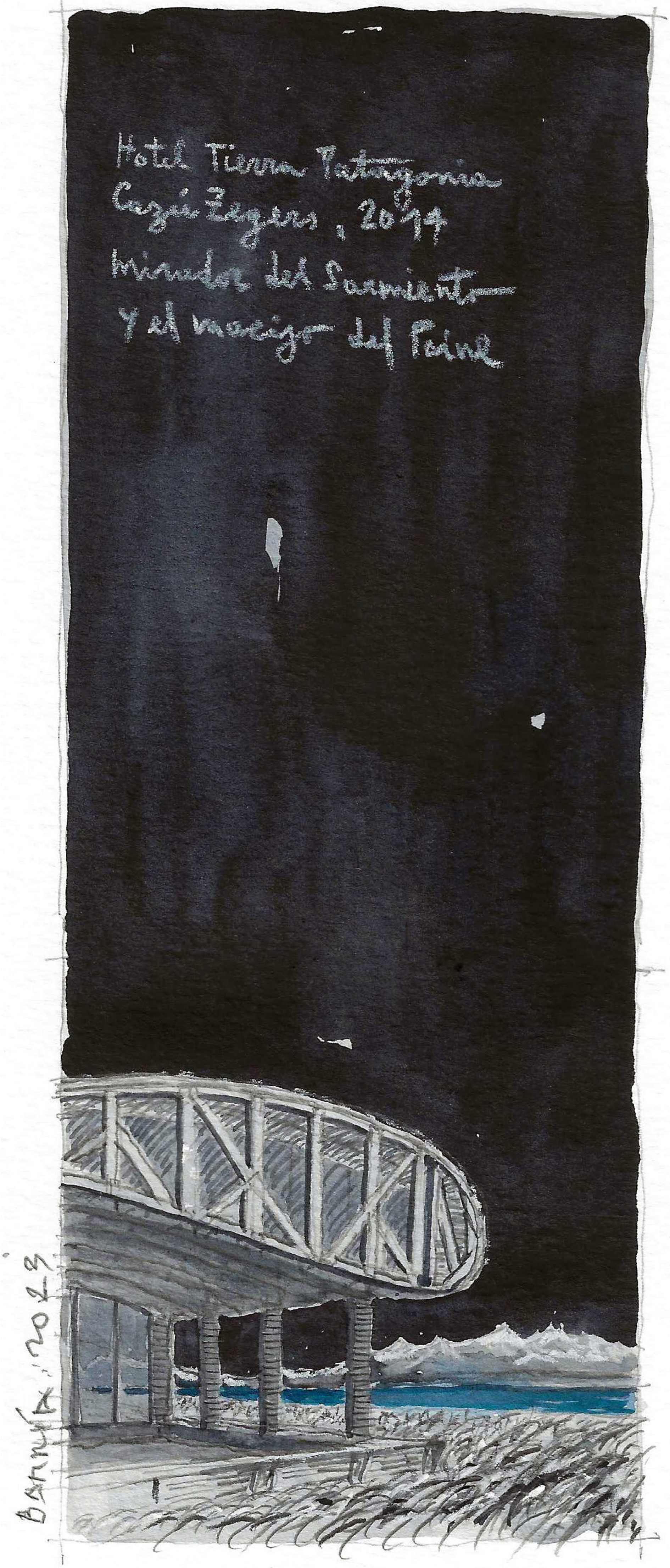

HS

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EDITORIAL

La editorial de la Revista Hábitat Sustentable V13N1 no puede comenzar de otra manera que expresando nuestro más sincero agradecimiento a la Dra. Claudia Muñoz Sanguinetti por su arduo trabajo durante los últimos ocho años. Gracias a su labor, la revista ha logrado ser incluida en indexaciones tan relevantes como SCOPUS, SCIELO, EIHPLUS y EMERGING SOURCES CITATION INDEX (ESCI-WOS).

El constante esfuerzo de la Dra. Muñoz, junto con el equipo editorial, los autores, los revisores y el interés de los lectores, ha permitido mejorar el impacto de la Revista HS. Este año 2023, nos complace anunciar que ha ingresado al tercer cuartil en el área de Arquitectura de SJR (Scimago Journal & Country Rank). Esperamos que, con el trabajo conjunto de todos, la revista continúe mejorando su impacto y alcance.

Como nuevos editores, deseamos enfatizar nuestro compromiso con la importancia de la investigación en los campos del diseño y la construcción del entorno construido, desde una perspectiva local y cercana a la realidad del Sur Global.

El Sur Global es un concepto que fue desarrollado por el economista alemán Willy Brandt en la década de 1980. Se utiliza para describir las diferencias económicas, políticas y sociales entre los países del hemisferio norte (conocido como el Norte Global) y un grupo de países y regiones ubicados principalmente en el hemisferio sur, especialmente en África, Asia y América Latina.

Este término surgió como una forma de abordar las dinámicas de poder y las desigualdades que existen entre los países en el orden global. Reconoce las disparidades y desafíos que enfrentan los países del Sur Global, donde persisten niveles significativos de desigualdad en los estándares de vida, la esperanza de vida y el acceso a los recursos.

En esta zona del planeta donde existe un predominio de los climas tropicales, las estrategias pasivas, los sistemas constructivos vernáculos, la arquitectura bioclimática y el uso de materiales locales desempeñan un papel relevante para abordar los desafíos asociados con el cambio climático, la descarbonización y otros problemas ambientales.

Además, este contexto socioeconómico implica adaptaciones climáticas y respuestas diferentes a la "necesidad" de confort ambiental. Es importante destacar que se estima que más de 120 millones de personas viven por encima de los 2,500 metros de altitud en el Sur Global. Todos los países con más de un millón de habitantes en estas altitudes extremas se encuentran en esta región.

Ante la escasez de recursos económicos, las condiciones climáticas extremas y la falta de acceso a soluciones tecnológicas avanzadas, existe una mayor adaptación al ambiente. Acciones personales, que requieren poco o nada de energía, predominan en aquellos lugares donde no se puede costear la energía, o no se tiene acceso a ella. En cierto modo, las prioridades son otras en muchas zonas de África, Asia y América Latina. Por otro lado, el cambio climático tiene y tendrá un impacto muy importante en el hemisferio sur, implicando en muchos casos una reducción de las condiciones de confort ambiental y en otros un incremento del consumo energético por la penetración masiva de sistemas de climatización.

En las últimas dos décadas, muchos países del Sur Global han impulsado políticas y regulaciones en el acceso a la energía, la eficiencia energética y la energía renovable, sin embargo, aún existen brechas importantes en la región. Si bien la Línea de Brandt tiene más de 40 años, a la vista de los desarrollos en materia de sustentabilidad, eficiencia energética, uso de energías renovables y otros aspectos relacionados con el confort ambiental, su demarcación territorial parece tener vigencia en la mayoría de los países respecto a dichas temáticas, teniendo además relación con aspectos climáticos, de altitud, de emisiones y acceso a la energía.

Las barreras en el Sur Global a las que se enfrentan las áreas del diseño y construcción de edificios son más y mayores que en la mayoría de los países del Norte Global. Además, los conceptos han sido desarrollados en el hemisferio norte, lo cual hace que sus definiciones en muchos casos no se correspondan con las realidades del hemisferio sur, implicando no solo ajustes en torno a los conceptos, también nuevas formas de evaluarlos y medirlos En este sentido, la Revista Hábitat Sustentable busca ser un referente en el desarrollo de investigaciones relacionadas con el Sur Global desde una mirada propia desarrollada en la región. Es importante que se promueva la investigación y el desarrollo de soluciones específicas, teniendo en cuenta la realidad arquitectónica, constructiva, socioeconómica, tecnológica y ambiental de la región, para poder abordar los desafíos y brechas existentes.

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EDITORIAL

The Editorial of Hábitat Sustentable V13N1 cannot begin in any other way than by expressing our most sincere gratitude to Dr. Claudia Muñoz Sanguinetti for her hard work over the last eight years. Thanks to her work, the journal has been included in important indexations such as SCOPUS, SCIELO, EIHPLUS, and EMERGING SOURCES CITATION INDEX (ESCI-WOS).

The constant efforts of Dr. Muñoz, together with the editorial team, the authors, the reviewers, and the interest of the readers, have allowed us to improve the impact of Hábitat Sustentable. This year 2023, we are pleased to announce that it has entered the third quartile in SJR's Architecture area (Scimago Journal & Country Rank). We hope that, with everyone's joint work, the journal will continue to improve its impact and reach.

As new editors, we wish to emphasize our commitment to the importance of research in the fields of design and construction of the built environment, from a local perspective and close to the reality of the Global South.

The Global South is a concept developed by the German economist Willy Brandt in the 1980s. It is used to describe the economic, political, and social differences between the countries of the northern hemisphere (known as the Global North) and a group of countries and regions located mainly in the southern hemisphere, especially in Africa, Asia, and Latin America.

This term emerged as a way to address the power dynamics and inequalities that exist between countries on a global scale. It recognizes the disparities and challenges faced by the countries of the Global South, where significant levels of inequality in living standards, life expectancy, and access to resources persist.

In this area of the planet, where tropical climates predominate, passive strategies, vernacular building systems, bioclimatic architecture, and the use of local materials play an important role in addressing the challenges associated with climate change, decarbonization, and other environmental problems.

In addition, this socio-economic context implies climatic adaptations and different responses to the "need" for environmental comfort. It is important to note that it is estimated that more than 120 million people live above 2,500 meters of altitude in the Global South, and all countries with more than one million inhabitants at these extreme altitudes are located in this region.

Faced with scarce economic resources, extreme climatic conditions, and the lack of access to advanced technological solutions, there is a greater adaptation to the environment. Personal actions, which require little or no energy, predominate in those places where energy cannot be afforded, or where there is no access to it. In some ways, the priorities are different in many areas of Africa, Asia, and Latin America. On the other hand, climate change has and will have a major impact on the southern hemisphere, often involving a reduction in environmental comfort conditions, and in others, increased energy consumption due to the massive penetration of air conditioning systems.

In the last two decades, many Global South countries have promoted policies and regulations in energy access, energy efficiency, and renewable energy. However, there are still important gaps in the region. Although Brandt's Line is now over 40 years old, given the developments in sustainability, energy efficiency, the use of renewable energies, and other aspects related to environmental comfort, its territorial demarcation seems to be valid in most countries regarding these issues but is also related to climate aspects, altitude, emissions, and access to energy.

The barriers in the Global South faced by the areas of building design and construction are more and greater than in most countries of the Global North. In addition, the concepts have been developed in the northern hemisphere, which means that their definitions often do not match the realities of the southern hemisphere, implying not only adjustments around the concepts but also new ways of evaluating and measuring them. In this sense, Hábitat Sustentable seeks to be a reference in the development of research related to the Global South from a perspective developed in the region itself. It is important to promote the research and development of specific solutions, taking into account the architectural, constructive, socio-economic, technological, and environmental reality of the region, to address existing challenges and gaps.

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EDITORIAL

O editorial da Revista Hábitat Sustentable V13N1 só pode começar expressando nossos mais sinceros agradecimentos à Dra. Claudia Muñoz Sanguinetti por seu trabalho árduo nos últimos oito anos. Graças ao seu trabalho, a revista foi incluída em índices relevantes, como SCOPUS, SCIELO, EIHPLUS e EMERGING SOURCES CITATION INDEX (ESCI-WOS).

O esforço constante do Dr. Muñoz, juntamente com a equipe editorial, os autores, os revisores e o interesse dos leitores, nos permitiu melhorar o impacto da Revista HS. Neste ano de 2023, temos o prazer de anunciar que ela entrou no terceiro quartil na área de Arquitetura do SJR (Scimago Journal & Country Rank). Esperamos que, com a colaboração de todos, a revista continue a aumentar seu impacto e alcance.

Como novos editores, queremos enfatizar nosso compromisso com a importância da pesquisa nas áreas de projeto e construção do ambiente construído, com uma perspectiva local e mais próxima da realidade do Sul Global.

O Sul Global é um conceito que foi desenvolvido pelo economista alemão Willy Brandt na década de 1980. Ele é usado para descrever as diferenças econômicas, políticas e sociais entre os países do hemisfério norte (conhecido como Norte Global) e um grupo de países e regiões localizados principalmente no hemisfério sul, especialmente na África, Ásia e América Latina. Esse termo surgiu como uma forma de abordar a dinâmica de poder e as desigualdades que existem entre os países na ordem global. Ele reconhece as disparidades e os desafios enfrentados pelos países do Sul Global, onde persistem níveis significativos de desigualdade nos padrões de vida, na expectativa de vida e no acesso a recursos.

Nessa área do planeta, onde predominam os climas tropicais, as estratégias passivas, os sistemas de construção tradicionais, a arquitetura bioclimática e o uso de materiais locais desempenham um papel relevante no enfrentamento dos desafios associados às mudanças climáticas, à descarbonização e a outros problemas ambientais.

Além disso, esse contexto socioeconômico implica adaptações climáticas e diferentes respostas à "necessidade" de conforto ambiental. É importante ressaltar que se estima que mais de 120 milhões de pessoas vivam acima de 2.500 metros de altitude no Sul Global. Todos os países com mais de um milhão de habitantes nessas altitudes extremas estão nessa região.

Diante da escassez de recursos econômicos, das condições climáticas extremas e da falta de acesso a soluções tecnológicas avançadas, há uma maior adaptação ao meio ambiente. Ações pessoais, que exigem pouca ou nenhuma energia, predominam onde a energia é inacessível ou financeiramente inviável. De certa forma, as prioridades são outras em muitas partes da África, Ásia e América Latina. Por outro lado, a mudança climática teve e terá um grande impacto no Sul Global, em muitos casos levando a uma redução nas condições de conforto ambiental e, em outros, a um aumento no consumo de energia devido à penetração maciça de sistemas de climatização.

Nas últimas duas décadas, muitos países do Sul Global promoveram políticas e regulamentações sobre acesso à energia, eficiência energética e energia renovável, mas ainda há lacunas significativas na região. Embora a Linha Brandt tenha mais de 40 anos, em vista dos desenvolvimentos em sustentabilidade, eficiência energética, uso de energia renovável e outros aspectos relacionados ao conforto ambiental, sua demarcação territorial parece ainda ser válida na maioria dos países no que diz respeito a essas questões, bem como em relação ao clima, altitude, emissões e acesso à energia.

As barreiras no Sul Global nas áreas de projeto e construção de edifícios são maiores e mais numerosas do que na maioria dos países do Norte Global. Além disso, os conceitos foram desenvolvidos no hemisfério norte, o que significa que suas definições, em muitos casos, não correspondem às realidades do hemisfério sul, implicando não apenas ajustes nos conceitos, mas também novas formas de avaliá-los e mensurá-los. Nesse sentido, a Revista Hábitat Sustentable busca ser uma referência no desenvolvimento de pesquisas relacionadas com o Sul Global a partir de uma ótica desenvolvida na região. É importante promover a pesquisa e o desenvolvimento de soluções específicas, levando em conta a realidade arquitetônica, construtiva, socioeconômica, tecnológica e ambiental da região, de modo a abordar os desafios e as lacunas existentes.

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EVALUATION OF THE THERMAL CONDUCTIVITY AND TRANSMITTANCE COEFFICIENT OF EARTHEN CONSTRUCTIVE ELEMENTS

EVALUACIÓN DEL COEFICIENTE DE CONDUCTIVIDAD Y TRANSMITANCIA TÉRMICA DE ELEMENTOS CONSTRUCTIVOS DE TIERRA

VALIAÇÃO DO COEFICIENTE DE CONDUTIVIDADE E TRANSMITÂNCIA TÉRMICA DE ELEMENTOS CONSTRUTIVOS DE TERRA

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RESUMEN

En este trabajo se pretende determinar la conductividad térmica de diferentes elementos constructivos de tierra producidos con materiales característicos del centro este de la provincia de Santa Fe (Argentina) y evaluar su aptitud para ser empleados en la construcción de envolventes que cumplan con los requerimientos de aislación térmica solicitados por la normativa nacional correspondiente. Para ello se confeccionaron probetas siguiendo las diferentes técnicas de construcción con tierra empleadas en la región (bloque de tierra comprimida, adobe, tapia, quincha y revoques) y se midió su coeficiente de conductividad térmica, con el cual se calculó la transmitancia térmica de diferentes paquetes constructivos de tierra. Los resultados obtenidos indican que las técnicas de construcción con tierra evaluadas presentan, en todos los casos, un mejor desempeño térmico que los tradicionales muros de ladrillo cerámico macizo o bloques de hormigón, siendo la quincha la técnica con mayor capacidad de aislamiento térmico.

Palabras clave
aislamiento térmico, muros, materiales de construcción

ABSTRACT

The aim of this work is to determine the thermal conductivity of different earthen constructive elements produced with materials typical of the central-eastern part of the Province of Santa Fe (Argentina), and to evaluate their suitability to be used in the construction of envelopes that comply with the thermal insulation requirements of the corresponding National Regulations. For this purpose, test specimens were made following the different earth construction techniques used in the region (compressed earth block, adobe, rammed earth (*tapia)*, wattle and daub (*quincha*), and plaster), and their thermal conductivity coefficient was measured, with which the thermal transmittance of different earth construction packages was calculated. The results obtained indicate that the earth construction techniques evaluated show, in all cases, a better thermal performance than traditional solid ceramic brick or concrete block walls, with wattle and daub being the technique with the highest thermal insulation capacity.

Keywords
climate change, housing, sustainable development, resilience

RESUMO

O objetivo deste trabalho é determinar a condutividade térmica de diferentes elementos construtivos de terra produzidos com materiais característicos do centro-leste da província de Santa Fé (Argentina) e avaliar sua adequação para uso na construção de envelopes de edifícios que atendam aos requisitos de isolamento térmico dos regulamentos nacionais correspondentes. Para isso, foram feitos corpos de prova de acordo com as diferentes técnicas de construção com terra utilizadas na região (bloco de terra comprimida, adobe, tapia, quincha e gesso) e foi medido seu coeficiente de condutividade térmica, com o qual foi calculada a transmitância térmica de diferentes pacotes construtivos de terra. Os resultados obtidos indicam que as técnicas de construção com terra avaliadas apresentam, em todos os casos, melhor desempenho térmico do que as tradicionais paredes sólidas de tijolos cerâmicos ou blocos de concreto, sendo a quincha a técnica com maior capacidade de isolamento térmico.

Palavras-chave:
isolamento térmico, paredes, materiais de construção.

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INTRODUCTION

The use of context-appropriate envelopes, when faced with a continuous rise in international energy prices and the need to support global efforts to mitigate global warming, becomes a strategy to improve the energy efficiency of buildings. The choice of suitable envelopes has benefits, not only in terms of obtaining energy savings for spaces, improving the indoor microclimate, and reducing polluting emissions, but also regarding the project's technical and economic viability (Balter et al., 2020).

In this context, the potentialities of earthen-built enclosure walls can be highlighted, whose historical continuity is largely due to the abundance of its raw material, the economy of its construction processes, its bioclimatic qualities, and the harmony of its interrelation with its natural environment (Pacheco-Torgal & Jalali, 2012). This is known, sustained, and defended by the peoples with their local traditions, especially those linked to the ancestral worship of Mother Earth, who with popular wisdom produce architecture adapting it to the climate and customs of each site and society (Fernandes et al., 2019).

