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Interdependent response of three critical infrastructures in a South American megacity

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Abstract

Critical infrastructures (CIs) are key for the functionality of urban areas. Their failure due to natural disasters or manmade disruptive events could severely obstruct normal city activities, producing considerable social and economic impacts. Understanding CI performance and interdependence during these events is imperative. This study aims to comprehend the independent and interdependent response of three CIs in a South American megacity: Lima, Peru. Topological indicators were used to study three CIs: potable water distribution, electricity distribution and natural gas distribution; five disruption scenarios were modeled. Results show that, compared to the other CIs, the potable water system has the highest redundancy, while the electricity network has the best capacity to connect among all elements. The structure of the natural gas system makes it fragile and susceptible to failures, generating the lowest values across indicators. Regarding the interdependence analysis, certain elements (e.g., medium- and high-voltage substations, water treatment plant, pressure stations) with a high degree of connectivity influence the entire performance of the systems; the interdependent effect exposes some CIs to damage more than others. Earthquakes have a comparatively more negative impact on the CIs studied than manmade disruptive events. In order to reduce vulnerability factors in the three systems, an important mitigation action would be to reduce the centralization of the systems.

1. Introduction

Critical infrastructures (CIs) are part of the built environment in urban areas and are subject to impacts that could damage their capacity to operate normally. Regardless of the nature or intensity of the damage, system recovery requires a rapid response, otherwise economic and serviceability losses which can increase over time will be generated (Tierney 2000). Usually, CIs and related policies are defined by their respective government agencies. For example, in the United States (US), the Department of Homeland Security (DHS) identifies 16 types of CIs, which include services and industries (e.g., communications, financial services, commercial facilities, chemical and agricultural sectors) and other physical infrastructures (e.g., dams, transportation systems, nuclear reactors and waste, and water and wastewater systems) (DHS—Department of Homeland Security 2015). In contrast, the European Union Council (EU-C) identifies 8 CIs, only in the energy and transportation sector (EU Commission 2006). Both the DHS and the EU-C concur that CIs are ‘assets, systems, parts and networks’ considered essential or vital, and that their interruption, failure or collapse would have a significant impact on security and the well-being of people (DHS—Department of Homeland Security 2015, EU Commission 2006).

CIs are complex, adaptive systems composed of a collection of elements and agents that exhibit specific traits such as emergent, evolutionary behavior, self-organization, adaptation, and irreversibility (Rinaldi 2001, Oughton *et al* 2018). The intricacy of the CIs has evolved to the point where there are complex mutual, bidirectional interactions among elements of different CIs, this particular feature is known as interdependence

(Thacker *et al* 2017, Liu *et al* 2019). Interdependence becomes increasingly visible when impact scenarios manifest (Ouyang 2014); various impact events in recent decades can illustrate these phenomena. Chang *et al* (2007), developed a framework of impacts related to power outages caused by the 1998 Ice Storm in Canada; the database showed 107 records of infrastructure-failure interdependencies that affected 11 sectors, including emergency services, food supply, transportation, telecommunications, among others. Mendonça and Wallace (2006) studied the effects of the 2001 World Trade Center attack and the behavior of CIs in the event of a disruption which can cause interference in services provided by the CIs. They found that the attack induced utility outages, which caused 238 disruptions in eight types of CIs; among these, 46 involved interdependencies between infrastructures. In 2007, water flooding in the UK triggered the failure of several infrastructures, demonstrating their interdependency (Bloomfield *et al* 2009). More recently, Hurricane Maria, which struck several islands in the Caribbean, markedly affected Puerto Rico, causing major damage to the electricity infrastructure. The power outages caused disruptions in other infrastructure systems such as health services, transportation, communication services and water. Due to the frailty of the infrastructure at the time, there were difficulties in restoration to a functional state, causing several deaths, even after the event had passed (Sutter and Santiago 2018). More recently, a power failure in Argentina, Paraguay and Uruguay caused an outage that affected more than 55 million people, affecting the provision of other resources such as water and telecommunications (Dangelis 2019).

In current literature several interdependence typologies can be found. Relevant classifications of interdependence are provided by Rinaldi (2001), Duedenhoeffer (2006) and Zhang and Peeta (2011): physical, cyber, geographic, information and monetary interdependencies. While all of them are valid types of interdependencies, for the aims of this research, we only focus on physical interdependencies.

Various modeling methods aim to analyze interdependencies of CI; classifications of these modeling techniques have been developed in the literature. For example, Ouyang (2014) categorizes CIs network studies as topology-based methods (analytical and simulation-based), flow-based methods, and other methods such as hierarchical holographic modeling, dynamic control system theory and Bayesian networks. The approach proposed by Sarriegi *et al* (2008) includes evaluating the fundamental issues in CI assessment while also detailing the key elements of three modeling methods (agent-based modelling, input–output, and system dynamics). Iturriza *et al* (2018) also deemed network-based models and high-level architecture to be relevant modeling methods in addition to the three proposed by Sarriegi *et al*.

Network-based interdependence is an approach designed to represent CIs as networks, in which systems can be described as a collection of nodes and edges. Nodes represent components or subsystems in the infrastructure which perform certain functions; the latter can be represented as states. Edges embody the connection between infrastructures; they possess the capacity of movement of flow and can evolve over time.

A review of the extensive literature about network-based interdependence, which includes a variety of case studies, was performed and is summarized below. For example, the performance assessment at a local scale of water and electrical power systems wherein disruptive events can affect the supply of water and electricity to critical consumer nodes: up to a probability of 0.6 (Val *et al* 2014). The inclusion of recovery rates after an event, providing the amount of time necessary to return to full working capacity of urban food distribution, considering the interdependence to electrical and water systems, was studied by Nozhati *et al* (2018). Mao and Li (2017) performed a resilience analysis of the water, electrical power and telecom systems in a middle-sized city in China. Their simulations showed that interdependencies can reduce the resiliency of the system in the event of a hazard; however, interdependencies can improve performance in the recovering stages of a system. Assessment of hazardous conditions in an interdependent system of water, waste water and electric systems considering production, storage and commodity flows and using linear optimization models to improve the infrastructure performance in monetary terms was studied by Holden *et al* (2013). Also, a multi-scale disruption analysis of the electricity supply, transmission and distribution and domestic flight network by Thacker *et al* (2017), and an assessment of the robustness of the communication networks and the power grid, taking into account sequential and coincidental failure with several hazards affecting the system, where sequential hazards create the lesser impact to both interdependent systems by Kong and Simonovic (2019). Yodo and Afrin (2021) developed a resilience analysis of interdependent multi-energy systems, gas and power networks, taking into account cascading failures, recovery and costs, and proposing microgrids as an effective solution to improve the performance of the networks interdependency. Moreover, the inclusion of earthquake scenarios in the assessment of CIs acknowledges that these natural phenomena have the potential to cause failure in the interconnected systems. For example, Dueñas-Osorio *et al* (2007a) developed interdependency models with topological matrices and probabilistic failure among disturbance scenarios, and elaborated uncertainty and structural performances for two infrastructures. Hernandez-Fajardo and Dueñas-Osorio (2011), based on the methodology developed by Dueñas-Osorio *et al* (2007b), added the probabilistic fragility of systems using

types of failure and response of the CI elements. Yoon *et al* (2018) developed a framework to assess the vulnerability of the water transmission network affected by earthquakes in a South Korean city using connectivity and serviceability indicators. Results showed that in lower magnitude earthquakes, the effect of interdependencies is not significant; as well, some infrastructure elements can deteriorate over time, affecting the overall capacity of the system. Finally, a novel framework and mathematical formulation to model interdependencies were proposed to be applied in a North American county based on an earthquake scenario (Sharma and Gardoni 2022).

