). Optimization of Construction Material Cost through Logistics Planning Model of Dragonfly Algorithm — Particle Swarm Optimization. *KSCE Journal of Civil Engineering*.

Su, Y. (2020). Selection and Application of Building Material Suppliers Based on Intuitionistic Fuzzy Analytic Hierarchy Process (IFAHP) Model. *Ieee Access, 8*, 136966-136977.

Taghaddos, H., Hermann, U., AbouRizk, S., & Mohamed, Y. (2010). *Simulation-based scheduling of modular construction using Multi-Agent Resource Allocation.* Paper presented at the Proceedings - 2nd International Conference on Advances in System Simulation, SIMUL 2010.

Thunberg, M. (2016). *Developing a framework for supply chain planning in construction* (Vol. 1782): Linköping University Electronic Press.

Tserng, H. P., Yin, S. Y. L., & Li, S. (2006). Developing a resource supply chain planning system for construction projects. *Journal of Construction Engineering and Management*, *132*(4), 393-407.

van der Beek, T., van Essen, J. T., Pruyn, J., Aardal, K., & Hopman, H. (2019). *Optimizing inventory strategy for modular shipbuilding*.

Xanthopoulos, A., Aidonis, D., Vlachos, D., & Iakovou, E. (2012). A planning optimisation framework for construction and demolition waste management. *International Journal of Industrial and Systems Engineering, 10*(3), 257-276.

Yazdi, A. J., Fini, A. A. F., & Forsythe, P. (2020). *An Integrated Product Planning and Design Platform in the Context of Housebuilding Industry.* Paper presented at the Construction Research Congress 2020: Computer Applications.

Zhu, M., Dai, J., Liu, R., Xu, J., & Alwisy, A. (2021). Two-period based carbon-economy equilibrium strategy for modular construction supply planning. *Journal of Cleaner Production, 290*.

Pikas, E., Seppänen, O., Koskela, L., and Peltokorpi, A. (2021). "Challenges in Industrialized Renovation of Apartment Buildings." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 985–994, doi.org/10.24928/2021/0155, online at iglc.net.

CHALLENGES IN INDUSTRIALIZED RENOVATION OF APARTMENT BUILDINGS

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ABSTRACT

Motivated by the European Green Deal framework, an ambitious 30-years long renovation strategy has been established in Estonia. This renovation strategy requires a substantial increase in the annual renovation capacity. New capabilities in terms of industrialization and digitalization of sustainable renovation processes need to be promoted. This explorative research aims to identify and understand existing practices, main barriers, and opportunities to industrialize and digitalize sustainable renovation of existing apartment buildings. Interviews and secondary data sources are used for data collection and analysis. Still many barriers exist, and more research and development in core elements of the industrialized renovation of apartment buildings is required. For example, further standardization of renovation products and processes is needed. Also, digitalization and automation of industrialized renovation of apartment buildings were the least developed core element.

KEYWORDS

Sustainability, renovation, industrialization, lean renovation, standardization.

INTRODUCTION

In the new European Green Deal framework, an ambitious objective to renovate existing building stock within the next 30 years has been established (Commission 2020a). To achieve the required volume at the reduced cost and lead time, the European Commission promotes the industrialization and digitalization of sustainable renovation of existing buildings (Commission 2020b).

However, the EU Commission's recommendations are eclectic and come short in providing a coherent framework and conceptualization for the renovation wave. Lean construction provides a conceptualization and framework to project-based renovation production systems. Kemmer (2018) proposed the renovation management method based on the transformation, flow, and value (TFV) theory. Kemmer's management method, however, did not address the industrialization and digitization of renovation processes as systemic means to improve renovation processes.

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This research aims to identify and understand existing practices, main barriers, and opportunities to develop the sustainable renovation of existing Soviet-time apartment buildings in Estonia. A qualitative approach is used, and interviews and secondary data sources are used to collect, analyze, and interpret data. The paper is structured as follows: (1) background study, (2) research method; (3) results; (4) discussion and conclusions.

BACKGROUND

The European Green Deal framework sets the policy to "building and renovating in an energy and resource-efficient way" (Commission 2020a). A roadmap for renovation has been established for improving the quality of the built environment for 80% of Estonian citizens by 2050. The roadmap sets objectives to reduce thermal energy needs up to 70%, electricity consumption up to 20%, and CO2 emissions up to 90% (Kurnitski et al. 2020). According to the strategy, 141 000 (27 000 public, 100 000 single-family, and 14 000 residential) buildings with a total area of 5.4 million m^2 need to be renovated (Kurnitski et al. 2020). This requires at least 2 to 4 times increase in the sector's current renovation capacity.

During the Soviet time in Estonia, large suburban areas were rapidly built using standardized designs and industrialized (Meuser and Zadorin 2015) mineral-based construction products (Kurnitski et al. 2020). Timber is considered a substitute for mineral-based construction products to promote sustainable construction (Lazarevic et al. 2020): (1) to reduce the CO_2 emissions (Balasbaneh et al. 2018; Skullestad et al. 2016); (2) to compress project lead time (Bertram et al. 2019); and (3) to tailor solutions that meet individual customer's needs (Wang et al. 2014). Timber-based construction also comes with the focus on industrial efficiency, underpinned by two broad strategies (Pelli 2021): (1) standardization of products and standardization of processes and (2) continuous improvement.

Renovation projects, however, have unique characteristics (e.g., existing assets and operations) and are subject to construction peculiarities (e.g., one-of-a-kind production, site production, and temporary organization) (Kemmer and Koskela 2020; Koskela 2000). Lean construction provides the conceptual framework of production and production management (Koskela 2000). Based on the TFV theory, Kemmer proposed a management method for renovation projects consisting of three elements (2018): including the conceptual model, the characterization of reconstruction projects, and the best practice guidelines for improving the reconstruction processes. However, the scope of Kemmer's (2018) study did not include the utility of industrialized practices and digitization of renovation processes.

The primary motivation for the industrialized renovation of buildings includes reducing lead time and cost and improving delivery and product quality. Also, industrialization helps to address construction peculiarities (Vrijhoef and Koskela 2005). It is a change in the construction system (Larsson et al. 2014), enabled by standardization of products and processes, underpinned by repetition, continuous learning, and experience feedback (Bertelsen 2004). Larsson et al. (2014) proposed the industrialized construction framework with five core elements and barriers. Although the framework was developed for infrastructure projects, the general conclusions also apply in the renovation of buildings.

The five core industrialization elements identified by Larsson et al. (2014) include: (1) Prefabrication related to product standardization strategy; and (2) integrated design and construction, (3) collaborative planning, (4) continuous improvement, and (5) digitalization and automation related to process standardization. Larsson et al. (2014) also identified five barriers to industrialization: (1) conservatism, (2) lack of repetition, (3) norms and codes, (4) procurement practices, and (5) regulatory framework.

In terms of the digitalization and automation of renovation processes, many relevant construction technologies are developed. For example, for mapping (e.g., scan to BIM, drone imaging, photogrammetry) (Wang et al. 2019) and sensing (e.g., physics-based sensors, computer vision) (Martinez et al. 2021) technologies are used to collect data. Building information modeling and simulation (Alwisy et al. 2019) and advanced data analytics (e.g., machine learning), utilizing collected data, are used to plan and design solutions. Building cloud-based common data environments (ISO 2018; Patacas et al. 2020) and digital twins (Sacks et al. 2020) could be used to manage data in the sustainable delivery of renovation projects.

