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IMPROVING THE THERMAL PERFORMANCE OF SCHOOLS IN THE HIGH ANDEAN REGION OF PERU. THE CASE OF "PRONIED'S PREFABRICATED FROST-TYPE MODULAR CLASSROOMS"

MEJORA DEL DESEMPEÑO TÉRMICO DE COLEGIOS EN LA REGIÓN ALTOANDINA DEL PERÚ. EL CASO DEL "MÓDULO PREFABRICADO AULA TIPO HELADAS - PRONIED"

MELHORIA DO DESEMPENHO TÉRMICO DE ESCOLAS NA REGIÃO ALTO-ANDINA DO PERU. O CASO DAS "SALAS DE AULA MODULARES PRÉ-FABRICADAS DO TIPO HELADA DO PRONIED"

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RESUMEN

Frente al déficit cualitativo y cuantitativo de infraestructura educativa en las zonas rurales altoandinas del Perú, el estado peruano ha venido invirtiendo y apostando en los últimos años en soluciones modulares, buscando la eficiencia en los procesos constructivos. La propuesta específica, con énfasis en el diseño bioclimático, es el "Módulo Prefabricado Aula tipo Heladas"; sin embargo, los usuarios han venido manifestando una falta de confort en estos nuevos ambientes. El presente estudio muestra el desarrollo de mediciones realizadas en un módulo construido, que permitieron la calibración y validación del modelo en un software de simulación, con el fin de proponer mejoras en el diseño que aporten a las futuras construcciones. Tomando como referencia el modelo de confort térmico adaptativo, se comprobó que las temperaturas interiores estaban por debajo de la zona de confort en las primeras horas de la mañana y muy por encima cerca del mediodía, alrededor de 6 °C y 7 °C respectivamente. Con la aplicación de estrategias bioclimáticas complementarias se logró mejorar considerablemente las condiciones térmicas interiores, aunque no lo suficiente para alcanzar la zona de confort en las primeras horas de la mañana; ello debido a que las temperaturas exteriores nocturnas son muy bajas, a que el edificio está deshabitado toda la noche, a la ausencia de masa térmica en la envolvente y a que no cuenta con sistemas solares activos ni de climatización artificial.

Palabras clave
diseño bioclimático, estrategias pasivas, desempeño térmico, simulación energética.

ABSTRACT

Faced with the qualitative and quantitative deficit of educational infrastructure in Peru's rural high Andean areas, in recent years the Peruvian State has been investing in and supporting modular solutions, seeking efficiency in the construction processes. The specific proposal, with special emphasis on bioclimatic design, is the "Prefabricated Frost-type Modular Classroom". However, users have been expressing discomfort with these new facilities. This study shows the measurement process carried out on a built module, which allowed calibrating and validating the model using simulation software, to propose improvements in the design that may contribute to future constructions. Taking the adaptive thermal comfort model as a reference, it was confirmed that indoor temperatures were below thermal comfort limits in the early hours of the morning and well above them close to noon, by around 6 °C and 7 °C respectively. With the application of complementary bioclimatic strategies, it was possible to considerably improve indoor thermal conditions, although not enough to reach comfort early in the morning. This is because the night-time outdoor temperatures are very low, the building is uninhabited all night long, there is no thermal mass in the envelope, and there are no active solar systems or mechanical air conditioning.

Keywords
bioclimatic design, passive strategies, thermal performance, energy simulation.

RESUMO

Diante do déficit qualitativo e quantitativo de infraestrutura educacional nas áreas rurais alto-andinas do Peru, o Estado peruano vem, nos últimos anos, investindo e apoiando soluções modulares, buscando eficiência nos processos de construção. A proposta específica, com ênfase especial no design bioclimático, é a "Sala de aula modular pré-fabricada do tipo Helada". No entanto, os usuários têm expressado desconforto com essas novas instalações. Este estudo mostra o processo de medição realizado em um módulo construído, que permitiu calibrar e validar o modelo usando um software de simulação, para propor melhorias no projeto que possam contribuir para futuras construções. Tomando o modelo adaptativo de conforto térmico como referência, confirmou-se que as temperaturas internas estavam abaixo dos limites de conforto térmico nas primeiras horas da manhã e bem acima deles perto do meio-dia, em torno de 6 °C e 7 °C, respectivamente. Com a aplicação de estratégias bioclimáticas complementares, foi possível melhorar consideravelmente as condições térmicas internas, embora não o suficiente para alcançar o conforto no início da manhã. Isso se deve ao fato de as temperaturas externas noturnas serem muito baixas, de o edifício ficar desabitado durante toda a noite, de não haver massa térmica no envelope e de não haver sistemas solares ativos ou ar-condicionado mecânico.

Palavras-chave
projeto bioclimático, estratégias passivas, desempenho térmico, simulação de energia.

INTRODUCTION

The need to provide thermal comfort in classrooms is indisputable and a priority in the design of education centers. Students and teachers spend a lot of time inside these environments and having suitable air thermal conditions has positive effects not only on the comfort and health of occupants but also on their performance (Zomorodian et al., 2016; Geng et al., 2017; Wargocki et al., 2019; Kükrer & Eskin, 2021). Having acknowledged the low general performance of Peruvian students in international tests, and that the thermal conditions of schools in Peru negatively affect their academic performance (Torres, 2021), it is essential to prioritize infrastructure quality in these specific terms. The associated conditions of poverty and rurality are two additional aspects that influence low performance (Bos et al., 2012), problems that are accentuated as climatic conditions become more acute.

Faced with the challenge of a quantitative and qualitative deficit in school infrastructure in high Andean areas above 3,500 m.a.s.l., the National Program for Educational Infrastructure (PRONIED, 2021) of the Ministry of Education of Peru has developed a "Prefabricated Frost-type Modular Classroom". The technical specifications for the module were approved in 2021 and hundreds of them have already been built[1]. This article presents a study to improve the thermal performance of these modules, as users have been expressing discomfort in these new classroom environments. This study was based on monitoring existing infrastructure in two locations within the Cusco and Puno regions, using computer tools for energy modeling and simulation. The particular geographical and climatic scope of the high Andean region is described below, while the architectural characteristics of the prefabricated modules are detailed.