Robustness is defined as the capacity of a network system to remain functional or connected when there is a disruptive event that affects the network by removing nodes. This is a particular feature of complex network assessment since it provides a measure of the resilience of a system in case of a targeted attack. Among the topological metrics to determine resiliency are clustering coefficient, average path length, betweenness centrality. Rueda *et al* (2017) gathered the most relevant metrics in terms of structural properties, centrality measures and services supported by networks. Applications to these measures in case studies have been developed by Wandelt and Sun (2018); they compared robustness indicators in three CI: transport network, power network and airport network. Additionally, Bhave *et al* (2016) assessed the topological metrics of a hypothetical electricity network, Rueda *et al* (2017) developed a robustness analysis of 15 telecommunication systems, Agatholekus *et al* (2017) used betweenness centrality as a robustness metric for the analysis of the water distribution networks of a city in Cyprus. Finally, a series of UK and US infrastructure networks (energy, road transportation, rail transportation, telecommunications and air transportation systems) were analyzed using robustness metrics such as betweenness centrality and degree (Robson *et al* 2021).

Studies about infrastructure vulnerability and interdependence are primarily based on developed countries. Pagani and Aiello (2013) compiled most of the studies related to the analysis of power grid infrastructure using complex network theory. Of them, only one had as a case study a developing country. However, cities and their CIs systems in the global south present unique characteristics that are reflected through different responses to disturbances. Because these countries are experiencing higher rates of urbanization, and thus establishing megacities, it is important to expand the understanding of the CIs in these particular cases. The objective of this paper is to develop a performance analysis of a system of three CIs in a Latin American megacity: Lima, Peru. This analysis was done by establishing interdependencies between three infrastructures and developing a model in which topological indicators were utilized, so they can reflect particular features of the system. We performed an independent and interdependent analysis of the vulnerability of the networks by using five scenarios, three based on the topological properties, and two pertaining to natural disasters, specifically to earthquakes. This is one of the few studies that have used a city in a developing country as a case study, and it is the first time that an assessment of this sort has been undertaken in a South American metropolis. Peru is located in a seismic zone known as ‘the ring of fire’ on which earthquakes are common, therefore, built infrastructure should be constructed to withstand these events. Also, issues related to infrastructure condition can affect performance. In the case of the city of Lima, disturbances in CI will potentially affect ten million residents dependent on the services provided by CI. Thus, awareness of the vulnerability of critical elements may bring about the development of risk assessment plans and policies. Also, this could disseminate and incorporate, into development plans, the concepts of infrastructure resilience. While existing policies address some issues of the current state of the infrastructures in the city, they analyze each infrastructure in an isolated manner and do not emphasize the concepts of interdependency.

2. Methodology

We use topological indicators in simulations-based methods to quantify the performance of the interdependent network systems. The main attribute of this method relies on the assessment network-based systems by using disruption scenarios (Ouyang 2014). Unlike analytical models, this more accurately resembles all physical systems that depend on real-life conditions, since infrastructures can be represented as networks of nodes and edges as components. Topological models focus on using information about the structure of the system rather than physical properties and constraints, which pertain to flow-based models. This has advantages and disadvantages, which are reflected in the tradeoff between computational efficiency to accuracy in the representation of a real-life model. One of the main setbacks in the use of flow-based models is the availability of information, in this case, supply and demand data at an accurate scale. The approach used for this study consists of the following steps: (1) elaborate a network based on three CIs (adjacency matrix), (2) model the performance of the networks using topological indicators at a normal/regular state, (3) develop a simulation of failures using different scenarios, (4) evaluate the simulations while considering interdependencies between CIs.

The case study is in a seismic zone and vulnerability was assessed assuming interdependence. Therefore, after defining the system as a group of nodes (i.e., gate stations, substations in the power system, and

Table 1. Summary of scenarios used in the vulnerability assessment.

Scenario	Node rank ordering
Scenario 1	Random failure
Scenario 2	Vertex degree (topological indicator)
Scenario 3	Betweenness (topological indicator)
Scenario 4	1966 earthquake (real-life phenomenon)
Scenario 5	1974 earthquake (real-life phenomenon)

pumping stations and elevated storage in the case of potable water systems) and edges (i.e., transmission lines and pipelines) vulnerability was assessed using indicators of geographical risk. The case of the European gas and electricity network (Poljanšek *et al* 2012) provides another insight in the use of simulation methods for interdependent infrastructures. We assessed the importance of infrastructure interdependence in the event of a disruption which can be displayed in the failure of the system: through changes in the topology structure. In this case, we measured performance with stochastic numerical simulations (i.e., Monte Carlo).

We considered the following CIs: potable water distribution, electricity distribution and natural gas distribution. These three infrastructures are considered critical based on the definition established above, and because they are necessary for the proper operation of cities in the less developed world, including Lima. The type of interdependence used in this study is a combination of physical and geographical; the linkages between infrastructures are determined from a physical standpoint in which each infrastructure provides a commodity or material required by other infrastructures to operate normally. We developed the clustering of certain interdependent elements using geographical proximity assuming that a local environmental variable can affect the state of the elements of the system.

The network model was developed using the following programs: the NetworkX Python package was used for indicators such as efficiency and rank ordering criteria such as betweenness, ArcMap was used for the assignment of failure probabilities [employing peak ground acceleration (PGA) maps], Matlab for the vulnerability assessment of the interdependent networks, and *R* was used for the clustering algorithm (DBSCAN) used in the interdependency analysis.

2.1. Analysis of the vulnerability of the network

Four topological indicators were selected to assess the performance of the network when a disruption occurs in three infrastructures: vertex degree, clustering coefficient, efficiency and redundancy ratio. These indicators were selected due to their use in several case studies in network assessment literature. Furthermore, a detailed description of these indicators is shown in the supplementary information (S1) (<https://stacks.iop.org/ERIS/2/025003/mmedia>). In this case, a disruption means the elimination of nodes and edges due to a random failure, deliberate attack, or natural hazard (Poljanšek *et al* 2012). Five scenarios were assessed. Three of them are based on arbitrary system failure assumptions and two of them were from a probable failure in a natural event, as explained below. The first elimination approach is the advent of a random failure (scenario one). The second and third elimination approaches consist of the removal or elimination of nodes from the rank of topological properties. In the case of degree (scenario two), highly connected nodes will be first in the rank of elimination. Betweenness (scenario three) describes a characteristic of specific nodes in networks that represent the relation between the number of shortest paths in a network and the amount passing through a specific node (Newman *et al* 2001; Borgatti 2005): if a node with high betweenness is removed, part of the system may become isolated (table 1).