There are numerous construction techniques and systems that use earth as the predominant raw material (Rotondaro, 2018). However, these can be simply classified within the following categories:

- Mixed techniques: The earth is used as a filling and covering material, using an independent load-bearing structure, usually built with wood. The most commonly used techniques in Argentina are wattle and daub (*quincha*), which is characterized by its secondary structure of reeds or wooden slats equally spaced between 10 and 15 cm apart and arranged horizontally or diagonally; the lightened earth or formwork straw and the elongated mass (*enchorizado*) (Esteves & Cuitiño, 2020).
- Monolithic techniques: Monolithic walls with load-bearing capacity are built using direct molding by hand or mobile formworks filled with compacted or poured mortars. The greatest exponent of these techniques is the rammed earth (*tapia*) (Tepale Gamboa, 2016).
- Masonry techniques: Those that use prefabricated small-sized components, produced before building the house. These components attach to each other using earthen mortars. The walls built with compressed earth blocks (CEB) or adobe are examples of these techniques (Dorado et al., 2022).

One of the most important characteristics of earth as a building material is related to its thermal properties, in particular its ability to transmit heat. This capacity can be defined based on one of its fundamental physical properties: the thermal conductivity coefficient (λ), whereby the thermal transmittance of an envelope (K), directly linked to its thermal insulation, can be determined (Cuitiño et al., 2020).

Despite extensive literature on the thermal properties of materials, research on the thermal conductivity coefficient of earthen building elements produced with materials from the Province of Santa Fe (Argentina) has not been published in academic texts, which makes it impossible to accurately calculate the thermal transmittance of enclosure walls built with these elements.

With regard to the regulatory framework in Argentina, several standards define guidelines for the thermal conditioning of buildings. For example, the IRAM 11601:2010 Standard establishes the apparent density and thermal conductivity of the country's most widely used construction materials and the calculation procedure to determine the thermal resistance and its inverse. It also determines the thermal transmittance (K) of walls and enclosures, whose values should be lower than the maximum permissible values established by the IRAM 11605:2010 and IRAM 11900:2017 Standards for each region of the country, defined in IRAM 11603:2012. However, for the thermal properties of earthen building elements, this set of standards only indicates the thermal conductivity value of CEB with a density of 1800 kg/m^3. In this way, the determination of the thermal conductivity coefficient for different earthen building elements produced with local materials is crucial for regulatory development in Argentina. Therefore, the objective of this work is to determine the thermal conductivity coefficient of different earthen building elements produced with typical materials from the central-eastern sector of the Province of Santa Fe (Argentina), and evaluate their suitability to be used in building walls that meet the thermal insulation requirements requested by the national regulations.

BACKGROUND

The measurement of the thermal conductivity coefficient (λ) of different earthen building elements has been widely studied internationally, with the articles published by Laborel-Préneron et al. (2018), Saidi et al. (2018), and El Fgaier et al. (2016), where the thermal conductivity coefficient of adobe was determined, standing out. On the other hand, there are also the determinations made by Millard and Aubert (2014) on extruded earth blocks; and those performed by Cagnon et al. (2014) and Ouedraogo et al. (2020) on CEB. In addition, the research conducted by Mosquera Arancibia (2013) for his doctoral thesis on the effectiveness of using the "hot needle" method to determine the λ in adobe and CEB; the study conducted by Wieser et al. (2018), where the thermal conductivity was evaluated on samples of wattle and daub, lightened earth, and earth mortars; and, finally, the thesis of Cabrera Córdova (2019) where, among other parameters, the thermal conductivity of adobe, earth plasters, and palm matting was determined.

Despite the aforementioned studies, there are few lines of research in Argentina to quantify the thermal properties of earthen materials. In this regard, the works by Costantini Romero et al. (2021) and Costantini Romero and Francisca (2022) are mentioned, where the thermal conductivity coefficient of CEBs produced in the city of Córdoba (Arg.) was determined, and the one by Cuitiño et al. (2015), where the thermal transmittance (K) of different wattle and daub panels was determined.

It should also be mentioned that the results published in the referenced research, despite being within similar ranges, have significant differences, mainly caused by the type of soil used to prepare the test specimen, their molding methodology, and the test equipment used. With regard to the equipment and methodologies used to determine λ, the so-called hot-box[1], thermal needle[2], and hot plate[3] methods have been used.

Finally, it is important to highlight the work carried out by the RILEM Committee (Fabbri et al., 2022), Volhard (2016), Cuitiño et al. (2020), and Minke (2005) who, despite not making direct thermal conductivity determinations of the earthen constructive elements, make an in-depth analysis of the variation of this coefficient considering variables such as the construction technique and the density of constructive elements.

METHODOLOGY

MATERIALS

The earth used to manufacture the different samples was obtained from a quarry in the municipality of Monte Vera (Santa Fe, Arg.). In previous work (Cabrera et al., 2022), the soil used was identified as a "CL low plasticity clay" with 54% silt, 32% clay, and 14% fine sand. Likewise, the semi-quantifications carried out by DRX confirm that, from the mineralogical point of view, the predominant mineral is quartz (65%), followed by phyllosilicates (clays) (25%), and feldspars (9%). The diffractograms of oriented aggregates of the earth's clay fraction indicate that the phyllosilicates present are illite, kaolinite, and smectite.

The fine sand used in the granulometric correction has a uniform size distribution, in that more than 90% of its particles are between 0.5 and 0.1 mm in size. In addition, there are no edges or angular shapes in its grains, with all of them presenting a rounded shape. From the mineralogical point of view, its grains consist mainly of quartz (95% by weight), with only 1% of clays.

The coarse sand, also made of silica and with a size distribution of between 2 and 3 mm, was purchased from the company Gravafilt in the city of Paraná (Arg.), which extracts it by dredging the upper Paraná River basin, classifying it, and commercializing it with different granulometry. This sand was used only in the preparation of the rammed earth samples.

To manufacture the adobe, wattle and daub, and coarse plaster test specimens, wheat straw purchased near the city of Santa Fe (Arg) was used as vegetable fiber. Although the straw used in making the different types of test specimens was the same, it was cut into different lengths: 2 cm for coarse plasters, 3 cm for adobe, and between 10 and 12 cm for the wattle and daub filling. The materials used in the manufacture of the different types of specimens can be seen in Figure 1.

1 Determines the λ coefficient and the conductivity, K, of an enclosure in a stationary regime and on a real scale, with the test specimen being a wall that separates two environments with different temperatures.

2 Determines the λ coefficient in a non-stationary regime by introducing a metal needle with a heater and thermocouple inside the material being evaluated, measuring its temperature variation over time.

3 Determines the λ coefficient under a stationary regime on a 10 to 90 mm thick plate-shaped test specimen, which is placed between 2 plates at different temperatures. The plates are confined inside a parallelepiped box with high thermal insulation.

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Figure 1. Materials used in the manufacture of the specimens: (a) earth, (b) mud (mixture of earth and water), (c) fine sand, and (d) wheat straw, 3 cm in length. Source: Preparation by the authors.

Table 1. Dosage used in the preparation of the test specimens. Source: Preparation by the authors.

Material	Dry weight proportion in %				Water* (%)	Water/earth ratio
	Earth	Fine sand	Coarse sand	Straw		
(a) CEB	70.0	30.0	-	-	11.7	0.17
(b) Adobe	96.5	-	-	3.5	32.6	0.34
(c) Wattle and daub	93.8	-	-	6.2	60.1	0.64
(d) Rammed earth	60.0	20.0	20.0	-	11.0	0.18
(e) Coarse plaster	67.5	29.1	-	3.4	23.3	0.34
(f) Fine plaster	35.0	65.0	-	-	16.3	0.47

* % determined based on the dry weight of the earth.

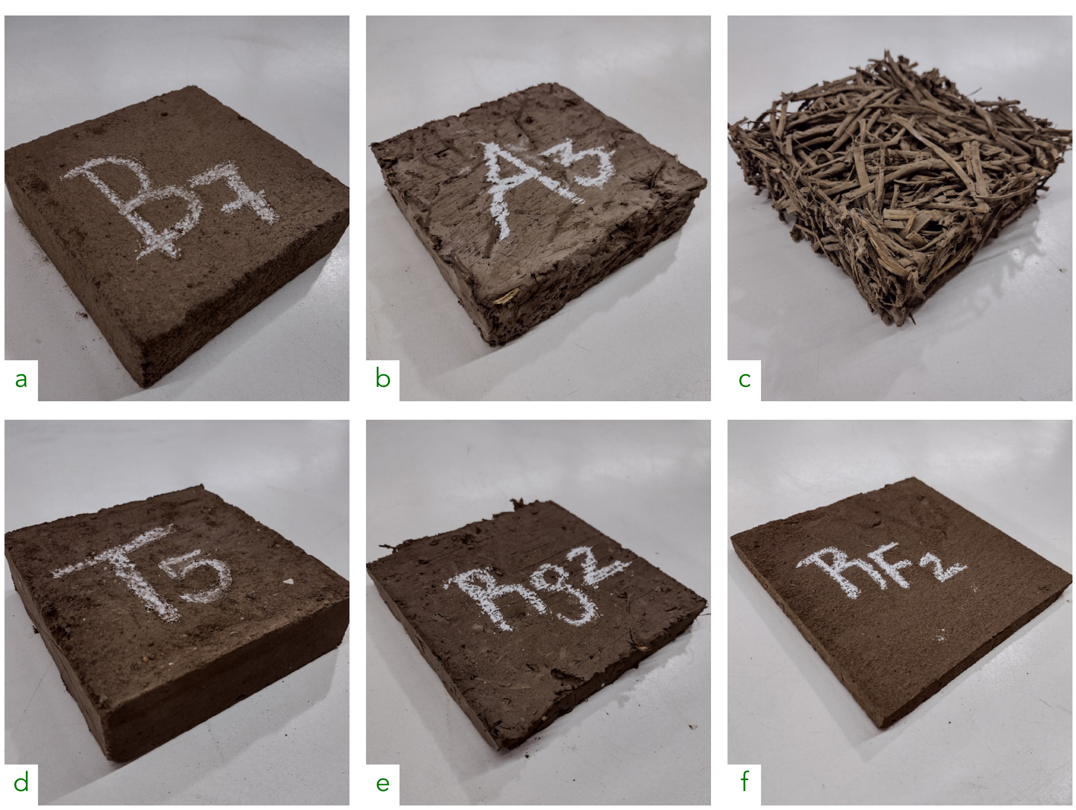

Figure 2. Representative specimens of the different earth construction techniques: (a) CEB, (b) adobe, (c) wattle and daub, (d) rammed earth, (e) coarse plaster, and (f) fine plaster. Source: Preparation by the authors.

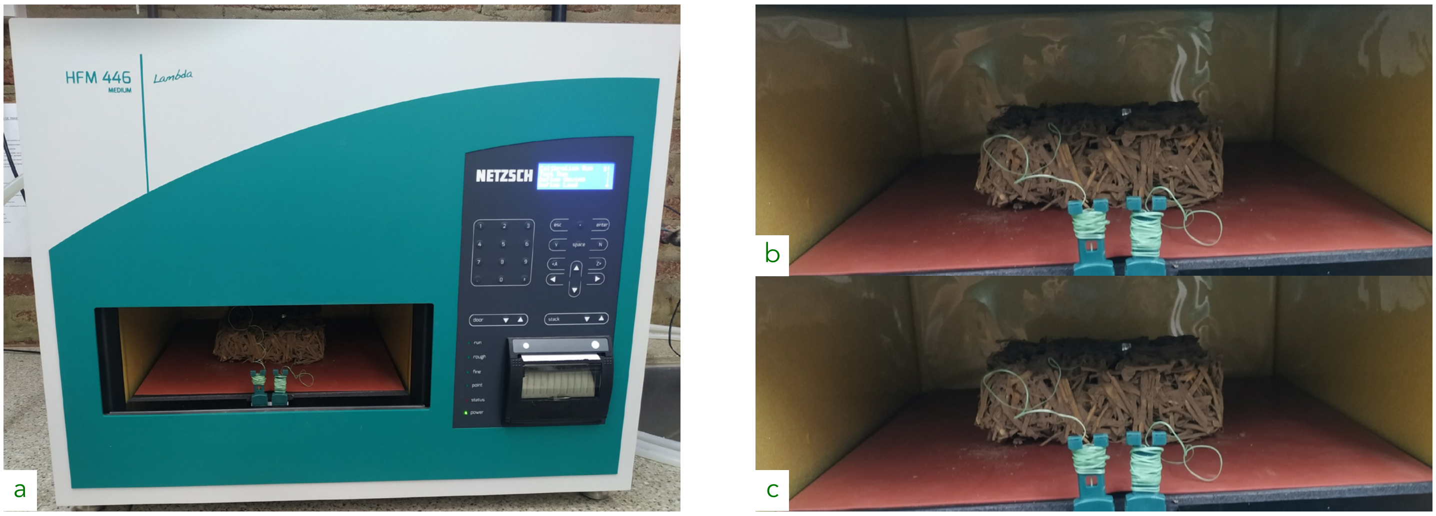

Figure 3. (a) HFM 446 equipment, (b) additional thermocouples, and (c) silicone film used to determine the thermal conductivity coefficient. Source: Preparation by the authors.

MANUFACTURE OF TEST SPECIMENS

For each construction technique, three 13 x 13 x 4 cm test specimens were made (except for the thin plaster ones, which were 2 cm thick), thus generating a total of 18 test specimens, whose dosages are presented in Table 1. The CEB test specimens were made by cutting, with a circular bench saw, whole blocks produced in the laboratory with an Altech Geo 50 manually operated press. These, because they were not stabilized with Portland cement, were not cured, and were left to dry for 7 days sheltered from the weather.

The adobe, coarse plaster, and fine plaster specimens were made by pouring the wet mixture into each mold, accommodating it to not generate vacuums or voids. After 24 hours, the specimens were removed from the mold, allowing them to dry for 7 days under laboratory temperature and humidity conditions (24 °C < t < 27 °C and 35% < RH < 45%). The molding of the rammed earth specimens was done in 3 layers, introducing third parts of the wet material into the mold and compacting each layer with 25 strokes of a 550 g block ramming machine, before sanding the upper surface with sandpaper. These specimens were immediately removed from their molds, being allowed to dry, like the rest, for 7 days inside the laboratory.

For the molding of the wattle and daub specimens, the straw was submerged in slip (mud of liquid consistency) and, after a few seconds, it was extracted. The excess liquid was then drained and the straw covered with the slip was introduced into the mold, thus intertwining the fibers embedded in the slip (Figure 2.c). Then, they were left to dry for 7 days and removed from the mold.

DETERMINATION OF THERMAL CONDUCTIVITY AND TRANSMITTANCE

For each of the specimens made, the dry apparent density and then the thermal conductivity coefficient were determined first, using an HFM 446 Lambda Medium heat flow meter model from the German firm Netzsch (Figure 3.a), adopting an average test temperature of 17 °C and a variation of ± 10 °C, following the procedure stipulated by the IRAM 1860:2002 Standard. Before the tests, all the test specimens were dried in an oven at 100 °C until mass consistency was achieved. Given the irregularity of the specimens' surface, they were tested using a complementary kit, provided by the equipment supplier, consisting of a silicone film and additional thermocouples (Figure 3.b and Figure 3.c), whose purpose is to improve the contact interface between the thermal plates and the rough surface faces of the specimens.

Once the thermal conductivity coefficient of each type of sample tested had been determined, the thermal transmittance coefficient (K) of different earthen building packages was calculated following the procedure indicated by the IRAM 11601:2010 Standard; adopting the interior and exterior surface thermal resistance values proposed by it. The formulas used to calculate K were those indicated in Equation 1, Equation 2, and Equation 3:

$$R_i = e_i \ / \ \lambda_i \qquad \text{(Equation 1)}$$

$$R_t = R_{ext} + R_i + R_{int} \qquad \text{(Equation 2)}$$

$$K = 1/R_t \qquad \text{(Equation 3)}$$

Where:

- R_i: thermal resistance of each constituent layer of the wall, in m²K/W
- λ_i: thermal conductivity coefficient of each material, in W/mK
- e_i thickness of each material the wall comprises, in m
- R_t: total thermal resistance of the wall, in m²K/W
- R_{ext}: external surface thermal resistance, adopting a value of 0.04 m²K/W
- $R_{int:}$ internal surface thermal resistance, adopting a value of 0.13 m²K/W
- K: total thermal transmittance of the wall, in W/m²K

RESULTS

The apparent density (ϱ) and thermal conductivity coefficient (λ) values obtained for each specimen tested are shown in Table 2, together with the corresponding average value, the standard deviation (S_d), and the variation coefficient (V_c).

On the other hand, Table 3 presents the thermal transmittance coefficient (K) values calculated for different wall construction packages using the earth components analyzed in this work, proposed based on local construction practices. In this table, the column called "main element" refers to the thickness of the adobe, CEB, rammed earth, or wattle and daub, as applies.

DISCUSSION

ON THE DETERMINATION OF THE THERMAL CONDUCTIVITY COEFFICIENT

As can be seen in Table 2, there is a correlation between the density of the construction elements

Table 2. Apparent density and thermal conductivity coefficient of the test specimens. Source: Preparation by the authors.

Material	Density				Thermal conductivity			
	ρ_i (kg/m3)	ρ_{prom} (kg/m3)	S_d (kg/m3)	C_v (%)	λ_i (W/mK)	λ_{prom} (W/mK)	S_d (W/mK)	C_v (%)
CEB	1587	1595	13.4	0.8	0.59	0.60	0.01	1.7
	1588				0.61			
	1611				0.59			
Adobe	1353	1352	12.2	0.9	0.46	0.43	0.05	11.4
	1364				0.45			
	1340				0.37			
Wattle and Daub	341	429	76.4	17.8	0.11	0.13	0.02	15.3
	478				0.14			
	468				0.15			
Rammed Earth	1634	1687	48.9	2.9	0.58	0.67	0.10	15.0
	1697				0.64			
	1730				0.78			
Coarse plaster	1348	1329	22.8	1.7	0.49	0.48	0.08	16.0
	1303				0.41			
	1334				0.56			
Fine plaster*	1233	1260	37.6	3.0	0.23	0.25	0.04	15.8
	1286				0.28			

* Only 2 measurements could be made on this series.

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Table 3: Calculation of the thermal transmittance coefficients of different earth construction packages. Source: Preparation by the authors.

