

Interrelation between constructive characteristics and modes of inhabitation in the thermal performance of *putucos* in Puno, Peru

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This study analyzes the thermal performance of *putucos*, vernacular earth dwellings located in the Peruvian highlands at over 3,800 m.a.s.l., currently used for sleeping, cooking, and storage. Despite their cultural relevance, there is limited technical documentation on these constructions. Using a mixed-methods approach, thermal measurements were taken in five inhabited *putucos* during representative seasons of the local climate, surveys were conducted to understand the thermal perception of the occupants, and graphical simulations were developed to comprehend the passive strategies employed. The results revealed significant thermal variations depending on space usage and showed that these dwellings do not meet the temperature and humidity levels established by conventional thermal comfort standards. Despite this, the inhabitants reported high thermal satisfaction, revealing a strong capacity for cultural adaptation. Additionally, vernacular construction strategies that contribute to passive interior conditioning were identified. These findings challenge the universal applicability of thermal comfort criteria and propose their evaluation from an occupant-centered perspective. The architectural qualities of *putucos* highlight how local empirical knowledge has generated functional and resilient solutions over time. The study underscores the need to preserve these buildings as architectural heritage and to promote research that integrates both physical and perceptual variables to understand their habitability.

Keywords: putucos, vernacular architecture, thermal comfort, passive design

1. Introduction

In recent decades, climate change has caused significant impacts in various regions of the world (Cui et al., 2021). A sustained increase in temperature is consistently observed, along with changes in precipitation and the intensification of extreme weather events, such as frosts and prolonged droughts. Despite these adverse conditions, highland rural communities continue to inhabit and preserve their traditional dwellings known as *putucos*, which have been present in the area for hundreds of years.

Located in the Peruvian highlands, *putucos* represent a unique example of vernacular housing, still inhabited by Andean peasant communities who preserve their culture, language, and a distinctive building tradition passed down from generation to generation. Oral memory plays a fundamental role in reconstructing and narrating this architecture, as it is deeply connected to social values and traditions that can be projected into the future (Ardhyanto et al., 2023).

Putucos consist of a single interior space used for activities such as cooking, sleeping, and/or storage (Marussi, 1999). In the past, a household unit often comprised three or more *putucos*. Their design stands out within the local architecture due to the shape of their roofs and the construction materials used. They typically have a square or rectangular floor plan, and as the structure rises, the courses of blocks gradually incline inward, forming what is known as a corbelled dome or false dome (Abril Revuelta & Lasheras Merino, 2017), allowing *putucos* to reach an approximate height of four meters. The primary construction material, commonly referred to in Quechua as *champa*, consists of sod blocks—pieces of soil extracted directly from the ground—which, when placed upside down, form both the walls and the roof. *Champa* is highly resistant to the region's frequent flooding, contributing to the long-term durability of the *putuco* (Vitulas-Quille, 2022). However, some *putucos* are also built with adobe or a combination of both materials.

The architectural features of the *putucos* (Figure 1) are defined by the absence of openings, with only small holes provided for ventilation, which may be located on the walls or the roof. Additionally, there is a single entrance opening, which may or may not be protected by a door. Some *putucos* incorporate wooden logs that serve as horizontal structural elements; these may span across the roof or function as lintels

above the entrance. The interior of the *putucos* is extremely austere, and in some cases, includes furniture made from the same earthen material as the structure itself.

In this way, this traditional construction represents a reflection of its society, as it makes use of locally available materials and responds to the customs of its inhabitants. It stands as a form of constructive heritage preserved across generations (Marussi, 1999), promoting self-construction, where each family is responsible for building its own dwelling. The way of life in the rural highlands of Peru is particularly unique, as people maintain their customs and traditions, which reflect a deep connection to the land and an Andean worldview that transcends the material and is expressed in everyday life. This architecture gives rise to a singular typology that, in order to be fully understood, requires a deep appreciation of the inhabitants' way of life (Gutiérrez, 2013).

Finally, due to their sober, beautiful, and functional architecture, *putucos*—which embody a deep cultural, traditional, and identity-based significance—form part of the cultural and historical landscape of the region. This led to their designation as Cultural Heritage of the Nation by the Peruvian government (Ministerio de Cultura, 2014). However, this designation has not been sufficient to ensure their recognition and protection at the local level, as the number of *putucos* continues to decline, with many now abandoned and in ruins. Moreover, there is a significant intangible loss occurring, such as the gradual disappearance of traditional construction knowledge in the region.

In this context, this research examines the relationship between thermal comfort and Alto Andean vernacular architecture, taking the *putucos* as the object of study. Despite their multiple architectural qualities, their thermal performance has been little explored.

The main objective of the study is to identify the constructive strategies and everyday habitation practices that enable these dwellings to achieve thermal comfort. Through fieldwork and direct dialogue with their inhabitants, the aim is to broaden the understanding of thermal comfort assessment in vernacular architecture. Furthermore, the study seeks to contribute to the appreciation and preservation of traditional construction knowledge, highlighting its relevance in addressing current challenges related to climate change and housing sustainability.

The central hypothesis of this work posits that putucos are capable of achieving adequate indoor thermal comfort conditions in an extreme climatic environment, owing to an adaptive capacity that responds not only to functional needs, such as the use of local materials and traditional construction techniques, but also reflects ancestral knowledge deeply rooted in the lifestyles of their inhabitants. The analysis of their thermal conditions therefore allows for the identification of their constructive features while simultaneously providing insight into the daily practices and modes of dwelling of Alto Andean communities, offering an integral perspective of this vernacular architecture.

The findings of this research have direct applicability in high Andean regions, both in the Peruvian Altiplano and in other areas of Latin America where rural communities face similar conditions of environmental vulnerability. The results can inform architectural design processes and housing policies that integrate vernacular knowledge and climate adaptation strategies.

This research is significant as it presents a model of resilient housing adapted to extreme conditions, built with local resources and sustained by ancestral knowledge passed down through generations. As such, it offers valuable insights for researchers, professionals, and policymakers interested in sustainable architecture, climate

adaptation, and the recovery of vernacular practices in rural and environmentally vulnerable contexts. Moreover, it contributes meaningfully to global efforts aimed at revaluing intangible heritage and promoting culturally appropriate and environmentally responsible housing solutions.

2. Literature review

2.1 Thermal performance of the putucos

Research related to *putucos* is scarce, and even more limited is the number of studies that specifically address their thermal performance.

The book *Arquitectura vernacular: Los putucos de Puno* (Marussi, 1999) is the primary academic reference for this architectural typology. The work presents a field study that comprehensively describes the *putucos*, including their location, historical background, and the architectural survey of six cases. It analyzes aspects such as function, form, materials, construction processes, and durability. Thanks to its approach, this book has served as the foundation for subsequent research and theses on the *putucos*.

Guevara Lactayo (2015) is the only study that specifically addresses the thermal performance of these buildings. Using simulations in Autodesk's Ecotect software, the study models two hypothetical dwellings and concludes that *putucos* respond efficiently to the cold climate of the region and high solar radiation. This efficiency is attributed to the use of passive strategies such as solar gain, high thermal mass, the airtightness of walls, roofs, and floors, as well as their compact form, which reduces wind exposure. However, this study does not consider the interaction between thermal performance and user perception or adaptation, nor does it include the collection of real data from the study area.

2.2 Thermal performance in vernacular dwellings construction

The climatic potential of vernacular architecture has gained relevance in recent years, with multiple studies linking this type of housing to variables such as temperature, humidity, ventilation, and natural lighting (Yang et al., 2022)

The choice of passive systems to achieve comfort requires a deep understanding of the place, considering variables such as the immediate environment, material availability, and solar and wind paths. Additionally, intangible factors such as sociocultural and economic aspects must be incorporated. However, these passive strategies should not be limited to the local context; rather, they should be promoted as viable solutions at a global level (Toroxel & Silva, 2024).

The envelope of vernacular buildings, constructed with local materials, plays a fundamental role in achieving thermal comfort. Likewise, their relationship with open spaces and the orientation of their openings in relation to the sun and wind direction is a key factor in their climatic performance (Moscoso-García & Quesada-Molina, 2023).

Several studies have demonstrated that high levels of thermal comfort can be achieved exclusively through passive strategies, such as thermal mass, insulation, solar gain, natural ventilation, shading, and the daily practices of occupants (Fernandes et al., 2020; Sghiouri et al., 2020). These strategies, inherent to vernacular architecture, significantly reduce the reliance on mechanical systems and represent a valuable contribution to sustainability (Amraoui et al., 2021). However, it is important to assess whether the incorporation of architectural improvements could further optimize the energy performance of these buildings, in view of environmental, economic, social, and cultural considerations (Fernandes et al., 2019; Philokyprou & Michael, 2021).