RESEARCH METHOD

A case study was carried out to identify and understand existing practices, main barriers, and opportunities: the Akadeemia 5A student apartment building. The renovation project was completed in 2018, using industrialized wooden walls and roof panels to achieve a nearly zero energy building certification. Two additional interviews with the two timber building manufacturers in Estonia were carried out. These interviews were carried out to study their perspectives on the industrialized renovation of buildings.

Altogether seven semi-structured interviews were conducted. As part of the case study, five interviews with the client (two interviews), academic (one interview), designer (one interview), and manufacturer (one interview) were carried out. Project documents were also collected and used to analyze and interpret the best practices and problems. Two interviews from two different manufacturers included the project manager from the first manufacturer and the development manager from the second manufacturer. Interview questions were sent with an email invitation to take part in the interview. Participants were asked to prefill the interview answers before the online interview meeting.

THE CASE PROJECT DESCRIPTION

The renovation project initiated by the Tallinn University of Technology established the objective to renovate an existing building into a nearly zero energy building using an industrialized construction approach. The five-story building (Soviet building type 121) with 80 apartments was built in 1986. The building was constructed using prefabricated large reinforced concrete floor and wall elements and sandwich elements for external walls. External walls could not be removed as these formed an important part of the existing structural scheme. The measured primary energy use was 300 kWh/(m^2 a). The building before and after renovation is shown in Figure 1.

Figure 1. The building before (left) and after (right) renovation.

The total cost of renovation was 822 €/m^2 of which 121 €/m^2 was spent on general construction works, 251 €/m^2 on finishing works, 334 €/m^2 on energy efficiency works and 116 €/m^2 on nearly zero energy building research related works. The scope of the energy performance works included the general works and renovation or construction of facade, roof, ventilation, and heating systems. Currently, costs for renovation are different and are rapidly changing. According to Kredex (established by the Ministry of Economic Affairs and Communications in 2001 to provide financial solutions) that has supported around 1200 renovation projects within the last ten years, today the traditional renovation costs between 300-350 €/m^2 and industrialized renovation between 400-450 €/m^2.

RESULTS

Based on the interviews and documents collected, lessons learned about the practices, barriers, and opportunities are summarized. The discussion is organized around the typical value chain phases of renovation projects: planning, design, manufacturing, logistics and transportation, and installation.

STUDENT APARTMENT BUILDING CASE

Practices

According to interviewees, the main challenge was studying and measuring the building's existing conditions in the planning phase. Archived project documents were collected and studied to map the existing conditions. For mapping the building's geometric conditions, laser scanning was used to measure the envelope. The measured point deviation from the ideal reference wall plane with a minimum average distance to points was visualized in a color-coded manner. 50 sections were produced to analyze and communicate deviations. The locations and perimeters of 80 windows were checked manually.

In the design of industrialized renovation solutions, the solutions based on the existing geometric conditions, moisture safety, and energy performance to achieve the nearly zero energy building certification were prioritized. Due to the lack of standardized renovation solutions, technical solutions for wall and roof panels were developed with the university's researchers (the right picture in Figure **2**). Wooden wall elements included embedded ventilation ducts and windows. Two measures were developed to address existing conditions' geometric variation and install new prefabricated walls. First, a new 3D connection was developed (left picture in Figure **2**). Second, an additional buffer layer of insulation was added to the wooden wall panels' interior side (number 2 on the right picture in Figure **2**). The total duration of the design process was six months.

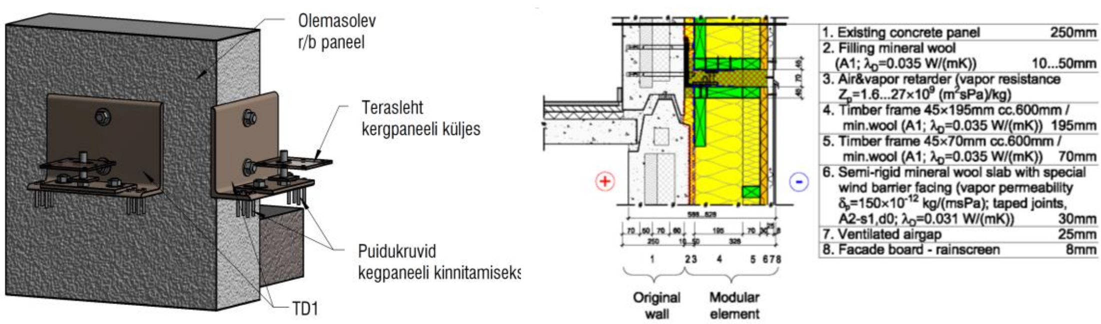

Figure **2**. Newly developed 3D connection (left) and wall panel cross-section (right).

The manufacturer of wall and roof elements was also responsible for delivering shop drawings. In the factory, the volume and sequence of production were determined based on the installation sequence. Windows were installed to the wall elements in the factory to avoid the interior environment being exposed to the exterior environment. Also, ventilation ducts embedded in wall panels were installed in the factory.

For logistics and transportation, materials were packaged and delivered according to the installation sequence. On the site, trucks with cranes were used to transport wall panels for the lower floors. For higher floors, a separate mobile crane was used to lift elements for installation. A truck with a crane was preferred due to its faster lifting speed.

For installation, the trade partner was procured based on the lowest bid price. First, the foundation insulation works were carried out. The installation of a new technical room on the roof was completed in parallel. After that, the preparation for installing the wall and roof panels was carried out, including the installation of 3D connections, new roof trusses, and structures. Finally, wall and roof panels were installed, and joints were insulated and covered. The projected speed of installation was achieved after two-thirds of the panels were installed.

Barriers

Several problems in the planning phase were discovered. Finding proper project documents from the archive was more time-consuming than expected. The scanned data was not accurate enough, and some information was missing. As the building façade was scanned from the ground, some features (e.g., the bottom line of an exterior window) on the façade were hidden from the measurement by elements (e.g., window rain stain or balconies) extending out the façade. The problem is more extensive with the higher buildings. Also, different organizations and people measured the exterior and interior, which led to the situation that information was not fully compatible.

According to interviewees, designers lacked a specialized knowledge of moisture engineering and an understanding of industrialized processes in the design phase. The needs from a process perspective were not considered in the design. This was partly caused by the procurement model used by the client, which did not allow to involve the manufacturer and installer in the preliminary design and design development stages.

Some problems during the manufacturing were encountered. As nearly zero energy certification was targeted, much material was used to produce elements, which made elements heavy and challenging to handle in the factory. Also, the soft wind barrier used in the wall elements complicated the manufacturing of elements.

According to the manufacturer, there was not much space around the building regarding logistics and transportation, making the coordination of manufacturing, transportation, and installation crucial. Interviewees suggested keeping in mind also the weather conditions and elements' installation locations. When materials (e.g., insulation and timber) were transported to the site in large volumes, much of it was left unused for an extended period, which increased the possibility of weather damage to the materials.

In the installation phase, two major problems were faced. First, the inappropriate installation of connections on the exterior walls caused some wall elements not to fit between the new 3D connections on different floors, slowing down the construction process significantly. Handwork to fit the elements on the site was required. Tape measure and the string was used to determine the locations for installing the connections. However, the locations were not compared against the design model, and the distances between connections on different floors were also not verified.