Constructive package	Thickness of each layer (m)						K (W/m²K)
	External fine plaster	External coarse plaster	Main element	Internal coarse plaster	Internal fine plaster	Total	
CEB (12 cm)	-	-	0.12	-	0.01	0.13	2.443
CEB (25 cm)	0.01	0.02	0.25	0.02	0.01	0.31	1,337
CEB with air chamber (4 cm)	0.01	0.02	0.25 + 0.12	-	-	0.44	0.969
Adobe	0.01	0.02	0.30	0.02	0.01	0.36	0.972
Plastered rammed earth (30 cm)	0.01	0.02	0.30	0.02	0.01	0.36	1,282
Visible rammed earth	-	-	0.55	-	0.01	0.56	0.969
Wattle and Daub	0.01	0.02	0.15	0.02	0.01	0.21	0.675

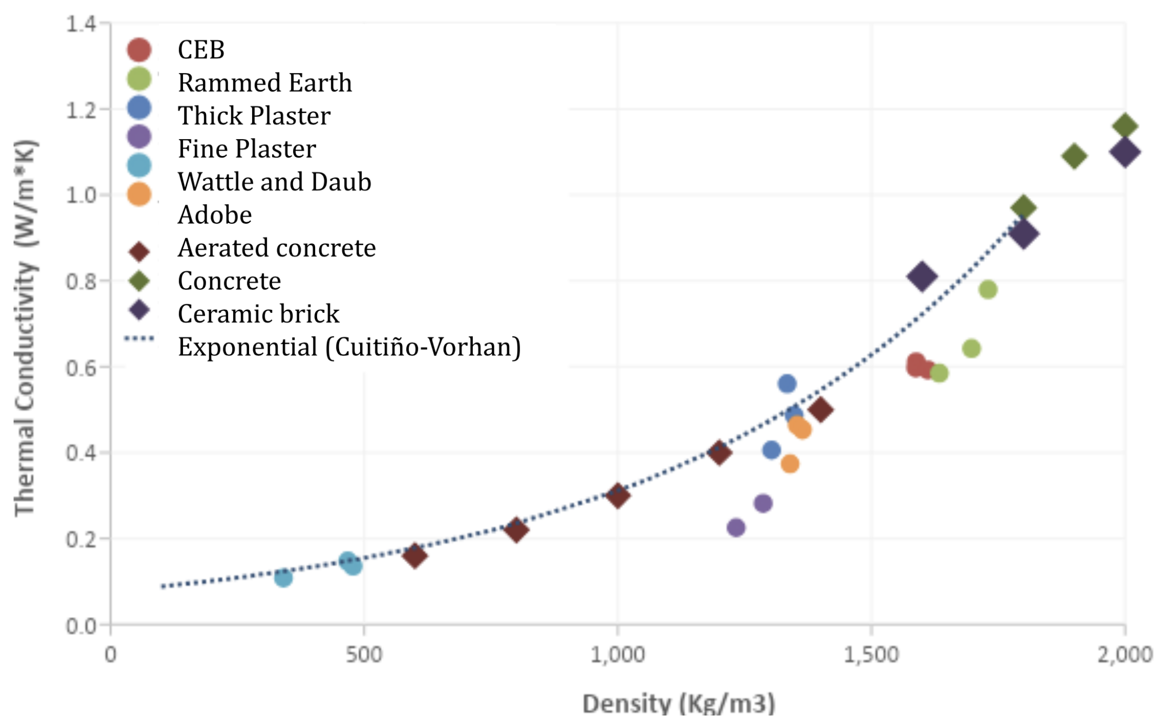

Figure 4. Correlation between the density of building elements and their thermal conductivity coefficient. Source: Preparation by the authors.

and their thermal conductivity coefficient, with the wattle and daub, whose density is around 400 kg/m^3, being the one with the lowest thermal conductivity coefficient, with about 0.13 W/mK. This coefficient is comparable to that of cellular concretes of similar density (IRAM 11601:2010), but significantly higher than that of conventional insulating materials, such as glass wool, expanded polystyrene, or polyurethane foam (Navacerrada et al., 2021). After the wattle and daub, the constructive element with the lowest thermal conductivity coefficient is adobe with an $_{average}$ λ of 0.43 W/mK, followed by CEB with an $_{average}$ λ of 0.60 W/mK, and finally rammed earth with an $_{average}$ λ of 0.67 W/mK.

According to this data, the spread in the results of the wattle and daub samples becomes evident, which can be associated with greater variability in the densities of each sample, typical of the process to make these, namely manual filling with a large volume of voids due to the intertwining of straw fibers in the wattle and daub and dynamic compaction for rammed earth.

As far as the coarse plaster samples are concerned, both their density and λ are similar to those of the adobe samples. This similarity is attributed to the fact that, regardless of the materials used (straw for adobe and sand + straw for coarse plaster), the water/earth ratio of both, the main cause of the porosity and apparent density of the earthen constructive elements (Laborel-Préneron et al., 2018), are equal, with 0.34. Similarly, the coarse plaster samples with a water/earth ratio of 0.47 - the highest after the wattle and daub - have the lowest density and average λ.

In Figure 4, the experimental results obtained in this research (colored dots) can be compared with those collected and published by Volhard (2016) and Cuitiño et al. (2020) for different earth-building elements (dotted line). In this, it can be seen how, despite the spread in the results achieved in this work, the exponential correlation between the density of the earthen constructive elements and their thermal conductivity coefficient is similar to that determined by the cited authors. This allows thinking that, regardless of the mineralogical characteristics of the earth used, the amount and type of sand, along with the vegetable fibers used in the stabilization, the main determinant of the thermal conductivity coefficient of these constructive elements is their final apparent density.

In addition, Figure 4 includes the thermal conductivity values for different traditional constructive elements, corresponding to their densities. It can be seen how aerated concrete, whose densities resemble that of the different earthen constructive elements, has thermal conductivity coefficients very similar to those determined by Cuitiño et al. (2020) and Volhard (2016) (dotted line), and that both concrete and solid ceramic brick, despite being in a range of densities higher than those studied by the aforementioned authors, follow the same trend.

ON THERMAL TRANSMITTANCE

The Argentine regulation IRAM 11605:2010 establishes three levels of hygrothermal comfort in winter and summer for the country's different bioclimatic zones, depending on the average outdoor temperatures. Thus, for the central-eastern sector of the Province of Santa Fe (bioclimatic zone IIb), the thermal transmittance values for each comfort level are as follows:

- Level A: 0.38 W/m²K
- Level B: 1.00 W/m²K
- Level C: 1.85 W/m²K

Table 4. Calculation of the thermal transmittance coefficient of different construction packages. Source: Preparation by the authors based on data from the IRAM11601:2010 Standard.

Material	Thickness (m)						K (W/m²K)
	External fine plaster*	External coarse plaster*	Main element	Internal coarse plaster*	Internal fine plaster*	Total	
Common brick 25 cm	0.01	0.02	0.25	0.02	0.01	0.31	1.505
Common brick with air chamber	0.01	0.02	0.25+0. 25	0.02	0.01	0.56	0.924
Hollow brick 18 cm	0.01	0.02	0.18	0.02	0.01	0.24	1.390
Hollow brick with air chamber	0.01	0.02	18 + 12	0.02	0.01	0.36	0.927
Concrete block 20 cm	0.01	0.02	0.20	0.02	0.01	0.36	2.226
Concrete block with air chamber	0.01	0.02	0.20+0.20	0.02	0.01	0.36	1.540
Aerated concrete (600 kg/m3)	0.01	0.02	0.15	0.02	0.01	0.21	0.843

* Cementitious plasters

Based on the thermal transmittance coefficient values determined in Table 3 for different earthen construction packages, to meet the hygrothermal comfort level B –minimum level requested by the Ministry of Housing (Arg.)-, the most suitable alternative is the plastered wattle and daub wall, which, with a total thickness of 21 cm, has a K of 0.675 W/m²K.

In the case of using 30 cm adobe walls, with thick and thin plasters on both sides, comfort level B (0.972 W/m²K) can be reached with a total wall thickness of 36 cm. On the other hand, to achieve this level of comfort with a CEB wall, the best alternative is to use double walls (25 + 12 cm) with an inner air chamber of 4 cm and plasters only on the outer face of the wall, generating a wall whose final thickness is 44 cm, which is the common practice in the region (Dorado et al., 2022). Finally, using the exposed rammed earth technique (only with thin interior plaster), 56 cm thick walls should be used to achieve comfort level B.

Despite the high thicknesses of the adobe, CEB, and rammed earth walls required to reach comfort level B, it should be considered that, as shown in Table 4, except for walls built with hollow bricks and aerated concrete blocks, none of the so-called "traditional" construction packages reaches this level of insulation without the use of air chambers and a total wall thickness greater than 50 cm.

CONCLUSIONS

The evaluation of the results obtained in this research allows concluding the following:

- There is a direct correlation between the thermal conductivity coefficient and the apparent density of constructive elements made with earth, sand, and vegetable fiber from the central-eastern part of the Province of Santa Fe. This coincides with what is reported by different researchers from the national and international contexts.
- The earthen construction technique with the highest thermal insulation capacity is wattle and daub, complying with the requirements stipulated by current Argentine regulations, with a 21 cm thick package.
- For wall thicknesses of less than 40 cm, among the construction packages proposed in Table 3, the adobe walls (36 cm) present, after the wattle and daub (21 cm), the best thermal insulation level, followed by the rammed earth walls (36 cm), and finally the CEB ones (31 cm).
- The earth construction techniques all have better thermal performance than the traditional solid ceramic brick walls or concrete blocks, requiring lower thicknesses to achieve equal thermal insulation levels.

Finally, it can be stated that the main contribution of this research is strengthening public policies that look to encourage energy efficiency in Argentine homes, as is the case of the National Housing Labeling Program, implemented in 2023, in whose database the option of using walls built with earth elements in the envelopes is not available. This situation is mainly motivated by the shortage of reliable technical data on the thermal properties of earthen building elements produced with local materials.

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SUSTAINABILITY IN THE BRAZILIAN TIMBER HOUSING VIRTUAL MARKET

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SUSTENTABILIDAD EN EL MERCADO VIRTUAL BRASILEÑO DE LAS VIVIENDAS DE MADERA PROCESADA

SUSTENTABILIDADE NO MERCADO VIRTUAL BRASILEIRO DE CASAS DE MADEIRA

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RESUMEN

Las viviendas de madera procesada son sustentables y basadas en biorecursos, siendo una alternativa a la construcción tradicional de albañilería y acero y estudios recuentes han demostrado que este sector, en Brasil, cuenta con cientos de pequeñas y medianas empresas dedicadas a este tipo de vivienda. Este estudio exploratorio, a la vez que analizó esta población, evaluó los perfiles disponibles en Instagram®, observando sus estrategias de negocio y lo que revelan a sus clientes sobre los beneficios en cuando a sustentabilidad y asuntos relacionados a esta. Todos los perfiles corporativos disponibles fueron estudiados y se compiló una muestra significativa de alrededor del 80% de un sector, desde un mercado actualmente compuesto por más de 400 empresas. Sin embargo, alrededor del 70% de estas empresas brasileñas aún no exploran adecuadamente los temas de sustentabilidad de sus productos y servicios de viviendas de madera, lo que evidencia un escenario incipiente. Además, existe una clara oportunidad para aprovecharse de los argumentos publicados en sus perfiles de Instagram® como una estrategia de concientización afirmativa. Aunque se sugirieron algunas justificaciones para convencer a los clientes nacionales para considerar las viviendas de madera, este mercado virtual puede mejorar sustantivamente.

Palabras clave
industria de la construcción, estructuras de madera, estudios de mercado, sustentabilidad

ABSTRACT

Timber housing is a sustainable bioresource-based alternative to traditional construction with masonry and steel, and recent studies have shown that this sector in Brazil has hundreds of timber housing SMEs. This exploratory study, while analyzing this population, evaluated the profiles available on Instagram®, observing their business strategies and what they have disclosed to clients on sustainability benefits and issues. All the available corporate profiles were surveyed, and a significant sample of about 80% of a sector was compiled, from a market currently formed by over 400 companies. However, about 70% of these Brazilian companies still do not adequately explore sustainability issues in their timber housing products and service, evidencing an incipient scenario. Moreover, there is a clear opportunity to leverage the arguments posted on their Instagram® profiles as an affirmative awareness strategy. Although some justifications were suggested to convince domestic customers to consider timber housing, this virtual market has a lot of room for improvement.

Keywords
construction industry, wood structures, market studies, sustainability

RESUMO

As casas de madeira são uma alternativa sustentável e baseada em biorrecursos à construção tradicional com alvenaria e aço. Estudos recentes mostram que esse setor no Brasil é representado por centenas de PMEs focadas em casas de madeira. Este estudo exploratório analisou essa população por meio de uma avaliação dos perfis disponíveis na rede social Instagram®, observando suas estratégias de negócios e o que divulgavam aos clientes sobre benefícios e questões relativas à sustentabilidade. Todos os perfis corporativos disponíveis foram pesquisados e uma amostra significativa de cerca de 80% do setor foi compilada, em um mercado atualmente formado por mais de 400 empresas. No entanto, cerca de 70% dessas empresas brasileiras ainda não exploram adequadamente as questões da sustentabilidade em seus produtos e serviços de habitação de madeira, evidenciando um cenário incipiente. Além disso, existe uma clara oportunidade para aproveitar os argumentos publicados em seus perfis do Instagram® como uma estratégia afirmativa de conscientização. Embora algumas justificativas tenham sido sugeridas para convencer os clientes domésticos a considerarem a habitação de madeira, ainda resta muito espaço para melhorias nesse mercado virtual.

Palavras-chave
setor da construção, estruturas de madeira, estudos de mercado, sustentabilidade

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INTRODUCTION

As many around the world wonder about the few rationalized solutions there are in the market and search for new sustainable responses, a wholesome way has favored the development of contributions to promote environmentally friendly alternatives.

In this context, wood could be used in greener products to provide a sustainable lifestyle. For example, Maldonado et al. (2020) suggested that wood could boost job and wealth development for micro and small-sized businesses. The advantages of timber used in construction have also been widely shown in research, for example, lower energy consumption for production and lower carbon emissions of timber buildings compared to masonry ones, as verified by Gustavsson and Sathre (2006) and Oliver et al. (2014), more efficient use of resources in the sustainability context for wood against masonry as studied by Svajlenka and Kozlovská (2018), the heating efficiency of timber houses as measured by Svajlenka and Kozlovská (2020a), wood solutions as lower carbon options in the life cycle as stated by Hart and Pomponi (2020), multiple uses of forestry species and wood products and efficient carbon fixation in different wood-based construction techniques as identified by De Araujo et al. (2020b), and other contributions. However, Heräjärvi (2019) suggests that marketing on timber construction can be fallacious when, specifically, it is described as an effective tool to mitigate climate change since the effects of replacing traditional resources multiply the outcomes for physical carbon stocks. Heilmayr et al. (2020) warn that the misuse of forestry subsidies undermines increased carbon storage and biodiversity objectives. Thus, policies should address the protection of natural forests aligned with plantations, which are weakened when popular solutions are still based on non-renewable sources such as minerals.

Hence, wood is the only widely used building material that can be regarded as a genuinely sustainable solution (Ramage et al., 2017) for timber products (De Araujo et al., 2022b). As experts have confirmed, this vision coincides with evidence that this bioresource offers superior credentials to other construction materials (Wang et al., 2014), where timber buildings could ensure a brighter future with lower liabilities (Heräjärvi, 2019).

Except for some Northern Hemisphere nations, the timber housing model is at an incipient stage. However, this solution is still latent in the rest of the world, specifically if compared to masonry. Even so, numerous countries are looking to add timber housing as a modern construction solution. In these territories, which are more closely connected to a spontaneous movement towards a consumption transition, the timber industry could become a real protagonist due to its processing with higher levels of prefabrication, utilization of renewable resources, and rationality of production inputs as well as lower environmental pollution. The advantages of low carbon emissions from the wood sector identified by Fujii and Managi (2013) and from sustainable timber construction made in industrial plants analyzed by Svajlenka and Kozlovská (2020b) add to this perspective. Fujii and Managi (2013) confirmed that the wood industry, especially for products and construction, is greener than the food, tobacco, petrochemical, mining, metallurgical, and transport sectors.

Even without a government plan to effectively promote timber housing and its industry, Brazil is ahead of many nations. For example, Brazil currently has multiple forest resources available (IBÁ, 2020; Rabelo et al., 2020), uses numerous native and exotic species in wood construction (De Araujo et al., 2021a), has dozens of large industrial parks for a domestic sector formed by hundreds of compact-sized timber house developers located in different states (De Araujo et al., 2021b), has both domestic and foreign markets for timber houses (De Araujo et al., 2020a) and among these, markets that are receptive to certified goods from sustainable practices (Lima, 2017; Meijueiro et al., 2020; Ribeiro, 2020). Despite the positive factors, illegal deforestation remains a domestic problem, as confirmed by Leite-Filho et al. (2021). There is also an apparent lack of incentives to use sustainably certified wood, as cited by Romero et al. (2015) and De Araujo et al. (2021a). However, there are few standard studies on the timber housing market and only from the last two decades, for example, Wahl (2008), Morgado and Pedro (2011), Wherry and Buehlmann (2014), Hurmekoski et al. (2015), Moore (2015), Egan Consulting (2017), Koppelhuber et al. (2017), Shigue (2018), De Araujo et al. (2020a), Ahmed (2021), MBIE (2021), and Garay-Moena et al. (2022). Unfortunately, these contributions fail to address contemporary topics such as virtual spaces and platforms, used to disseminate socioeconomic and environmental aspects. Though, in one recent study by De Araujo et al. (2022a) which addressed the electronic timber house market, the companies surveyed shared basic graphic and textual information. However, e-commerce could not be confirmed due to a lack of product pricing.

The purpose of this sectorial study prioritized research into the business strategy and disclosure to customers regarding sustainability approaches in the context of timber houses produced and/or marketed by companies specialized in timber construction in Brazil. Using the Instagram® profiles of each domestic developer, a sectorial scenario was analyzed to verify flaws through a lack of limitations of the sustainable contents on timber housing in the corporate profile of the companies sampled. Affirmative suggestions were proposed to include, improve, and reinforce content using arguments based on literature and authors' opinions to

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endorse and complement the possible strategies for the Brazilian timber housing sector.

METHODOLOGY

Due to restrictive impositions caused by the Covid-19 pandemic ravaging the world, traditional scientific studies and commercial activities are suffering repeated setbacks imposed by the global crises. As a result, virtual activities have intensified, becoming an excellent resource to research innovation. In the context of timber houses, virtual methods have been efficiently used by De Araujo et al. (2019), De Araujo et al. (2021a), and De Araujo et al. (2021b). Given this scenario, sustainability in corporate profiles of Brazilian timber housing producers and dealers virtually available on Instagram® was investigated. As Instagram® is used for trading goods, the goal was to evaluate active profiles.

This exploratory study started by identifying companies using the search terms shown in Table 1 (with plural versions). The search was made using Brazilian Portuguese terms in the Instagram® platform's search engine. The lead researcher's knowledge of the Brazilian timber construction sector, from previous scientific studies on this topic, was vital for this process. The search concluded when no unprecedented profile was found in the search engine results for individualized inquiries. In this process, every repeated profile was disregarded. In addition, after a detailed investigation of the content and posts in each profile, those companies outside the studied topic were discarded as having goals that fell outside the scope of this study. These included the rental of timber houses for vacations, timber-built hotels, as well as wood product enthusiasts and fans, and construction specialists who used other non-wood-based materials.

The method was based on a similar replication and update of the e-commerce and virtual sales research of De Araujo et al. (2022a). The lead researcher confirmed the absence of some companies in the new profile listing. These missing profiles were individually prospected by their corporate names, as a previous list led by De Araujo et al. (2021b) did not disclose information or identify the Instagram® profiles. Some profiles not previously prospected were found based on new searches using their names, which allowed listing their new profiles. Several companies on the previous list were not found on Instagram®, which suggested that they did not have a profile on this network.