GEOGRAPHY, CLIMATE, AND ARCHITECTURE OF THE HIGH ANDEAN REGION

Approximately 20% of Peruvian territory is found in the high Andean region, specifically above 3.500 m.a.s.l., and approximately four million inhabitants, around 13% of the country's population, reside there. This situation is extremely unusual when considering what happens in the rest of the world, where around 14.5 million people, only 0.19% of the world's population live above 3.500 m.a.s.l. Of this population, almost the entirety (13 million) is distributed in similar numbers in three countries: China, Peru, and Bolivia (Tremblay & Ainslie, 2021). However, Peru and Bolivia have a distinctive feature. They are located in a tropical zone, which conditions a high-altitude climate with very intense solar radiation, little variation between seasons, moderate temperatures during the day, and very cold ones at night (Vidal, 2014). Except for areas with steep relief (associated with mountains, snow-capped peaks, and ravines) that are practically uninhabited, a considerable part of the high Andean topography, where populated centers are located or agricultural and livestock activities take place, is formed by gentle valleys and plateaus.

In this high Andean region, the seasons are differentiated mainly by rainfall regime and night-time temperatures. In the summer months, from December to March, which coincide with school holidays, there is recurrent rainfall. Temperatures are usually slightly above 0 °C at night and above 15 °C during the day. In the coldest months, between June and August, the rains are scarce, the sky is usually clear, and the nights are colder, with regular frosts, which implies night temperatures below 0 °C. In general, daytime temperatures remain stable throughout the year and the relative humidity of the air is low.

In this unique and harsh climate, traditional construction techniques have resorted to massive materials for walls, such as stone or raw earth, while natural fiber fabrics were generally used for roofs (Burga, 2010; Chui et al., 2022). The high thermal inertia of the walls and the high level of insulation of the ceilings, added to the compactness of the shape and extremely small openings, ensured a certain internal thermal stability. Even so, the absence of translucent material and the difficulty of achieving a minimum level of hermeticity always conditioned the presence of significantly low indoor temperatures. Construction traditions in this high Andean area, both in urban and rural areas, as in the rest of the country, have changed abruptly in recent decades due to multiple factors. The reasons range from the association of certain building techniques with progress to greater durability and practicality in the construction process. This assimilation of modern techniques without a further adaptive process, generally with lighter structures and without thermal inertia or insulation (such as brick walls and corrugated metal sheets on the roofs), not only breaks with the landscape and local traditions (Sáez & Canziani, 2020) but also significantly worsens their thermal performance (Wieser et al., 2021; Molina et al., 2021). Bioclimatic design strategies for cold climates are well identified, with several authors agreeing that they are mainly based on the insulation capacity and thermal inertia of the envelope, on hermeticity, and on the use of solar radiation (Givoni, 1992; Szokolay, 2012; Manzano-Agugliaro et al., 2015).

1 The technical specifications of the module can be seen on the following webpage: https://www.gob.pe/institucion/minedu/campa%C3%B1as/2209-proyecto-de-ficha-de-homologacion-modulo-prefabricado-aula-tipo-heladas

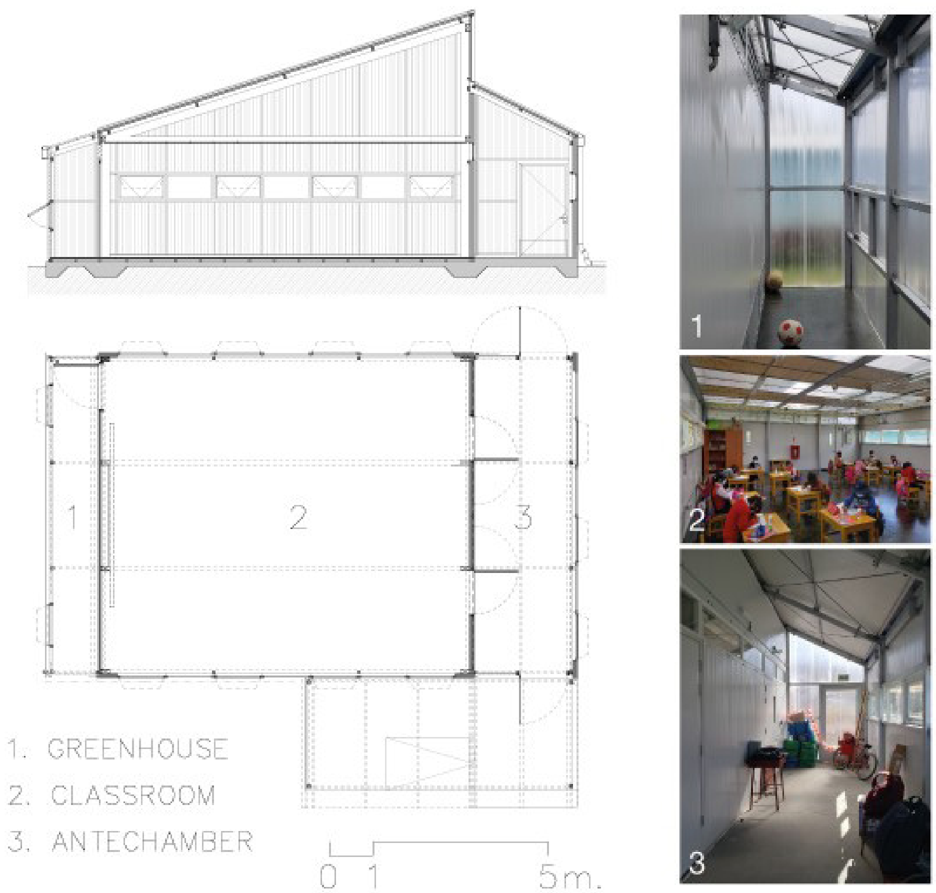

Figure 1: Plan, section, and photos of the "Plan Heladas" module (Second version, 2020). Source: Specifications Report, National Program for Educational Infrastructure (PRONIED, 2021). Photos by the authors.