Finally, the last two scenarios relate to the occurrence of an earthquake in the city. The assessment of these scenarios was based on the PGA maps from Rios *et al* (2017). These maps were developed from two previous earthquakes, one in 1966 (scenario four) and the other in 1974 (scenario five), reaching values of magnitude 8.1 and 8.0, respectively. The epicenters were located 233 and 113 km away from the city. Then, from the fragility curves developed by Federal Emergency Management Agency—FEMA (2005) and the American Lifeline Alliance (ALA), the order of nodes removed were defined by the probability of failure from the fragility curves; the higher the probability, the earlier the node removal. Thus, nodes located in a place with higher PGA are likely to fail when a seismic event occurs. The relationship between damage to any of the nodes and ground velocity was determined following ALA guidelines (Eidinger 2001).

Earthquakes are relevant to this case study because of the constant seismic activity that occurs in this region. Peru has a history of very large earthquakes, with events of more than 6.0 of magnitude. Moreover, the city of Lima has not had a large earthquake since the 1970s but experts agree that a high-magnitude earthquake

Table 2. Network components and main features.

System	Ownership	Elements	Number of nodes	Physical properties
Water distribution	SEDAPAL (public)	Water pipelines Storage tanks Treatment plants	49	Pipeline material: ductile iron, prestressed concrete, coated steel Pipeline Diameter: 700–1800 mm
Power network	ENEL/LUZ DEL SUR (private)	220 kV substations 60 kV substations Transmission lines Power plants	75	
Natural gas distribution	CALIDDA (private)	Pressure regulation stations Gas pipelines	88	Pipeline material: steel Pipeline diameter: 4"–30"

could affect the capital in the near future (Andina 2021). Therefore, an analysis developed for Lima or any other Peruvian city should consider the effects of an earthquake.

2.2. Interdependence assessment

As mentioned above, we considered a combination of two types of interdependencies: physical and geographical interdependencies. In the case of physical interdependencies, the flow of each utility service is useful for the operation of an infrastructure. The electricity system powers the water treatment plant, water reservoirs and pumps, and monitor and control distribution flowsystem. Thermoelectric power plants in Lima are fueled with natural gas and therefore, there is a physical relationship between these elements and pressure regulation stations. Consequently, the performance of the network system is defined by the connecting relationships between the three systems. The interdependent edges were defined by the proximity from each of the nodes of the three systems. For example, a substation closer to a reservoir or to pressure regulation stations is linked with both systems since it supplies them with electricity.

Moreover, the assessment of geographic interdependencies initially consisted of the development of clusters or groupings of elements (clusters), given that one of the interdependencies we assume in this study is the proximity of services. A cluster analysis was developed for both of the earthquake scenarios. The procedure is the following: from all the infrastructure elements in the city, regardless of their importance or hierarchy in the distribution of flows, groups were defined. This was done to assess the possibility of failure in close interdependent elements.

The clustering of elements was performed using a density-based clustering algorithm, namely DBSCAN (Hahsler *et al* 2019). DBSCAN allows the arrangement of elements using as basis the underlying density while discarding outlier elements, considering them as noise. The reason behind our choice of this algorithm, instead of other more common clustering algorithms, such as k -means (Jin and Han 2011), was because of its sensitivity to the number of clusters and centroids (i.e., outliers tend to drag the centroid). In our study, there are highly dense areas and some sparse elements in the peripheral areas of the city, for that reason, it was important to choose a more intuitive clustering algorithm.

The analysis was developed by quantifying the performance of topological indicators (redundancy ratio and efficiency) considering both earthquake scenarios. Each earthquake event was structured by ranging levels of soil acceleration chosen from low to high. For the 1974 earthquake, five levels were defined, with a range of 100 cm s^{-2} for each level, in the 1966 earthquake, six levels were defined with a range of 70 cm s^{-2} for each level. This means that, in each level the elements had similar probabilities of failure. From the set of clusters as a result of the analysis, those that contain more than one CI were considered as interdependent. The interdependencies between CI components were defined by a probability of failure that ranged between 0 and 1, where 0 is a completely independent coupling and 1 is an entirely interdependent coupling. Since failure of the elements is contingent on a probabilistic reliability model, the performance of the interdependent network was determined by using a Monte Carlo simulation.

The Monte Carlo simulation followed the same step process as the probabilistic reliability model developed by Yoon *et al* (2018). Failure probabilities were generated or collected, then a set of N random correlated samples between 0 and 1 were created; if the probability of the element was higher than the sampled number, then the component was damaged. Then, the damaged components were represented in a binary state in the adjacency matrix (1 is intact and 0 is damaged), the changes in the matrix displayed a new simulated event, and the four topological indicators were calculated. This simulation was performed N times, and each run provided a set of topological indicators displayed as a distribution.

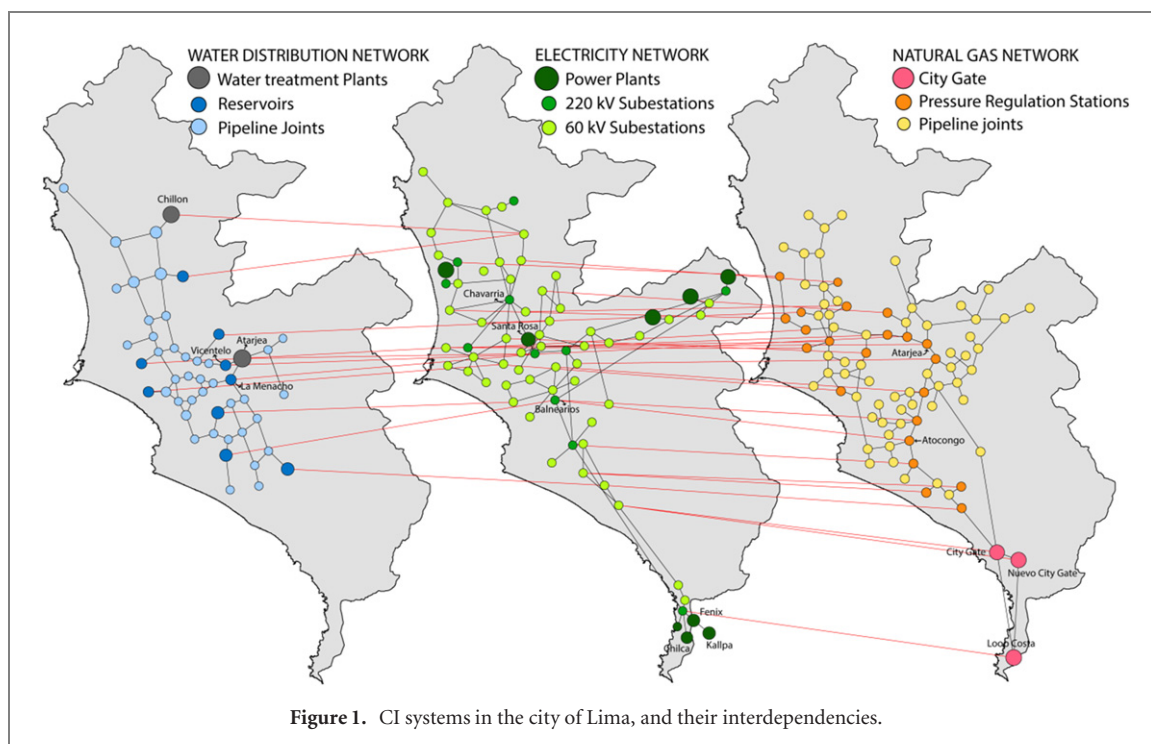


Figure 1. CI systems in the city of Lima, and their interdependencies.