In practice, the term-based searches returned random results. After three months, the list of profiles was rechecked using signs of activities and posted content to confirm all the companies were operational. After this validation, profiles, and information were noted in a database built using Microsoft Excel 2010.

Table 1: Search terms used in the company identification and respective English term. Source: Prepared and translated by the Authors.

Search term in Brazilian Portuguese	Search term translated into English
Habitação em madeira	Timber housing
Casa de madeira	Timber house
Construção em madeira	Timber construction
Casa pré-fabricada em madeira	Prefabricated timber house
Construção sustentável em madeira	Sustainable timber building
Construção verde em madeira	Green timber building
Madeira pré-fabricada	Prefabricated timber
Kit pré-fabricado	Prefabricated kit
Construção seca em madeira	Dry timber construction
Construção modular	Modular construction
Casa modular	Modular house
Madeira lamelada colada cruzada	Cross-laminated timber
Casa de toras	Log-home
Enxaimel	Half-timbered frame
Tábua e mata-junta	Clapboard and wainscot
Casa náutica	Nautical house
Chalé	Chalet (A-frame)

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Table 2: Issues and aspects under evaluation in this exploratory sectoral survey. Source: Prepared by the authors

Issue	Justification	Alternative
Issue 1: investigate the existence of posts on sustainability	Understand whether companies are using sustainability topics for products and services	Yes; No
Issue 2: investigate types of subjects contained in the posts with direct relation to sustainability and their main arguments	Understand all arguments used in the contents posted about sustainability related to their goods and services	Sustainable product; Certifications and seals; Environmental awareness; Greater cleaning and lower waste generation; Greater carbon fixation in wooden materials; Lower carbon emissions from production; Greater production and time efficiency; Ecological and renewable materials

Table 3: Sector and sampling populations obtained in this exploratory sectoral survey. Source: De Araujo et al. (2022a).

Company Population	Unitary Volume (Companies)	Sector Percentage (%)	Margin of Error (%)
Overall sector	402	100	–
Without profiles	87	22	–
With profiles	315	78	–
Sampling	315	78	2.57%

The second stage involved the compilation of profiles to form the regular listing, enabling effective sampling. All the profiles were evaluated to obtain a significant sampling. Then, the margin of error was calculated considering the sector's total population, which included companies with corporate profiles on Instagram® and without any profile on this social network. Statistical software developed by Raosoft (2004) was used, as well as its prescriptions of 50% response distribution and 95% confidence level. Alongside this method, both the total population and sampled population were input to verify the margin of error for this study.

The third stage was marked by the definition, justification, and evaluation of the issues presented in Table 2, both to identify the presence of sustainability and to define issues about this topic in the posts available in each corporate profile. It was possible to analyze the panorama in this context under evaluation. While the first issue was dichotomous and was based on the absence/presence of posts on sustainability, the second considered multiple responses with one or more different contents addressed in these posts (Table 2). As a result of the different contents, for issue 1 the quantification of alternatives was binary with the presence or absence of each alternative studied per issue. Whereas for issue 2, the number of arguments about sustainability posted by each corporate profile was counted to identify the frequency of contents used to emphasize the sustainable vocations of disclosed products and services. Regarding the approaches related to the second issue, analyses were made to reveal affirmative paths to explore each studied alternative. The final part proposed affirmative strategies for electronic commerce through Instagram® and clarified topics to customers on the potential of timber houses in the context of sustainability.

RESULTS AND DISCUSSION

In mid-2020, De Araujo et al. (2021b) reported a Brazilian sector formed by 378 companies dedicated explicitly to timber housing production and its market. At the end of 2020, this sectorial listing needed updating as the severe pandemic had devastated all global economies and many negative scenarios had been confirmed, for example by Bartik et al. (2020), Chen et al. (2021), Egger et al. (2021), Iqbal et al. (2021), Verschuur et al. (2021), and others. Due to the challenging moment, the companies operating had been expected to have fallen by the end of 2021. However, this update confirmed a 6.35% increase in the sectoral volume (Table 3).

Through systematized searches using the Instagram® search engine, 301 profiles of timber housing companies were found using the terms listed in Table 1. These profiles included 14 new companies apart from the previously listed 378 companies. Ten new companies were potentially retrieved during the analyses, although none of these names and location points was hyperlinked to any active Instagram® profile. Thus, with these 24 additional companies, the sectorial population increased from 378 to 402 in 2022. As only 301 companies were identified among those 378 companies in the previous listing, the names of the other 77 companies not found by term-based searches were also inserted in the Instagram® search engine. Using this alternative search, a further 14 previously absent profiles were identified, expanding the current listing to 315 companies with profiles.

After this was done, all the companies were ranked according to the availability/unavailability of their profiles on Instagram®. The ranking discarded companies without any active official profile, as it is impossible to analyze something that does not exist. The sectorial survey targeted the available profiles; obtaining a margin of error for the national sector – which also included companies of the sector without available profiles (Table 3).

From the sectoral survey (Table 3), the sampling considered a significant fraction of nearly 4/5 of the Brazilian timber housing sector. This represented 100% of the timber housing producers and dealers with corporate profiles on Instagram®.

This sampling showed a high representation of this studied sector (Table 3). Using the standard prescription of ± 2.5% for an ideal level, following Pinheiro et al. (2011), the sample coincides with their statistical recommendation since the margin of error obtained in this study was about ± 1.28% (or 2.57%) as confirmed in Table 3; which provides a highly reliable analysis both for the population with corporate profiles and the entire sector – including those companies without profiles on this virtual platform.

The initial query was asked about the presence of sustainability topics on Instagram® posts on those profiles of the Brazilian timber housing sector (Table 2). From the representative sampling (Table 3), higher results prove the low exploration of sustainability topics in the virtual space by those companies dedicated to timber housing production and market in Brazil (Figure 1).

The presence of posts about the sustainability levels of products and services in the sampled companies reflects a behavior already produced by a group of corporations that are seeking to clarify and makes potential customers aware of the advantages and features of timber housing as a more ecological constructive option. However, a significant number of the profiles still have not made any posts about the sustainable aspects of timber housing products and services (Figure 1). The results highlight potential sustainability topics to be studied. In addition to environmental conservation and protection, Rattner (1999) cited that sustainability requires economic

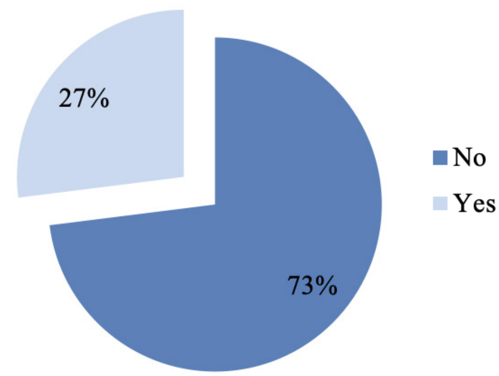

Figure 1: Presence of posts about sustainability on the corporate profiles (n = 315). Source: Preparation by the Authors.

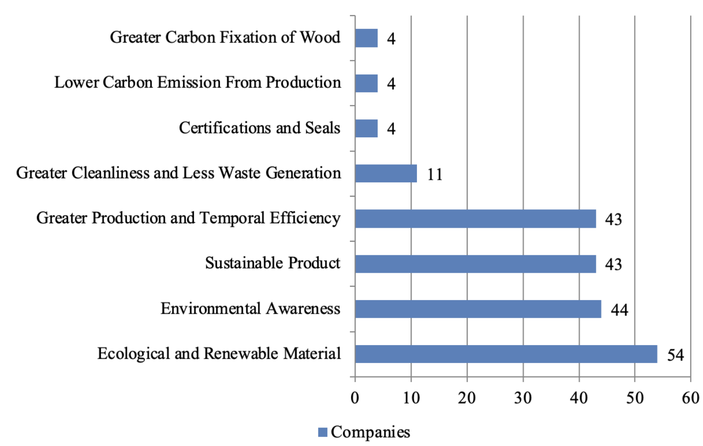

Figure 2: Types of topics approached in the contents posted on sustainability (n = 315). Source: Preparation by the authors.

efficiency, political democracy, social equity, and cultural diversity. This vision forms the precepts of environmental-social-corporate governance. In this sense, Brazilian companies still need to value the potential of their solutions and, if necessary, adapt their activities to ensure more sustainable timber houses.

From the corporate profiles classified positively in the first issue about sustainability (Table 2), the second issue identified all the themes found in the available posts. According to Figure 2, eight sustainability issues were identified in the posts published by the sampled companies, although other correlated issues were not confirmed.

'Ecological and renewable material' was the argument used most by over 17% of the sampled population to emphasize sustainable purposes of products and services related to timber houses (Figure 2). It is expected that this argument will be used more by this sector in the future since silvicultural-based materials are among the most requested resources – both by Brazilian forestry industries, as cited by IBÁ (2020), and by more than three-

Table 4: Corporate analysis by number of sustainability arguments (n = 315). Source: Preparation by the authors

Quantity	Arguments							
	1	2	3	4	5	6	7	8
Companies	25	24	22	7	4	1	2	0

quarters of the timber housing sector, according to the scenario verified by De Araujo et al. (2021a). In addition, Ramage et al. (2017) suggested that coniferous wood represents an attractive choice for efficiently sustainable buildings. Practically 14% of profiles published posts, looking to develop 'environmental awareness' among their customers (Figure 2). They included clarification on the consumption of wood from a legal origin, of native wood from forest management, of wood from legal silviculture, silviculture far from protected native areas, preservation of biomes and ecosystems, dangers of forest fires, and the production of non-timber forest products from company produced/managed forests.

To emphasize a vital production aspect for clients, 'greater production and temporal efficiency' was confirmed in more than 13% of the samples (Figure 2). The arguments to be explored on this topic are considerable – because rapid production is a positive production attribute of timber construction, as cited by De Araujo et al. (2016) as the conclusion time in civil construction is strictly related to higher costs and delays in conclusion as evaluated by Singh (2010), Larsen et al. (2016), Senouci et al. (2016), Bauer et al. (2017), Chandragiri et al. (2021), and others.

Equal participation was noted for companies that stated that they sold a 'sustainable product' (Figure 2). Despite this, there is still a demand for greater awareness by developers of the environmental benefits of their products. The clarification may consider arguments from De Araujo et al. (2016), Ramage et al. (2017), Heräjärvi (2019), Svajlenka and Kozlovská (2020b), and other studies.

Over 3% of the sampled public already uses 'greater cleanliness and less waste generation' in their products and services as a sustainable justification. This item agrees with the studies of Yazdi et al. (2014), which suggest that material manufacturers are changing their concerns to produce materials from renewable resources considering the increased use of waste streams and, consequently, a lower waste generation. Thus, governments together with industries can develop markets for manufactured goods with fewer wood and lignocellulosic by-products while eliminating incentives for sectors fueled by wood-burning (Pomponi et al., 2020).

Individually, about 1% of the sample highlights 'greater carbon fixation of wood', 'lower carbon emission from production', and 'certifications and seals' for other opportune arguments for greater sustainability of their products and services in Brazil. These arguments may be better explored due to the numerous advantages of wood-based resources. For example, Burnard et al. (2017) mentioned that resources from solid wood with lower processing levels (*e.g.* lumber and machined wood) are more natural than other contemporary solutions with higher manufacturing levels (*e.g.* engineered beams and composite boards); while the use of resins and chemical additives in the production of engineered wood products makes these glued solutions less sustainable compared to products based on solid wood. In the same vein, Yazdi et al. (2014) cited that a healthy building must have zero embodied energy to minimize the environmental impacts of carbon emissions and, therefore, to satisfactorily meet sustainability principles.

Considering the analysis of the types of arguments used by the companies in their posts on corporate profiles (Figure 2), there was a quantification of the number of sampled companies according to the number of arguments shared in their posts. 85 companies declared one or more arguments about the sustainability of their products and services (Figure 1). Many of this population used few arguments to clients (Table 4), for example, 29% with one argument, 28% with two arguments, and 26% with three arguments. Sequentially, 8% of the companies showed four arguments, 5% had five arguments, 1% had six arguments, and 2% had seven arguments.

There is a good opportunity to be explored by this sector by using more arguments to provide clients with clarification regarding the potential and advantage of their products and services (Table 4), both from those topics listed in Figure 2 and other absent arguments. This strategy should be clear and assertive since Wang et al. (2014) verified that end users, usually unfamiliar with wood products, have shown visible preconceptions regarding wood used for construction.

Strategically, Viholainen et al. (2021) suggested the need for a fine approach to the business ecosystem to offer a mindset reversion to develop a sustainability-oriented logic in line with profitable businesses and value creation for clients for construction. Companies may consider the sustainability indicators proposed by Garay et al. (2021) as the right strategy to emphasize timber houses under sustainable descriptions.

The authors of this study suggest further arguments to support an effective promotion and specification of sustainable features of timber houses:

- Lower embodied energy and carbon of timber-based products compared to mineral products, as exemplified by Hammond and Jones (2008) and Oliver et al. (2014);
- Efficient energy consumption from production to wood processing, especially from using low-power machines, as verified by Wargula et al. (2022);
- Multiple wood-based products and diversified wood species suitable as construction inputs, as listed by De Araujo et al. (2020b) and De Araujo et al. (2021a);
- Virtually zero water consumption in timber-based buildings, as cited by De Araujo et al. (2016);
- Lower internal heating to maintain thermal comfort for users, as determined by Svajlenka and Kozlovská (2020a);
- Clean building sites with efficient assembly, as mentioned by De Araujo et al. (2016);
- Easier revitalization, as argued by Ivanov (2005) and Domljan and Jankovic (2022);
- Combination with other materials, achieving good performance and representing a modern action as verified by Harris and Socratous (2013) and Høibø et al. (2015);
- Lower waste generation from periodic maintenance and retrofit procedures, as wood requires periodic maintenance for a long service life as recommended by Highley and Scheffer (1989) and Pearson et al. (2012);
- And as suggestions for more appropriate disposal of construction materials at the end of the service life of timber buildings, the authors also propose the possible reuses of:
    - ¤ Chemically treated timber in sleepers, decks, and fences;
    - ¤ Untreated timber in crafts, furniture, and gardening items.

CONCLUSION

The assessment of timber housing producers and dealers with corporate profiles on Instagram® confirmed their significant participation on this social platform in Brazil. On the other hand, a low margin of error was ensured by comprehensive data collection.

This significant sample revealed an unexpected fact, as there is a well-marked perception that numerous companies still undervalue the sustainability arguments of their products and services. This statement is supported by the limited number of posts about the benefits and characteristics of timber construction, using few arguments in their publications. There is a highly favorable environment and by outlining these arguments fully and intensively, new consumers can be attracted and enlightened about the benefits of timber solutions compared to traditional masonry and steel buildings.

To strengthen the list of justifications identified, further arguments could be raised to convince and attract new clients for timber housing. It is expected that the visibility and commerce of timber construction solutions will be boosted in the Brazilian virtual markets when further clarification and the promotion of sustainable dwellings are implemented.

The replication of this virtual methodology to other territories would allow representative observations through low-cost demands since this survey is suitable to analyze sectors – both nationally and regionally – through a proactive strategy to understand and promote virtual markets for sustainable-oriented products.

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FUTURE EFFECTIVENESS OF PASSIVE HOUSE DESIGN STRATEGIES

EFECTIVIDAD A FUTURO DE LAS ESTRATEGIAS DE DISEÑO PASIVAS EN VIVIENDAS

EFICÁCIA FUTURA DE ESTRATÉGIAS DE PROJETO PASSIVO EM HABITAÇÃO

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RESUMEN

Las estrategias de diseño arquitectónico pasivo han sido una respuesta efectiva a la crisis energética del siglo XX. En climas templados, su integración resulta en comportamientos térmicos en los que se combinan el confort interior y la eficiencia energética. Sin embargo, los escenarios de cambio climático proyectados a futuro no ofrecerán los mismos rendimientos, resultando dichas estrategias menos efectivas. El objetivo de este trabajo es la cuantificación del cambio relativo en la efectividad de las estrategias de diseño pasivas en viviendas para clima árido templado-frío (Bwk), tomando como ejemplo la ciudad de Mendoza (Argentina). Respecto de las proyecciones de clima futuro para clima árido cálido (Bwh), utilizando el escenario RCP8.5 del CMIP5, equivalente al escenario SSP85 del CMIP6 del IPCC, los resultados muestran una disminución del 20% en la cantidad de horas en confort anual, con un incremento del 24% en la necesidad de estrategias pasivas de verano.

Palabras clave
cambio climático, arquitectura sustentable, viviendas unifamiliares

ABSTRACT

Passive architectural design strategies have been an effective response to the energy crisis of the 20th century. In temperate climates, their integration results in thermal behaviors that combine indoor comfort and energy efficiency. However, projected future climate change scenarios will not offer the same performances, resulting in such strategies being less effective. The objective of this work is to quantify the relative change in the effectiveness of passive design strategies in dwellings for arid temperate-cold climates (Bwk), taking the city of Mendoza (Argentina) as an example. Regarding future climate projections for warm arid climates (Bwh), using the CMIP5's RCP8.5 scenario, equivalent to the IPCC's CMIP6 SSP85 scenario, the results show a 20% decrease in the number of hours in annual comfort, with a 24% increase in the need for passive summer strategies.

Keywords
climate change, sustainable architecture, single-family houses.

RESUMO

As estratégias de projeto arquitetônico passivo têm sido uma resposta eficaz à crise energética do século XX. Em climas temperados, sua integração resulta em comportamentos térmicos que combinam conforto interno e eficiência energética. No entanto, os cenários de mudanças climáticas projetados para o futuro não oferecerão os mesmos desempenhos, tornando essas estratégias menos eficazes. O objetivo deste trabalho é quantificar a mudança relativa na eficácia das estratégias de projeto passivo em habitações para clima árido temperado-frio (Bwk), tomando como exemplo a cidade de Mendoza (Argentina). Com relação às projeções climáticas futuras para o clima árido quente (Bwh), usando o cenário CMIP5 RCP8.5, equivalente ao cenário CMIP6 SSP85 do IPCC, os resultados mostram uma redução de 20% no número de horas de conforto anual, com um aumento de 24% na necessidade de estratégias passivas de verão.

Palavras-chave
mudanças climáticas, arquitetura sustentável, habitações unifamiliares.

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INTRODUCTION

Argentina has seen unfavorable climate changes since the second half of the last century, which, according to climate model projections, could intensify this century (Agosta et al., 2015) (Flores-Larsen et al., 2019). As a result of these changes, heat waves have become commonplace throughout the region.

An intense heat wave began in mid-December 2013, the longest and most intense recorded until 2021, which lasted until almost mid-January and geographically covered the center of Argentina, including Buenos Aires, Córdoba, and Mendoza, with maximum temperatures above 40 °C and minimum temperatures above 24 °C.

Electricity distribution collapsed in many sectors of the Buenos Aires metropolitan area; the result of record consumption due to the intensive use of air conditioning equipment. More recently, between December 2022 and February 2023, 10 heat waves were recorded in Argentina, 3 of which were particularly intense and prolonged. Figure 1 presents the records of said temperature anomalies.