To determine whether the passive techniques used in vernacular constructions are efficient, it is necessary to conduct constant and critical analysis in a holistic

manner, through experiments, field measurements, mathematical models, and dynamic simulations. These methods allow for the evaluation of their efficiency and benefits based on reliable results, facilitating decision-making geared toward sustainable construction practices aligned with global climate change mitigation goals (Toroxel & Silva, 2024).

2.3 Thermal performance in modes of inhabitation in vernacular dwellings

The relationship between the thermal performance of vernacular dwellings and the perception of the inhabitants represents a gap in knowledge today (Hermawan & Švajlenka, 2022; Yang et al., 2022). Studying thermal comfort from a qualitative perspective presents challenges such as the scarcity of data, limited access to representative case studies, and the potential mistrust of the population towards external researchers. Therefore, it is crucial to develop methodologies adapted to the local context that include participatory tools and field measurements (Costa-Carrapiço et al., 2022a).

The use of perception scales, such as the Likert scale, has proven effective for analyzing thermal comfort perception (ANSI/ASHRAE, 2023). However, further research is still needed to confirm whether traditional dwellings truly generate positive thermal preference, satisfaction, and well-being for their occupants (Hailu, Gelan, & Girma, 2021). Or, conversely, if users of vernacular dwellings exhibit greater thermal tolerance that challenges conventional comfort ranges. This suggests that traditional methodologies may be limiting our understanding of what truly constitutes thermal comfort, highlighting the need for the development and application of alternative approaches (Costa-Carrapiço et al., 2022b).

Furthermore, it is important to understand that both open and closed spaces exhibit varying thermal behaviors depending on the time of day and the season. This

influences the decisions of the inhabitants about where to stay, highlighting the existence of adaptive strategies in response to the environment (Chang et al., 2021).

Similarly, the worldview of the inhabitants represents an additional challenge for researchers, as vernacular spaces not only serve thermal functions but also social, cultural, and spiritual ones. These spaces are deeply connected with sociocultural, psychological, and aesthetic values that reflect the adaptation of architecture to the daily life of its users (Philokyprou, Michael, & Malaktou, 2021).

It is demonstrated that traditional solutions not only effectively address environmental challenges but also reflect cultural values and enduring ways of inhabiting. Therefore, it is crucial to collect and recover these practices to build sustainable and meaningful architecture (Nasir & Kamal, 2021).

3. Research methodology

3.1. Geographical context

The dwellings studied are located at an altitude of over 3,800 meters above sea level, in the districts of Samán, Taraco, and Huancané, in the Puno department, in southern Peru. They are concentrated in an area south of Lake Arapa and west of Lake Titicaca, a region frequently irrigated by the Ramis River (Figure 2). This river plays a crucial role in sustaining agriculture and livestock, activities that are essential to the way of life of the local inhabitants.

This region is characterized by extreme and demanding climatic conditions, which pose a constant challenge for habitability. According to the Köppen–Geiger climate classification (Cui et al., 2021), two types of climate dominate, influenced by altitude and precipitation patterns. In the areas where the case studies are located, the classification is Cwb, corresponding to a temperate highland climate with a dry season

in winter, moderate temperatures during the day, and cold nights, with temperatures in winter often dropping below 0°C. On the other hand, at the peaks of the hills above 4,000 meters above sea level, the climate shifts to an Et classification, corresponding to an alpine tundra climate, characterized by low temperatures year-round and sparse vegetation.

In addition, the Peruvian Andes are characterized by two clearly defined seasons: a wet season and a dry season. The wet season coincides with the rainy period and spans several months of spring and summer, from November to March, whereas the dry season, marked by intense droughts and extremely low temperatures, corresponds to the autumn and winter months, extending from April to October. This period generates frost waves that are a distinctive feature of the Altiplano Puno landscape (Figures 3 and 4). The marked seasonality of the climate in the Altiplano is due to variations in atmospheric circulation throughout the year. During the wet season, humidity and zonal winds predominate, conditions that favor precipitation formation. In contrast, for the rest of the year, the dry season develops, characterized by the transport of dry air from the Pacific Ocean, which contributes to the reduction of rainfall and an increase in aridity (Zubieta et al., 2021).

3.2 Selection of case studies

The data collection in the field, both on the architecture of the *putucos* and the opinions of the inhabitants, was essential to carry out an adequate thermal analysis. To do so, five *putucos* were selected based on the following criteria:

- Geographical distribution: The selected *putucos* are spread over 10 kilometers in the rural communities of Chucaripo and Chacamarca, Samán district, Puno

department, Peru. This location was chosen to analyze different exposures to the environment and external conditions (Figure 5).

- Internal thermal activity: Habited *putucos* were included, where activities such as cooking, storing, and sleeping, or a combination of these, take place. The variation in internal activities among the selected *putucos* allowed for a comparison of their thermal behavior.
- Accessibility and consent: The feasibility of installing equipment inside the *putucos*, taking photographs, and conducting surveys with the owners was evaluated, considering their availability and willingness to collaborate.

Based on these criteria, the following *putucos* were selected with the following codes: PUT01, PUT10, PUT15, PUT20, and PUT23 (Table 1). This coding is part of a previous cataloging carried out within the framework of a general investigation corresponding to a doctoral study. The original numbering was maintained to ensure consistency and traceability of the study, without influencing the results of the specific analysis conducted at this stage.

The personal data of the participants were anonymized, and they were clearly informed about the informed consent in compliance with Regulation (EU) No 2016/679, ensuring the protection and confidentiality of the information provided.

3.3 Air temperature and relative humidity measurements

The air temperature (°C) and relative humidity (%) measurements were taken inside and outside the selected *putucos*, recording data at one-hour intervals over seven consecutive days during two representative periods of the local climate. The first period corresponded to the wet season, from November 20 to 26, 2023, and the second to the dry season, from July 12 to 18, 2024.

The selection of monitoring periods was based on the need for climatically stable days, considered typical days for each season, and the recommendation to use a one-week monitoring period as a representative sample in tropical zones (Giraldo – Castañeda, Czajkowski & Gómez, 2021; Hermawan, & Švajlenka, 2021). To ensure this stability, the weather forecast for Huanané (Puno), provided by the National Service of Meteorology and Hydrology of Peru (SENAMHI), was consulted in advance, and the selection criteria for stable conditions were applied (Lopes et al., 2021).

The planning of the measurements was based on three main criteria: (i) to obtain a representative climatic evaluation of each season and in each space, (ii) to ensure the presence of the research team in the area during the monitoring, and (iii) to facilitate logistical coordination and supervision with the homeowners to ensure the protection and proper functioning of the instruments.

For the recording, six data logger devices from the brand HOBO, manufactured by Onset Computer Corporation, were used, calibrated from the factory. In interior spaces, USB devices model UX100-003 were employed, with an operational range of -20°C to 70°C for air temperature and 0% to 95% for relative humidity. In interiors with direct exposure to cooking steam, Bluetooth data loggers model MX2301A were used, with a hermetic design and a wider measurement range of -40°C to 70°C for air temperature and 0% to 100% for relative humidity.

The sensors were installed in the center of the space of each analyzed *putuco*, at an approximate height of 1.10 meters, following the recommendations of ASHRAE 55 (ANSI/ASHRAE, 2023). To prevent direct exposure to the sun and other disturbances, the devices were placed on small wooden surfaces designed to hang from the transverse roof beams. The owners were asked not to manipulate or relocate the equipment, as the

putucos are typically open and accessible to other household members and even domestic animals.

The exterior measurement was complemented with the use of a solar radiation shield model RS3-B, from HOBO, manufactured by Onset Computer Corporation, with an operational range of -40°C to 75°C. It is designed to minimize the direct influence of solar radiation and other meteorological factors on the readings. This sensor was installed in an outdoor courtyard, fully exposed to the elements, at one of the homes selected for the study.

Data download and management were carried out using the free HOBOWare software (desktop application) and HOBObconnect (mobile application with Bluetooth connectivity), both provided by the manufacturer. The temperature and relative humidity data recorded by the sensors were processed in Microsoft Excel. A descriptive statistical analysis was applied, including the calculation of measures of central tendency (mean, median) and dispersion (minimum, maximum, and standard deviation) for each monitoring day. Additionally, line graphs were produced to visualize hourly variations in indoor and outdoor temperature, as well as relative humidity, throughout the study periods. These analyses allowed the identification of the periods of greatest thermal discomfort and their comparison with the reference comfort standards (Hermawan & Švajlenka, 2022).