THE PREFABRICATED "FROST-TYPE" MODULES (PLAN HELADAS)

The proposed modules are part of the Modular School Catalog proposed by the National Educational Infrastructure Program (PRONIED, 2021), to develop a system where the module designs meet the following criteria:

- Relevance: adaptation to each locality's climatic conditions to have educational spaces with adequate thermal comfort and lighting requirements.
- Quality: improve the conditions of pedagogical, operational, and support spaces in educational institutions, offering a modular repertoire for different bioclimatic zones, as considered in the Peruvian building codes; above 3500 m.a.s.l.
- Efficiency: Standardized design of the modules and their technical specifications to make the module acquisition, transport, and installation processes more efficient.

The design of the module's first version was carried out during 2017 and 2018. It was finally implemented between 2019 and 2020 with a total of 342 modules being built. This study considers a second version of the "Frost-Type" modules, designed in 2020 and implemented from 2021 onwards. Currently, 274 modules of this second version have already been built (Figure 1) and 233 are being built. The most significant difference between the first and second versions is found in the antechamber. While its enclosure is completely translucent (polycarbonate) in the first version, in the second it is opaque (thermopanel). As part of the process, a third version is currently in the draft stage and proposes grouping two classrooms per module, with a greenhouse in between. It is at this juncture that this study is considered appropriate; seeking to contribute to improving the third version's design through the monitoring and thermal validation of the module's second version.

In general terms, walls and ceilings are made up of thermo-acoustic polyurethane sandwich panels and the translucent surfaces of cellular polycarbonate panels, while the floor is made of reinforced concrete with mineral wool insulation (for more details see Table 1, Calibrated Base Model). The hours of use of the classrooms are from half past eight in the morning to half past one in the afternoon.

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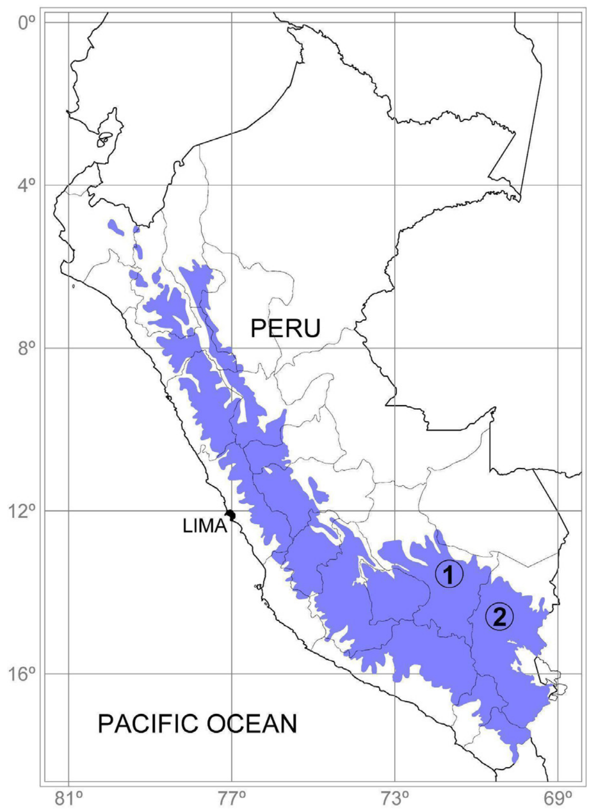

Figure 2: High Andean region of Peru, altitude equal to or greater than 3,500 m.a.s.l. and the location of the schools monitored for this study: (1) EI 50425, Cusco, latitude -13.42°, longitude -71.65°, altitude 3,737 m.a.s.l. and (2) EI 72073, Puno, latitude -14.68°, longitude -70.35°, altitude 3,913 m.a.s.l. Source: Prepared by the authors

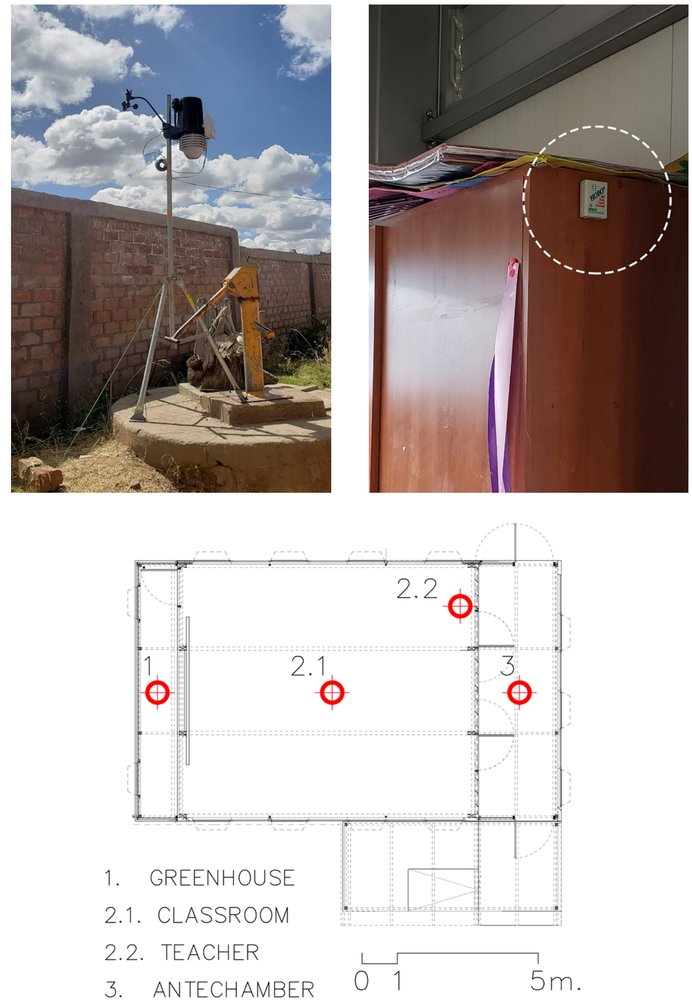

Figure 3: Mounting of meteorological station (left), view of indoor datalogger located in the classroom (center), and location of all data loggers within the module (right). Source: Prepared by the authors

METHODOLOGY

THERMAL MONITORING OF SCHOOLS

The first step, before modeling the module and validating the simulation, was the choice of two schools to be monitored. This process was carried out in coordination with PRONIED (2021) and was based on the criteria of accessibility, representativeness, and ability to take measurements in schools. Ultimately, the schools chosen were "Educational Institution 50425" and "Educational Institution 72073", located in Cusco and Puno respectively (Figure 2).