Climate change is having and will have major impacts on buildings' energy consumption and the design of future buildings should consider this. The building sector, including the residential and commercial sectors, is responsible for between 30% and 40% of the world's total energy demand and emits one-third of the world's GHG emissions (Bhamare et al., 2019). Likewise, energy use and related emissions are expected to double, or even triple, by mid-century due to several key trends, especially as population living standards rise. In this context, buildings represent a critical part of a low-emission future and, at the same time, a global challenge for integration with sustainable development (Barea, 2022; Flores-Larsen et al., 2019; Flores-Larsen et al., 2021; Ganem et al., 2021; Rubio et al., 2015; Ruiz et al., 2022; Sánchez et al., 2017).

It is important to point out that the severity of the weather has a great influence on building design. Therefore, a thorough review of current architectural designs and the adoption of new strategies adapted to climate change are required. The potential for energy savings in both new and existing buildings ranges from 50% to 90% (Chalmers, 2015).

According to Lacaze et al. (2021), said saving potential depends on the strategy implemented in the building. These authors prepared an energy consumption estimate and identified the most favorable alternatives for consumption savings, GHG emissions, and their associated costs. Figure 2 shows the estimated savings by implementing efficient materials, certified equipment, and smart devices for Argentina.

Elias (2017) and Brager and de Dear (1998) have suggested that predictions about future climate conditions in different cities should be known to design buildings and optimize their thermal comfort

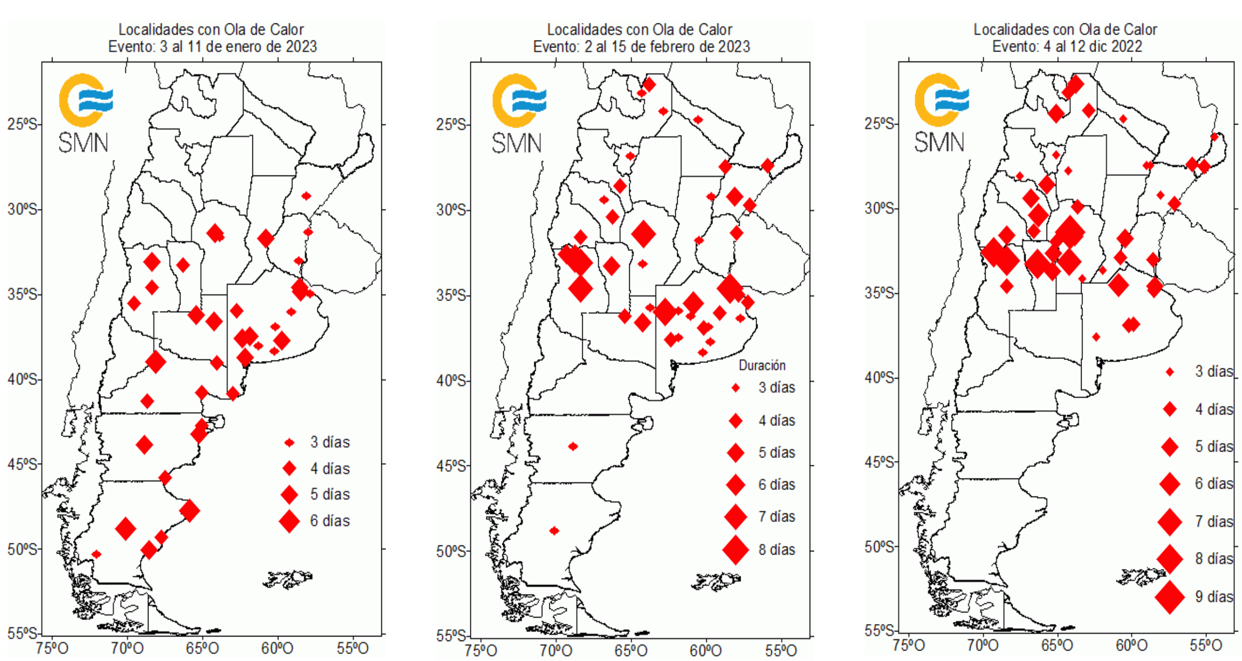

Figure 1. Heat waves recorded in Argentina during the 2022-2023 summer period. From left to right: a) December 4th to 12th, 2022; b) January 3rd to 11th, 2023, and c) February 2nd to 15th, 2023. Source: Argentine National Meteorological Service. (2022, 2023a, and 2023b)

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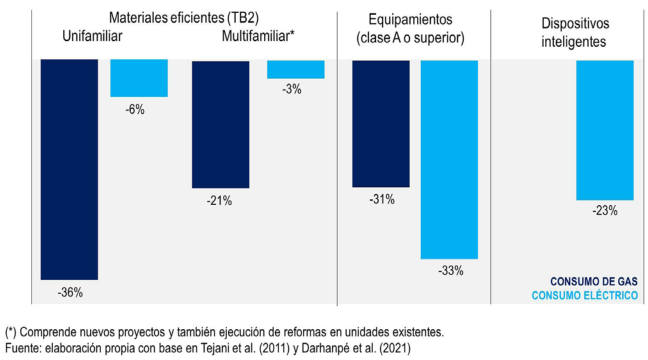

Figure 2. Savings percentage estimate by model and intervention strategy. Source: Lacaze et al., 2022.

in the coming years, without burdening the ecosystem with further environmental degradation. In this way, any changes can be anticipated and their effects counteracted through energy efficiency, better design, and, ultimately, energy savings (Li et al., 2012).

In Argentina, the Center for Marine and Atmospheric Research (CIMA, in Spanish) prepared a report on climate trends (second half of the 20th century) and a projection of the future climate (21st century) as part of the reference studies for the third National Report to the United Nations Framework Convention on Climate Change (3CN Cima, 2022). The study focuses on the observed and projected trends of surface temperature and precipitation and on some of the extreme indices that can cause relevant impacts.

Considering what has been said, the main goal of this work is to quantify the relative change in the effectiveness of passive design strategies in housing, in a temperate-cold arid climate (Bwk), using the city of Mendoza (Argentina) as a case study.

This will make it possible to identify the design measures that will gain or lose importance due to global warming and the correlation between the effectiveness of the passive systems analyzed. The results of the analysis will be directly applicable to building designers. Likewise, this work tries to contribute to the development of methodologies to prepare climate change files for dynamic building simulation.

METHODOLOGY

Initially, the bioclimatic potential of the temperate continental climate of Argentina (Mendoza, -33° 9' LS, 69° 15' LO) was analyzed using the BcChart tool (Košir, 2018).

The analysis of the bioclimatic potential correlates the essential climatic characteristics, such as air temperature, relative humidity, and solar radiation, with the ability to achieve comfort for the building's occupants through passive solar systems. This study allows representing, through passive potential, the climatic adaptation of buildings for

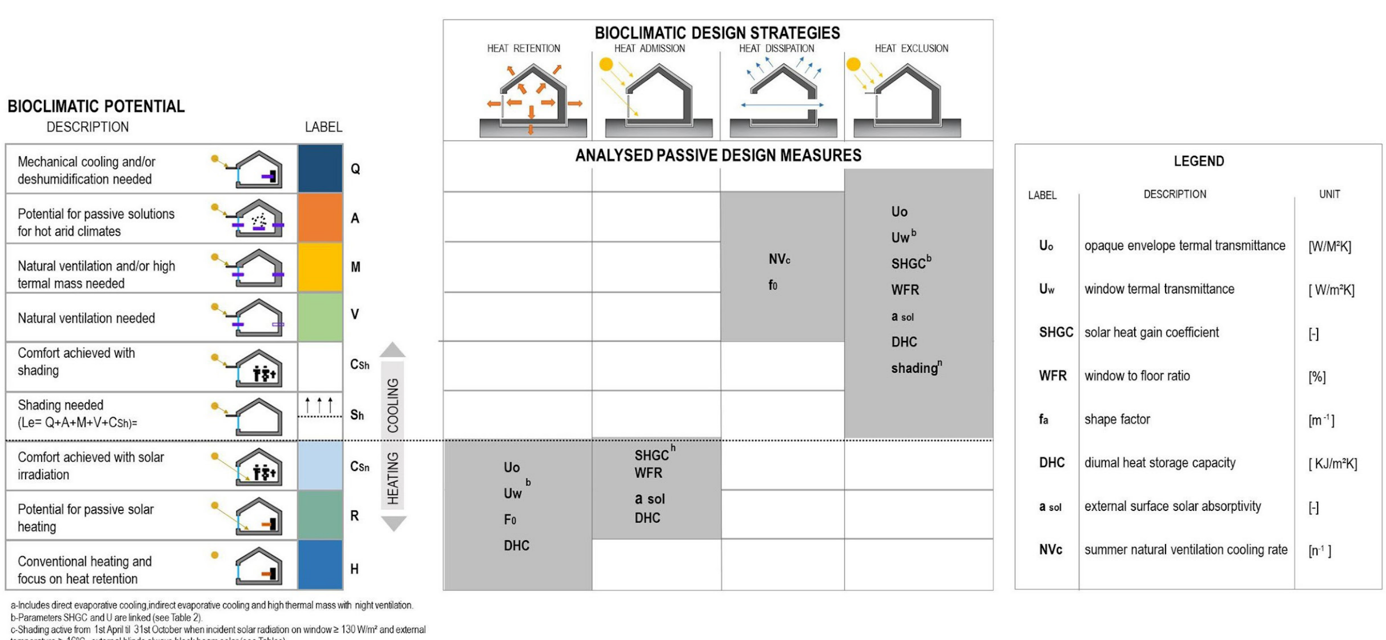

Figure 3. Bioclimatic potential measures calculated by BcChart as well as the passive design measures analyzed. Source: Košir et al., 2017; Košir, 2019.

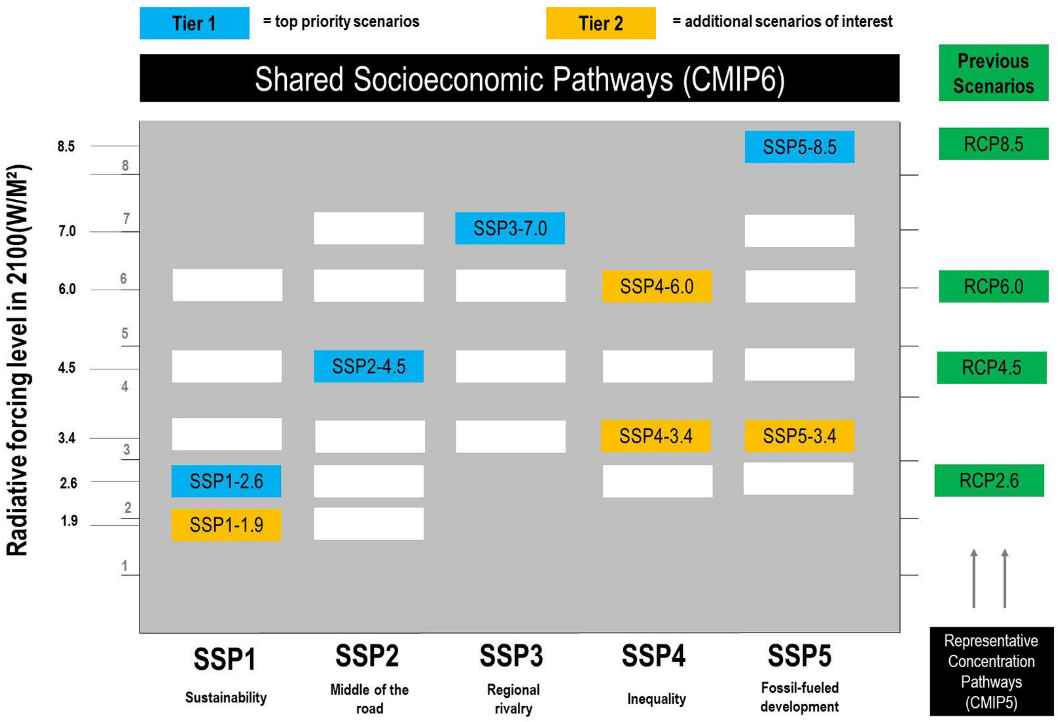

Figure 4. Shared socio-economic pathways and 2100's radiative forcing combinations used in MIP Scenario. Source: O'Neill et al., 2016.

the studied climate. The calculations are based on Olgyay's bioclimatic graph theory (1963), using air temperature, relative humidity (RH), and global solar radiation. The comfort zone is defined as between 21 °C and 27 °C with an RH between 20% and 80 %.

The combinations of the climatic variables will determine whether certain passive solutions can be used to achieve thermal comfort, or whether active systems (mechanical cooling, conventional heating) will be needed.

Figure 3 presents the definitions of each bioclimatic potential determined by BcChart. The relationship between the bioclimatic potential and the passive design measures analyzed is indicated whenever a certain design measure can be used to facilitate a better passive thermal response of a building and, consequently, greater energy efficiency.

Subsequently, how the bioclimatic potential of the studied climate would be changed towards 2100 was analyzed. The choice of that specific year responds to the following hypotheses: First of all, it is important to clarify that, although the average life cycle of a building is approximately 50 years, some buildings are designed and built to last longer. On the other hand, it is expected that, by that time, the effects of climate change will be more evident and may have a significant impact on the behavior and energy efficiency of buildings.

For this, future climate scenario data from the IPCC were used. The IPCC's Fifth Assessment Report has defined four new emission scenarios, the so-called Representative Concentration Pathways (RCP), which take into account the effects of 20th-century policies on climate change mitigation.

The total radiative forcing (RF) predicted for 2100 ranges from 2.6 to 8.5 W/m^2. The four RCPs comprise a scenario where mitigation efforts lead to a very low level of forcing (RCP 2.6), two stabilization scenarios (RCP 4.5 and RCP 6.0), and one scenario (RCP 8.5) with a very high level of GHG (greenhouse gas) emissions.

It is important to mention that, until the middle of the 21st century, the differences in the results between the RCPs are very small, as the climate system responds relatively slowly to changes in GHG concentration. Therefore, the RCP 8.5 scenario has been taken for subsequent analyses, as it provides a much faster warming and more pronounced changes in important indicators such as river flow, temperature, and precipitation.

The IPCC's sixth assessment report (AR6) has been fed with the development of a new set of scenarios, called SSP, which is formed through the Coupled Model Intercomparison Project 6 (CMIP6) of the World Climate Research Program (WCRP), which updates the CMIP5's RCP. The new scenarios represent different socio-economic developments, as well as different pathways of greenhouse gas concentration in the atmosphere (Falco et al., 2019; López-Franca et al., 2016).

Figure 4 shows a matrix representing all possible combinations of SSP and radiative forcing (RCP), which are color-coded to show the priority of each scenario. The level 1 or top priority scenarios are SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (in blue). Three of the four Level 1 scenarios are updated versions of previous CMIP5 CPR scenarios (RCP2.6, RCP4.5, and RCP8.5) to facilitate the comparison between CMIP5 and CMIP6 projections. The Level 2 scenarios are SSP1-1.9, SSP4-6.0, SSP4-3.4, and SSP5-3.4 (in orange). All other combinations of radiative forcing and SSP are not feasible or are not designated as a priority by ScenarioMIP (O'Neill et al., 2016). As observed in Figure 4, the RCP8.5 scenario of the CMIP5, which is the one that has been used in this work, is equivalent to an SSP85 scenario of the CMIP6, with a priority of 1.

The methodology used to generate the future hourly data is known as *morphing* (Jentsch et al., 2008), which is a method that uses both a real-time weather file and predictions of average future monthly data of the variable of interest. Using mathematical "displacement" and "stretching" transformations based on the present and future monthly averages of the variables, a present weather file is transformed into a future weather file. The nature of the transformations ensures that the relationship between the meteorological variables is maintained in the future meteorological file. From this article, the current hourly data were those of the Typical Meteorological Year (TMYx) based on the averages of the 2007-2020 period.

For future predictions, the ACCESS 1-3[1], RCP8.5, r1i1p1 model was adjusted (with a grid of 1.875 by 1.25 degrees; or 68.7km by 111.1 km), with CRU TS4.05 reanalysis observational data, to corroborate the goodness of fit in the area of study. Data were taken from 1901 to 2021.

It is important to note that the ACCESS 1-3 model has been used in other studies to simulate the climate in regions of continental temperate climates similar to the case study (Bi et al., 2020; Lorenz et al., 2014; Stone et al., 2016; Ziehn et al., 2020).

To quantify the agreement between the reanalysis data and the future model (annual average data), the following widely used calculated statistical indicators were used: d (Equation 1), MAE (Equation 2), RMSE (Equation 3), and BIAS (Equation 4):

$$d = 1 - \frac{\sum_{i=1}^{n} (obs_i - sim_i)^2}{\sum_{i=1}^{n} \left(|sim_i - \underline{obs}| + |obs_i - \underline{obs}|\right)^2} \quad \text{(Equation 1)}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |sim_i - obs_i| \quad \text{(Equation 2)}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (sim_i - obs_i)^2} \quad \text{(Equation 3)}$$

$$BIAS = \frac{1}{n}\sum_{i=1}^{n} (sim_i - obs_i) \quad \text{(Equation 4)}$$

Where:
d = Concordance or Willmott index
MAE = Mean absolute error
RMSE = Mean square error.
BIAS = Mean error
simi = Future model data
obsi = Measured reanalysis data
obs = Mean measured reanalysis data
n = Sample size

Then, anomalies were analyzed for 50-year periods up to 2100, and future EPWs were put together. The data were downloaded from the Climate Explorer site of the KNMI (Koninklijk Nederlands Meteorologish Instituut), for Mendoza, Argentina.

It should be mentioned that, as a limitation of the study and also for this work, the terrestrial temperature variable was taken every 3hs (from the ACCESS 1-3 RCP8.5 model, or *r1i1p1*). Subsequently, they were interpolated to obtain hourly data. The other climatic variables were extracted from the original TMYx. Energy Plus' Weather converter software was used to set up the future EPW.

RESULTS AND DISCUSSION

The results of the study are presented in two sections. The first part presents the bioclimatic analysis of the studied locality (Mendoza) with the current climate, TMY. The influence of climate change on bioclimatic strategies is shown below.

1 ACCESS 1-3 is a global climate model developed by the CSIRO Research Center in Australia and the Joint Research Center of the European Commission. It is used in climate change studies and future climate projections, as it can simulate changes in surface temperatures, precipitation, wind, cloud cover, sea level, and other climatic factors.

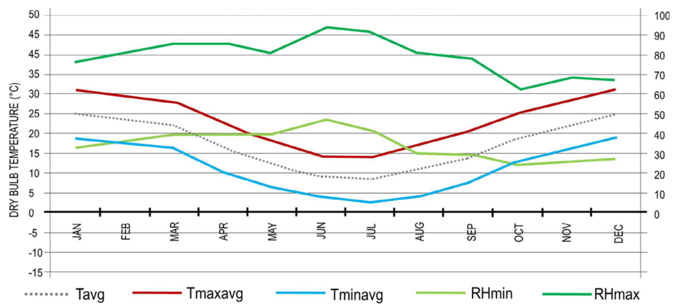

Figure 5. Relative humidity and temperatures of Mendoza. Source: Prepared by the authors using the BcChart software.

