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Improving Thermal Performance of Traditional Cabins in the High-Altitude Peruvian Andean Region

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Abstract: Communities in the high-altitude region of the Peruvian Southern Andean Mountains are located over 4200 meters above sea level. Communities organize in isolated cabins dispersed in an extensive area surrounding the community center. The harsh natural environment and poor living conditions affect people's health and increase child mortality, especially in winter. Daytime solar radiation is of high intensity. At night exterior temperatures are -10^{o}C, while indoor temperatures of cabins barely reach 0^{o}C. This research sought to improve the thermal performance of these cabins with passive design strategies and local resources. The methodology included: a) collection of weather data versus indoor thermal performance, availability of local resources and understanding domestic organization patterns; b) definition of comfort temperature range and analysis of local materials; c) technology transfer by involving the population in the construction of a prototype. Simple passive strategies of air tightness and solar gain with local available materials (adobe for walls, totora reed (Schoenoplectus tatora) and sheep wool for insulation, and stone and wood to waterproof the floor) improved night thermal performance in these isolated areas. Although local people are starting to implement these techniques in their own cabins, this is just the starting point towards appropriate thermal comfort.

Keywords: Thermal Performance, Passive Solar Design, Totora Insulation, Vernacular Architecture, Tropical high altitude climate

Introduction

The high-altitude Southern region of the Peruvian Andean Mountains is located in between 4000 and 5000 meters above sea level. The main economic activity of communities in this region is alpaca breeding, which organizes the community in isolated cabins dispersed in an extensive area surrounding the community center and market. Agriculture is not feasible; only "ichu" grass (Stipa ichu) grows everywhere, which is the main food for alpacas. People live in extreme poverty and poor living conditions, with neither electricity nor water system. These circumstances affect people's health and increase child mortality, especially in winter, when "heladas", nighttime frost, are frequent; young alpacas' mortality also increases during this season thus affecting their main income.

The typical cabin in this region has three separate modules: bedrooms, kitchen and storage room, made of stone walls and occasionally with adobe bricks, earth floor, small or no window holes, metal doors and roof, and no insulation. Originally the roof was thatched with the local "ichu" straw, but currently it has been replaced by tin metal roof sheets over thin wood rafters, given that it is more economic, it is more "modern", and nowadays it is not feasible to get "ichu" straw with the required length. This change worsened the thermal performance of cabins. Field measurements during the coldest months showed indoor temperatures around 0^{o}C at night.

Figure 1. Quella-Quella, a typical cabin and landscape of the high altitude region

According to weather data collected for three months in one of these communities, Orduña, average air temperature during the day is 12.5°C and -4.1°C at night. There is not a significant seasonal variation and the diurnal thermal range is moderate to high (around 16°C). However, due to climate change, climatic conditions are unstable, unpredictable and there are more frequent frost events at night. Relative humidity has significant variation during the day and day after day. However, on average, relative humidity is low at midday, in between 10% and 40%.

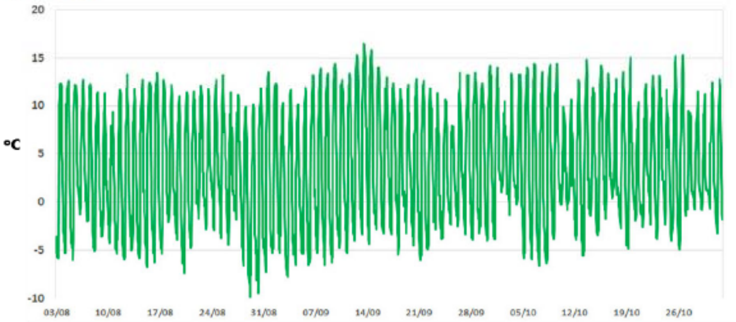

Figure 2. Outdoor Temperature in °C

Solar radiation is constant and very high throughout the year. The average daily total of the three months of measurements is 6kW/m^2. However, maximum daily total can reach 8kW/m^2, and minimum daily total is around 3.5kW/m^2. It is important to note that 75% of the time solar radiation was over 5kW/m^2, while only 5% of the time solar radiation was below 4kW/m^2. Winds are constant, with moderate speed and coming from diverse directions. Maximum speed is in the range of 3 and 5 m/s at noon, and decreases significantly at night, becoming completely calm at dawn, when it is also the moment of the day with the lowest air temperature.