In each of them, an outdoor weather station (DAVIS Vantage Pro 2 Plus model) was installed to measure air temperature and relative humidity, as well as hourly solar radiation. The equipment was located in an open space, away from elements that could cast shadows on it. Eight Data Loggers (ONSET Hobo H08-003-02 model) were placed in each school (2 classrooms with 4 data loggers each) to record the temperature and relative humidity variations every 60 minutes inside the module over a month in the year's coldest season. In the first school (IE 50425, Cusco), measurements were made between 04/05/22 and 05/13/22, while in the second school (IE 72073, Puno) the period was from 05/13/22 and 06/14/22. Data loggers were distributed as follows (Figure 3):

- One in the antechamber, placed approximately 30 cm below the roof's supporting structure.
- One in the classroom, placed in the center approximately 30 cm below the plywood false ceiling.
- One in the greenhouse, placed in the center of the space and approximately 30 cm below the structure that supports the polycarbonate roof. This was placed inside a white cardboard box with perforations to protect it from direct solar radiation.
- One inside the classroom, on the upper frame of the blackboard.

MODEL CALIBRATION

To calibrate the model and future simulations, it was finally decided to work only with data obtained in one of the

Figure 4: Location (left) and view of the modules (right) in Educational Institution 72073, Puno. Source: Prepared by the authors

second school's modules. The choice of classroom, school, and representative week considered that the climatic conditions and the use of interiors in this period were more consistent with a typical period in terms of the temperatures expected for the season and regular class schedules. The willingness of both students and teachers to allow entry to the classroom, as well as to record the activities that took place there was also appreciated.

The data obtained from the loggers were used to calibrate a thermal simulation within the *DesignBuilder*[2] software, which reflected the current state of the modules. The capabilities and reliability of this and other dynamic thermal simulation software based on the Energy Plus calculation engine have been widely demonstrated in the last two decades (Mazzeo et al., 2020; Haves et al., 2019). Considering the geographical coordinates of the school, the "*Meteonorm*"[3] software was used to generate a file with an EPW (EnergyPlus Weather Format) extension, which contains information about what is known as a "typical meteorological year". This file was integrated into the DesignBuilder model and allowed choosing a period where the temperature conditions were equivalent to those measured in situ over five working days, from Monday to Friday.

Once the week was chosen, simulations with the temperatures of the registered environments (antechamber, classroom, and greenhouse) were run.

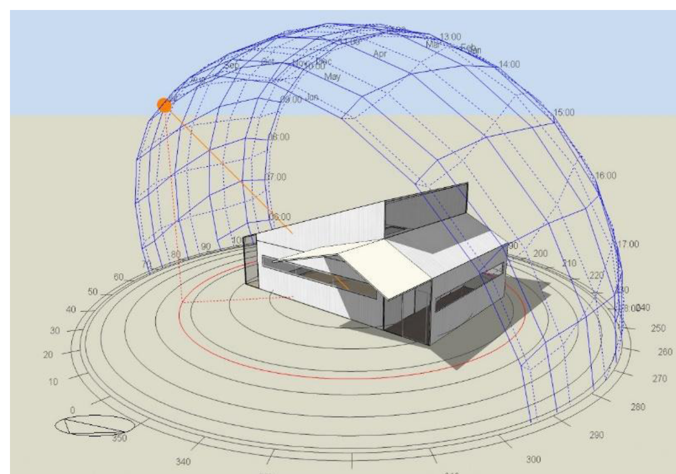

Figure 5: Screenshot of the model in the DesignBuilder software. Source: Prepared by the authors

To the extent that the geometry, materials, and use of the module were sufficiently reliable variables, different air tightness values (air changes per hour) were assigned to the rooms until the coincidence between the measured and the simulated was as close as possible. The use of the spaces and the openings were identified through field observations, interviews, and a record that was made during two visits. These schedules were incorporated into the model. Below is the screenshot of the module in the software (Figure 5).

2 DesignBuilder is one of the best-known computer tools in the field for performing dynamic thermal simulations. It uses a calculation engine provided by EnergyPlus. https://designbuilder.co.uk

3 Meteonorm is a computer program developed by Meteotest, which provides and generates climate data from anywhere in the world using satellite information and the interpolation of data from nearby stations. https://www.meteonorm.com/

Table 1: Scenarios simulated with additional strategies. Source: Prepared by the authors