Table 3. Main indicators of the three systems.

	Nodes N	Mean distance L'	Vertex degree $d(G)$	Clustering coefficient γ	Redundancy ratio R_r
Water supply	49	0.2354	2.408	0.068	0.188
Electricity	75	0.2599	2.667	0.181	0.159
Natural gas	88	0.1877	2.205	0.027	0.164

2.3. Infrastructure overview

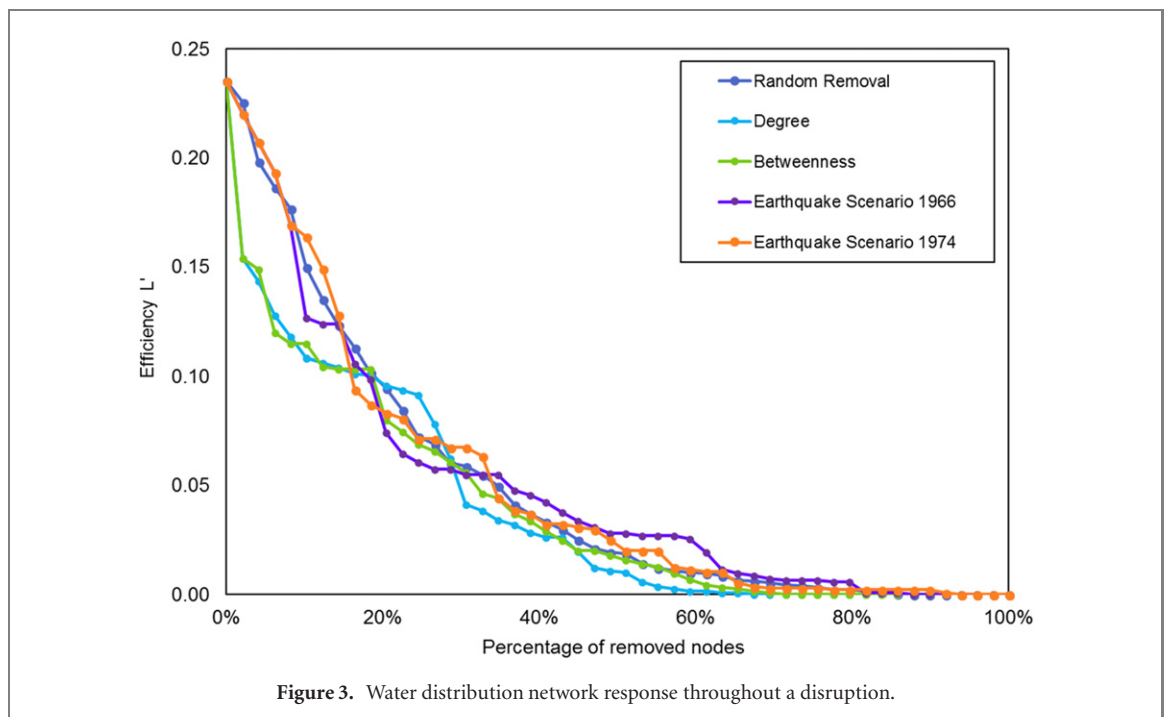
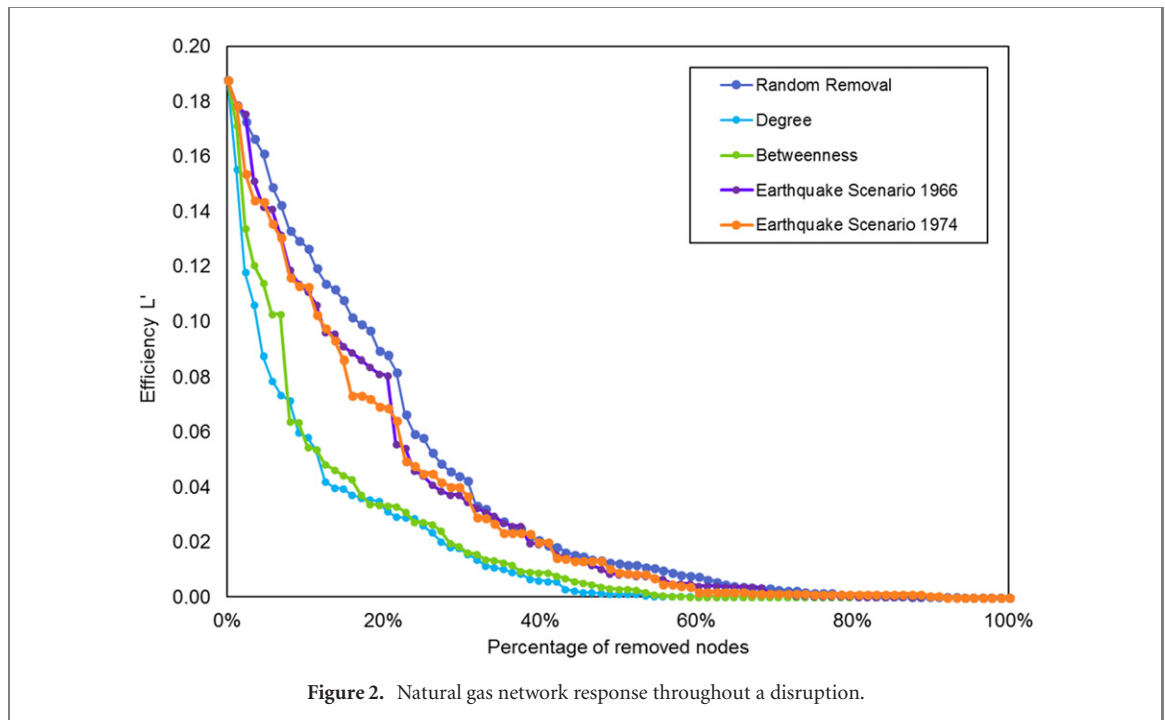
The analysis considered three infrastructure systems: potable water distribution system, electricity and natural gas. These three systems are within the administrative jurisdiction of the city. In addition, these infrastructures are important for the development of basic activities within the city and have a physical flow for which interdependencies can be defined.

The potable water treatment and distribution network has ‘La Atarjea’ as the main water treatment plant in the system, with an average production of $18 \text{ m}^3 \text{ s}^{-1}$. The other water treatment plant is ‘Chillon’, providing $2.5 \text{ m}^3 \text{ s}^{-1}$. The water reservoirs are storage elements distributed throughout the city. There are over 200 reservoirs, however, this study includes only reservoirs with a capacity greater than 4000 m^3 . Other secondary sources of potable water come from the extraction of groundwater from wells, which provide about 12% of the total distribution (Vázquez-Rowe *et al* 2017); however, due to the unavailability of information on the provision of these specific infrastructure elements, they were not considered in the assessment.