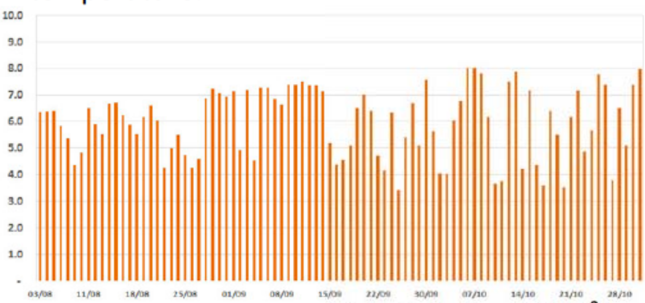

Figure 3. Global Horizontal Solar Radiation (kW/m^2)

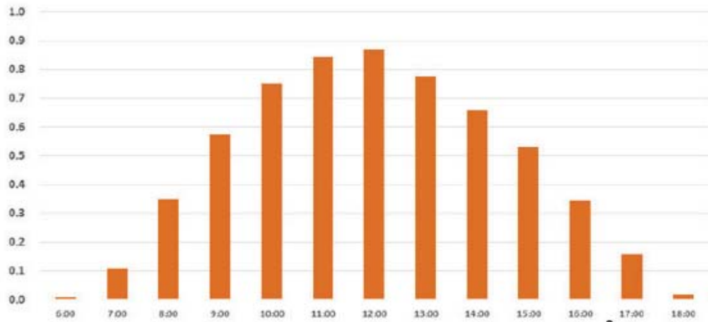

Figure 4. Daily Average Solar Radiation (kW/m^2)

Given these conditions, this is a proposal to improve the thermal performance of the dwellings in these isolated communities, by means of bioclimatic design strategies, local resources available in the region and active participation of the local people.

Methodology

The research focuses on Orduña and is a section of a multidisciplinary project on technological transfer in high-altitude communities (Rodriguez Larrain et al, 2016). Orduña is a characteristic community of this region, at 4800 meters above sea level. It has the typical climate of the high altitude region: cool during the day and very cold at night. In addition to collecting weather data, there was a previous study on the habitat, the typical dwellings and the living practices and patterns of its inhabitants.

A portable weather station, Davis Vantage PRO2 Plus, was used to register exterior information, and data loggers ONSET Hobo H08-003-02 and Extech registered air temperature and relative humidity within the cabins. Actual air temperature data was collected in different months from 2014 to 2016, with a total of 150 days of measurements. Only 7 of the 150 days air temperature at night was above 0°C, giving an average minimum temperature of -5°C. It may be concluded that frost occurs throughout the year, and is not related to a particular season, but rather is a constant condition in Orduña.

There are no specific studies on thermal comfort in high altitude tropical climates. Therefore, the adaptive comfort method of Nicol and Humphreys (2002) was taken as reference to calculate and define a thermal comfort range for Orduña, based on the monthly average outdoor air temperature. From the air temperature data collected, the calculated lower limit of the comfort zone is around 12°C, which is much higher than the indoor temperature registered in the cabins, generally in between -2°C and 2°C.

Representative cabins were measured and occupation patterns and users' needs were defined in group sessions with local people.

The proposed bioclimatic design strategies focuses on increasing heat generation/gain and reducing heat losses with local resources and materials, especially the "totora" reed mattress as insulating material. The "totora" is abundant in the high Andean lakes, and for a 5cm thick mattress the average R-value is 0.74m^{2}K/W (Ninaquispe Romero et al, 2012). The strategies were evaluated with Design Builder software to select those which best improve thermal performance and are economically accessible to local people. Conductivity of selected local materials was evaluated at the laboratory to select the thermally best combination.