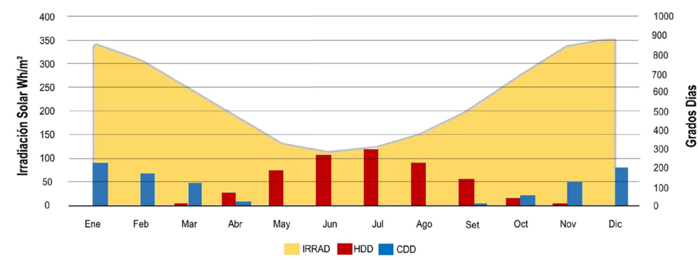

Figure 6. HDD and CDD function of solar irradiance. Source: Preparation by the authors.

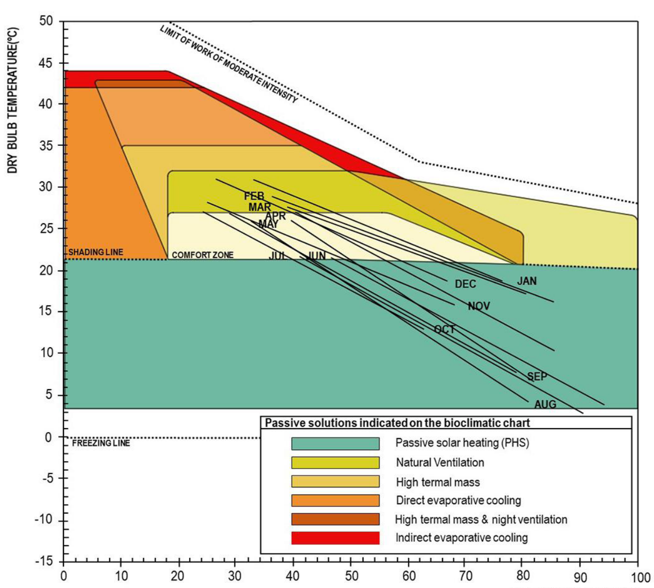

Figure 7. Givoni's chart as modified by Košir et al. (2017), with current data for Mendoza, Argentina. Source: Preparation by the authors using BcChart software.

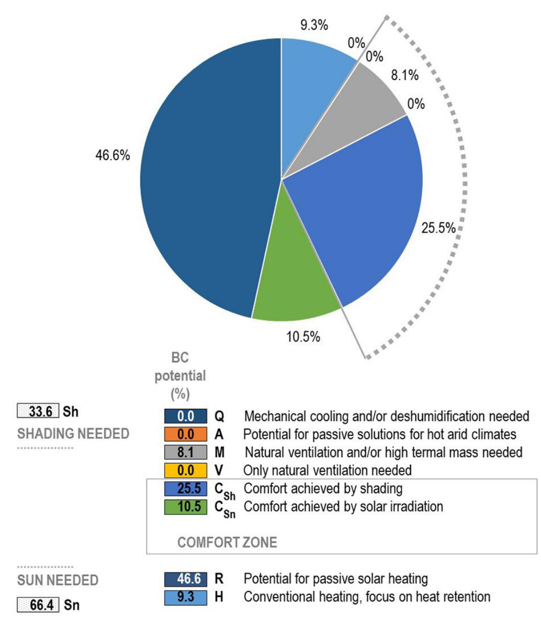

Figure 8. Bioclimatic potential with the current climate. Source: Preparation by the authors using the BcChart software.

BIOCLIMATIC POTENTIAL WITH CURRENT CLIMATE

Mendoza has a cold temperate continental desert climate with significant daily and annual variations. According to the Koeppen classification (Kottek et al., 2006), it has a Bwk climate. The letter "B" defines a dry climate, the letter "w" refers to annual rainfall below 250 mm, and the letter "k" is related to annual average temperatures below 18°C. Therefore, the Bwk nomenclature refers to an arid-temperate-cold climate. Figure 5 shows the monthly maximum, minimum, and average temperatures, along with the monthly minimum and maximum relative humidity. The average annual temperature is 17.2 °C, with the monthly average temperature of January (summer) being 24.8 °C., and for July (winter), the monthly average temperature is 8.2 °C.

The annual HDD (Heating Degree-Days, base 18.3) is 1231 HDD, while the CDD (Cooling degree-days, base 18.3) is 911 CDD (Figure 6). This shows the monthly need for heating and cooling.

The bioclimatic potential can be a practical starting point to define climate-appropriate building design strategies. Figures 7 and 8 show the possible bioclimatic solutions with the current climate data. Figure 7, which follows Olgyay's graph (1963), shows the monthly data on passive strategies. The tool's authors add the influence of the average and maximum daily solar irradiance received, which modifies the original graph (Košir & Pajek, 2017).

Most of the data are on the passive solar heating strategy and, to a lesser extent for the intermediate

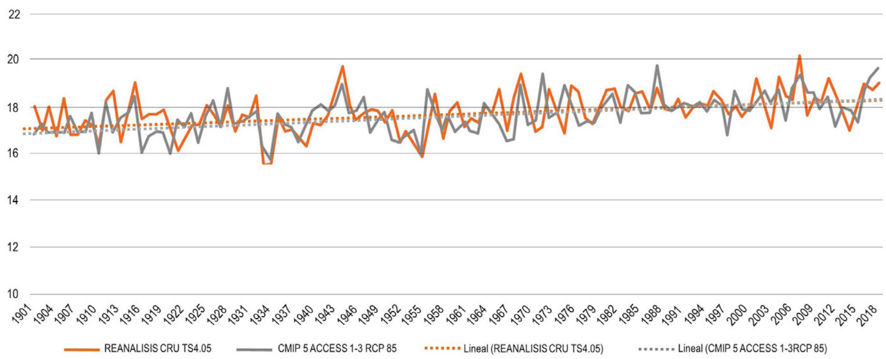

Figure 9. Comparison of annual mean temperatures from 1901 to 2020: CRU TS4.05 and the ACCESS 1-3 climate simulation model. Source: Preparation by the authors.

and summer months, natural ventilation combined with indoor thermal mass.

In Figure 8, it can be seen that the passive strategy requirements are divided into two groups: Shading Needed – Nh, and Sun Needed – Sn. The strategies to dissipate heat (SH) have a potential of 33.6% (8.1% of natural ventilation with thermal mass, and 25.5% by the use of shading). Note that the strategies for hot arid climates are at 0% because Mendoza is an arid-temperate-cold climate, where the combination of ventilation and shading suffice to achieve comfort through passive natural conditioning strategies. On the other hand, the strategies to collect solar radiation (Sn) have a potential of 66.4% (46.6% by passive solar heating, 9.3% by auxiliary heating, and 10.5% in comfort by the use of direct solar radiation).

INFLUENCE OF CLIMATE CHANGE ON PASSIVE HOUSING STRATEGIES

As anticipated in the methodology section, a CMIP5 model (ACCESS 1-3) was chosen to set up future EPW files and adjusted with the reanalysis data measured (CRU TS4.05). The period analyzed was from 1901 to 2020. Figure 9 shows the adjustment of the annual average temperatures of both models.

The results of the statistical indicators, as seen in Table 1, show acceptable errors according to the ASHRAE Guideline 14 (Clarke et al., 1993). The *BIAS* between the data results is 0.099°C. The mean absolute error *MAE*, discarding the outliers, turns out to be 0.68°C on average. When analyzing the coefficient of concordance *d*, this is 72%. Finally, the standard deviation of the residual values, *RMSE*, is 0.88°C.

Table 1. Statistical indicators of the fit between the CRU TS4.05 reanalysis data and the ACCESS 1-3 model for the RCP8.5 scenario. Source: Preparation by the authors.

INDICATORS	CRU TS4.05 vs ACCESS 1-3 RCP8.5
d	0.72
MAE (°C)	0.68
RMSE (°C)	0.88
BIAS (°C)	0.099

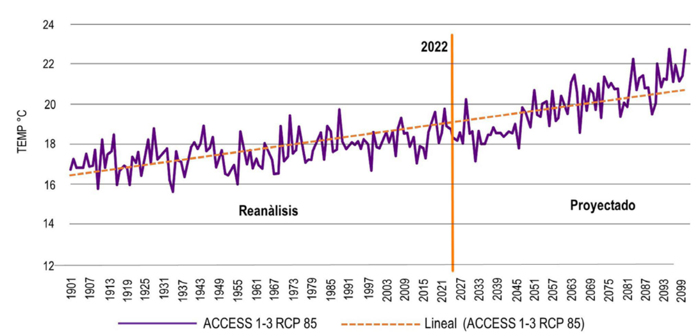

Figure 10. Average annual temperatures, RCP8.5. Source: Preparation by the authors.

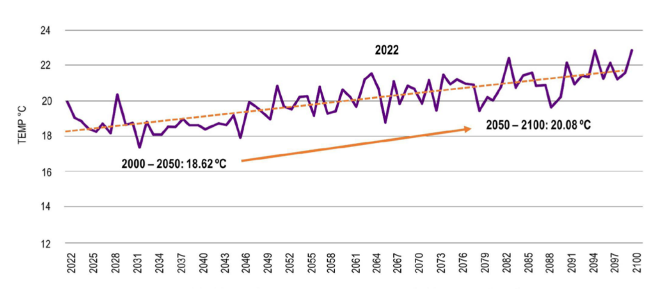

Figure 11. Average annual temperatures for the RCP8.5 scenario, future period, 2022-2100. Source: Preparation by the authors.

Table 2. Comparison of observed changes over 50-year periods. Source: Preparation by the authors.

	ACCESS 1-3	Difference to the base period 1900-1950
1900-1950	17.37	
1950-2000	17.77	0.40
2000-2050	18.62	0.85
2050-2100	20.80	2.18

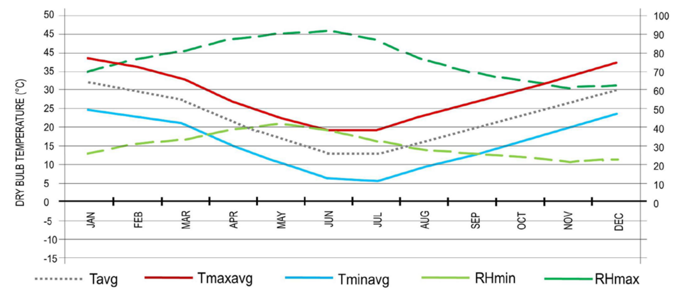

Figure 12. Temperatures and relative humidity in 2100 for Mendoza. Source: Preparation by the authors using the BcChart software.

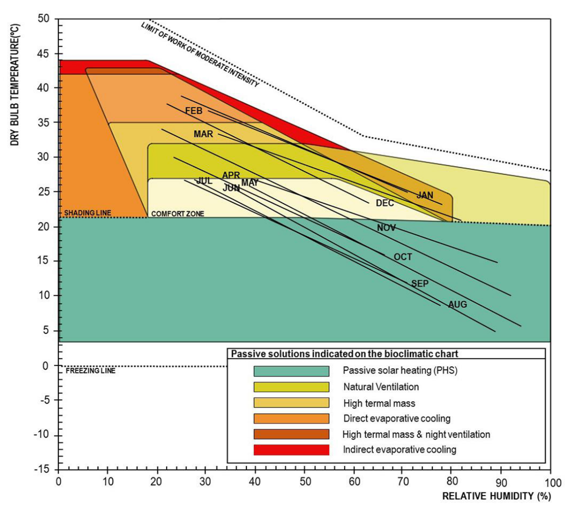

Figure 13. Temperatures and relative humidity in 2100. Source: Preparation by the authors using the BcChart software.

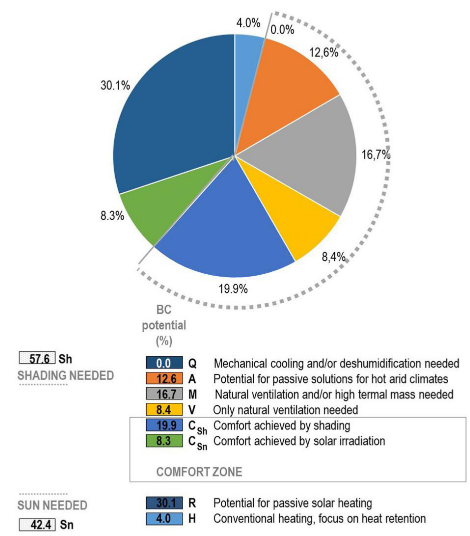

Figure 14. Future bioclimatic potential, 2100. Source: Preparation by the authors using the BcChart software.

Figure 10 shows the average annual temperatures of the calibrated model, from 1901 to 2100, for the RCP 8.5 scenario.

Figure 11 shows the data predicted for the future in the range between 2022-2100. Here, the temperature increase trend towards 2100 can be seen. If the anomalies in 50-year periods since 1900 are compared, the temperature towards 2100 could increase by around 2.18°C compared to the pre-industrial period for the climate studied, as can be seen in Table 2.

With the adjusted ACCESS1-3 model, the data were used to put together the *EPW* and to simulate the projected effect of climate change on the bioclimatic potential for Mendoza (Figure 12) in BcChart. The average annual temperature for 2100 is expected to be 22.50°C (5°C more than the current *TMY*), while for January of that year, the monthly average temperature is 31.88°C (7°C higher than the current one). It is expected that in July, the monthly average temperature will exceed the current one by 4.4°C (12.7°C).

The results of Figure 13 and Figure 14 clearly show that the bioclimatic potential is expected to shift towards the heat dissipation strategies.

Figure 14 shows that the Shading needed, *Sh*, is estimated at 57.6%, i.e., 24% more than the current climate. Within this percentage, there was a considerable increase (from 0% to 12.6%) in strategy A, which refers to a set of passive solutions for arid and hot climates, including direct and indirect evaporative cooling and the use of thermal mass with natural ventilation. The need to integrate passive strategies in the design for hot arid climates means that the average annual temperature is estimated to be above 18°C by 2100. The climate that today is classified as *Bwk* will become *Bwh*, i.e., hot arid climate, with precipitation below 250 mm, so the use

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of evaporative cooling is possible. The comfort zone, from using shading, is estimated to decrease from 25.5% to 19.9%.

For winter strategies, *Sn*, its potential is expected to decrease from 66.4% to 42.4%, which leads to a decrease in all the strategies inherent in the collection of solar radiation and thermal heat. The potential of passive heating will increase from 46.6% to 30.1% and auxiliary heating from 10.5% to 4%.

CONCLUSION

This paper addresses the impact of climate change on the effectiveness of passive strategies and the adaptation opportunities of buildings in different extreme future conditions, according to CMIP5's RCP8.5 scenario, equivalent to the SSP85 scenario of IPCC's CMIP6, in an arid-temperate-cold (Bwk) climate today, and in the future an arid-warm (Bwh) one, with important daily and annual variations.

This is a contribution to a relevant issue in passive and energy-efficient architecture: Would the current design still be energy-optimized in future emission scenarios?

Architectural design faces a double challenge: on one hand, buildings must work well today, achieving thermal comfort with close to zero consumption. On the other hand, they must be able to adapt to future climate scenarios, so it is very important to recognize the main trends and take into account the big picture.

The work contributes to the methodological development in the preparation of future climate files according to climate change projections (IPCC) for the dynamic simulation of buildings, with specific scope to the terrestrial temperature. A CMIP5 model is chosen (in this case, ACCESS 1-3 RCP8.5) to build future EPW files, and adjusted with measured reanalysis data (CRU TS4.05). The choice of this model is based on its high degree of fit and the availability of data for the region. Therefore, this work limits its results, discussions, and conclusions to the scenarios calculated with this model.

The dynamic simulation of buildings with the author's climate files, adjusted and validated for both the current and future situation, is consolidated as an indispensable tool to assess design decisions from a holistic perspective, which guarantees the proper operation of our buildings throughout their service life. The transfer of the results obtained to the building designers makes it possible to know which passive strategies will gain or lose importance due to climate warming and the relative magnitude of this change.

For the case presented in Mendoza (Argentina), annual average temperatures could increase by 5°C by 2100, with increases of 7°C in the summer monthly averages, and 4.4°C in the winter monthly averages. The results show a 20% decrease in the number of hours spent in comfort with a 24% increase in the need for passive summer strategies.

Regarding the latter, currently, the main passive strategies recommended are shading or radiation protection and natural ventilation, together with the incorporation of thermal mass in the envelope. To cope with future climate change scenarios, these strategies will need to incorporate direct and indirect evaporative cooling. This is because the current temperate climate will become a warm climate with average annual temperatures above 18°C and, due to the low relative humidity, these will have a high degree of effectiveness. If the arid territory where water scarcity is a constant is added to this situation, the research related to the correct design of passive strategies in housing becomes increasingly important.

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SUSTAINABILITY STRATEGIES FOCUSED ON THERMAL COMFORT AND EMBODIED ENERGY OF EMERGING HOUSING IN THE ANDEAN REGION OF ECUADOR

ESTRATEGIAS DE SOSTENIBILIDAD ENFOCADAS AL CONFORT TÉRMICO Y LA ENERGIA INCORPORADA DE UNA VIVIENDA EMERGENTE EN LA REGIÓN ANDINA DEL ECUADOR

ESTRATÉGIAS DE SUSTENTABILIDADE FOCADAS NO CONFORTO TÉRMICO E NA ENERGIA INCORPORADA DE UMA HABITAÇÃO EMERGENTE NA REGIÃO ANDINA DO EQUADOR

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RESUMEN

Ante los constantes desastres naturales de regiones andinas de Ecuador, se han planteado varias soluciones habitacionales, sin embargo, estas no consideran el confort térmico del usuario ni el impacto ambiental que generan. Esta investigación aborda esta problemática desde una perspectiva bioclimática a través de un modelo de vivienda emergente en un clima andino orientado a asegurar el confort térmico y reducir el impacto ambiental de la construcción. El análisis se enfoca en la temperatura interior y la Energía Incorporada Total (EI_T) del modelo de vivienda. La metodología se divide en la definición del modelo y las estrategias, por un lado y, por el otro, el análisis de estos parámetros a través de simulaciones y cálculos. Además, se realiza un análisis comparativo con otros estudios. Las estrategias definidas fueron la captación solar, masa térmica, compacidad, materiales locales-reciclados y la modulación. Los resultados muestran que el modelo planteado alcanza, de manera pasiva, las temperaturas de confort y la EI_T (2135.38 MJ/m^2) es menor que la de otras viviendas de carácter social.

Palabras clave
masa térmica, habitabilidad, eco-arquitectura

ABSTRACT

Faced with the constant natural disasters in the Andean regions of Ecuador, several housing solutions have been proposed. However, these do not consider the user's thermal comfort or the environmental impact they generate. This research addresses this issue from a bioclimatic perspective through an emerging housing model in an Andean climate, oriented to ensuring thermal comfort and reducing the environmental impact of the construction. The analysis focuses on indoor temperature and the Total Embodied Energy (EE_T) of the housing model. The methodology is divided into the definition of the model and strategies, on one hand, and, on the other, the analysis of these parameters through simulations and calculations. In addition, a comparative analysis with other studies is carried out. The strategies defined were solar gain, thermal mass, compactness, local-recycled materials, and modulation. The results show that the proposed model passively reaches comfort temperatures, and that the EE_T (2135.38 MJ/m^2) is lower than that of other social housing.