The natural gas infrastructure in the country is recent, since natural gas reserves were only found in 2004 and commercial distribution started a few years later. However, for many residential areas in the city, natural gas is an important source of energy. The elements considered for the analysis are: the City Gate, the main station where the flow is primarily distributed; pressure regulation stations; specific elements of the main pipeline.

The power network is run by two companies, which oversee the distribution of electricity to the northern and southern parts of the city, respectively. All power plants within the administrative territory of the city are considered to be in the network, which includes five thermoelectric power plants (i.e., Ventanilla, Santa Rosa, Fenix, Chilca and Las Flores) and two hydroelectric power plants (i.e., Callahuanca and Huampani). The 220 kV and 60 kV substations were also considered. Table 2 presents the main characteristics of the CIs selected in this study.

Figure 1 presents an overview of the three networks. Among the three interconnected networks, the natural gas and electricity share more links than the water system. The natural gas entrance to the city (City Gate and New City Gate) relates to the substation that is directly connected to four thermoelectric power plants also located in the southern area of the city (i.e., the Chilca district). The Fenix, Chilca, Kallpa and Las Flores power plants have produced some of the highest electricity levels per year in the country. In 2016, they were



responsible for 31% of the electricity produced in the country (COES 2016). These four plants supply the city directly and are also connected to the national grid. The power plants are distributed throughout the city, unlike the natural gas network, which is centralized.

The distribution natural gas system runs from south to north, since the main distribution pipeline originates in the southern part of the country, and connects to the city through the Loop Costa. Most of the interdependent networks between the water and electricity system are located in the mid-eastern area of Lima, where the main river (i.e., Rimac River) enters the city. The Atarjea water treatment plant is the system's largest; its failure would mean a collapse of the entire water distribution system in the Peruvian capital. A precedent occurred in the summer of 2017 when unexpected precipitation patterns and high-water turbidity in the Rimac River restricted the capacity of the Atarjea water plant to treat surface water, resulting in a major water shortage in the city of Lima (Vázquez-Rowe *et al* 2017).

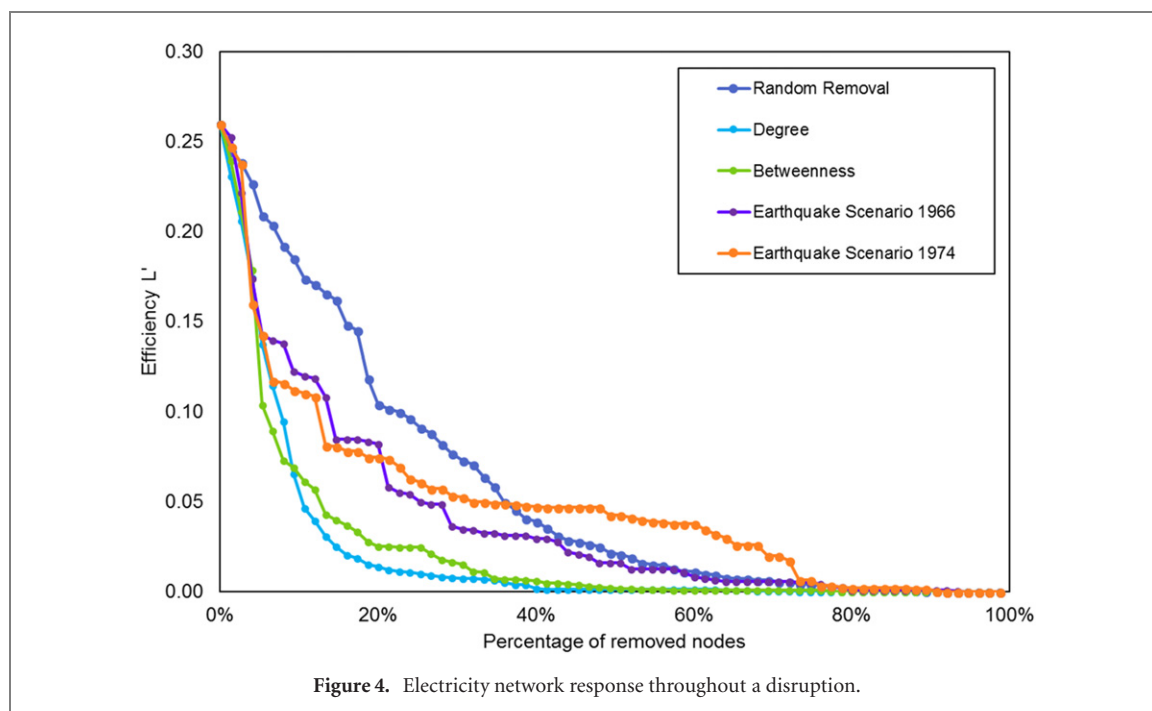


Figure 4. Electricity network response throughout a disruption.

Table 3 shows the topological indicators of the individual networks. While if the natural gas network is bigger than the power network, the gas system has a higher degree (i.e., more edges). The reason is that while the electricity and water systems have several generation nodes located throughout the city and properly scattered through the entire area, the natural gas network has a main pipeline that enters the city of Lima and branches in the central area of the city. For comparison purposes, the mean degree results for the European power grids, obtained using topological properties, ranged from 2.18 to 2.70 (Rosas-Casals and Corominas-Murtra 2009).

The electricity network has the highest clustering coefficient, since the flow distribution starts from the generating power plants, from there to the 220 kV substations and subsequently to the 60 kV substations (local substations) which distribute the energy to the consumer. Clusters may be formed in 220 kV substations, which explains the highest clustering coefficient. Compared to the Nordic power grid and the US network (Holmgren 2006), the city's power system is more clustered, however, the difference between coefficients may be due to the size of the US and Nordic graphs. The natural gas and water networks do not have the same element organization and have lower coefficients, due to the distribution shape of those two systems.

The capability of redistributing flows after small disturbances is higher in the water distribution network due to the high connectivity of the pipelines in the central districts, unlike the power network, which is divided between the two utility companies that each manage a separate portion of the infrastructure.

The electricity and water supply systems have the highest efficiency L' (i.e., the capacity to connect among all elements of the network system), due to the distribution of their nodes. The water distribution system, for example, is well connected since the reservoirs in the southern and northern areas are well distributed in the city, unlike the natural gas system, comprised of a single main path.

3. Results and discussion

3.1. Independent assessment of vulnerability

As shown in figures 2–4, overall, performance is better in the random and earthquake scenarios than in the degree and betweenness scenarios. Therefore, targeted attacks at nodes with higher degree and betweenness have a more damaging effect than would a random attack or the event of an earthquake. The natural gas system shows a marked difference between scenarios, since its topological configuration is more scattered and hierarchical. Furthermore, more nodes in the natural gas network have a high degree than the other two networks, which suggests that there is a lesser ability of recovery in the latter two scenarios.