Basic concepts on climate and thermal performance of buildings were deployed to local people in group sessions. They were also trained in the selected bioclimatic design strategies and construction techniques by applying them in remodeling some sections of their own cabins.

A prototype cabin applying the bioclimatic design strategies was built by the local people in the communal center town with the supervision of the project team members. Once completed, the weather station and data loggers were installed to register new measurements. ONSET Hobo data loggers were placed in the three rooms of the bedroom unit (two sleeping rooms and one distribution room in the middle) to register air temperature and relative humidity. Two data loggers were placed in each room at 0.40 and 1.40 meters above floor level. Data was registered every hour from August 3 to October 31, with a total of 2160 data per item. Given that the prototype cabin was more hermetic than the standard cabin, interior air quality was also measured, specifically the CO_2 concentration with Sper Scientific 800050 equipment.

Traditional Dwelling Design and Practices

The organization pattern of the cabins has a "U" shape: the bedroom unit on the East side has two rooms with doors facing West, towards a central patio. On the North side is the kitchen unit, usually the only building with a thatched "ichu" roof; and on the South side is a storage room. The West side of the central patio has a "pirka" stone fence. One family or extended family (grandparents and/or oldest son's family) lives in a cabin.

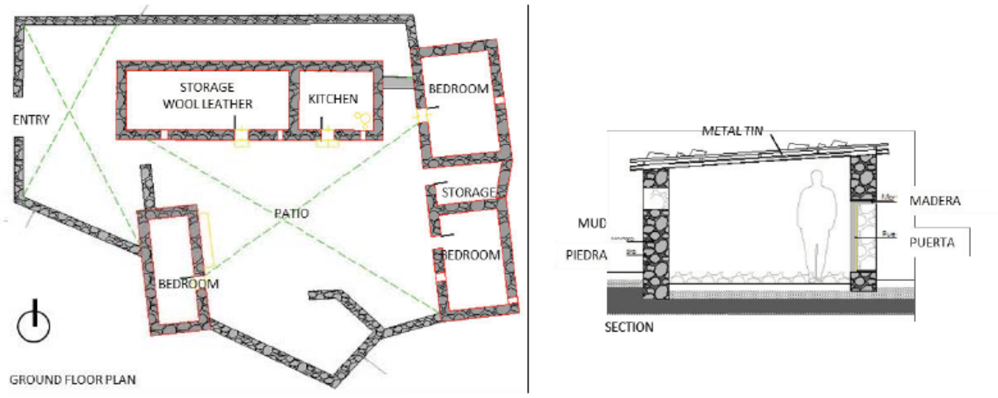

Figure 5. "Quella-Quella" Plan and section of traditional cabin in Orduña

During the day men and women are in the field pasturing the alpacas; only small children, pregnant women and elderly members of the family stay in the cabin. They usually sit in the kitchen, which is warmer, or in the sunny area of the patio. They all gather in the kitchen at about 5 to 6 in the afternoon for supper and then go to the bedroom unit. Usually two to four members of the family sleep in one room. At 5 to 6 in the morning they gather again in the kitchen for breakfast, before leaving for their daily activities.

Most of the cabins and fences are made of dry stone, which is the material readily available in the region. In the cabins, the holes among stones are covered with mud. Floors are just earth without any treatment, thus usually they are damp and increase the cold sensation within the cabin. The gaps left by the rafters in between the stone walls and the metal roof remain open. The door of each room is poorly built with cracks all around the border. The little heat generated by the people in the bedrooms, escapes from the room through the materials by conduction and through all the gaps and cracks.

Proposed Design Strategies

The bioclimatic design strategies recommended for Orduña to reduce heat loss were: materials with lower U-value, elimination of cold air infiltration through cracks and gaps, small windows to allow solar heat gain and natural light, insulated doors and window shutters. Regarding heat gain, solar radiation became the main source available, especially via skylights. These strategies are congruent with those of other authors (Olgyay, 2008) (Szokolay, 2014) (Givoni, 1998).