Second, the trade partner did not follow the manufacturer's recommendations to structure and organize the installation works. The manufacturer recommended using three crews to improve flow: crew for installing elements, crew for sealing joints, and crew covering joints with façade plates. Instead, the trade partner installed all wall and roof elements first, and only after that started to seal exterior wall and roof joints. This delayed the learning significantly as the hard work of sealing wall and roof joints was discovered late in the process. It also appeared that the 5 cm gap between two wall panels (placed vertically on top of each other) is not a safe and effective solution for someone to stick their hand into the joint to insulate the gap between panels.

Opportunities

For addressing the laser-scanning challenges, interviewees suggested developing guidelines and implementing the 'scan to BIM' workflow to automatically or semi-automatically reconstruct the building's as-is model. There are already software tools (e.g., PointCab or EdgeWise) for that, and much research is done in this area.

Several design related recommendations were made regarding technical product solutions. It was suggested that more research and development on wall panel connections should be done to simplify installation. Also, with better technical solutions, the building's additional waterproofing and insulation and covering of wall panel joints could have been avoided and simplified.

A general recommendation to integrate the different phases of the renovation processes was suggested for improving the design process. Some interviewees also argued that designing renovation solutions should be automated. A knowledge library of renovation solutions and BIM technology could be used to automate design work. Also, the workflow from the early design phase to the later design phases and manufacturing could be improved. That is, going from scan to BIM and BIM to computer-aided manufacturing (CAM) was recommended to be studied.

Several opportunities concerning logistics and transportation were identified. Interviewees suggested developing proper lifting equipment, considering the manufacturing, transportation, and installation needs. It was also suggested that the just-in-time and material kitting principles should be used to organize the transportation and installation of elements to avoid water and moisture damage.

Several recommendations to improve the installation process were made. Interview respondents suggested that the surveyor should have been involved throughout the installation process to double-check the locations of connections. It was also suggested to prototype the installation of wall panels on the site and use the production flow logic. The problem with the installed connections on existing exterior walls could have been discovered earlier through this approach. Namely, the connections were misplaced and placed into locations where there was a large volume of existing reinforcement, making the drilling of holes time-consuming. Instead of Excel, a general recommendation to use better software to coordinate and synchronize manufacturing, transportation, and installation was made.

INTERVIEWS WITH TWO MANUFACTURERS

Two additional interviews were conducted. The first manufacturer is currently delivering an industrialized renovation project in Saue, Estonia. The second is now preparing their industrialized renovation projects or products and services. According to the interviewees, their focus of developing industrialized solutions is to analyze business prospects, assess the renovation solutions' suitability for manufacturing, study automation possibilities, and digitalize processes. The main challenges are related to assuring high quality and efficiency. Also, according to interviewees, another main challenge is that traditional design and construction companies lack an understanding of industrialization and standardization and their role in cost-effectiveness and quality.

These companies are now analyzing the technical renovation solutions (e.g., studying fire safety and moisture safety requirements); collecting and digitalizing original project documents for Soviet time building types; preparing design templates and libraries; developing design and installation requirements for new assembly lines; and finding partners. Interviewees were also concerned with balancing the manufacturing supply with demand. In terms of logistics and transportation, participants think about packaging and storage of elements, access to sites, and developing special lifting equipment for elements. Regarding installation, problems foreseen are related to tolerance management and lack of skilled installation labor.

SUMMARY OF PRACTICES, BARRIERS, AND OPPORTUNITIES

Table 1 summarizes the practices, barriers, and opportunities for the industrialized and sustainable renovation of apartment buildings. Although there are many product and equipment specific problems, the majority seem to stem from the poor management of renovation projects. Establishing a proper management framework to enable continuous improvement within and across projects should be the priority. Next, the findings will be discussed within the industrialization framework proposed by Larsson et al. (2014).

Table 1. Summary of identified practices, barriers, and opportunities for the industrialized renovation of apartment buildings.

	Practices	Barriers	Opportunities
Planning	Studying archived project documents; laser scanning	Time-consuming to find; poor practices of scanning	Digitalizing original project documents; implement Scan to BIM
Design	Prefabricated wall and roof elements; 3D connections	Lack of knowledge and understanding of industrialization	Standardization of products; integration of value chain; automation and digitalization
Manufacturing	Sequencing; windows and ducts installed in the factory	Heavy elements; inappropriate materials for manufacturing	Special lifting equipment; proper choice of materials
Logistics and Transportation	Sequencing; different equipment	Lack of space around the building; weather	Proper lifting equipment; just in time delivery; material kitting
Installation	Procurement of trade partners based on lowers bid price	Installation of connections; poor installation management	Involvement of surveyors I the installation process; prototype installation; implement flow

DISCUSSION

BARRIERS TO INDUSTRIALIZATION

Based on the literature review, case study, and interviews, improving the sustainable renovation of existing buildings requires a comprehensive and systemic approach. That is, barriers, sub-systems and aspects of delivering renovations projects need to be addressed simultaneously. Larsson et al. (2014) identified five barriers to industrialization. Except for legal framework, all other barriers were identified through the case study and interviews. Conservatism was identified in several instances of the case study and interviews: (1) client and manufacturer used traditional procurement methods; (2) instead of the production flow logic, the trade partner focused on optimizing resource consumption; (3) traditional design and construction companies do not understand industrialized processes and the importance of standardization.

Repetition in the renovation of existing apartment buildings is probably not going to be a significant issue. Although changes were made, the Soviet time apartment buildings' designs were highly standardized. Instead, the problem is the lack of standardized products and processes. Challenges related to the norms and codes were related to fireproofing, waterproofing, and moisture safety engineering during the construction and in the building made of timber roof and wall panels.

Procurement and contracting practices influence renovation projects' organization and the possibilities to implement and integrate industrialized solutions. The design-bid-build model limits the scope of implementing industrialized solutions as knowledge and experience exchange and integration are limited (Koskela and Vrijhoef 2001). Owners should promote collaborative procurement and contracting models.

In this study, the lack of competencies was also identified as one barrier to implementing industrialized construction. For example, designers' lack of moisture safety and manufacturing constraints competencies and knowledge caused several challenges.

CORE ELEMENTS OF INDUSTRIALIZATION

All interviewees are currently developing or interested in developing standardized solutions to (1) prefabricate. However, the Akadeemia 5A project demonstrated that more product development and standardization are needed. For example, problems related to manufacturability (weight, rigidity, lifting, and selection of materials), transportation, and assembly (installation, sealing joints, and covering joints with façade panels) should be addressed.

More elements are related to process standardization. Better (2) integration between design, manufacturing, and installation could have helped avoid problems with manufacturing, transportation, and installation of elements. More coupled integration between the design information flow from design to manufacturing, transportation, and installation, and constraints flow from manufacturing, transportation, and installation to design is required (Jensen et al. 2012). Proper procurement and contracting methods to enable integrated processes (e.g., improving installation speed and safety) and tolerance management (ensuring that elements fit on the site) need to be implemented by clients.

For just-in-time delivery, to avoid material storage and moisture damage on the site, (3) collaborative planning and control are required. This also requires a shift in thinking as demonstrated in the organization of work by trade partner from transformation to flow view of renovation projects. Prototyping during design, manufacturing, and at the beginning of installation to test the feasibility of solutions and plans is also necessary. Many problems in the Akadeemia 5A case could have been avoided, such as the complexity of drilling holes on site, installing roof panels, the insulating of joints and covering of joints could have been discovered earlier.

Rapid learning and (4) continuous improvement within and across projects are necessary for industrialized renovation. Continuous learning is enabled through product standardization, process integration, collaborative planning and control, facilitated by experience feedback. Hence, systemic learning needs to be integrated into the industrialized renovation of sustainable apartment buildings.