Scenario	Model specifications
Calibrated Base Model	Modeled without alterations following the project's original technical specifications. *Envelope and orientation*: Enclosure made up of thermo-acoustic polyurethane sandwich panels - 50 mm and 100 mm thick on walls (U-Value: 0.375 and 0.193 W/m^2 °C) and 45 mm on ceilings (U-Value: 0.413 W/m^2 °C); in addition to 30 mm thick polycarbonate walls and roof (U-Value: 1.065 W/m^2 °C). Southwest orientation of the greenhouse. *Slab*: Vinyl floor (e=2.5 mm) on a phenolic plywood subfloor (e=45 mm), supported on wooden slats with a 50mm x 50mm section and glass wool insulation (e=50 mm) between slats; all on a reinforced concrete slab (U-Value with bridging: 1.065 W/m^2 °C). *False ceiling*: Frames with polycarbonate sheets (e=10mm, U-Value: 1.057 W/m^2 °C) and phenolic plywood sheets (e=8mm, U-Value: 3.093 W/m^2 °C). *Natural ventilation*: According to field observations and interviews, a window opening time from 8:30 am - 4:00 pm was considered. The scheduled ventilation mode was used, with a maximum ratio of 10 ac/h and a temperature setpoint of 24°C. A constant infiltration rate of 1.5 ac/h was assigned. *Door scheduling*: All remain closed during the weekend. During the week all are also kept closed, except the one between the classroom and the antechamber and the door between the antechamber and the exterior. The latter two are open 100% of the time between 8:30 am and 4:00 pm. *Lattice scheduling*: The metal lattices that connect the classroom to the greenhouse are permanently closed.
1 Infiltration reduction / Increased ventilation capacity	*Envelope and orientation*: Infiltration in all rooms was reduced by approximately 60% and ventilation capacity through openings was increased by 50%.
2 Orientation and tightness of the greenhouse	*Envelope and orientation*: East orientation of the greenhouse and reduction of its infiltration to 50% (increased air tightness). *Lattice scheduling*: Opening hours between 8:30 am and 10:30 am.
3 Increased insulation and replacement of transparency on roofs	*Envelope and orientation*: Replacement of the transparent polycarbonate on the classroom's sloping roof with insulating thermopanel instead. *False ceiling*: Insulation added with expanded polyurethane (e=50mm) on top of the plywood false ceiling and doubling the thickness of the polycarbonate placed in it (e=20mm).
4 Exposure of thermal mass of the floor	*Envelope and orientation*: Same as scenario 3 *False ceiling*: Same as scenario 3 *Lattice scheduling*: Same as scenario 2. *Slab*: Removal of the insulating layer. The vinyl floor is maintained on a reinforced concrete slab (e=250 mm) and a 300 mm gap is placed between the bottom of the slab and the ground.
5 Strict opening hours for doors and windows	*Envelope and orientation*: Same as in scenarios 3 and 4. Additionally, the orientation of the greenhouse and the infiltration are the same as in scenario 2. *False ceiling*: Same as scenario 3. *Slab*: Same as scenario 4, without considering a separation from the ground. *Natural Ventilation*: An opening time for the windows was applied between 10.30 am and 3.30 pm. *Door Scheduling*: All doors are kept closed throughout the weekend without an opening schedule. During the week these are also kept closed; but in the case of the doors between the classroom and the antechamber, as well as the door between the antechamber and the exterior, these are opened temporarily throughout the day with the entry and exit of students during class hours (between 8:30 a.m. and 1:30 p.m.). *Lattice scheduling*: Opening hours of the metal lattices are between 8:30 am and 10:30 am and between 3:30 pm and 6:00 pm.
6 Thermal mass addition	Same conditions as the previous scenario but adding thermal mass with the placement of a thick adobe wall (e=40 mm, U-Value: 1.627 W/m^2 °C) between the classroom and the greenhouse.

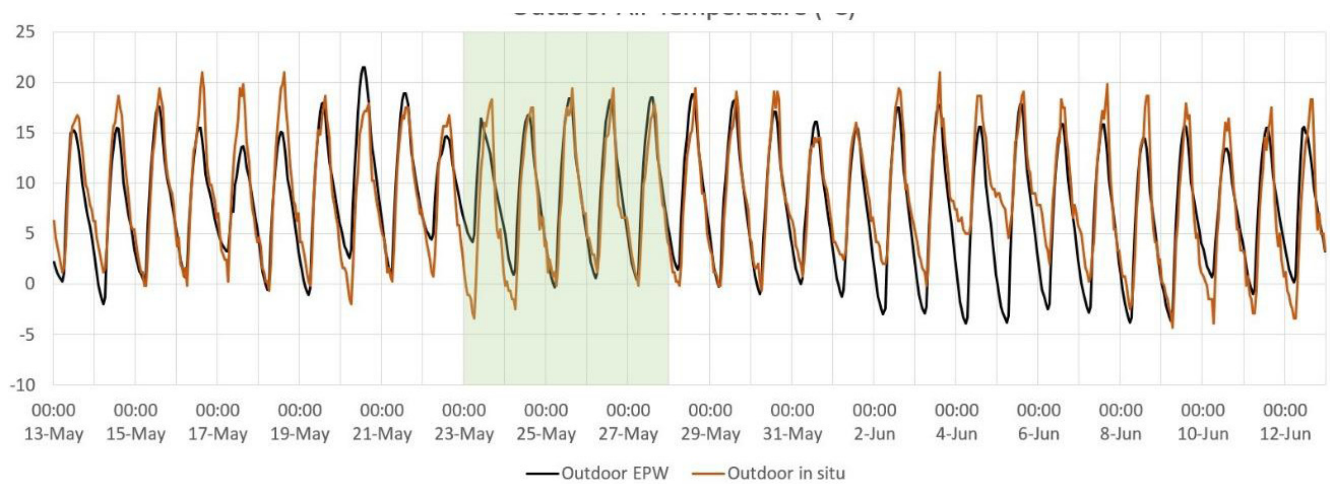

Figure 6: Comparison between the outdoor temperatures of the representative week based on on-site measurements and the outdoor temperatures based on the .epw file. Source: Prepared by the authors

THERMAL COMFORT LIMITS

To assess environmental thermal conditions inside the classrooms, and considering there are no national standards or norms that delimit a comfort zone, the theory of adaptive comfort was used, taking as reference the ASHRAE (2017) Standard 55-2017. Complying with the conditions of indoor spaces of free-running buildings, the formulas used to define the limits are (Equation 1 and Equation 2):

Equation 1

$$80\% \text{ acceptability over } (°C) = 0.31 \times (t_{pma}(out)) + 21.3$$

Equation 2

$$80\% \text{ acceptability under } (°C) = 0.31 \times (t_{pma}(out)) + 14.3$$

where $t_{pma}(out)$ is the mean outdoor temperature.

PROPOSED SCENARIO SIMULATIONS

Once the model had been calibrated, additional simulations were run with different strategies. Bioclimatic strategies were applied recognizing the specific features of the high altitude tropical cold climate and based on the temperatures reached as well as the thermal balance presented by the software. Five different scenarios based on the original model were run, incorporating the strategies detailed in Table 1 into the base scenario.