The base module selected to evaluate the recommended strategies was a sleeping room of 3.00 by 4.00 meters with stone walls, metal tin roof, earth floor and metal door. The longer sides of the wall face East and West. Two windows were located on the West wall, with single pane glazing and wood frame. Results from simulations with Design Builder software proved that insulation of walls and roof with 5 cm thick "totora" reed mattress was the most effective strategy to improve the thermal performance of the room (Figure 6), and to determine the following materials (Table 1):

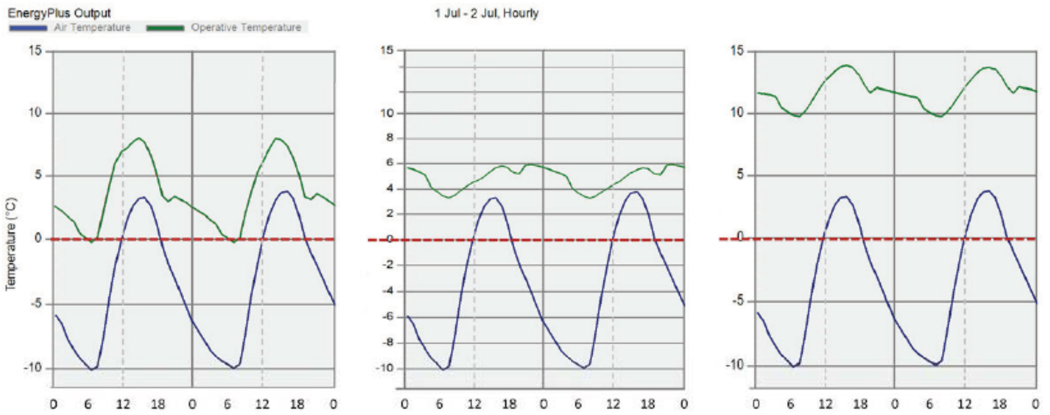

Figure 6. Results of simulations with Design Builder

Table 1. Recommended materials to improve thermal performance in Orduña cabins

Element	Materials	U-value W/m^2 ^{o}K
Roof	Metal tin sheets in the exterior for rain protection; 5 cms of a mix of mud with straw; 5 cms of insulation made of "quesanas de totora" reed mattress; wood rafters, and gypsum plaster in the interior	0.979
Walls	Adobe 40 cm thick, 5 cm of "totora" reed mattress on the exterior, and 2.5 cm of clay coating on both sides of the wall	0.581
Floor	Three layers of stone of different sizes totaling 25 cm thick, 5 cm of a mix of mud with straw, and 3 cm of hardstand earth to reduce sub-soil damp reaching the surface	1.516
Windows	Single glazing with wood frame, facing West, with 2.5 cm thick shutters made of two layers of plywood with sheep wool in between as insulation	1.370
Entry Door	Wood frame with a layer of metal sheet in the exterior, 2.5 cm thick of sheep wool insulation and a layer of plywood in the interior. It should not open directly into bedrooms but rather to an intermediate room	1.164
Skylight	Wood frame and a transparent plastic sheet. Only in the room with day-activities	5.995

Some modifications were done for the construction of the prototype cabin. The "quesana de totora" reed mattress was placed in the interior instead of the exterior of the adobe wall, due to practical purposes of maintenance and durability. Windows were open on both sides of the room, facing East and West, and the floor was completed with wood planks (Figure 7). The skylight was 0.80 x 1.00 meters and located in the distribution room Local people painted the walls white and bought furniture (beds, small tables and chairs) for the cabin bedroom unit.