Industrialized construction could be further facilitated by (5) digitalizing and automating processes. The digitalization level in industrialized renovation is low. Interviewees suggested that a scan to BIM framework should be adopted. Also, recommendations to automate design processes, utilizing BIM elements for standardized solutions, parametric design, and BIM to CAM were made. For information management in manufacturing, transportation, and installation, utilizing better digital solutions was recommended. The conceptual framework on the construction digital twin system has been proposed to address this limitation (Sacks et al. 2020). However, it has not yet been implemented nor tested in the context of renovation projects.

CONCLUSIONS

Large scale renovation brings forth challenges and opportunities for a systemic change in the construction industry. New capabilities for delivering industrialized renovation of sustainable buildings are needed. This research aimed to understand existing practices, main barriers, and industrialization opportunities for renovating existing apartment buildings. Several barriers need to be addressed for achieving new capabilities, and more research and development in core elements of the industrialized renovation of apartment buildings is required. Based on the literature review, case study, and interviews, improving the sustainable renovation of existing buildings requires a comprehensive and systemic management approach. Further standardization of renovation products and processes is needed, and digital and automation capabilities should be developed.

REFERENCES

Alwisy, A., Bu Hamdan, S., Barkokebas, B., Bouferguene, A., and Al-Hussein, M. (2019). "A BIM-based automation of design and drafting for manufacturing of wood panels for modular residential buildings." *International Journal of Construction Management*, Taylor & Francis, 19(3), 187–205.

Balasbaneh, A. T., Marsono, A. K. B., and Khaleghi, S. J. (2018). "Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment." *Journal of Building Engineering*, Elsevier, 20, 235–247.

Bertelsen, S. (2004). "Lean Construction: Where are we and how to proceed." *Lean Construction Journal*, 1(1), 46–69.

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., and Woetzel, J. (2019). *Modular construction: From projects to products*. McKinsey and Company, Chicago, USA, 34.

Commission, E. (2020a). *The European Green Deal*. COM(2019) 640 final, Official Journal of the European Union Brussels, Brussels, Belgium.

Commission, E. (2020b). *A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives [COM(2020) 662 final]*. Communication from the Commission to the European Parliment, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, Belgium.

ISO. (2018). "ISO 19650-1, Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM) — Information Management Using Building Information Modelling — Part 1: Concepts and Principles." *International Standards Organisation*.

Jensen, P., Olofsson, T., and Johnsson, H. (2012). "Configuration through the parameterization of building components." *Automation in Construction*, Elsevier, 23, 1–8.

Kemmer, S. (2018). "Development of a Method for Construction Management in Refurbishment Projects." PhD Thesis, University of Huddersfield.

Kemmer, S., and Koskela, L. (2020). "Lean as an appropriate approach for managing production in refurbishment projects." *Lean Construction: Core Concepts and New Frontiers*, Routledge, 230.

Koskela, L. (2000). "An exploration towards a production theory and its application to construction." Doctoral Dissertation, VTT Technical Research Centre of Finland, Espoo, Finland.

Koskela, L., and Vrijhoef, R. (2001). "Is the current theory of construction a hindrance to innovation?" *Building Research & Information*, 29(3), 197–207.

Kurnitski, J., Kuusk, K., Kuivjõgi, H., Lihtmaa, L., Uutar, A., Pikas, E., Kalamees, T., and Simson, R. (2020). *Hoonete rekonstrueerimise pikaajaline strateegia*. Majandus- ja Kommunikatsiooniministeerium, Tallinn, Eesti.

Larsson, J., Eriksson, P. E., Olofsson, T., and Simonsson, P. (2014). "Industrialized construction in the Swedish infrastructure sector: core elements and barriers." *Construction Management and Economics*, Routledge, 32(1–2), 83–96.

Lazarevic, D., Kautto, P., and Antikainen, R. (2020). "Finland's wood-frame multi-storey construction innovation system: Analysing motors of creative destruction." *Forest Policy and Economics*, Forest-based circular bioeconomy: matching sustainability challenges and new business opportunities, 110, 101861.

Martinez, P., Barkokebas, B., Hamzeh, F., Al-Hussein, M., and Ahmad, R. (2021). "A vision-based approach for automatic progress tracking of floor paneling in offsite construction facilities." *Automation in Construction*, Elsevier, 125, 103620.

Meuser, P., and Zadorin, D. (2015). *Towards a typology of Soviet mass housing: prefabrication in the USSR 1955-1991*. DOM publishers Berlin.

Patacas, J., Dawood, N., and Kassem, M. (2020). "BIM for facilities management: A framework and a common data environment using open standards." *Automation in Construction*, Elsevier, 120, 103366.

Pelli, P. (2021). "Service innovation and sustainable construction: analyses of wood vis-à-vis other construction projects." *Cleaner Engineering and Technology*, 100061.

Sacks, R., Brilakis, I., Pikas, E., and Xie, H. S. (2020). "Construction with digital twin information systems." *Data-Centric Engineering*, 1, 26.

Skullestad, J. L., Bohne, R. A., and Lohne, J. (2016). "High-rise timber buildings as a climate change mitigation measure–A comparative LCA of structural system alternatives." *Energy Procedia*, Elsevier, 96, 112–123.

Vrijhoef, R., and Koskela, L. (2005). "Revisiting the Three Peculiarities of Production in Construction." 19–27.

Wang, Q., Guo, J., and Kim, M.-K. (2019). "An application oriented scan-to-BIM framework." *Remote sensing*, Multidisciplinary Digital Publishing Institute, 11(3), 365.

Wang, Z., Chen, L., Zhao, X., and Zhou, W. (2014). "Modularity in building mass customization capability: The mediating effects of customization knowledge utilization and business process improvement." *Technovation*, Elsevier, 34(11), 678–687.

Espinoza, L. R., Herrera, R. F. and Brioso, X. (2021). "Use of Value Stream Mapping in a Case Study in Basement Construction." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29), Alarcon, L.F. and González, V.A. (eds.)*, Lima, Peru, pp. 995–1004, doi.org/10.24928/2021/0189, online at iglc.net.

USE OF VALUE STREAM MAPPING IN A CASE STUDY IN BASEMENT CONSTRUCTION

Lisseth R. Espinoza[1], Rodrigo F. Herrera[2], and Xavier Brioso[3]

ABSTRACT

The Value Stream Mapping (VSM) as a management tool helps evaluate the waste within the workflow. However, it must be adapted to the construction since it was originated in manufacture. This adaptation is possible through appropriate process mapping. This study aims to map the process of the basement construction system in the execution of a building in Lima-Peru city. The building in the case study will have nine basements and 11-floor levels. An adaptation of the optimization cycle for construction projects was used. It allows mapping all the relevant activities and proposing and implementing improvements in the construction system. As a result, three maps were obtained. The first one is a map of the current state (VSM 1). The second one is a map of the current state with improvements (VSM 2). Finally, a third map of the future state with improvements (VSM 3). This study demonstrated that it is possible to adapt the VSM in basement construction and the usefulness of this tool to evaluate and reduce waste within the workflow.

KEYWORDS

Value stream mapping, lean construction, production, continuous flow, VSM in construction.