RESULTS AND DISCUSSION

The outdoor temperature values are presented first, both from the monitoring and the generated .epw file (Figure 6). The week for running the simulations is identified based on the greatest match of the values reached in both cases. In addition, the resulting graphs with the calibrations performed are presented; note the overlap of the grey line with the measurements made in situ (Figure 7).

Applying the formulas of the adaptive comfort model and having identified the month's average temperature at 8.5 °C, the thermal comfort zone in the weeks measured would be between approximately 17 °C and 24 °C. This "comfort zone" can be seen plotted on the results of the measurements in Figures 8 and 9. According to the measurements conducted (see Figure 8), a minimal variation is observed between the temperatures of the antechamber, the greenhouse, and the classroom. In all environments, there is an extremely broad thermal oscillation of approximately 25°C, with temperatures well above the comfort limit in the hours close to noon. In the coldest moments, which coincide with the start time of classes, the temperatures in the classroom are also very far from the comfort zone, about 8 °C below it. The greenhouse is the first environment to heat up and cool down, but its temperatures do not usually differ from the other environments, on some days even being lower than those of the antechamber.

The average temperature in the classroom when considering the 24 hours of the day, is approximately 17.7 °C. This value is just inside the adaptive comfort range (see the green band in Figure 8), but as already mentioned, the main problem is the high thermal oscillation. This situation conditions temperature values that are within the comfort zone only 25% of the time, while 25% of the time they are above the comfort zone and 50% of the time they are below it. If this is limited to the hours when the students use the classroom, a third of

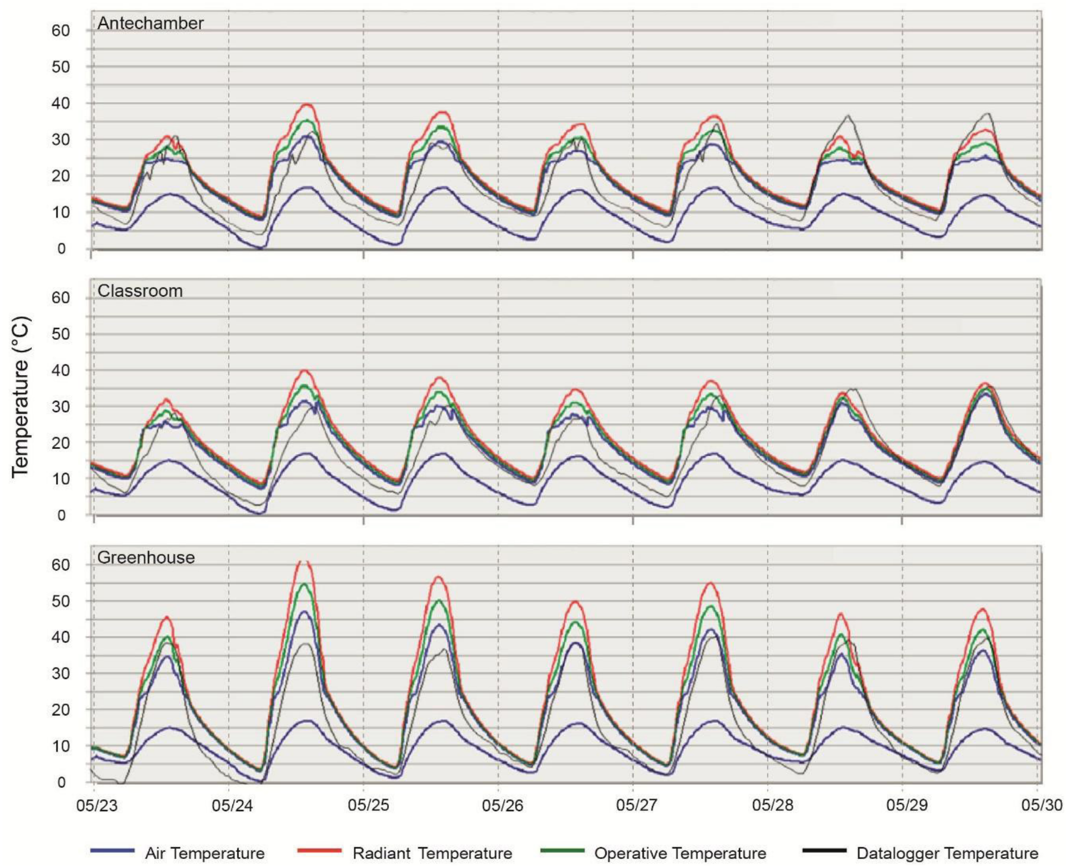

Figure 7: Calibration of antechamber (top), classroom (center), and greenhouse (bottom) with radiant temperatures (red), operative temperatures (green), simulated external air temperature (blue) and on-site measured external air temperature (grey). Source: Prepared by the authors