3.3.1 Psychrometric diagram of Givoni

The Givoni psychrometric diagram is used as a tool to define the comfort zone and complement the thermal analysis (Hermawan & Švajlenka, 2021). Based on the recorded data of temperature and relative humidity inside and outside the analyzed *putucos*, it was possible to graphically represent the thermal conditions and compare them with the comfort ranges proposed by the author. This allowed determining the

time occupants remain in comfortable conditions and also facilitated the identification of the most suitable bioclimatic design strategies to improve the thermal performance of the dwellings (Lozoya-Peral et al., 2023).

3.4 Thermal comfort survey

During both seasons, thermal comfort surveys were conducted with the members of the families living in the selected *putucos*, in parallel with the in-situ thermal measurements. At the beginning, data such as date, code, and location of the *putuco* were recorded. The body of the surveys was structured into three parts (Figure 6):

The first part characterized the respondents through direct observation, noting their gender, age, language, approximate weight and height, along with their metabolic rate (met) and clothing level (clo), following tables 5-1 and 5-2 of the ASHRAE 55 standard (ANSI/ASHRAE, 2023).

In the second part, questions were asked about the passive strategies used by the inhabitants to modify their environment and achieve greater thermal comfort. These included changes in clothing, consumption of hot beverages or food, and adaptations in the use of the *putuco* (Chang et al., 2021). Additionally, activities performed inside and outside the dwelling were documented, along with their usage schedules, in order to understand both the use of the architectural space and the territorial dynamics associated with life in the *putucos*.

The third part involved the implementation of three scales to evaluate thermal perception comprehensively (Hailu, Gelan, & Girma, 2021; Kajjoba et al., 2022): Two Likert scales based on 5 points (very cold -2, cold -1, neutral 0, warm +1, very warm +2) according to ASHRAE 55 standards (ANSI/ASHRAE, 2023), with the aim of assessing thermal sensation and preference (Hermawan, & Švajlenka, 2021). Additionally, the Bedford scale, also based on 5 points (very dissatisfied -2, dissatisfied

-1, neutral 0, satisfied +1, very satisfied +2), was used to measure thermal satisfaction (Lopes et al., 2021), and was complemented with explanatory drawings to facilitate understanding by the participants.

The surveys were coded and analyzed in Microsoft Excel. For the closed-ended questions, descriptive statistics were applied, including absolute and relative frequencies, as well as measures of central tendency. In addition, the Mean Thermal Vote (MTV) was calculated to identify the overall trend of respondents' thermal perception. Open-ended questions were analyzed through a qualitative thematic analysis, which involved the identification and categorization of recurring patterns in the responses, allowing for the contextualization and complementing of the quantitative results (Giraldo–Castañeda, Czajkowski & Gómez, 2021).

3.4.1 Sample

To define the sample of respondents, those who make more frequent use of the *putucos* were selected. In the case of PUT01, the couple who reside regularly in the space was surveyed. In the *putucos* used as kitchens or storage, all family members who regularly interact with the environment were included, which, in some cases, involved extended families (Table 1).

3.4.2 Pilot test of the survey

In February 2023, a pilot test was conducted to validate the instrument, which was carried out with a couple residing in PUT31, a dwelling that is not part of the final sample of this study. The initial version was designed with a technical and self-filling approach, but difficulties were identified among the respondents in understanding and completing the form autonomously. One of the main challenges was the language, as

the inhabitants of the *putucos* are mostly Quechua speakers and, in many cases, have limited knowledge of Spanish.

The survey was simplified since the respondents were interviewed while performing their daily activities in the field. The number of questions was reduced, direct observation items by the interviewer were added, and illustrations or explanatory drawings were included, especially to facilitate the understanding of the thermal perception scales.

3.5 Graphical simulation of the incidence of sun and wind

The simulation of solar and winds incidence was a methodology proposed in this research to analyze the indoor environmental behavior of the *putucos* and how the immediate surroundings influence their passive performance, allowing the identification of favorable aspects of traditional construction design.

For this, real characteristics of each *putuco* and its surroundings were considered, including its shape, dimensions, nearby buildings, as well as its orientation and exact location (Hermawan & Švajlenka, 2022). A digital photogrammetry of the *putucos* was carried out, processing multiple photographs to generate a point cloud using the Agisoft Metashape software. The generated 3D models were processed with Rhinoceros and visualized in AutoCAD, allowing a detailed analysis of the actual architectural and contextual dimensions and characteristics (Mallafre-Balsells et al., 2021).

The representations of solar incidence were created using the stereographic solar chart of the campesino community of Chucaripo, located at 15°13'59"S, 69°58'22"W, within the district of Samán, which was obtained through the online tool Sun Earth Tools (n.d.). These representations, along with the angles of altitude and solar azimuth, were extracted at two times of the day: 9:00 AM and 3:00 PM, during the summer

solstice, winter solstice, and both equinoxes. The goal of the solar analysis was to assess the amount of light and solar heat received by the *putuco*, considering three aspects: radiation on its exterior walls, heat entering the interior through the *putuco*'s opening, and the shadows cast by both other buildings and the *putuco* itself.

In addition, graphical simulations of wind penetration were created for the five *putucos*, using wind speed and direction data obtained from the Taraco station provided by the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI, 2023). Wind conditions were analyzed on four key dates of the year and at eight different times of the day, with the goal of evaluating the effect of prevailing winds on the exterior surface and their incidence inside through the entrance.

4. Results

4.1 Constructive characteristics related to their thermal behavior

4.1.1 Thermal results

Thermal measurements taken at the study site were compared with the ranges recommended by Givoni's psychrometric diagram for the comfort zone (21–26°C and 20–70%) and the permissible comfort zone (20–27°C and 20%–80%), highlighted in gray (Figure 7). The results showed significant variations between the interior and exterior of the *putucos*, between the dry and wet seasons, as well as notable differences between the uses of the *putucos*.

In both seasons, the minimum exterior temperatures were recorded below the measurements obtained inside the *putucos*, indicating the *putucos*' ability to protect the inhabitants from low temperatures during nighttime hours. At the same time, the relative humidity inside the *putucos* remained relatively stable in both seasons, which notably differed from the exterior climate.

It was also determined that the activities carried out inside the *putucos* are a key factor in understanding the observed thermal fluctuations. Thermal coincidences in temperature and relative humidity were identified in the *putucos* used for cooking (PUT01 and PUT20), which differ significantly from those recorded in the *putucos* used for storage (PUT15 and PUT23). Unfortunately, the data logger from PUT10 could not be retrieved, so thermal data could not be processed. This situation occurred because the family left the dwelling after the father's passing. For this reason, the analysis of PUT10 will not be included in this section.

The *putucos* where cooking is done inside exhibit significant fluctuations in temperature and relative humidity during both seasons. In this regard, the use of fire for cooking acts as an involuntary active measure. In PUT01 and PUT20, two peaks in temperature and relative humidity were recorded throughout the day, coinciding with the times when cooking takes place: around 7:00 and 8:00 AM, and again between 6:00 and 7:00 PM. These times align with the responses from the inhabitants regarding the moments they typically cook, as indicated in the surveys.

On the other hand, PUT15 and PUT23 maintain more stable temperature and relative humidity throughout the year, without the need for internal heat sources. These *putucos* stand out for the ability of the *champa* to maintain more balanced thermal conditions throughout the day. This results in a temperature and humidity level that is suitable for storage, as will be explained later in the section on how the *putucos* are inhabited.

4.1.2 Psychrometric diagram of Givoni

The thermal results, both internal and external, were presented in the Givoni psychrometric diagram (Figure 8). To plot the thermal behavior lines, the extreme values (maximum and minimum) of temperature and relative humidity corresponding to

the dry and wet seasons were used. The longer lines in the diagram indicate greater thermal and humidity fluctuation, while the shorter ones represent greater stability.

In this regard, the *putucos* PUT01 and PUT20, used for cooking, exhibit a wide range of variation, crossing areas of the diagram that indicate the need for both heating and passive cooling strategies. In contrast, the *putucos* PUT15 and PUT23, used for storage, display shorter lines that remain below the comfort zone. In these cases, the diagram suggests the implementation of passive heating strategies, such as the utilization of internal heat gains. The exterior climate (EXT), meanwhile, remains consistently outside the comfort zone throughout the year. Even during the dry season—which coincides with winter—the analysis indicates that active measures, such as conventional heating, would be necessary to achieve adequate thermal conditions.

Finally, according to the psychrometric diagram, only PUT01, which is also used for sleeping, shows certain moments within the comfort zone; in contrast, the other *putucos* remain outside this range. This demonstrates that, based on the quantitative data analyzed, the *putucos* do not consistently achieve the thermal comfort conditions proposed by Givoni.