Most of the natural gas nodes have low betweenness values and only six nodes have a betweenness higher than 0.3; they include the García Villon node, which is a connection located in the district of Lima that

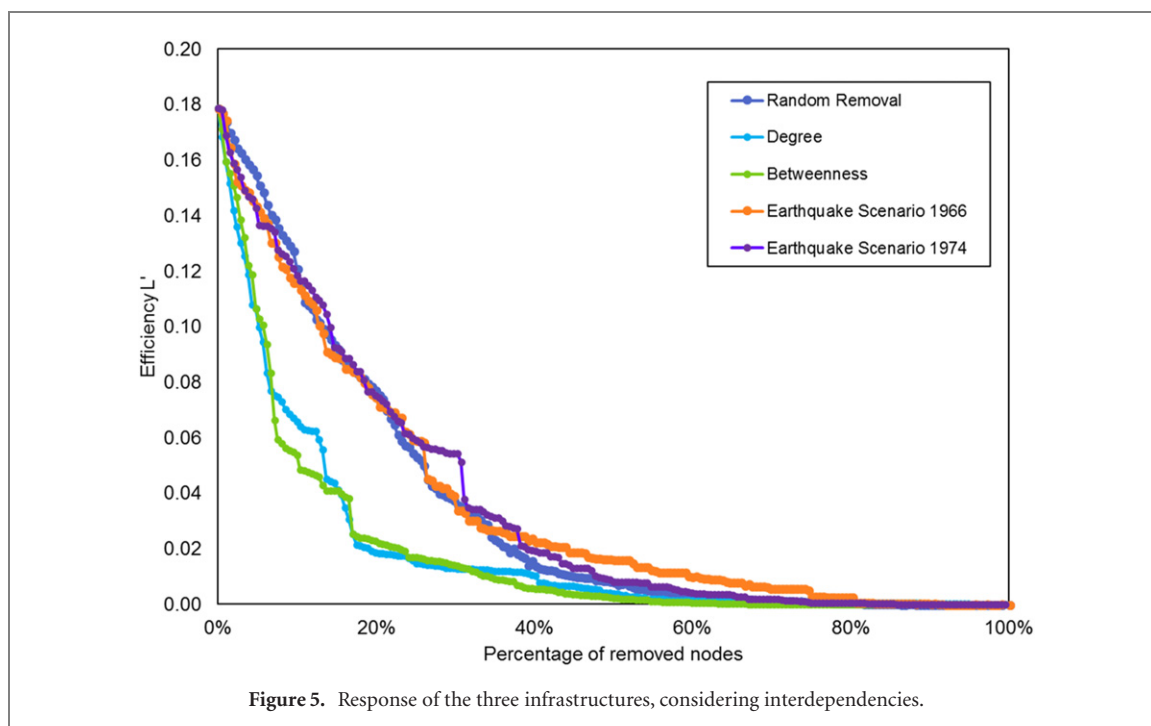


Figure 5. Response of the three infrastructures, considering interdependencies.

Table 4. Summary of cluster analysis of the three CIs (water, natural gas and electricity).

Level	Earthquake of '66'		Earthquake of '74'		Total clusters
	Number of interdependent clusters	Total clusters	Level	Number of interdependent clusters	
1 (280–350 cm s ⁻²)	4	5	1 (180–280 cm s ⁻²)	7	14
2 (350–420 cm s ⁻²)	17	28	2 (280–380 cm s ⁻²)	16	22
3 (420–490 cm s ⁻²)	7	14	3 (380–480 cm s ⁻²)	8	13
4 (490–560 cm s ⁻²)	2	2	4 (480–580 cm s ⁻²)	5	7
5 (560–630 cm s ⁻²)	4	6	5 (580–680 cm s ⁻²)	1	1
6 (630–720 cm s ⁻²)	2	2			

bifurcates into two principal pathways: toward the north of Lima and toward the central districts. Since the shape of the network is more like a tree than a grid, nodes with high betweenness are scarce.

The similarity of the performance of the degree and betweenness scenarios in the water network (see figure 3) implies that this network is better able to redistribute, connect and recover more than the other two networks can. A small group of nodes influence the overall connectivity of the system, especially in the early stages of the node failure. For example, the removal of the node representing the Atarjea water treatment plant, which has the highest degree and betweenness values, reduces the connectivity of the system by more than a third of its initial value in the respective scenarios.

Electricity network performance is shown in figure 4. Unlike the other two networks, there is a notable difference between both in the earthquakes scenarios and the random scenario, since the PGA maps indicate higher ground acceleration in the northern areas of the city, and elements located there are more likely to fail. In this case, a considerable number of nodes are affected by these two scenarios.

The Chavarria substation (220 kV), the entrance node for electricity distribution to the northern areas of the city, is one of the most critical elements in the system due to its high degree (number of edges) and high betweenness value. Other substations, such as Balnearios, which is the connection between the main 220 kV line and the distribution to the center and south of the city, and Chilca 1, connected to the main thermoelectric power plants of the country, have important values of betweenness or degree. It is important to note, however, that the connectivity of the power grid with other infrastructures does not depend on the nodes with the highest betweenness and degree.

3.2. Interdependent assessment of vulnerability

Figure 5 shows the performance of the three networks together. The nodes with the highest degrees are the most critical, followed by the betweenness of the system. In the case of the degree scenario, among the nodes that produces the highest reduction of connectivity are the ones that also have some interdependency with another