Keywords
thermal mass, habitability, eco-architecture

RESUMO

Diante dos constantes desastres naturais nas regiões andinas do Equador, várias soluções habitacionais foram propostas, mas elas não consideram o conforto térmico do usuário nem o impacto ambiental que geram. Esta pesquisa aborda esse problema a partir de uma perspectiva bioclimática por meio de um modelo de habitação emergente em um clima andino que visa garantir o conforto térmico e reduzir o impacto ambiental da construção. A análise se concentra na temperatura interna e na energia total incorporada (EI_T) do modelo de habitação. A metodologia é dividida, por um lado, na definição do modelo e das estratégias e, por outro, na análise desses parâmetros por meio de simulações e cálculos. Além disso, é realizada uma análise comparativa com outros estudos. As estratégias definidas foram ganho solar, massa térmica, compacidade, materiais reciclados localmente e modulação. Os resultados mostram que o modelo proposto atinge passivamente temperaturas de conforto e o EI_T (2135,38 MJ/m2) é menor do que o de outras habitações sociais.

Palavras-chave
massa térmica, habitabilidade, ecoarquitetura.

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INTRODUCTION

Natural disasters are an uncontrollable problem around the world and have had a great impact on the social, economic, and, of course, the built environment. Emergency Housing (EH) emerges within this context, defined as a fast temporary housing solution to solve the shelter needs of people affected by disasters (Secretariat for Risk Management, 2018). One of the areas with the highest rate of natural disasters is the Inter-Andean region of South America, mainly due to its geological aspects and extreme rainfall (Marocco & Winter, 1997).

There have been numerous natural disasters in the Andean region of Ecuador in recent decades. In 1993, the landslide of the Josefina-Azuay mountain left 100 dead, affected 5,631 people, and destroyed 1,800 hectares of agricultural and grazing land (Zevallos, 1994). In 1999, the eruption of the Pichincha volcano displaced 2,000 people and polluted the air in the surrounding 200 km (Álvarez & Avilés, 2012). The most recent catastrophe was the landslide in Alausí-Chimborazo in March 2023, which left 32 people dead, damaged 163 houses, affected 1,034 people, destroyed 2.32 km of roads, and hit 26 ha of agricultural area (Adverse Events Monitoring Directorate, 2023).

Given these needs, different proposals have been put forward to solve spatial requirements. However, a post-disaster situation demands much more than a spatial approach, with one of the most important shortcomings being that of Emergency Housing (hereinafter, EH), because this is the protection that people have against inclement weather (Espinosa & Cortés, 2015).

In the climate of this region, whose minimum temperatures drop below 9 °C (National Institute of Meteorology and Hydrology of the Republic of Ecuador [INAMHI], 2017), solving this thermal housing problem is a great challenge, since physical-mental well-being (Hughes et al., 2019), energy demand (Andersen et al., 2017), and occupant health difficulties (Fonseca-Rodríguez et al., 2021) must also be considered. This means that EH solutions must consider strategies to solve thermal discomfort.

Several institutions have led EH projects through prototypes that prioritize ease of construction (TECHO, 2020) because they are transitional solutions. For this reason, they opt for lightweight materials such as chipboard and zinc roofs for their construction, which do not solve deficient indoor comfort in this climate. In addition, these prototypes focus on providing a temporary housing solution, although affected parties have often turned them into a permanent homes.

Recovery for those affected by a natural disaster is a complex process that begins with the integration into a new social nucleus, finding land where they can build or a building they can rent and, of course, reestablishing their economic situation. This means that they are often forced to convert their temporary homes into permanent ones (Lines et al., 2022).

EH prototypes that consider the thermal aspect in their design and construction have been implemented in several countries. However, these are not completely sustainable, since many models focus on the use of heating and insulation to reduce losses in cold climates and, consequently, reduce operational demand (Thonipara et al., 2019).

In this regard, Hong (2016) proposes an EH prototype in Korea made of metal containers with insulation on the walls and ceilings, as well as heating. In turn, Sinohara et al. (2014) analyze the thermal comfort of three types of EHs in Japan with a low U-factor which, in winter, reach an average temperature between 11-14°C. This is because they do not use constant heating due to the high cost involved.

The reduction of the envelope's U-factor is a globalized strategy and regulation to achieve sustainable housing (Gullbrekken et al., 2019). However, other studies show that the effectiveness of insulation depends on the climatic context (Curado & Freitas, 2019) and can be replaced by solar gains and thermal mass (Santana Oliveira et al., 2022).

Although the use of insulating materials in these prototypes can ensure comfort in the spaces, it also implies a high environmental impact due to high Embodied Energy consumption (Torres-Quezada et al., 2022). As for materials, expanded polystyrene entails 127 MJ/kg (Azari & Abbasabadi, 2018), while brick involves 2.52 MJ/kg (González Stumpf et al., 2014). In terms of housing, buildings with high insulation standards, such as the case of Sweden, have a total Embodied Energy (EE_T) of 5,530 MJ/m^2 (Thormark, 2002), and in the Netherlands, 6,400 MJ/m^2 (Koezjakov et al., 2018). In Ecuador, on the other hand, common single-family homes have an EE_T of 3,600 MJ/m^2 (Torres-Quezada et al., 2022).

The concern to ensure the habitability of EHs in terms of thermal comfort has been addressed in several studies around the world, although research is scarce in Andean climates. It is also necessary to reflect that the time affected families stay in an EH varies from 0.5-5 years (Hong, 2016), and in many

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cases, it becomes permanent housing (Lines et al., 2022).

Thus, this study addresses the housing deficit due to natural disasters from a sustainable perspective, considering the thermal conditions through passive strategies and the environmental repercussions of their construction. The objective is to evaluate the impact of passive strategies applied to a transitory-permanent EH model on indoor temperature and Embodied Energy in a city in the Ecuadorian Andean zone.

METHODOLOGY

The methodology addresses two phases. The first defines the passive strategies and the model to be studied. In the second, the analysis of the thermal performance and the environmental impact of the proposal is made using digital simulations and an EE calculation, respectively. The city of Ambato, located 2,580 meters above sea level in the Andean region of Ecuador, has been taken as a case study (Figure 1).

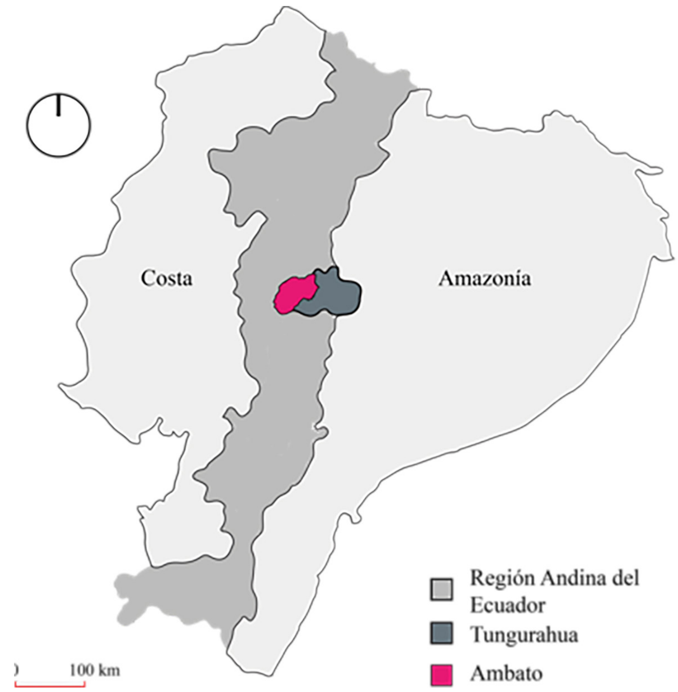

Figure 1. Location of the city of Ambato, Andean area of Ecuador. Source: Preparation by the authors.

The choice of this city is supported, on one hand, because its climate is characteristic of the Andean region of Ecuador, with low temperatures, high thermal oscillations, and moderate precipitation (Figure 2). On the other hand, its geographical location is in an area quite exposed to natural disasters (Secretariat of Risk Management, 2018).

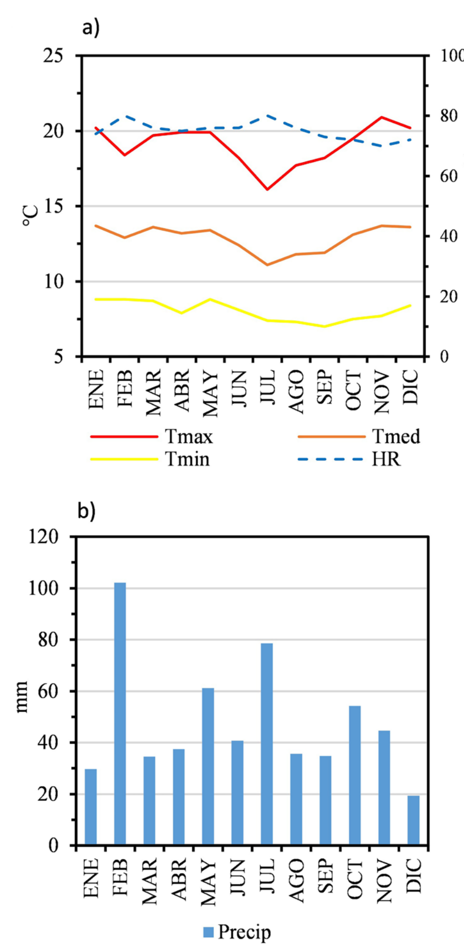

Figure 2. (a) Relative humidity (RH); Maximum (*Tmax*), mean (*Tm*), and minimum (*Tmin*), monthly average temperature, and b) monthly precipitation of Ambato. Source: Preparation by the authors based on data obtained from INAMHI (2017).

STRATEGIES AND MODEL

In this phase, passive strategies have been defined based on Givoni's psychrometric abacus (1969) (Figure 3), which has been used in previous studies to determine bioclimatic strategies in other regions (Da Casa Martín et al., 2019). For this analysis, the Climate Consultant 6.0.15 software has been used (Climate Consultant, 2020). The climate file (EPW) used in this software, and for the subsequent thermal simulations, was obtained from climate.onebuilding.org (2020).

According to this information, Ambato remains in thermal discomfort in most hours of the year (8,048), and only 8.1% of the annual hours in comfort. The most important guidelines defined are internal gains, heating and humidification, direct solar gains, and high thermal mass.

Based on the strategies, the literature on their passive application shows that the use of insulation to reduce heat losses is promoted most (Iwata et al., 2023). The strategy that follows it in importance is the use of the air chamber to reduce the thermal transmittance of

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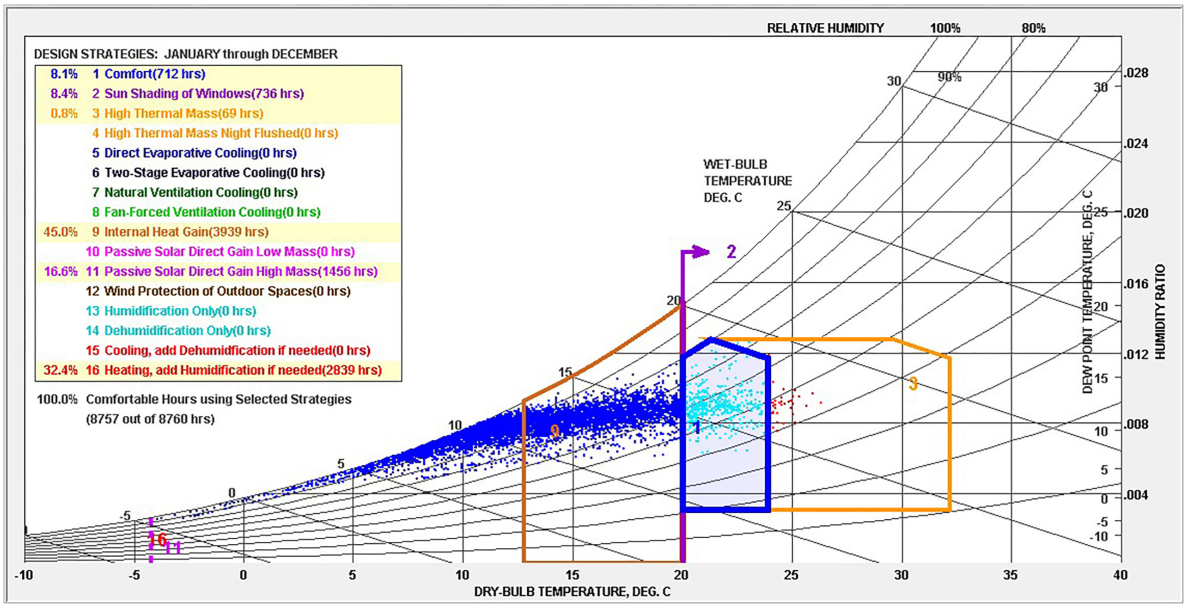

Figure 3. Givoni's psychrometric abacus (1969) of Ambato's climate. Source: Preparation by the authors in the Climate Consultant software (2020).

Table 1. EH model strategies Source: Preparation by the authors.

Strategy	Description
Internal gains	The internal distribution prioritizes adjoined spaces to take advantage of the heat from cooking, users, and lighting.
Solar gains	The openings are oriented to the east and west with an opening percentage of 30%, which allows capturing solar radiation during the day and controls heat losses at night.
Thermal mass	East and west walls with high thermal mass
Insulation	Air chamber on north and south walls, on roof and floor.
Orientation	Longer facades to the east and west.
Compactness	The houses are grouped in pairs to reduce the contact surface with the outside.

the envelope (O'Hegarly et al., 2021). It should be noted that this study focuses on minimizing the use of insulation materials to reduce the environmental impact.

As for internal gains and heating, the literature highlights the contributions made by individuals and equipment (Zhou et al., 2019). Finally, Curado and Freitas (2019) propose solar gains as a fundamental strategy for direct and indirect contributions. In addition to the strategies given by Givoni's abacus (1969), the application of an air-to-ground heat exchanger called the trombe wall or the green wall, stands out (Dabaieh & Serageldin, 2020).

The only strategy used for this study was compactness (García Mitjans, 2022) since the others involve a very high investment and upkeep. All these strategies are summarized in Table 1.

Next, research was made on materials with low environmental impact and the most representative vernacular construction systems in this region. Torres-Quezada & Torres-Avilés (2023a) determined that concrete and metal are the materials of the Andean region with the greatest impact on the total embodied energy of housing in the last 4 decades. In addition, this study shows that finishing materials such as cement plaster, porcelain, laminated wood, or stainless steel also have a high environmental impact. Another important point is that the excessive use of glass can drastically

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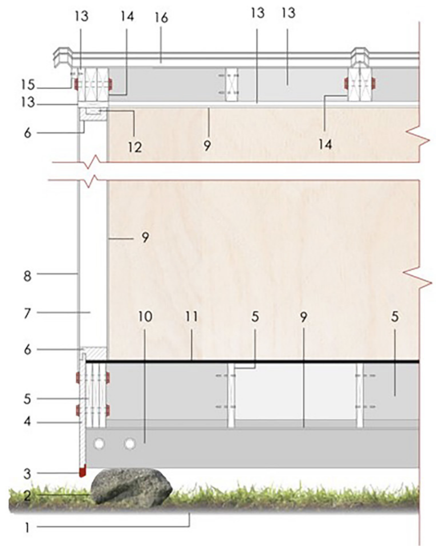

1. Natural soil
2. Stone base of the site.
3. Drip groove, Greentec (TPG2) 40x10mm
4. Greentec (TPG2) 200x10mm
5. Pine boards 195-19mm
6. Pine slats 1, 80x40mm
7. Air chamber e=80mm
8. Greentec board (TPG1) 2440x1220x5mm
9. Plywood board 2440x1220x5.2mm
10. Pine beam 145x38mm
11. Greentec board (TPG2) 2440x1220x10mm
12. Pine slat 2 40x20mm
13. Pine board 195x19mm
14. Pine beam 145x38mm
15. Pine slat 40x20 mm
16. Greentec board (TCP) roof cover type 2400x1160x5mm.

Figure 4. Constructive overview of the model. Source: Preparation by the authors.

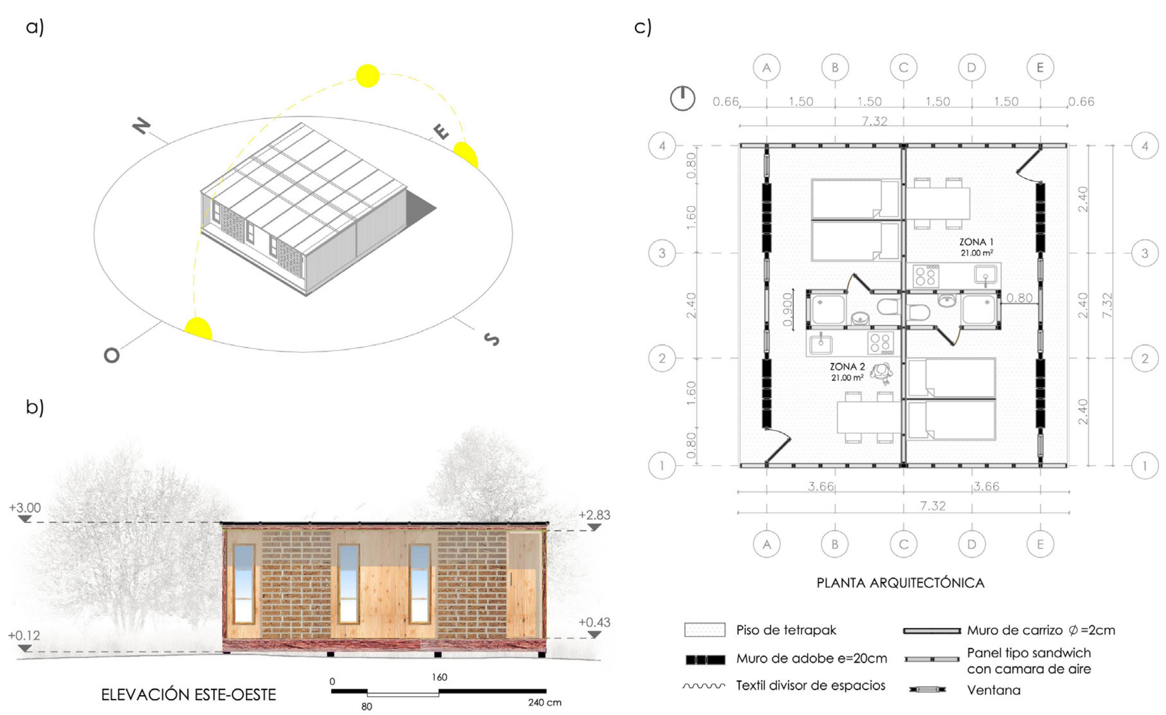

Figure 5. a) volume, b) east-west elevation, and c) architectural floorplan of the model. Source: Preparation by the authors.

increase the dwelling's EE, which in turn, reduces its thermal mass causing lower temperatures and greater thermal oscillations (Torres-Quezada & Torres-Avilés, 2023b).

On the other hand, other studies highlight the importance of using recycled materials to build EHs (Arslan, 2007; Arslan & Cosgun, 2008). Their most important considerations are the use of natural or recycled materials such as earth, wood, or recycled poly-aluminum. Natural materials which reduce the environmental impact of housing (Rodríguez et al., 2021) are a fundamental part of Ecuador's vernacular architecture (Yepez, 2012).