4.1.3 Graphical simulation of the incidence of sun and wind

Solar and wind incidence simulations were conducted for the case studies based on surveys carried out using photogrammetry (Figure 9), which enabled a detailed analysis of the actual dimensions of the *putucos* and their interaction with the immediate surroundings. Furthermore, this approach helped to understand the impact of both natural phenomena according to seasonal variations.

The solar incidence representation (Figure 10a) facilitated the understanding of common features among the studied *putucos* in terms of their passive solar gains.

The characteristic conical shape of the *putuco*, formed by inclined *champa* walls converging into a false dome at the top, achieved through the gradual inward placement of *champa* layers, ensures that, regardless of orientation, the building envelope receives a significant amount of solar radiation throughout the year and during the day. This design enhances the thermal performance of the earthen envelope and its thermal inertia, considering that the walls are approximately 0.35 m thick and have a thermal transmittance of 0.507 W/m²K. Furthermore, the conical form results in shorter shadow projections compared to adjacent orthogonal buildings. Consequently, the construction of orthogonal structures that obstruct solar incidence proves disadvantageous. This phenomenon was observed in the cases of PUT15 and PUT23, where proximity to nearby buildings resulted in lower recorded indoor temperatures and dry season. These neighboring structures blocked solar heat gain, especially during winter, when the sun's angle is lower and shadows are significantly longer.

It was also identified that the orientation of the entrance plays a crucial role in determining the amount of solar heat that enters the interior, directly influencing the thermal comfort conditions within the space. For this reason, it was observed that all studied cases feature entrance openings oriented toward cardinal directions with greater solar incidence, while avoiding the south-facing façade. This orientation facilitates heat gain primarily during the morning hours.

Moreover, it can be concluded that the other openings located on the walls and roofs are very small in size and do not follow any specific pattern. As such, they do not significantly contribute to the entry of heat or sunlight, but rather serve the purpose of allowing smoke to escape from the interior.

Regarding the wind penetration study (Figure 10b), it was revealed that wind speeds in the study area average between 2 and 3 m/s throughout the year, indicating

wind conditions ranging from calm to light breezes, which do not generate discomfort. However, there are periods during the year, particularly during the dry and cold season, when wind speeds can increase significantly. It was also observed that the strongest winds typically occur in the afternoon, specifically between 15:00 and 18:00 hours, and predominantly originate from the east—an effect related to the position of Lake Arapa in relation to Lake Titicaca. Therefore, the orientation of the entrance is crucial, as it is the only significant pathway for wind to enter the interior of the putuco due to its dimensions, given that the small openings in the walls and roof do not significantly affect interior airflow.

On the other hand, PUT10 features a protruding *champa* threshold above the entrance, which functions as an element that regulates wind penetration into the interior. According to interviews with residents, this feature was intentionally designed to provide protection against the wind, and its effectiveness was confirmed through the analysis. Furthermore, it is important to note that the absence of a threshold in the other *putucos* analyzed does not necessarily indicate that they were not originally built with one, as the threshold is typically constructed independently from the main structure of the *putuco*.

4.3 Modes of inhabiting related to their thermal performance

4.3.1 Survey results

Throughout the research, it was considered essential to incorporate the perceptions of the inhabitants of the putucos regarding thermal performance. This qualitative approach posed an additional challenge, which enriched the analysis and allowed for results more aligned with the reality of Andean highland living conditions.

The study included surveys of families who own the selected *putucos*. A higher participation of 57.1% males was observed compared to 42.9% females. The most representative age groups were individuals over 70 years old and those between 40 and 50 years old (both with 35.7%), followed by young adults aged 20 to 30 years (21.5%) and minors (7.1%). All the respondents have Quechua as their mother tongue; however, 28.5% do not speak Spanish, while the remaining 71.5% are bilingual.

According to field observations, the average weight of the inhabitants ranges between 50 and 70 kilograms, and their average height is between 1.40 and 1.60 meters. During the survey application, most participants were engaged in agricultural activities or livestock care, which translates to an estimated metabolic rate (met) range of 1.7 to 2.0. In both climatic seasons, a constant use of warm clothing was observed, with a thermal insulation level (clo) between 0.89 and 0.96. The way of dressing responds not only to thermal conditions but also to cultural factors, as traditional garments are preserved for both men and women (Figure 1).

Regarding the results from the third part of the survey (Figure 11), the majority of responses about thermal sensation indicated that 38.9% of the respondents felt neutral (0), while 52.8% reported warm sensations (+1) and 5.6% very warm sensations (+2). During the interviews, several inhabitants emphasized that their homes are "very hot," which supports these findings. Only 2.7% stated feeling cold (-1), and this was recorded solely during the dry season, corresponding to winter.

Regarding thermal preference, 61.1% of the inhabitants expressed a desire to maintain a neutral state (0), while the remaining 38.9% preferred a slight increase in temperature (+1). No responses were recorded for the other thermal preference levels, which reveals a general inclination toward warmer thermal conditions. This trend can be

explained by cultural factors, as the inhabitants, being accustomed to living in cold climates, have developed a preference for warmer environments.

Finally, regarding thermal satisfaction, 50% of the interviewees reported being very satisfied (+2) with the thermal comfort of their *putucos*, while 33.3% expressed being satisfied (+1) and 16.6% indicated feeling neutral (0). No respondents expressed thermal dissatisfaction.

A relevant point during the surveys is that individuals over 70 years old tend to report a very high level of thermal satisfaction (+2) while simultaneously indicating a neutral (0) or even slightly cold (-1) thermal sensation. This response suggests that older individuals, who have lived in the *putucos* for a longer period, seem to have developed greater thermal resilience compared to younger people, adapting more effectively to the thermal conditions of the space.

4.3.2 Modes of inhabitation

In the case of the *putucos* used as kitchens (Figure 12a), it was determined that they play a central role in the dwelling. These spaces house a clay stove with two burners, known as *q'uncha* in Quechua, which is primarily fueled by cow dung. It was found that this activity generates high temperatures inside due to the lack of an adequate smoke extraction system. This condition was observed in PUT01, PUT10, and PUT20, where the interior surfaces have a black tone due to the deposition of soot. Although this aspect is not the primary focus of the research, it is relevant to note that the absence of proper ventilation could have negative health implications for the occupants.

On the other hand, the *putucos* designated for storage (Figure 12b), specifically PUT15 and PUT23, exhibit temperatures below the comfort range, which is beneficial for their intended function. According to the inhabitants, these spaces allow for the optimal preservation of self-consumed food such as potatoes, barley, fava beans, chuño

(dehydrated potatoes), among others, for several months, ensuring their availability until the next harvest. It was observed that the products are stored in sacks placed on the floor, leaning against the internal walls of the *putuco*.

A particular case is PUT01, one of the few *putucos* still used for sleeping, in addition to cooking (Figure 12c). In this space, a couple in their 80s rests every night. It was recorded that they sleep on a raised platform made from a row of *champas*, known as *pataj'á* in Quechua, which is covered with sheep leather and blankets woven from sheep wool in various colors. Additionally, it was observed that the inhabitants wear warm clothing throughout the day, consisting of multiple layers of clothing and hats that protect them from the sun. This clothing, besides being their traditional attire, also provides protection against environmental conditions.

Regarding the interaction with the dwelling, it was identified that the *putucos* are not commonly manipulated by their inhabitants in terms of thermal regulation. The openings in the walls and roofs remain unchanged, and the only opening that is occasionally controlled is the access door, which is typically a rudimentary structure made of wood or metal. In some cases, such as PUT23, the absence of a door was observed.

Finally, it was determined that the use of open space is essential for the inhabitants of the *putucos*, surpassing the importance of the interior space (Figure 1). Based on testimonies gathered through interviews and surveys, it was verified that most of the time, the inhabitants remain in the fields, engaging in agricultural and livestock activities. In contrast, the interior of the *putuco* plays a secondary role in daily life, being primarily used for cooking, eating, and sleeping.

5. Discussion

The thermal results indicate that the indoor temperature and relative humidity

conditions in the *putucos* do not comply with international thermal comfort standards, such as ASHRAE 55. However, the universal applicability of these parameters has been widely questioned, particularly in non-conventional contexts, as comfort perception is strongly shaped by social, cultural, and identity factors (Philokyprou & Michael, 2021; Zong et al., 2024). This adaptive perspective, recurrent in vernacular architecture research, recognizes that thermal expectations are adjusted through local experience and daily practices (Hermawan & Švajlenka, 2022), positioning comfort as a contextual rather than a standardized construct (Lozoya-Peral et al., 2023).