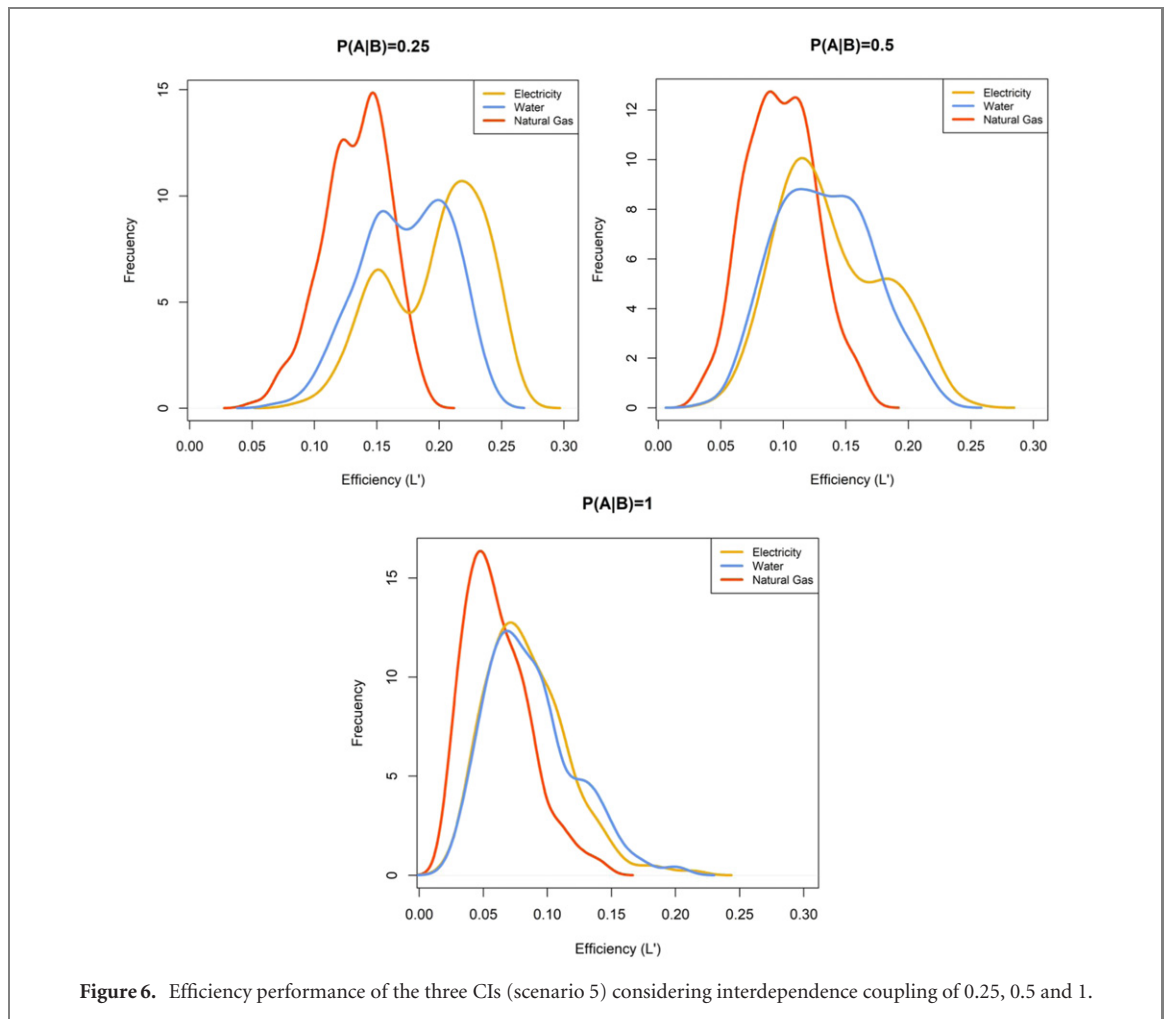


Figure 6. Efficiency performance of the three CIs (scenario 5) considering interdependence coupling of 0.25, 0.5 and 1.

network. For example, removal of the Chavarria substation (220 kV) node causes a significant decrease in efficiency (0.029). Similarly, failure of the Santa Rosa, Chavarria, Balnearios and Barsi substations together generates a connectivity reduction of 0.165, a significant variation compared with the effect of the removal of the other high-voltage substations.

These results explain which of the scenarios has a higher effect over its topological properties during the successive failure of the nodes (figure 5). In the water system, some of the elements in the earthquakes and redundancy scenarios affect connectivity in the early stages of the disruption, while the degree and betweenness affect the system later, since the elements with higher properties are not within this system. The earthquakes scenarios (four and five) affect later the system since the location of the areas with the highest seismic intensity are not necessarily the most critical in the system.

The electricity system is affected early on, due to its connectivity with the node with high degree and betweenness properties, which will later affect the other systems since the nodes with topological properties are the interdependent ones. This means that their interconnected nodes are also the most connected to the electricity system. The 1974 earthquake scenario has an effect on the system when removal of fractions is between 30% and 70% of the elements, given the fact that some of the most affected nodes are located in the northern part of the city, which does not have as much interconnectivity as does the central area of the city.

The natural gas system shows that in the degree and betweenness scenarios there is a heavy influence when the fraction of elements removed is less than 30%, in which the system nodes with high property index are also connected to other infrastructures. Moreover, the earthquake scenarios require the removal of more than 30% of the elements since the northern and eastern areas of the city are the most affected by earthquakes and the natural gas network does not operate in those areas.

Among the three infrastructures, the electricity network is the most vulnerable to a targeted attack to the system or to the other two systems as well. In the case of scenarios four and five (i.e., earthquakes), this is based on the distribution of the PGA, higher in areas where low efficiency, degree and redundancy nodes are pretty common; therefore, damage most likely occurs in less critical elements. Seismic hazards are events with

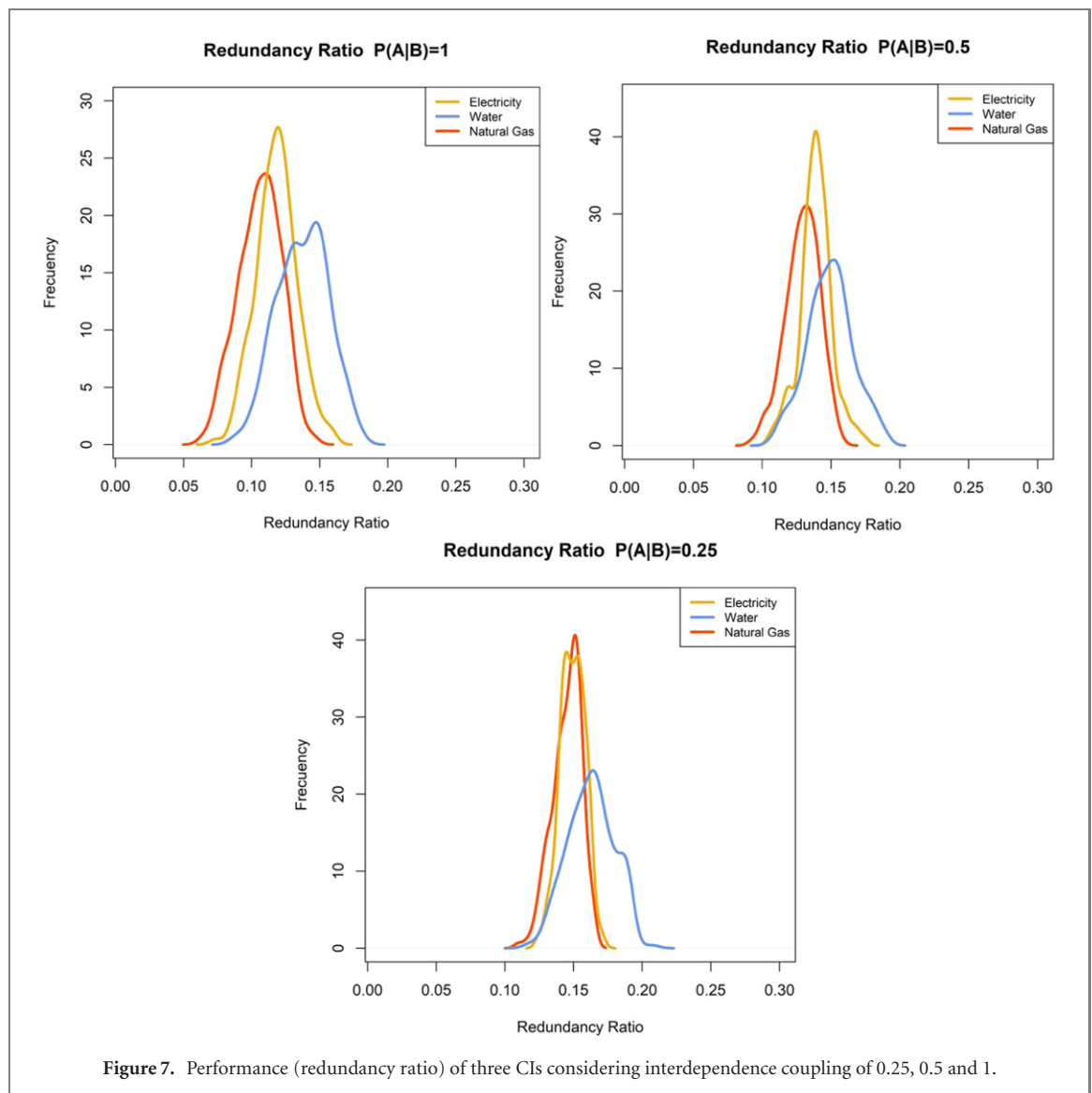


Figure 7. Performance (redundancy ratio) of three CIs considering interdependence coupling of 0.25, 0.5 and 1.

a potential for certain interdependent effects; however, a random order of failure from the element has effects that can greatly affect the total performance of the system (Dueñas-Osorio *et al*, 2007a).