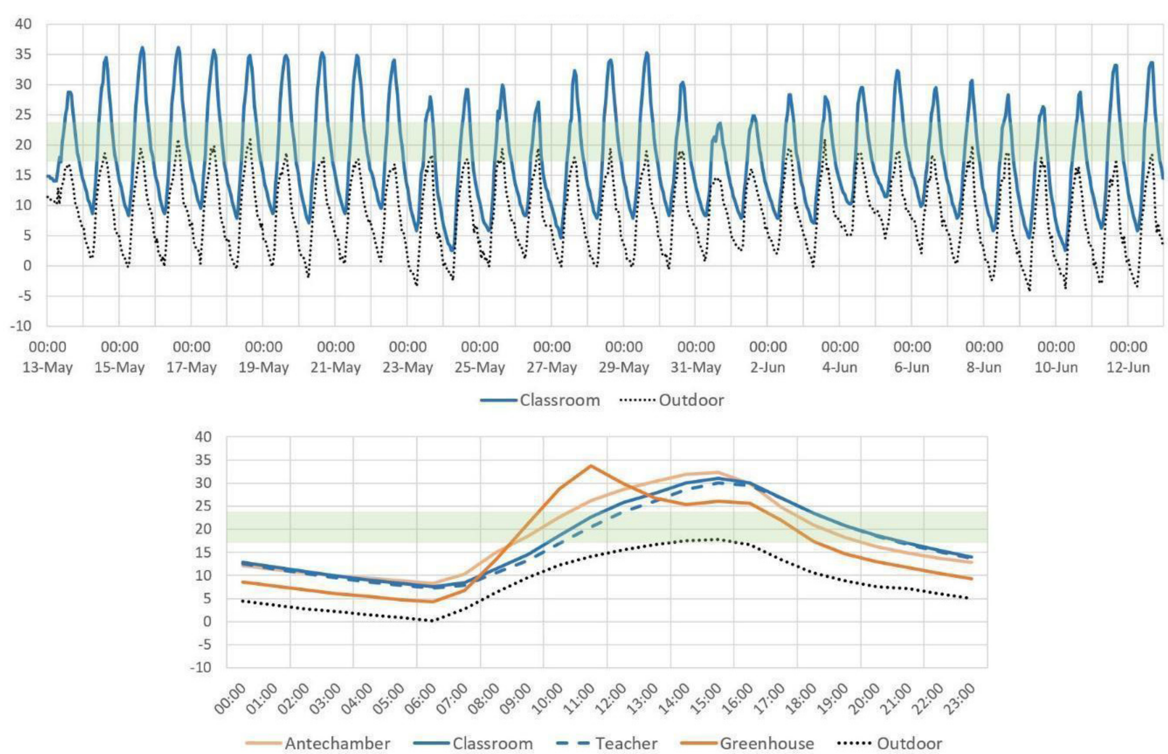

Figure 8: Classroom and outdoor air temperature (above); average hourly temperatures of all module rooms (below). The green zone indicates the comfort limits. Source: Prepared by the authors

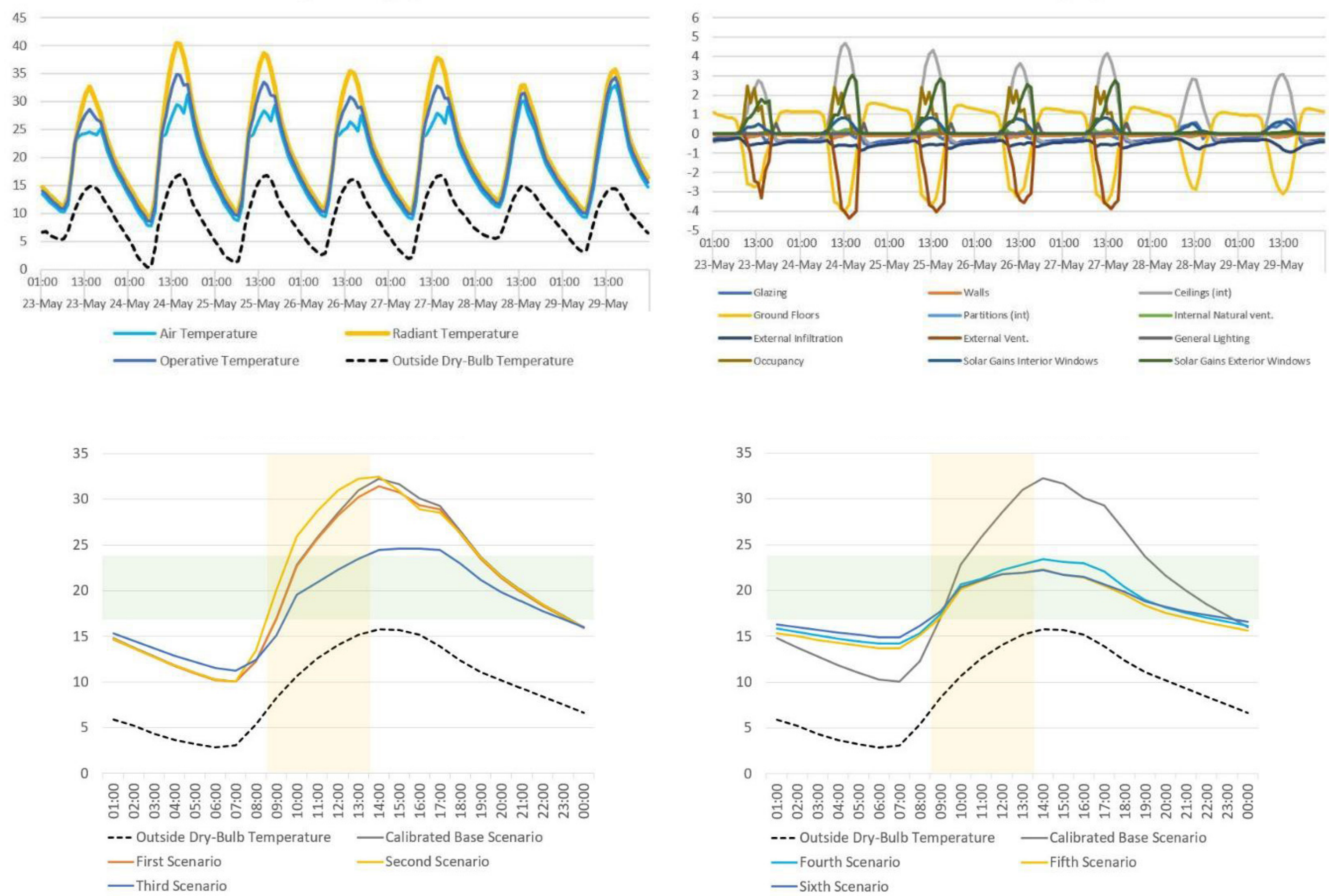

Figure 9: Temperature simulations and thermal balance of the base proposal (above) and temperature simulations of the base proposal with the 6 proposed scenarios (below). The green bar is the comfort zone and the yellow one is the hours of use of the classroom. Source: Prepared by the authors

the time there are comfort conditions, generally between 10:00 and 12:00, a third of the time there is discomfort due to cold (at the beginning of the day), and the other third due to excessive heat, past noon. On entering class, temperatures are around 11°C, and afternoon temperatures usually reach 31 °C. In singular cases, the lowest temperatures can reach 8 °C and the highest 34 °C. All this shows very unfavorable conditions in terms of thermal comfort that will probably have negative consequences for the attention span of students.