INTRODUCTION

In Lima-Peru, the total time whereby value-added work is carried out on average is 28% in building projects (Guio 2001); this reveals waste in workflows. In this sense, the Value Stream Mapping (VSM), a management tool, is useful for identifying and evaluating waste within the workflow. However, despite this being a potential tool, it has not been applied frequently in the construction industry compared with manufacturing. Unlike manufacturing, a construction project is unique, with no repetition of the production process, barely tracking construction processes and data, and highly variable. VSM has potential but cannot be used directly in construction. Some adaptations are necessary to use VSM during the construction process (Fernandez-Solis and Li 2018).

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In a review study, Fernandez-Solis and Li (2018) identified that only nine articles are related to the implementation of VSM in the construction industry. Among these studies, the application of VSM in a tile prefabrication company showed improvements in 25% of productivity in its administration and production process (Gallardo et al. 2014). Covarrubias improved the administrative operations of a construction company (Covarrubias et al. 2016). Shou studied the value stream mapping in the shot blasting and coating industry (Shou et al. 2017). However, in construction systems, VSM was only applied to improve the structural masonry execution process (Melo et al. 2017) and the column concreting process (Germano et al. 2017). In Peru, two studies are applying with VSM, the first of them in highway projects (Román and Juárez 2014); and the second, to identify the productive flow, focusing on the identification of waste in a residential building, improving the workflow of the finishing stage (Murguia et al. 2016). Rosenbaum, S., et al (2014) applied VSM with a green-lean approach in constructing a hospital to simultaneously evaluate environmental and production wastes during the execution stage of the project. Gunduz and Fahmi Naser (2017) used VSM as a sustainable construction tool in the installation of underground pipes, and as a result, showed a cost reduction of 20.8%. Therefore, this paper describes a methodology to design an integrated and customized value stream map for construction industry requirements. The approach was developed and verified based on a collaborative Project (Matt et al 2013)

Consequently, to our best knowledge, there is no previous research in the literature on projects associated with excavations and soil containment structures until now. Thus, this study aims to apply the VSM tool to improve the basement construction system in its execution stage. The case study is about constructing nine basements in a high-rise building located in Lima - Peru city during the COVID-19 pandemic. The scope of this study is focused on the excavation and construction of anchored walls. In this sense, this work seeks to answer the following research question: how to improve workflow? How to reduce non-productive activities in the basement construction system? This study carried out a VSM in current and future states to answer this question with innovative improvements.

BACKGROUND

BASEMENT CONSTRUCTION

In Lima - Peru, like many developing countries, in recent years, there is a needing to grow vertically, with buildings of 20 to 30 floors and with basements of up to 10 to 12 levels for parking vehicles (García 2020; Guio and Cayllahua 2019). However, these buildings are usually built-in reduced land areas and constructions on the sides (García 2020). This happens due to the housing deficit resulting from the migrant population from the province to the city of Lima - Peru (Santa María 2019). This context has made building companies take full advantage of land availability and make buildings taking account of height and depth to satisfy this demand (Guio and Cayllahua 2019). Based on this context, basement construction systems and deep excavations are created. It is worth mentioning that the soil in the city of Lima is highly compact and resistant, in addition to the absence of a water table, benefiting the land's stability to be excavated (García 2020; Guio and Cayllahua 2019).

Considering these conditions, the usual construction system to stabilize slopes in deep basements is the so-called anchored wall or known as a screen wall. This system consists of the design of reinforced concrete retaining walls of approximately 5x3m dimensions, which are retained through an anchor (Carbajal and Bermudez 2017; García 2020). This system is quite economical and manageable, especially in small spaces such as this case (García 2020).

VALUE STREAM MAPPING (VSM)

The Value Stream Mapping (VSM) is a Lean Production tool that allows visualizing and understanding the flow of material and information within a value chain. It is also defined as an improvement process that aims to maximize value by identifying and eliminating waste in the value chain (Rother and Shook 1998). With the implementation of the VSM in construction, it can systematically illustrate a construction stage or system with the ability to identify potential problems and waste.

The VSM considers productive activities, the times for each activity, the customers, the suppliers of the process, following a flow of value that identifies waste and shows the reasons for its existence (Pasqualini and Zawislak 2005). After identifying waste, VSM allows proposing an ideal production chain. It consists of producing only the necessary in the appropriate moment, improving the time for activities that add value to the system (Da Silva 2018).

Fernandez-Solis and Li (2018) identified VSM application in construction is hindered by the following factors: (1) with difficulty arises the repetition of the production process. Every construction project is unique. (2) most construction companies do not fully track construction processes and collect data from portraying the current state of the process and figuring out the future state. (3) concepts/elements used in VSM are defined in the manufacturing context; this differs from the construction context.

METHODS

This research is classified as an experimental-type case study based on procedures and techniques (Gil 2002). The focus of this study was the construction of nine basements entailed building screen walls. The screen wall execution process was chosen to be studied because it involves one of the most relevant activities in the budget and schedule in building projects. Therefore, the proposed improvements will significantly impact the building project (Guio and Cayllahua 2019). This study used the adaptation of the PDCA? Optimization cycle for construction projects proposed by Cabrera and Li (2014), shown in Figure 1.

This proposal is based on identifying the Value Stream Mapping and including improvements and innovations components. This procedure is subdivided (or broken down) into the following stages. (1) Definition: grouping the processes according to their sequence to shape a constructive system. (2) Measurement: diagnose the production flow to discover problems and waste (time, rework, among others). This stage defines deliverables and responsibilities; the result of this stage is the actual Value Stream Mapping (SVM 1). (3) Evaluation: in this stage, a meeting is carried out with a team shaped by the planning and engineering project members to share different approaches for a particular problem, drawing conclusions and possible solutions. The result of this stage is a future VSM (VSM2 and VSM3) (4) Intervention: once the problems are known, corrective actions are implemented. Many problems and wastes can be solved immediately by reducing non-productive time according to improved resource flow on-site. (5) Control: Finally, once most of the waste found has been reduced, other inefficiency sources and limitations of the current working method will require improved process innovation. For this case, an optimized VSM3 diagram is built to be implemented for future similar projects. In such a way, it would allow the building project to obtain a higher performance at levels that make the company more competitive.

CASE STUDY DESCRIPTION

This case study is justified because the company responsible for the project applies Lean principles and tools in some of the project stages, which is why this is a company that has a work team that adopts continuous improvement in its processes.

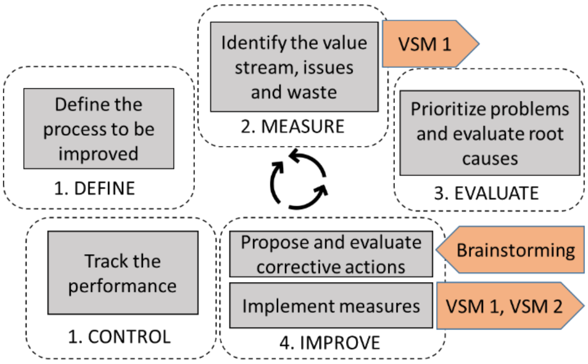

Figure 1. The adaptation of the optimization cycle proposal for construction projects by Cabrera and Li (2014)

The case study is a building destined for offices; it involves constructing nine basements destined for parking spaces and warehouses, and eleven mezzanine levels for offices. The project is located in Lima - Peru. This project is characterized by having a deep excavation of up to 30.55 m, with a medium-sized area of 1,487.65 m^2, as shown in Figure 2. The proposal was planned to make around 350 anchored walls; from them, the first eight basements were tensioned, and the latter, according to geotechnical studies, will not have an anchor. The project had nine months duration.