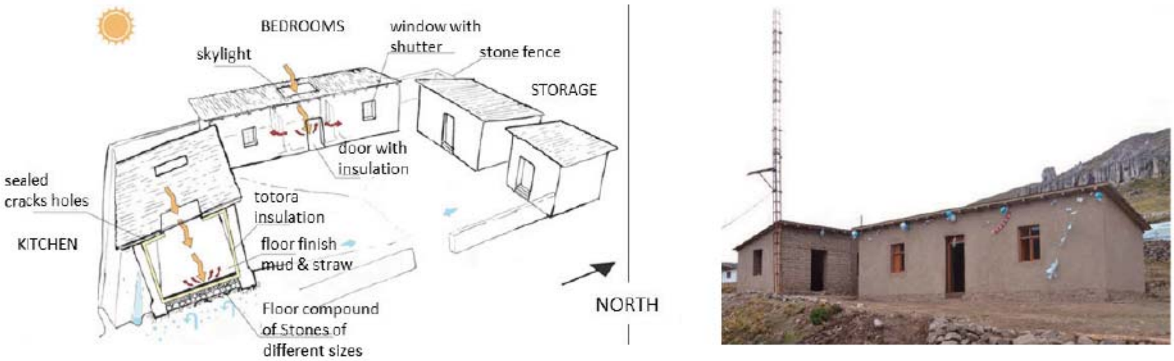

Figure 7. Proposed site plan of prototype and built cabin (bedroom unit and kitchen)

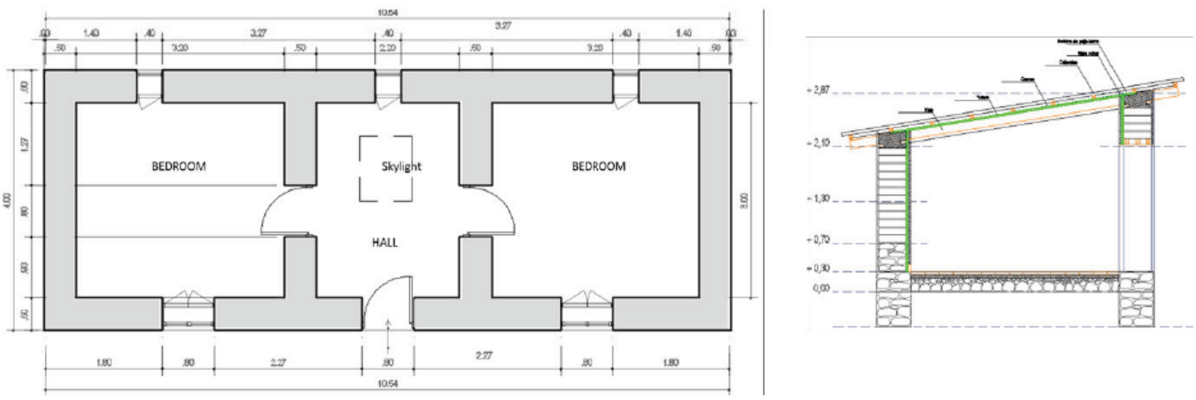

Figure 8. Floor plan and section of bedroom unit

Results

It is important to note that rooms were not consistently occupied during the three months of measurements. Results are the hourly average of the three months of registered data. In the case of the distribution room with the skylight, data was valid only for one month (August). The CO_2 concentration data was registered for 24 hours in one sleeping room with two people, who made sure the room was hermetic at night.

As indicated before, the exterior thermal range is 16°C with cold nights and cool days (Figure 9). The interior thermal range of sleeping rooms is only 4°C to 5°C, while in the distribution room with the skylight the thermal range is 12°C. During the coldest hours of the night, interior temperature of the prototype sleeping rooms are 8°C above exterior temperature and 4°C above temperature of traditional cabins, which is an improvement, but still not high enough to reach contemporary comfort standards, as previously defined.