The low temperatures in the classroom at the start of the day (only 5 °C to 8 °C above outdoor temperatures) show how easily heat is lost at night. On the other hand, it is striking how abruptly it can rise in the early hours of the morning; approximately 12 °C in just 3 hours. In the afternoon, classroom temperatures can even reach above 35 °C, which makes the space practically uninhabitable. The fact that the environment is not occupied throughout the night, in addition to the absence of thermal mass, means that temperatures in the early hours of the morning are quite low, at around 8 °C. On the other hand, the absence of thermal mass, the excess of translucent material (especially on horizontal surfaces), and the limited use of natural ventilation raise the indoor temperature abruptly and excessively.

The results of the simulations with the calibrated model are presented below with the different modifications mentioned in the methodology (see Table 1) using the DesignBuilder software. These results are expressed in operating temperature and thermal balance values, which allows a better understanding of the phenomena that explain them (Figure 9).

In scenarios 1 to 3, the changes that are implemented for the simulations alter specific aspects of the base module. On the other hand, in scenarios 4 to 6, certain previously tested and combined strategies are added according to their proven effectiveness. The first scenario shows that the decrease in infiltration and the increase in the possibility of ventilation are not decisive if they are not accompanied by other strategies. Despite the slight reduction in the maximum temperature, there are practically no changes

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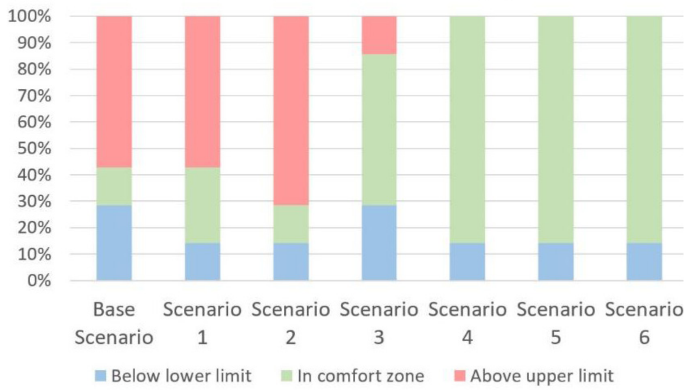

Figure 10: Percentage of time in thermal comfort during class hours in each scenario. Source: Prepared by the authors

in the minimum indoor temperatures. In a second scenario, the greenhouse is oriented towards the East, the most appropriate direction to take advantage of direct radiation early in the morning; conditions have very similar maximum and minimum temperatures, but the rise in indoor temperature is faster. As can be seen in Figure 10, the main problem in these first two scenarios, in addition to the base one, is excessive heat inside the classroom. The third scenario, where the transparency of the ceilings is removed, and the insulation of the false ceiling is increased, shows a substantial change in the behavior of the indoor temperature. The maximum temperatures are reduced by between 7 °C and 8 °C to around 25 °C, while the minimums rise slightly by around 2 °C, reaching approximately 12 °C.

In Scenario 4, the changes in the ceiling and false ceiling of the previous scenario are maintained and the air exchange between the classroom and the greenhouse is activated in the early hours of the morning. The strategy of removing the thermal insulation in the floor is added, recognizing this element as one of the few that provides thermal mass to the building. The result shows an improvement in the possibilities of providing thermal comfort. On one hand, the temperatures in the hottest moments of the day do not exceed 24 °C, while at the start of the day, the coldest temperatures are around 15 °C, five degrees above that of the base module. The fifth scenario, where the conditions of the previous scenario are maintained, considers the slab resting on the ground, as well as adding a greater capacity for natural ventilation in the hottest moments. Additionally, it was considered to keep the doors closed and the vents opened between the greenhouse and the classroom in the coldest moments of the early morning. With these changes, the minimum and maximum temperature values appear to be very similar.

Finally, a sixth scenario considered the incorporation of thermal mass in the indoor space; the element that divides the classroom and the greenhouse was replaced by a thick adobe wall, to heat it during the day and not be exposed to the outside environment at night. The results show an even better behavior, with minimum temperatures at the beginning of classes only 2 °C from the lower limit of the comfort zone. In general, from the fourth scenario where the mass of the ground is exposed, and even more so in the last scenario where the thermal mass of a wall is added, the importance of this strategy is evident, especially to control the rise in temperature around noon. However, its limitations also become apparent, since the absence of thermal loads when there are no classes and the harshness of the climate itself, do not allow ideal temperature values to be maintained until the next morning.

CONCLUSIONS

Although the module's original proposal rightly considers the inclusion of the solar capture strategy in a cold climate such as that of the Peruvian Puna, excess direct solar gain through the translucent roof implies a noticeable increase in temperature at times when it is no longer necessary to raise it further. The indirect capture through the greenhouse proves to be sufficient in achieving the desired increase, but conditioned to a strict orientation towards the East so that said temperature rise takes place during the first hours of the morning. A second determining condition is to recognize the little thermal mass that the project has and that it is located on the floor. Exposing said mass by removing the insulation allows indoor temperatures to be slightly cushioned throughout the day.

Together with the smaller translucent surface, the correct orientation of the greenhouse, the exposure of the thermal mass in the floor, and the versatility in the ventilation between the greenhouse, the classroom, and the outside, it is possible to improve conditions early in the morning and keep them within the comfort range in the early afternoon, allowing maintaining thermal comfort conditions during most of the hours of use. Finally, it is necessary to recognize the limitations that bioclimatic strategies have in a building with these characteristics and in a climate as harsh as that of the Puna, in the sense that the buildings do not have continuous use and that the consideration of thermal mass is limited by the lightness of materials that modularity requires. Although at noon it is possible to control conditions through the versatility of natural ventilation, it will be difficult to have thermal comfort early in the morning if there are no active solar heating systems or artificial heating systems.

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