Survey results revealed a high perceived comfort among occupants, despite physical conditions diverging from conventional standards. This suggests that thermal comfort in *putucos* should be evaluated from the inhabitants' perspective, considering environmental and cultural contexts (Vijayalaxmi & Banerjee, 2023). The *putuco* is conceived as a shelter, while most daily activities occur outdoors, influencing the way comfort is experienced indoors. Additionally, a strong cultural attachment to these dwellings reinforces their acceptance, highlighting comfort as a blend of thermal adequacy, cultural continuity, and territorial identity (Widera, 2021).

The analysis of passive design strategies was central to this study, identifying key features adapted to high-Andean climates: thermal mass of local materials, entrance orientation, solar gain, wind protection, and the conical roof geometry. These elements exemplify how empirical knowledge generates functional, resilient solutions aligned with environmental and cultural conditions, offering valuable insights for climate-responsive architectural design (Nasir & Kamal, 2021; Sharma, 2024). Recognizing these strategies is crucial for their integration into contemporary sustainable practices (Toroxel & Silva, 2024).

Despite these strengths, certain design limitations were observed. The scarcity of openings reduces natural ventilation, leading to smoke accumulation during cooking and soot deposition on walls and ceilings. Limited apertures also restrict daylight penetration. These deficiencies can negatively impact indoor air quality and occupants' health, contributing to respiratory and visual ailments and elevated CO₂ concentrations (Widera, 2021). Addressing these issues through context-appropriate interventions—such as improved stove programs—represents an opportunity to enhance performance without compromising cultural authenticity (Nuño et al., 2023; Philokyprou & Michael, 2021).

This research, by integrating objective thermal data, subjective user perception, and architectural analysis, provides a holistic assessment of thermal comfort in *putucos*. It advocates for a critical reassessment of habitability standards, emphasizing the relevance of traditional construction knowledge as a strategy for sustainability and climate resilience. Understanding comfort through its cultural dimension, specific highland microclimate, and empirical adaptive strategies is essential for developing housing solutions that strengthen, rather than replace, local knowledge (Hermawan & Švajlenka, 2022).

Although this work is rooted in a specific cultural and geographic context, its findings have broader applicability. The adaptive strategies identified in *putucos* can inform design approaches in other cold, high-altitude, or energy-constrained regions worldwide. As such, the *putuco* becomes both a heritage asset and a source of transferable resilient solutions for contemporary architecture, aligning with global efforts to address climate change through sustainable, culturally attuned housing (Nieto, Cubillos & Barrios, 2021; Sharma, 2024).

5.1 Limitations

One of the main limitations of this research was the difficulty in accessing the areas where the *putucos* are located. The lack of adequate infrastructure, such as the absence of public transportation, unpaved roads, and limited accommodation and food services, significantly hindered fieldwork, a common issue in rural areas in Peru. Additionally, there was observed resistance from the local community towards external researchers, especially those unfamiliar with their culture, which limited interaction with the residents. These conditions directly affected the scope of the research, restricting the sample size, the available time for indoor environmental monitoring, and the number of completed surveys. Such limitations have previously been documented in research that involves in situ measurements in vernacular architecture (Lozoya-Peral et al., 2023). Despite these challenges, it is recommended to extend the measurement period in future research. To achieve this, it is crucial to maintain a constant presence in the area and strengthen the relationships already established with the community (Zong et al., 2024), which would not only facilitate the collection of more comprehensive and representative data but also allow for the analysis of the thermal behavior of the *putucos* under different climatic conditions over time.

6. Conclusions

This study evaluated the thermal performance of five *putucos* located in rural communities in the district of Samán, Puno region. Fieldwork included indoor and outdoor thermal measurements, as well as surveys conducted with the families inhabiting these dwellings. The analysis was complemented by photogrammetric documentation and graphical simulations, which allowed the identification and representation of the passive design strategies embedded in these vernacular

constructions.

The central hypothesis proposed that *putucos*, despite being located in an extreme climatic environment, can achieve acceptable indoor thermal comfort conditions through an adaptive capacity rooted in the use of local materials, traditional construction techniques, and ancestral knowledge linked to the inhabitants' ways of life. The results show that, although measured values do not always align with international technical comfort standards, the residents perceive these conditions as adequate according to their experience, daily routines, and expectations. This supports the idea that the concept of comfort should not be restricted to physical parameters, but must also integrate cultural practices, modes of space use, and the symbolic relationship with the environment.

In conclusion, *putucos* represent a resilient architectural model that articulates construction with ways of inhabiting, offering valuable lessons to address the current challenges of climate change and sustainability. Their study demonstrates how local solutions, emerging from the territory and grounded in accumulated experience, can produce thermally habitable environments without relying on active systems or costly technologies.

Beyond their local significance, the adaptive strategies identified in *putucos* provide transferable insights for other regions with similar climatic constraints or environmental vulnerabilities. Such strategies, based on thermal mass, compact form, orientation, and wind protection, may inspire contemporary architecture and housing policies in high-altitude regions worldwide. Revaluing these traditional practices not only contributes to the preservation of cultural heritage, but also to the development of context-sensitive, energy-efficient, and culturally relevant architectural solutions.

6.1 Directions for future research

For future research, it is recommended to expand the thermal analysis through comparative studies between *putucos* and other construction typologies present in the region, such as orthogonal dwellings built with adobe, brick, or concrete and topped with corrugated zinc roofs, which are progressively replacing *putucos*. This comparison will provide critical insights into the environmental performance of *putucos* in relation to contemporary building solutions. It is further suggested to extend the monitoring period to capture thermal behavior under a broader range of seasonal climatic conditions.

Equally important is the adoption of a deeper ethnographic approach to better understand the social, cultural, and symbolic dynamics associated with the use and perception of inhabited space. This requires refining the design of data collection instruments, such as surveys and interviews, to ensure they reflect the cultural values of the community—for example, in aspects such as the significance of traditional clothing or the use of domestic space.

In addition, the potential impact of technical enhancements—such as natural ventilation and daylighting strategies—on occupants' health and thermal comfort should be investigated. These studies could inform the development of hybrid solutions that respect the cultural integrity of vernacular architecture while improving its environmental and sanitary performance.

Ultimately, the preservation of *putucos* must be regarded as a matter of urgency. These structures not only encapsulate empirical knowledge finely tuned to the demanding conditions of the high Andean climate, but they also represent a living cultural expression and an irreplaceable architectural heritage. Beyond their local significance, the adaptive strategies embedded in *putuco* design offer transferable

lessons for other high-altitude or extreme-climate regions worldwide. Recognizing, documenting, and safeguarding this heritage is therefore essential—not only as a cultural responsibility, but also as a contribution to the global discourse on climate-resilient and culturally grounded housing solutions.

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Declaration of interest statement

The authors report there are no competing interests to declare.

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Table 1. Characteristics of the selected *putucos*

Code*	Use	Material	Entry orientation	Picture	Exterior measures (m)	Occupants (role, age)
PUT 01	Sleep / Cook	Plastered <i>champa</i>	NE		L: 4,17 W: 3,04 H: 3,64	Father, 77 Mother, 78
PUT 10	Cook	Plastered adobe	NW		L: 4,01 W: 3,12 H: 3,48	Father, 70 Mother, 42
PUT 15	Store	Exposed <i>champa</i>	NE		L: 3,75 W: 2,84 H: 3,45	Father, 73 Mother, 73 Son, 27 Daughter-in-law, 31
PUT 20	Cook	Exposed <i>champa</i>	SE		L: 3,34 W: 3,24 H: 3,75	Father, 47 Mother, 42 Son, 15
PUT 23	Store	Exposed <i>champa</i>	W		L: 3,23 W: 2,68 H: 3,60	Father, 52 Mother, 50 Son, 20

N: North E: East W: West S: South

L: Length W: Width H: Height

* The coding of the *putucos* corresponds to a prior cataloging carried out in a broader research project and was maintained to ensure consistency in the study, without affecting the analysis results.



Figure 1. Exterior views of *putucos* across the territory and the daily life of their inhabitants. Photographic records captured during field visits.