Figure 2. Panoramic view of the building of the anchored wall

The building project was paralyzed on March 15, 2020 then that the national state of emergency was declared due to the serious circumstances that affected and continue affecting life as a result of the COVID-19 outbreak (PCM 2020). Under these circumstances, as a part restart of the building project. Actions indicated in the Ministry of Health ministerial resolution in Peru (MINSA 2020) were adaptation. This adaptation involves fulfilled the 1.5m distance social between the workers, Demand the mandatory use of masks, and have a limited capacity.

RESULTS AND DISCUSSIONS

CURRENT STATE MAP (VSM1)

As shown in Figure 3, it is a traditional construction system that uses concrete blocks measuring 1x1m on each side to support the struts, the same that support the formwork. The construction system begins with the (a) formation of a drilling safety bench, leaving the safety berm to construct screen walls. Then comes the (b) Perforation and injection, laying the cables, and the injection of the *grout*, following with (c) the dirty cleaning concrete of the higher screen wall and with (d) the joint splice. The (e) excavation with machinery, (f) manual excavation or manual profiling and placing of concrete grout, which provides security against any detachment. Then comes the (g) Armed and install steel mesh with the help of (g') the scaffolding placement. Sequentially comes the (h) placement of Styrofoam for the rest of the slab. Continuing with (i) the formwork surface placement, this activity comprises the shaping of the earth base to settle the formwork panels, and (j) formwork, this is a process that is intended to be modified in this study, which comprises (k) the of struts placement, (l) the flattening of the surface, (m) the laying concrete blocks in the surface, subsequently (n) the buried of the concrete blocks and (o) the support and adjustment of the struts. Finally, in this sub-process, there is the (p) adaptation of an emptying platform and (q) then the placement "*cachimba*". The latter is about adapting a funnel shape to facilitate concrete entry made with phenolic formwork panels. Continuing with (r) the pouring concrete, (s) the stripping, and with (t) the retouch for an architectural finish. Finally, (u) the placement of the anchors' caps and (v) the tauten.

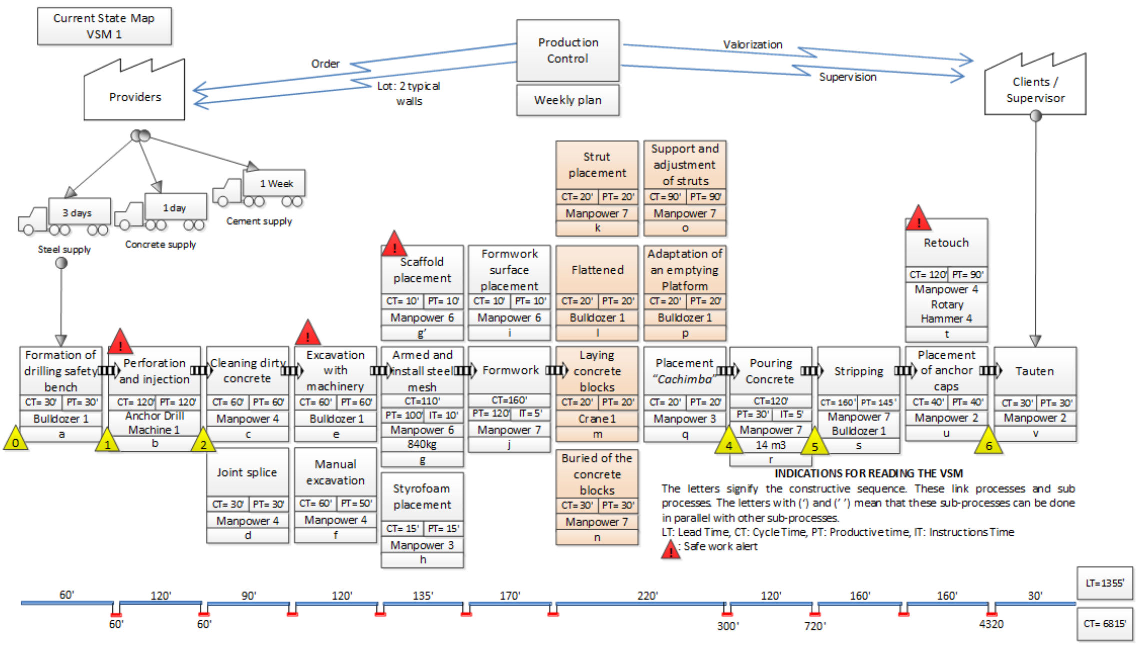

Figure 3. Current State Map (VSM 1)

This system has been running for years in the construction of screen walls (anchored). In this study using the VSM diagram, a Cycle time (CT) of 6815' and Lead Time (LT) of 1350' was observed. Some findings, such as waiting times, were identified in Figure 3, denoted with yellow triangles.

To eliminate these waiting times. First, the reason for these waits was identified. After that, brainstorming was carried out with the project team to find possible solutions for the wait-time problems. The result was a set of ideas and solutions for the wait-time issues. All the ideas were valued, and many of them were approved to be implemented (Figure 4).

Other findings identified activities that do not add value and lead to arduous, laborious work; these are contributory activities but not productive; these are part of the formwork work and are shown in Figure 3 (orange squares). Others would modify or change these activities to minimize the construction system's time and are shown in VSM 2 (Figure 5).

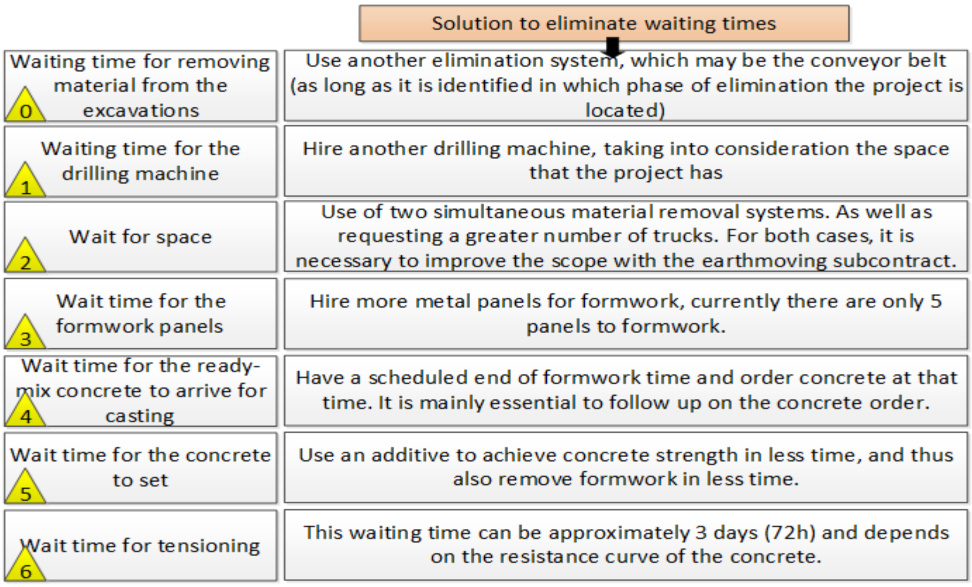

Figure 4. Solution proposals to eliminate waiting times

CURRENT STATE MAP WITH IMPROVEMENTS (VSM 2)

This is the current construction system implementing the proposed improvement mentioned in VSM 1 (Figure 3). A construction system that has already been used in different projects today. This system applies the formwork burial method. An improvement in the reduction of wait time was observed: CT of 6280 'and an LT of 1120' as shown in a VSM 2 (Figure 5).