The first step of the interdependence analysis is cluster analysis. The summary of the cluster results with DBSCAN are shown in table 4. Of all the generated clusters, only a fraction involve interdependencies. It is important to note that it is assumed that the components of these clusters are interdependent, and that the performance of the network considers interdependence coupling. Moreover, the interdependent conditional probability $P(A_i|B_j)$ is defined as the probability that the i th node of the CI A is defined as a CI (water, natural gas or electricity) failure, given that another node B of the cluster also fails.

The locations of clusters in each level are shown in figures S1 and S2. Once interdependencies were determined, a series of 200 Monte Carlo simulations of interdependence probabilities $P(A_i|B_j) = 0.25, 0.5$ and 1 were run. Results show that the performance of the three CI varied according to the interdependent designated probabilities. As the interdependent coupling decreased, the performance indicators (i.e., efficiency and redundancy ratio) tended to increase. As shown in the last section, the electricity and natural gas systems possess the highest and lowest efficiencies, thus, the average efficiency of the Monte Carlo analysis showcases similar values: 0.13 for natural gas, 0.17 for water, and 0.2 for electricity (figure 6). However, as the coupling between infrastructures is stronger (higher interdependence), the performance of electricity network reaches that of the water network. This may be due to the vulnerability of specific nodes, which create larger disruptions to the performance of the networks. In scenarios 4 and 5, the performance of each CI is similar, except for the performance of the water system, due to the location of certain nodes in a high-risk area (figure S3). On the other hand, the natural gas network displays a limited range of values with a lower performance than the other two CI, providing evidence that regardless of the scenario, the network will tend

to operate in the same manner, in this case, the distribution of flows from all parts of the network is less efficient.

Moreover, the performance of the network using the redundancy ratio gives us an idea of the capacity of the system of distribute flows. Figure 7 illustrates the performance using interdependence probabilities of 0.25, 0.5 and 1. Similarly to the efficiency simulations (figure 6), the average values of the R_r simulations tend to decrease as the interdependencies become stronger. For example, the water distribution system average values range between 0.07, 0.097 and 0.012 for probabilities $P(A_i|B_j)$ of 0.25, 0.5 and 1, respectively. Furthermore, the average values for the natural gas and electricity systems decrease from 0.15 to 0.12 and 0.145 to 0.11, respectively. The water network system also has a wider range of values; this system shows better performance than the other two (figures 6 and S4), giving evidence that this network has higher redundancy; and has the capacity to redistribute flows when a disturbance occurs, regardless of the scenario.

Although our assessment provides a general understanding of the potential vulnerability of the CIs, there are some drawbacks when using a topology-based method. Mainly, topological models are useful for assessing robustness of systems since infrastructures can be represented as networks. However, since physical flows are not considered in the analysis, certain functions and properties of the system's components are disregarded. That means that all components are considered homogeneous and thus the analysis does not fully reflect the performance of real-world infrastructure systems as much as physical flow models do. Further development would focus on the inclusion of resource flow modeling, considering the supply and demand of physical flows.

4. Conclusions

This paper assessed three CIs, individually and collectively, all of them considered important for the preservation of the daily life in the city. While several approaches to the analysis of the interdependency of the infrastructures are possible, we consider the network theory as the most appropriate alternative for this analysis.

The relationship between the number of degrees (edges) and the betweenness of the component of the network suggests that the topological conformation of the natural gas system is very fragile and more susceptible to failures than the other two infrastructure systems. This is due to the shape of the network, similar to a tree structure with the main distribution lines, Loop Costa and the City Gate station, as initial elements of the system. If the analysis had taken only the efficiency indicator into account, the electricity network could be considered a stable network. Other indicators, however, point out to the lack of redundancy in the electricity network, owing to the system's structure, which has a divided distribution of substations into north and south (i.e., ENEL in the North and Luz del Sur in the South). The water distribution system is better established than the other infrastructures because its configuration is more similar to a grid. This gives the convenience of a more connected and a more redundant structure as fewer nodes with high betweenness values in a system means a network is less likely to depend on certain specific nodes, the same can be said about the degree of an element. As all indicators are complementary and address different aspects of the systems, they should not be analyzed separately. An analysis that includes all of them is indispensable for major comprehension of the systems. In this study, this was developed for the earthquake-related scenarios, showing that as interdependent coupling decreases, efficiency and redundancy ratios tend to increase. The interdependent analysis of CI gives us a clearer view of what the behavior of the systems would be in earthquake scenarios. In general terms, the natural gas system seems to be affected more than the other two systems in both earthquake scenarios; however, the water system seems to perform better when interdependent with the other two CIs; this is due to topological characteristics, and the epicenter of the earthquake in the scenario. This means that the vulnerability of the interdependent systems may depend on the geographical characteristics as well as the topological; the latter were further assessed in this study. Moreover, the reduction of the centralization of the systems could play a major role in the reduction of the system's vulnerability. The construction of additional water treatment plants in Lima, for example, will reduce the probability of a potable water shortage in Lima due to an interruption of the main water treatment plant, as seen in 2017 (Vázquez-Rowe *et al* 2017).

There is a potential for further inquiry to continue this research. The model developed here can be used to plan mitigation activities for the infrastructures and is a first step for a more elaborated representation of the dynamics of these networks. Hernandez-Fajardo and Dueñas-Osorio (2011) explain that in interdependent networks, the dynamic of failure gives a new perspective on how operational a system is over time. Moreover, the analysis done here has the additional purpose of eliciting the idea that the electricity, water and natural gas distribution systems should not be segregated in their operations, and leads us to propose collaboration between the managers of each infrastructure.

Finally, as far as we know, most of the studies related to CI behavior have focused on more developed countries. However, most future megacities will appear in the developing world, where unique characteristics of the CI systems reflect different responses to disturbance. Usually, these characteristics are defined by the lack of urban planning which has an effect on how infrastructure is distributed in the city. This is reflected by the lack of redundancy in the electricity distribution system. Moreover, this case study presents an important scenario analysis related to natural disasters, more specifically to earthquakes. Since Peru is a seismic country, most of the infrastructures should be better prepared to withstand these occurrences. Issues with the state of the infrastructures can affect performance. Awareness of critical elements may allow the development of risk assessment plans and the setting of priorities.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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