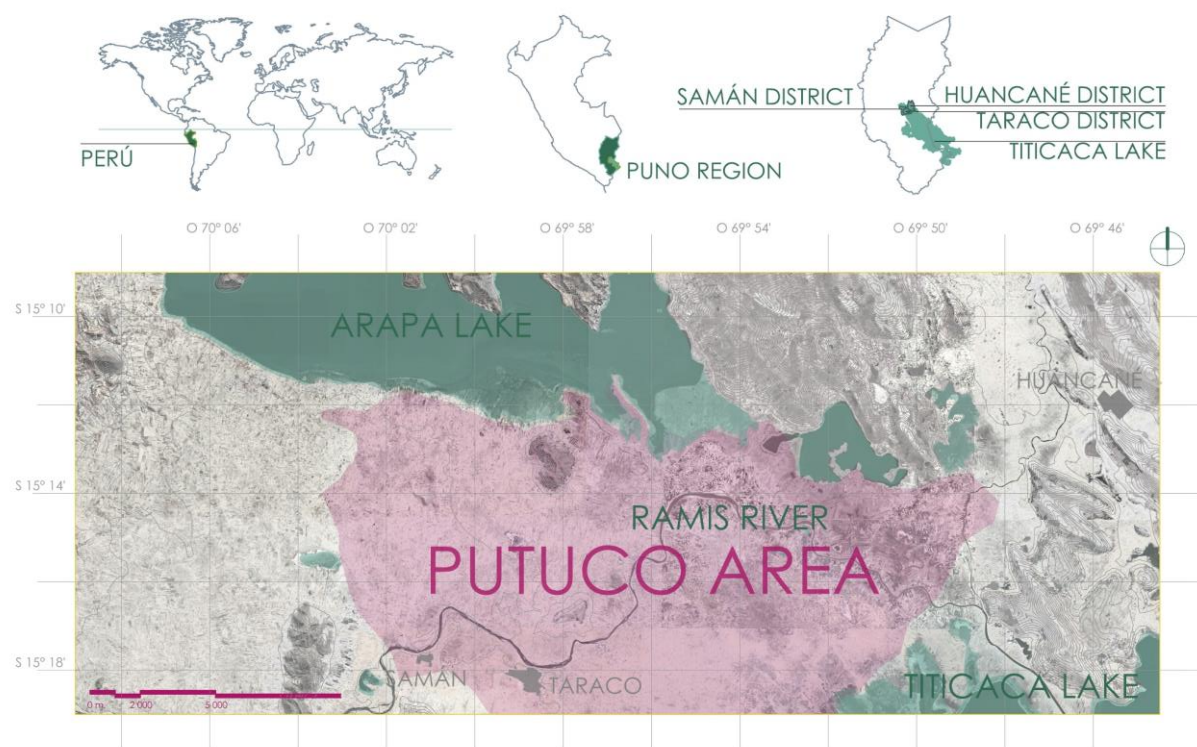


Figure 2. Location of the study area



(a)



(b)

Figure 3. Landscape views of the *putucos* in (a) the wet season and (b) the dry season

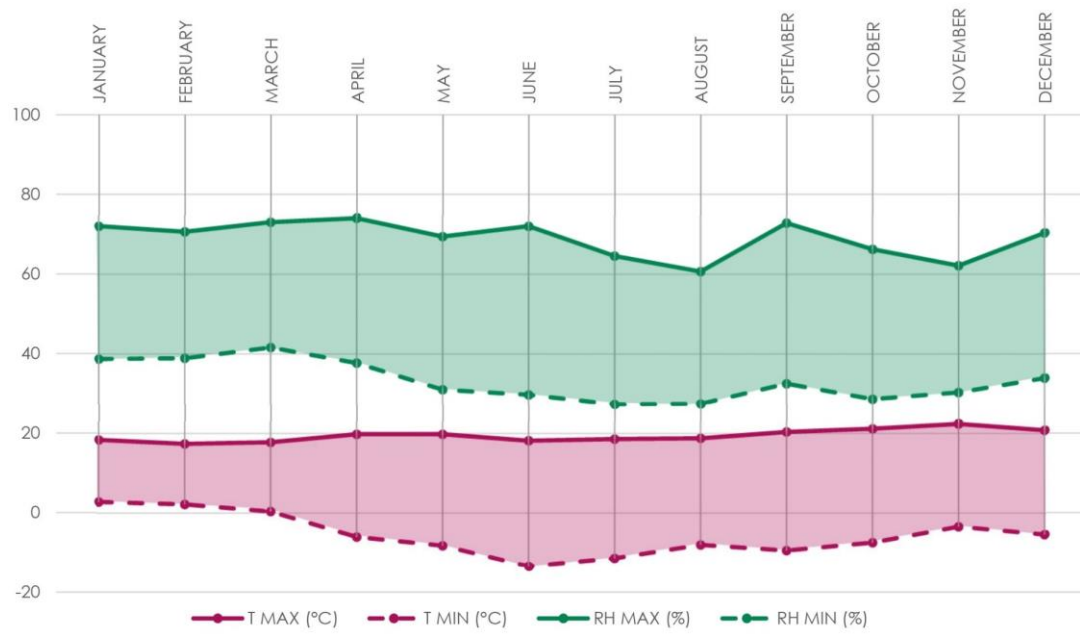


Figure 4. Temperature and relative humidity outdoors from the Taraco meteorological station, data extracted from SENAMHI 2022.

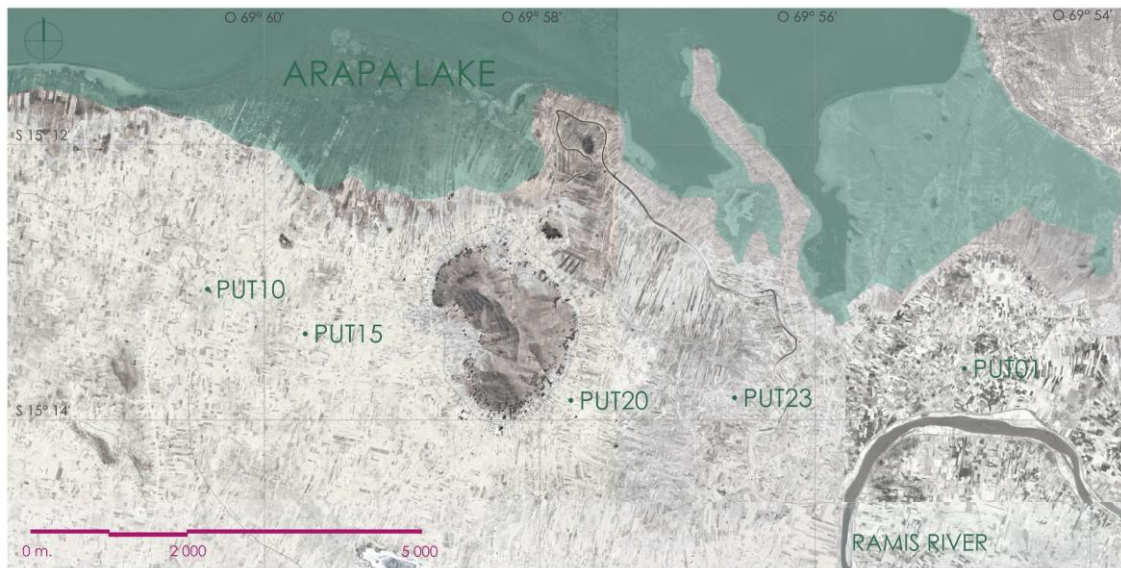


Figure 5. Location of the selected *putucos*

THERMAL COMFORT SURVEY

DATE: _____
CODE: PUT _____

LOCATION: _____

PROFILE OF THE PUTUCO INHABITANT

Language: Quechua ___ Aymara ___ Spanish ___

Age: _____ Sex: F ___ M ___

Approximate weight (Kg): 40 – 50 ___ 50 – 60 ___ 60 – 70 ___ 70 – 80 ___

Metabolic rate (met): 0.5 – 1 ___ 1 – 1.5 ___ 1.5 – 2 ___ > 2 ___

Place of birth: _____

Approximate height (cm): 140 – 150 ___ 150 – 160 ___ 160 – 170 ___ 170 – 180 ___

Clothing (clo): 0.3 – 0.6 ___ 0.6 – 0.9 ___ 0.9 – 1.2 ___ > 1.2 ___

PASSIVE STRATEGIES ADAPTED BY THE PUTUCO INHABITANT

What clothing do you usually wear in the putuco? _____ What foods do you usually eat inside the putuco? _____

What activities do you do during the morning, afternoon, and night inside the putuco? _____

Do you open or close the door? Do you cover the openings? _____

THERMAL PERCEPTION OF THE PUTUCO INHABITANT

	VERY COLD - 2.0	COLD - 1.0	NEUTRAL 0.0	WARM + 1.0	VERY WARM + 2.0
					
THERMAL SENSATION SCALE - How do you feel inside the putuco?					
In the morning					
In the afternoon					
At night					
THERMAL PREFERENCE SCALE - How would you like to feel inside the putuco?					
In the morning					
In the afternoon					
At night					
THERMAL SATISFACTION SCALE - How satisfied do you feel inside the putuco?					
	VERY DISSATISFIED - 2.0	DISSATISFIED - 1.0	NEUTRAL 0.0	SATISFIED + 1.0	VERY SATISFIED + 2.0
In the morning					
In the afternoon					
At night					