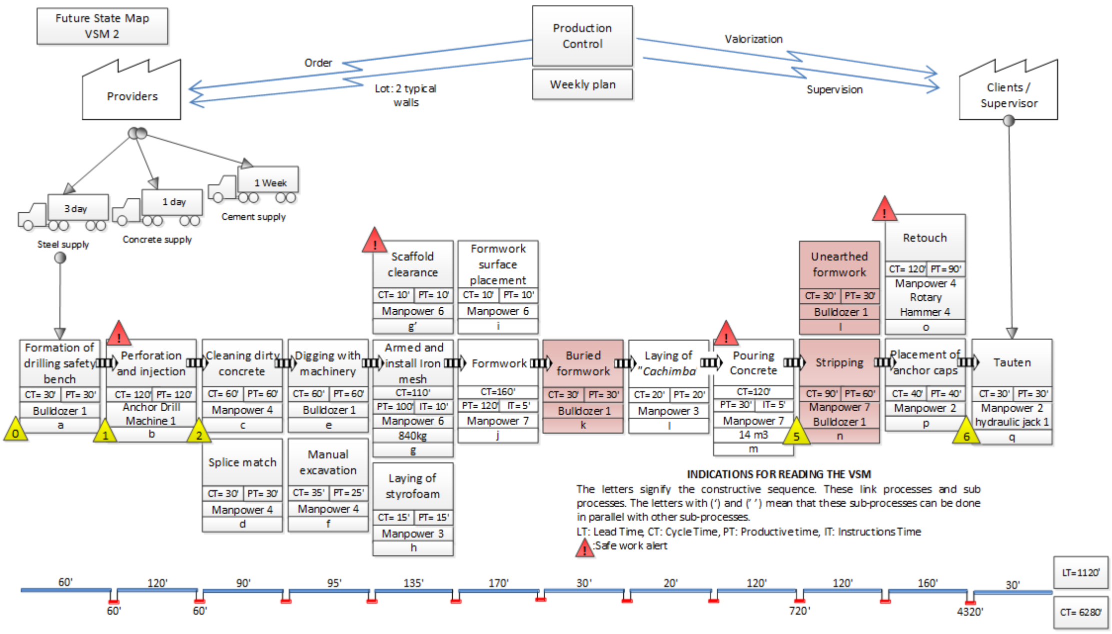

Figure 5. Current State Map with improvements (VSM 2).

This method consists of burying the formwork with the excavation material (Figure 6.A). Some of the benefits of this method are: less time in the formwork process compared to the previous system, less formwork equipment and resources, more space on-site to use the excavation material as support for the formwork, finally, the possibility to formwork two continuous walls. However, to achieve a uniform finish, controlling the alignment and verticality is essential to place concrete blocks before the formwork. Figure 6.B shows PVC pipes filled with concrete cut in a similar dimension of the screen wall thickness; these will be used like concrete blocks. This formwork system is recommended a pre-assembled metallic formwork in order to transport it quickly with the excavator.

The VSM 2 also revealed safe work alerts (Figure 5, red triangles). Such as, that after the buried formwork, in the process of pouring concrete, the workers there was difficulty in transferring through the provisional ramp, before which the workers stated that they perceived insecurity, despite the approval of the supervision. other alerts reveal the need for inspection of machinery and scaffolding.

Figure 6. Improvements and innovations in basement construction.

The VSM 2 map also shows the manual excavation activity's current time show in Figure 5 (f); in this activity previously was used a heavy metallic bar as a work tool. However, this tool was enhanced toward a concrete bar with a metal tip (Figure 6.D). Compared to the metal bar, this tool became lighter due to the concrete bar's lower weight. This improvement was a contribution of a master builder. The effort worked with this tool resulted in workers' more performance and less fatigue in this activity (Figure 6.C).

FUTURE STATE MAP WITH IMPROVEMENTS (VSM 3)

This is a proposal for the construction of screen walls for the future using shotcrete concrete. An innovation proposal would eliminate formwork activities shown in Figure 5 (red squares): formwork surface placement, formwork, stripping, and retouch. This system is shown in Figure 7 and could significantly reduce the CT in 5200 'and LT in 760'. This proposal allows a wall finish type plastering; the advantages of this system are: it does not require formwork, it does not require labour for formwork, it does not require burying the wall, it does not require demolishing hookahs, it allows having a larger area of land available for other activities.

This system has not yet been implemented; however, some pilot tests were carried out on its applicability. The new activities to make this work shown in Figure 7 (blue squares) would be: arming of the lateral formwork, laying of tecnopor, shotcrete, and scaffold clearance shown in Figure 8.

Regarding the formwork burial system (VSM 2), this system is not efficient, since it is excavated to re-bury, carrying out a rework. Thus, the new Shotcrete system shown in the VSM3 could replace it because it eliminates non-productive activities. If this new system is implemented, it is necessary to control the waste of concrete to avoid costs.

One limitation of the study is that it was not possible to observe more evidence of the proposed innovation in the future map (VSM 3). Therefore, it was not possible to observe all the strengths and threats of this proposal either.

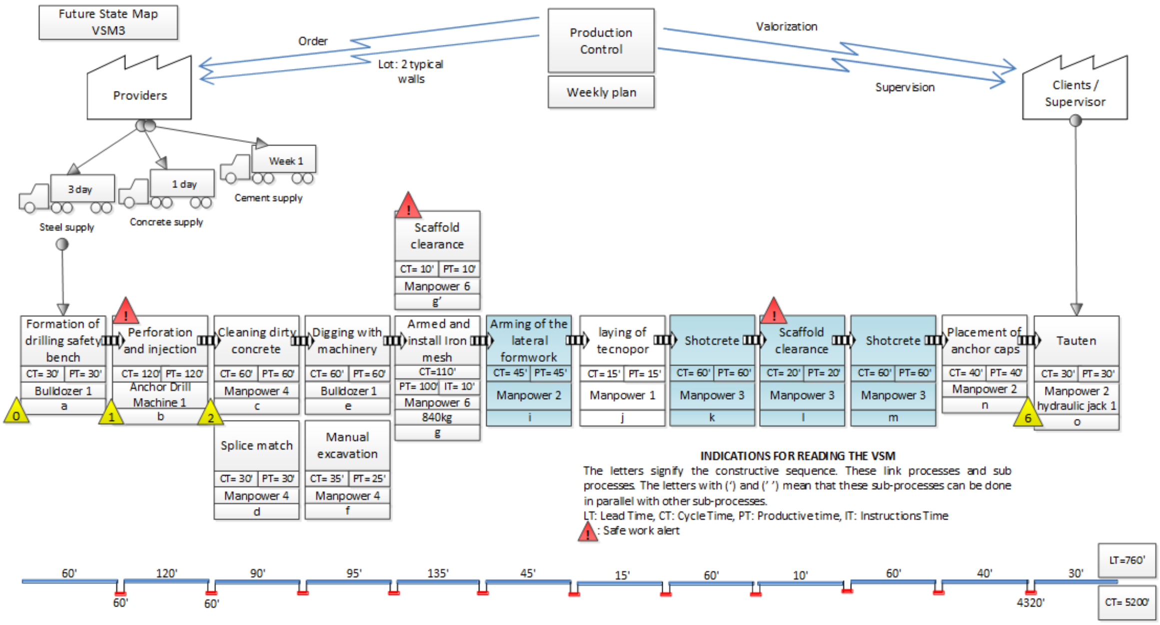

Figure 7. Future State Map with improvements (VSM 3).