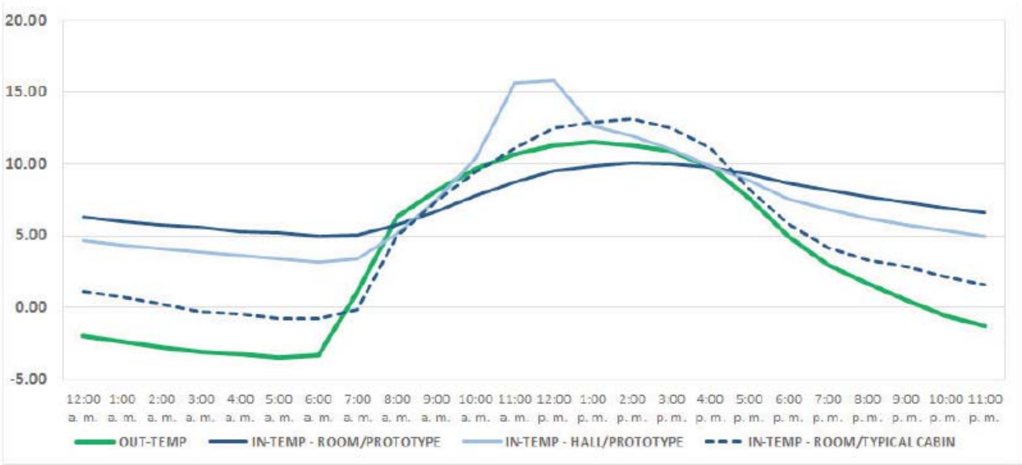

Figure 9. Air temperature in ^{o}C, of prototype bedroom unit compared to traditional cabin and outdoors

Air temperature in the distribution room is 5^{o}C higher than the sleeping rooms, but also 1^{o}C to 2^{o}C lower at night. The difference of the air temperature registered in the sleeping rooms at 40cm and 140 cm above floor level is greater when the temperature in the distribution room is the highest. This demonstrates that warm air from the distribution room enters the sleeping rooms by convection during the day. Concentration of CO_2 was slightly above 1000 ppm but still within an acceptable range.

Discussion

The results show progress towards thermal comfort in Orduña cabins, but also that it is necessary to consider further improvements and additional strategies to achieve a better thermal performance of the cabins. The "quesana de totora", reed mattress worked well as insulation on the roof and walls; however they could work better on the roof by adding a layer of clay mixed with straw to guarantee there is no infiltration through interstices among reeds.

The skylight in the hall proved useful for solar gain, which is potentially the most effective strategy to improve the thermal performance of the prototype. It could work even better if all the roof of the hall is transparent and become a hot-room to transfer heat to the sleeping rooms by convection through the open doors during the day, and to collect heat on the walls adjacent to the sleeping rooms and transfer it by conduction in the evenings. The option of adding skylights in the bedrooms would require shutters that guarantee hermetical closing at night, and also that are economical, and easy to use and maintain.

Insulation of doors and windows shutters with sheep wool worked well. The only consideration would be to make sure the frame has no gaps or grooves. The insulated floor would prevent it to becoming a source of heat loss, as long as the interior air temperature rises above the exterior mean air temperature. This is especially important at night.

The floor to ceiling height of the prototype could be lower thus reducing the volume of air in the rooms to warm up and the exterior surface exposed to cold winds. It also would allow the warm air to be closer to users due to thermal stratification of the air. The color of exterior walls should remain dark to reflect the least incoming solar radiation. This has to consider the possibilities of natural clay and the acceptance of users of the cabins.

Despite CO_2 concentration is within an acceptable range, it might be required to include a simple control system for fresh air intake, when more than two persons occupied the bedrooms.

Conclusions

The implementation of basic bioclimatic concepts of thermal comfort with local resources can improve the thermal performance of cabins in isolated areas of Andean high altitude regions of South Peru. The first objective must be to make the dwellings more hermetic and insulated to prevent heat loss by conduction and infiltration. Given that Peruvian Andean regions are within the tropics, solar radiation of high intensity is the main and most effective source of heat gain, specifically through skylights.

The “quesanas de totora”, reed mats, have proved to be a good insulation material; however it is only available in the southern part of Peru.

The recommended strategies could satisfy the thermal comfort requirements of current inhabitants, but they still do not satisfy contemporary international standards of thermal comfort. It might be necessary to consider complementing the passive strategies with active ones or even with conventional heating systems. However, current economic constraints make difficult the broad implementation of non-passive systems.

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