Figure 6. Thermal comfort survey

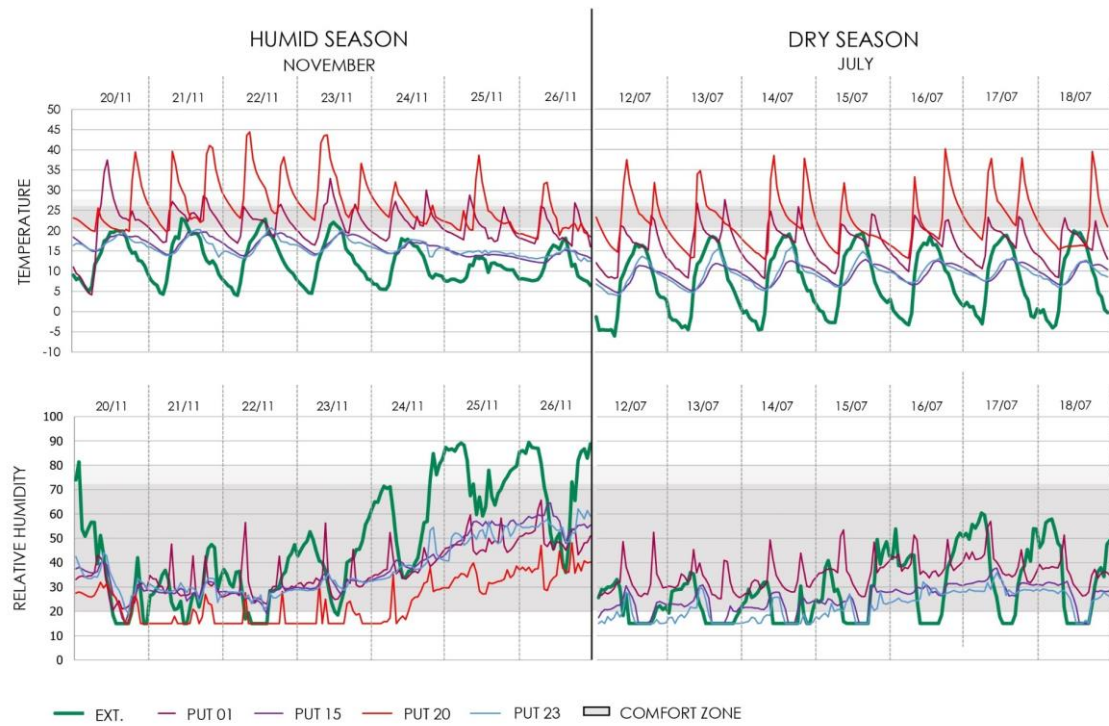


Figure 7. Results of thermal measurements outdoors and indoors in both seasons

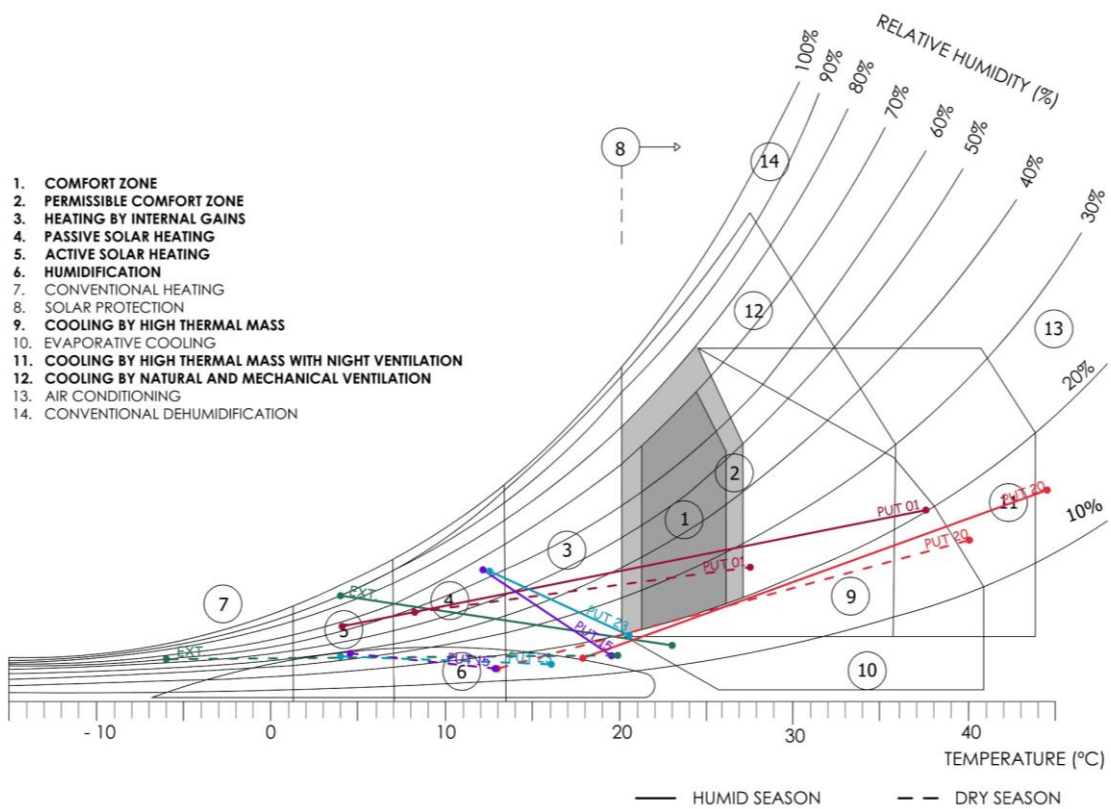


Figure 8. Results of thermal measurements outdoors and indoors placed on the Psychrometric diagram of Givoni