Figure 8. Additional activities with the Shotcrete System

After analyzing the VSM 1 (LT = 1355 CT = 6815), VSM 2 (LT = 1120 CT = 6280) and VSM 3 (LT = 760 CT = 5200) scenarios. It was observed that the LT of VSM2 concerning VSM1 was reduced by 17%. Comparing the VSM 1 and VSM 2 scenarios, they both have a similar amount of labor. The VSM 2 Scenario, although it is the one in use today, is not preferable for security purposes.

The LT of the VSM3 in relation to the VSM2 was reduced by 32%, as well as the number of workers, making this scenario the preferable one, not only to reduce the execution time but also to comply with the Measures provided for COVID-19, such as social distancing and recommended capacity (MINSA 2020). VSM, although in principle it is about identifying activities that add value in the value chain, it also allows the analysis of health and safety in the entire construction system studied.

CONCLUSIONS

The main contribution of this study is the application of the VSM tool in projects associated with excavations, where VSM improves the construction system through 3 continuous improvement scenarios. This research answers the research questions. A workflow can be enhanced by identifying all the activities that add and do not add value to the construction system through the VSM. Activities that do not add value are eliminated or reduced by adopting continuous improvement strategies. Strategies that were discovered by the project team in a brainstorm, where each idea was valued. The current map VSM 2 with the improvements allowed us to implement some of the proposed solutions. The future map VSM 3 allows exposing an improvement with innovation that could be applied in future projects with the execution of screen walls, reducing the number of activities within the construction system, reducing interruptions, reducing variability times, and therefore product delivery. One limitation of the study is that this construction system is only applicable for constructing basements with screen walls or anchored walls; therefore, biased information could be produced, since there is no information in the literature to compare it. A future study could be about applying this future map VSM3 and analyzing the activities that originated with this proposal, record the waste and the duration of Cycle time (CT) and Lead Time (LT). In comparison to the obstacles identified by Fernandez-Solis and Li (2018) and in other studies. This study evidenced (1) the construction of basements has become a systematic process, emerging a repetitive process, even when each project is unique (2) Data collection was not a problem since the company controls the activities. (3) There was no difficulty in adapting the concepts/elements used in the VSM; however, it would be helpful to add other concepts/elements typical of the construction.

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REFERENCES

Cabrera, B. R., and Li, G. J. (2014). "A lean-TRIZ approach for improving the performance of construction projects." *22nd annual conference of the international group for lean construction:* understanding and improving project-based production, Oslo, Norway, 883-894.

Carbajal G. G., and Bermudez P. D. L. (2017). "First run study and process optimization in the construction of anchored walls." *Research projects*. Faculty of Sciences and Engineering, Pontifical Catholic University of Perú, Lima, Perú.

Covarrubias, A., Mourgues, C. and Arroyo, P. (2016). "VSM for Improving the Certificate of Occupancy Process in Real Estate Projects – a Chilean Case Study." *24th Annual Conference of the International Group for Lean Construction*. Boston, Massachusetts, USA, Jul 2016, 20-22.

Da Silva Etges, B. M. B. (2018). "Value-Adding Activities Level in Brazilian Infrastructure Construction Companies-9 Cases Study." *IGLC 2018-Proceedings of the 26th Annual Conference of the International Group for Lean Construction*: Evolving Lean Construction towards Mature Production Management across Cultures and Frontiers, Vol. 2, 1323-1333.

Fernandez-Solis, J. L., & Li, Y. (2018). "A Structured Literature Review: Value Stream Mapping (VSM) In Construction Industry." *OAKTrust, Construction Science, Faculty Publications*. Texas A&M University. 1-24.

Gallardo, C. A. S., Granja, A. D., and Picchi, F. A. (2014). "Productivity Gains in a Line Flow Precast Concrete Process after a Basic Stability Effort." *Journal of Construction Engineering and Management*, 140(4), C4013004.

García Martín S. (2020). "Experiencias y peculiaridades de las obras de edificación en Lima, Perú." *CIMBRA Journal of the College of Public Works Technical Engineers*, 418, 48-49. (in Spanish).

Germano, A. V., Fonsêca, N. J. M., Melo, R. S. S. and Moura, A. (2017). "Value Stream Mapping: Case Study in Columns Concreting." *25th Annual Conference of the International Group for Lean Construction.* Heraklion, Greece, 9-12 Jul 2017, 821-828.

Ghio, V. (2001). "Productividad en proyectos de construcción: diagnóstico, crítica y propuesta.". Pontifical Catholic University of Peru, Lima, Peru. (in Spanish).

Gil, C. (2002). "How to develop research projects." São Paulo: Atlas, 2002, Vol. 4.

Guio S, J. D., and Cayllahua H, D. (2019). "Análisis de los métodos de eliminación de material para construcción de sótanos en Proyectos que presentan suelo granular en Lima Metropolitana." *Research projects*, Faculty of engineering, Civil Engineering academic program, Peruvian University of Applied Sciences, Lima, Peru. (in Spanish).

Gunduz, M., and Fahmi Naser, A. (2017). "Cost based value stream mapping as a sustainable construction tool for underground pipeline construction projects." *Sustainability*, 9(12), 2184.

Melo, L. A. P., Lima, V. F. C. and Melo, R. S. S. (2017). "Value Stream Mapping: A Case Study in Structural Masonry." *25th Annual Conference of the International Group for Lean Construction.* Heraklion, Greece, 9-12 Jul 2017, 755-762.

Ministerio de Salud (MINSA). (2020). Resolución Ministerial N° 448-2020-MINSA. Lineamientos para la vigilancia, prevención y control de la salud por exposición al SARS-CoV-2. Diario Oficial El Peruano, Lima, Peru. (in Spanish).

Murguia, D., Brioso, X., and Pimentel, A. (2016). "Applying Lean Techniques to Improve Performance in the Finishing Phase of a Residential Building." *24th Annual Conference of the International Group for Lean Construction*, Boston, MA, USA, sect.2, 43–52.

Pasqualini, F., and Zawislak, P. A. (2005, July). "Value stream mapping in construction: A case study in a Brazilian construction company." *Proceedings of the 13th Annual Conference of the IGLC*. Sydney, Australia.

Presidencia del Consejo de Ministros (PCM). (2020). Decreto Supremo Nº 044-2020-PCM. Decreto Supremo que declara Estado de Emergencia Nacional por las graves circunstancias que afectan la vida de la Nación a consecuencia del brote del COVID-19. Diario Oficial El Peruano, Lima, Peru. (in Spanish).

Rosenbaum, S., Toledo, M., and González, V. (2014). "Improving environmental and production performance in construction projects using value-stream mapping: Case study." *Journal of Construction Engineering and Management*, 140(2), 04013045.

Rother, M., and Shook, J. (1998). "Learning to See: Value Stream Mapping to Create Value and Eliminate Muda." v. 1.1. Oct., The Lean Enterprise Inst., Brookline, Mass.

Shou, W., Wang, J., Wang, X., and Chong, H. Y. (2016). "Examining the critical success factors in the adoption of value stream mapping." *24th Annual Conference of the International Group for Lean Construction.* Boston, Massachusetts, USA, 20-22 Jul 2016.

Shou, W., Wang, J., Wu, P., Wang, X., and Song, Y. (2017). "Application of lean production with value stream mapping to the blasting and coating industry." *25th Annual Conference of the International Group for Lean Construction*. Heraklion, Greece, 9-12 Jul 2017, 217-224.