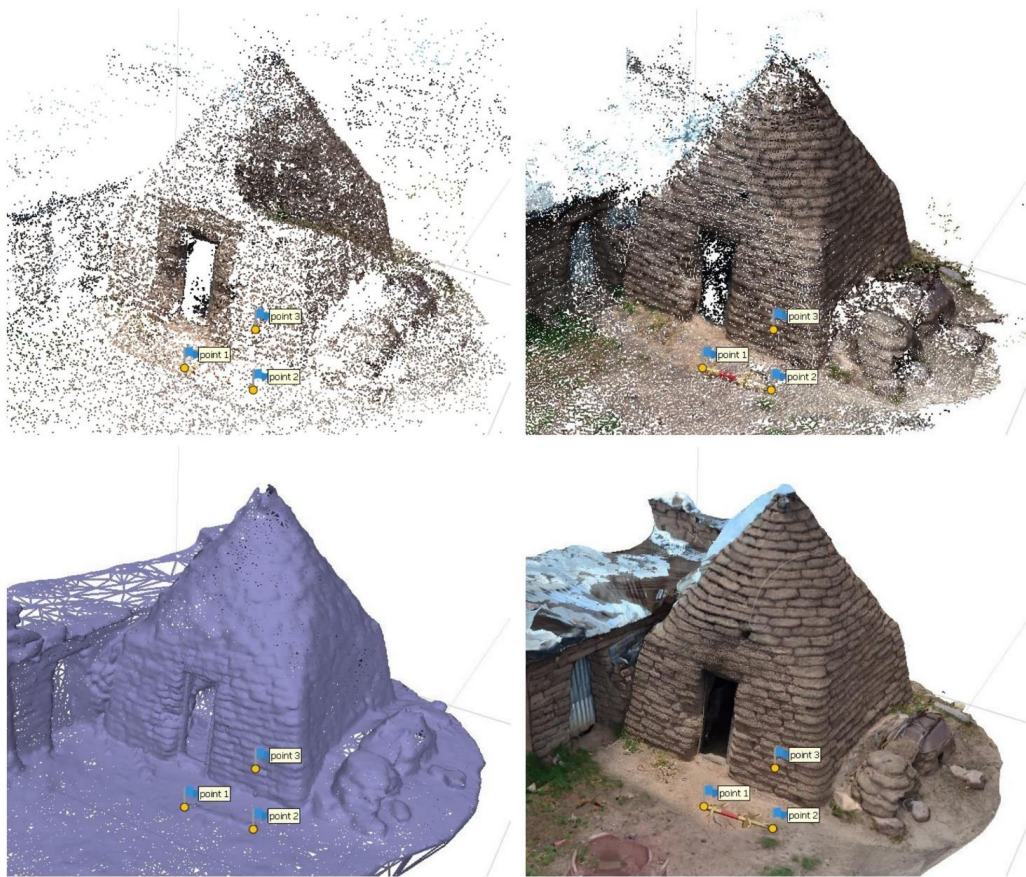
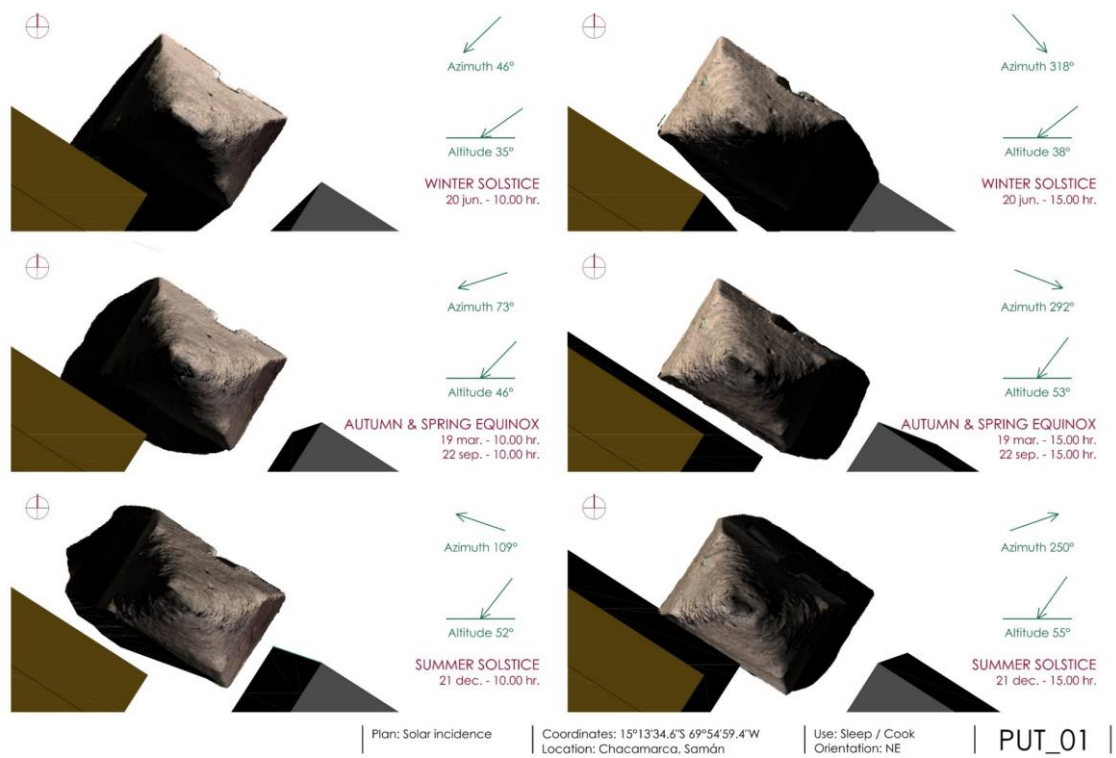
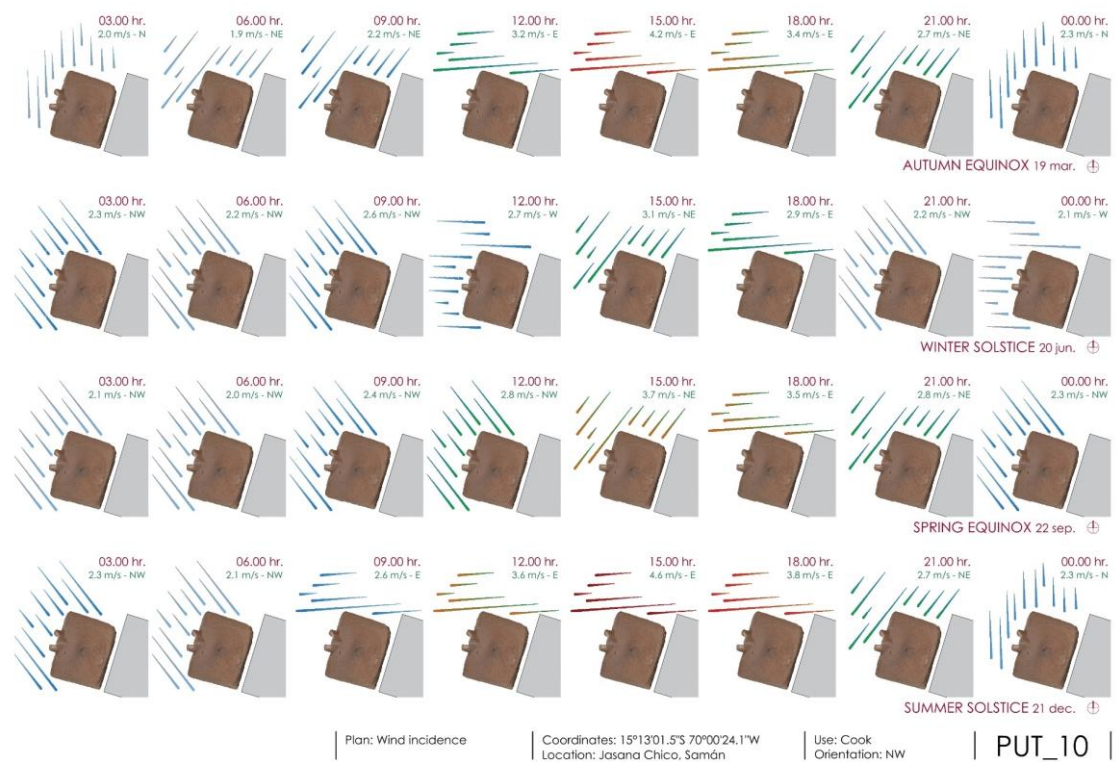


Figure 9. Photogrammetric survey process, PUT20



(a)



(b)

Figure 10. Graphical simulation of (a) solar incidence in PUT01 and (b) wind incidence in PUT10

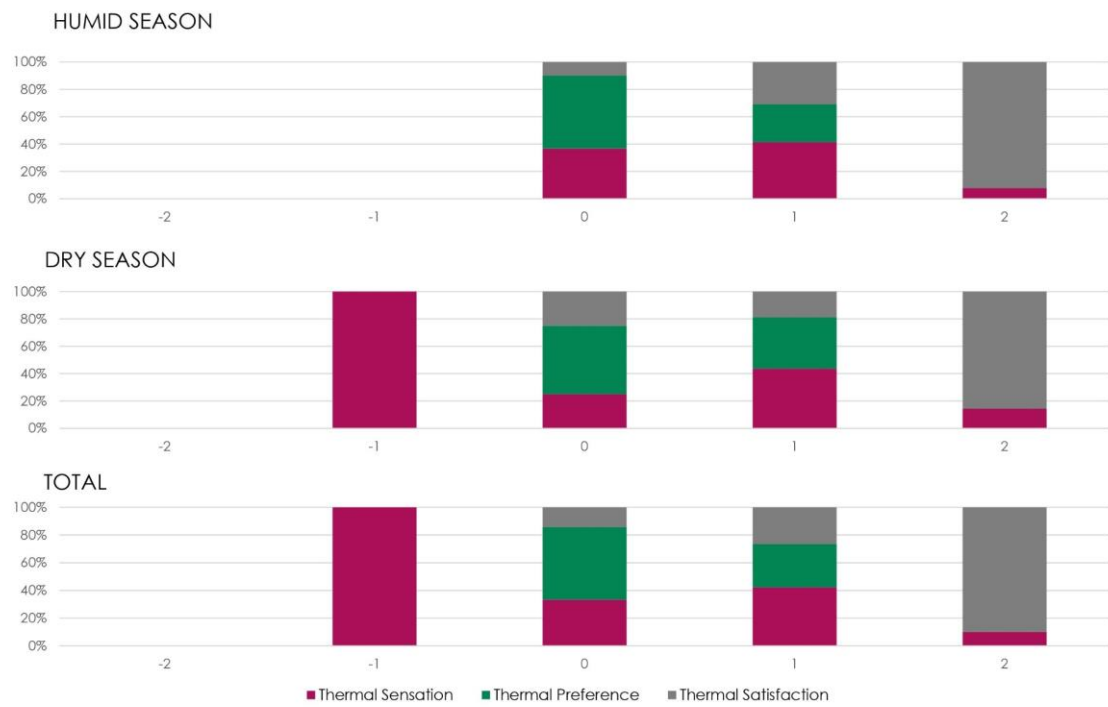


Figure 11. Results of the thermal perception surveys



(a)



(b)



(c)

Figure 12. Interior views of (a) Kitchen in PUT10, (b) Storage in PUT15 and (c) Sleep area in PUT01