Based on these studies, the specific characteristics of the proposed prototype's constructive system were defined (Figure 4).

The Andean EH model is based on the following: the north and south walls are made by a sandwich-type panel; the outer layer is a Greentec-type board made of poly-aluminum (TPG1); and the inner one is a plywood board, separated by an air chamber.

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Table 2. Simulation parameters. Source: Preparation by the authors using DesignBuilder (2016).

Element	Material	Thickness (mm)	λ (W/mK)	U (W/m²(k)
Floor	Greentec_TPG2	10	0.50	2.15
	Air chamber	200		
	Plywood	5.2	0.15	
North/south wall	Greentec_TPG1	5	0.50	2.20
	Air	80		
	Plywood	5.2	0.15	
East/west wall	Adobe	200	0.17	0.76
Interior wall	Plywood	5.2	0.15	2.08
	Air	80		
	Plywood	5.2	0.15	
Windows	Single glazing	4	0.90	6.121
Roof	Greentec flat type	5	0.50	2.20
	Air chamber	100		
	Plywood	5.2	0.15	
General simulation features				
Latitude/Longitude	-1.24908/-78.61675			
Altitude	2597 masl			
Surface Area	53.58m²			
Occupation	0.15 persons/m²			
Infiltrations	1.5 ren/h (constant)			
Lighting	2W/m² (18-22h)			
Kitchen	3W/m² (7-8h/12-13h/18-19h)			

The floor contains a TPG2 board and a plywood board inside, with an air chamber between them. The most concerning envelope surface in the thermal aspect was the roof, since it is where the greatest heat losses occur (Torres-Quezada et al., 2018). Therefore, the roof has a flat poly-aluminum (TCP) board on the outside and plywood on the inside that acts as the ceiling, separated by an air chamber. For the east and west walls, adobe has been used to increase the model's thermal mass. Finally, the windows are 4mm single glazing with wooden frames.

As for the morphological characteristics, the proposal combines 2 living spaces for Zone 1 (Z1) and Zone 2 (Z2), each intended for one family. The morphology is based on 2.40x1.20m modules, which are the panel's commercial modular units. Modulation as the basis of the design will avoid material wastage and, therefore, reduce the environmental impact.

Regarding the indoor layout, all the spaces have been linked around the kitchen to take advantage of the internal gains. The bathroom, which is accessed from the living, is placed next to this space (Figure 5).

In this way, the prototype is conceived as a short- and long-term habitable space that has an adobe wall which is not a quick constructive system, but whose inclusion solves thermal aspects that must be considered in EHs. According to this, and given its modular design, the model allows its

1 (ECU_TU_Ambato.Intl.AP.841470_TMYx.2004-2018)

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Table 3. Specifications and quantities of the materials used. Source: Preparation by the authors based on data obtained from: [1] Vázquez, (2001); [2] Shukla et al., (2009); [3] ECUAPLASTIC (2021); [4] Hammond & Jones (2008) [5] EDIMCA (2021); [6] González Stumpf et al., (2014); [7] TECNICGLASS (2021).

* the *EE* of poly-aluminum has been obtained based on the weighted values of polyethylene (89.96 MJ/kg) and aluminum (108.6 MJ/kg) recycled to 50%, which have a proportion of 80% and 20% respectively.

Product	P/u (kg)	Quantity (u)	EE (MJ/kg)
Adobe	9.6 [1]	266	0.97 [2]
TCP*	14.30 [3]	28	93.69 [4]
TPG1*	15 [3]	12	93.69 [4]
TPG2*	27.4 [3]	18	93.69 [4]
Beam	10.91 [5]	57	1.5 [6]
Board 1 [3]	7.34 [5]	118	1.5 [6]
Board 2 [3]	3.57 [5]	14	1.5 [6]
Slat 1 [3]	3.68 [5]	120	1.5 [6]
Slat 2 [3]	0.92 [5]	39	1.5 [6]
Plywood board [3]	7.66 [5]	63	15[4]
Glass plate [4]	10.8 [7]	6	16.81[4]

transformation into housing units with a larger area and with the capacity to house more users for extended periods.

CONFIGURATION AND CALCULATION OF THE MODEL

THERMAL SIMULATIONS

The DesignBuilder software is used with its Energy Plus calculation engine to analyze the model's internal thermal behavior and evaluate the effectiveness of the proposed strategies (DesignBuilder, 2016). The indoor air temperature (*Tai*) has been taken for this evaluation as a reference parameter.

As a first step, the climatic inputs and the characteristics of the model have been configured. The city's climate file was obtained from climate.onebuilding.org (2020).

After that, the thermal characteristics of all the material elements of the envelope have been defined. In addition, possible external infiltrations, occupation, and sources of internal loads are established. Infiltrations have been defined using Torres-Quezada et al. (2019), where the approximate values are stipulated considering the constructive characteristics of the houses in Ecuador. All these parameters are detailed in Table 2.

Below, two days of analysis have been chosen to accurately represent the average weather conditions (Average Day) and the average cold conditions (Extreme Day) in the city under study. These days have been determined from the outdoor temperature values obtained from INAMHI (2017).

For the Average Day, a mean temperature of 12.5°C has been considered, accompanied by maximum and minimum values of 17.9°C and 8.45°C, respectively. In the case of the Extreme Day, the lowest average temperature recorded monthly during the course of the year (11°C) has been chosen, along with a maximum temperature of 16.23°C and a minimum temperature of 6.82°C.

Once these data were obtained, two days were chosen from the simulation climate file that fit these values. As a result, 08/03 (Average Day) and 09/08 (Extreme Day) were chosen as the corresponding simulation days.

Finally, the thermal results will be analyzed against the comfort range (18-26°C) established by the Ministry of Urban Development and Housing (2011).

EMBODIED ENERGY CALCULATIONS

To evaluate the proposal's environmental impact, the Embodied Energy (*EE*) of the materials is taken as a parameter, which is the energy required by each material to produce one unit of weight (Kumar et al., 2022). Specifically, this study analyzes the total *EE* value of each material and the total value (EE_T) of the model. Additionally, to make comparisons with other studies, EE_T is related to the total construction area (MJ/m^2).

To obtain the EE_T (MJ) of the housing, equation 1 is used, which entails adding together the EE_T of each of the materials.

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$$EI_T = \sum(EIxP)$$ ....(Equation 1)

Where EE is the specific embodied energy of each material (MJ/kg) with a Cradle-to-gate calculation approach, with the exception of wood which has a Cradle-to-site approach. P is the total weight of each material (kg), obtained by multiplying the weight per unit of each material by the total number of parts used in the model. The specifications and quantities of each of the materials are shown in Table 3.

RESULTS AND DISCUSSION

THERMAL SIMULATIONS

Figure 6 shows the results of the indoor air temperature (*Tai*) of Z1 and Z2, and the outside air temperature (*Te*) on the Average Day. In addition, the comfort range (18-26°C) has been plotted. On one hand, in Z1, the average *Tai* is 22.2°C with a daily oscillation of 6.1°C, with a minimum *Tai* of 19.2°C (6 am) and a maximum *Tai* of 25.3°C (7 pm). On the other hand, in Z2 it is determined that the average *Tai* is 23.3 °C. The daily oscillation is 7.4°C with a minimum *Tai* of 19.9 °C (6 am) and a maximum *Tai* of 27.3°C (8 pm).

According to these results, the *Tai* de Z1 stays within the comfort range throughout the day. Also, in Z2 there are no thermal discomfort temperatures, except between 5 pm – 9 pm. During this period, the *Tai* of Z2 is 1.3°C above the comfort range.

To understand the strategies proposed and the results shown in detail, Figure 7 indicates the heat fluxes in Z1 and Z2 analyzed on the Average Day.

The maximum *Tai* in the two zones evidences an approximate delay of 6 hours compared to *Te*. This delay is mainly influenced by the thermal mass of the adobe walls, together with the lighting and cooking contributions, and in the case of Z2, by direct solar gain through the windows.

The minimum *Tai* in Z1 and Z2 stays at around 20°C, which reflects the effectiveness of the strategies proposed in the vertical and horizontal envelope. The losses through the roof and floors are minimal during the day. The greatest losses are due to the walls, mainly due to the north and south walls. On the contrary, the influence of the east wall on Z1 and the west wall on Z2 means the losses are reduced from 4 pm.

This flow is reduced and remains very close to 0 until 8 am, and in Z2 it even becomes positive. Finally, the heat flow through partitions is very close to 0 kWh throughout the day, because these walls exchange heat with adjacent areas, and not with the outside.

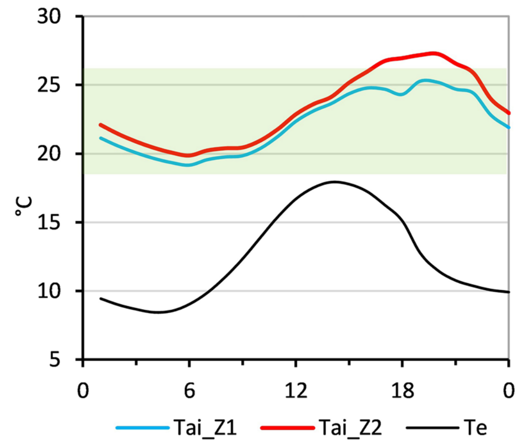

Figure 6. *Tai* of Z1 and Z2, and Te on the Average Day. Source: Preparation by the authors.

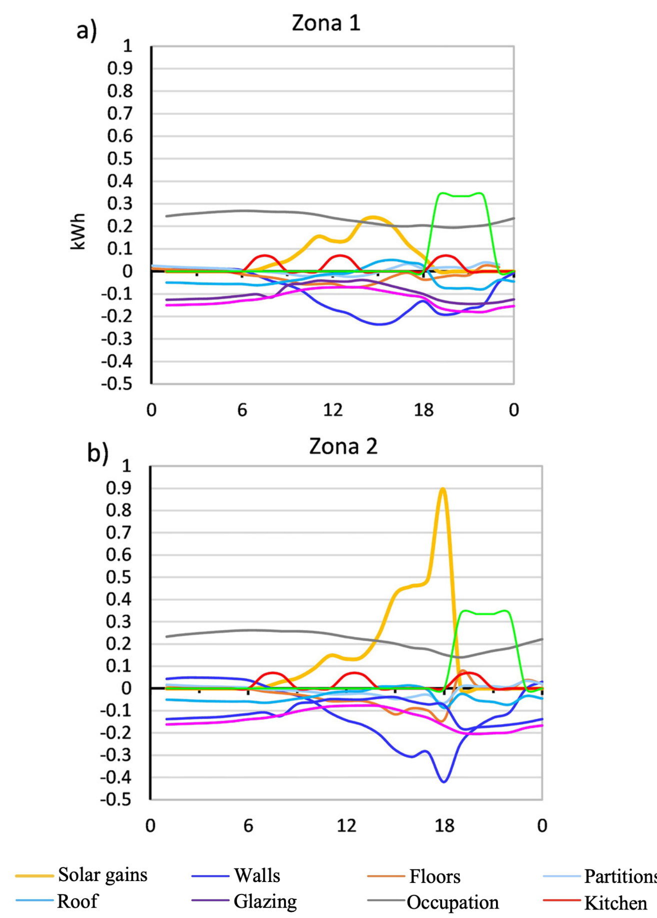

Figure 7. Heat fluxes of Z1(a) and Z2(b) on the Average Day. Source: Preparation by the authors.

On the other hand, on the Extreme Day (Figure 8), the average *Tai* of Z1 is 20.7°C, with a minimum *Tai* of 17.5°C and a maximum *Tai* of 23.7°C. The *Tai* of Z1 and Z2 are within the comfort range, except for a

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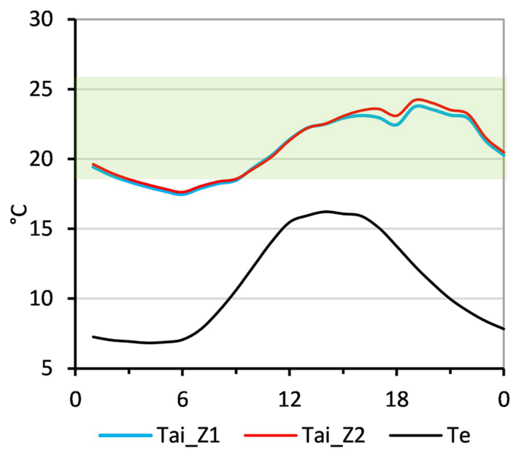

Figure 8. Tai of Z1 and Z2 and Te on the Extreme Day. Source: Preparation by the authors.

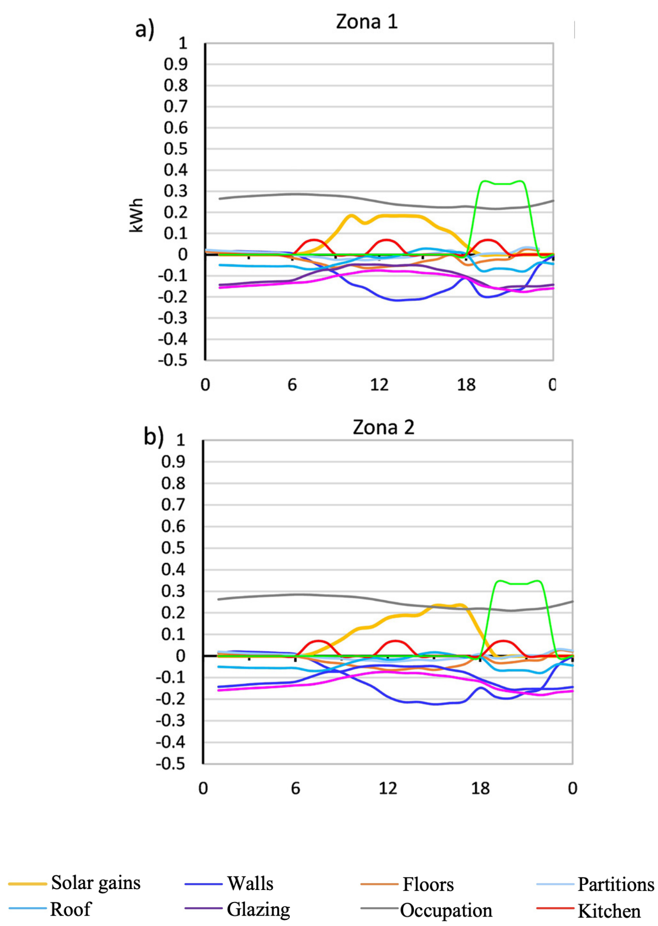

Figure 9. Heat fluxes of Z1(a) and Z2(b) on the Extreme Day. Source: Preparation by the authors.

few night hours. However, it is only 0.5°C below the comfort range.

In contrast to the Average Day, the maximum *Tai* does not exceed the upper limit and the thermal oscillation is lower. Again, the maximum *Tai* shows a delay of approximately 6 hours, which is mainly influenced by

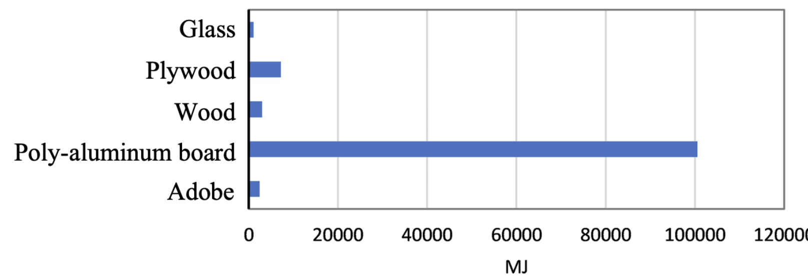

Figura 10. EE_T of the materials used in the Andean model. Source: Preparation by the authors.

the thermal mass of the east and west walls and by the contributions of lighting, cooking, and solar gains. The latter is much lower than on the Average Day, since on the Extreme Day most of the solar radiation is diffuse (Figure 9).

Finally, the minimum *Tai* reaches up to 17.5°C, which is lower than the Average Day. However, it remains within the comfort range.

If we compare these results with the other EH studies mentioned, emergency homes in other regions tend to use, as in the case of Korea, insulation and heating to achieve thermal comfort (Hong, 2016), or if one of these is not used, there will be thermal discomfort, as seen in Japan (Sinohara et al., 2014). In the case of the Ecuadorian Andean region, this study shows that there are other strategies to achieve a Tai of 24°C, so following models such as those of Korea and Japan would imply unnecessary economic and environmental expenditure.

EMBODIED ENERGY CALCULATIONS

Figure 10 shows the EE_T of each of the materials used in the model. The highest EE_T is found in poly-aluminum boards with 100,586 MJ, followed by plywood and wood with 7,239 MJ and 3,023 MJ, respectively. Finally, there is glass and adobe. It should be noted that glass, even with the small percentage used, has almost the same value as adobe, which is much more representative in the model. The EE_T of the whole house is 114,414 MJ.

For comparative analysis, Figure 11 shows the EE_T value related to the total area of the dwelling (53.58m²), along with the values of other social housing in Ecuadorian Andean climates. This typology has been chosen due to the lack of local EH data.

Table 4 shows the characteristics of the dwellings used for the comparative analysis.

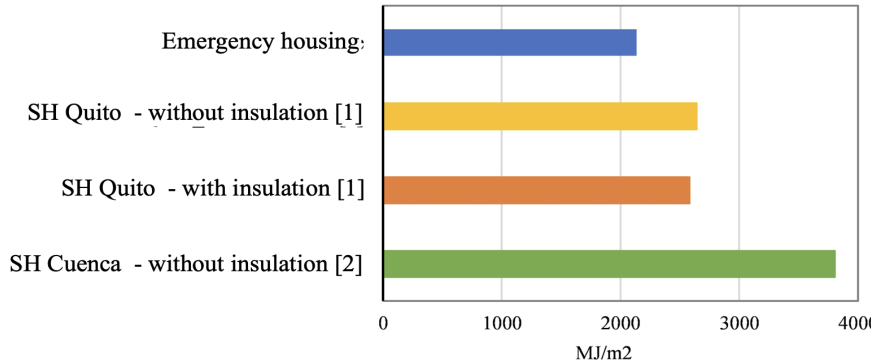

Figure 11. EE_T of the proposed model, and EE_T of social housing in Ecuador. Source: Preparation by the authors based on data obtained from: [1] Macias et al. (2017), [2] Torres-Quezada & Torres-Avilés (2023a).

Table 4. Characteristics of social housing in Ecuador. Source: Preparation by the authors based on data obtained from: [1] Macias et al. (2017), [2] Torres-Quezada & Torres-Avilés (2023b).

Housing	Walls	Roof	Area (m^2)
SH_Quito_without insulation [1]	10 cm concrete	Galvalume	55
SH_Quito_with insulation [1]	sandwich-type, fiber cement boards, and 8 cm expanded polystyrene	Galvalume	55
SH_Cuenca_without insulation [1]	Plastered concrete block	Fiber Cement	60

The results show that the proposed model has an EE_T of 2,135.38 MJ/m², which is less than the energy spent by social housing in Quito and Cuenca. In the case of the Quito SH without insulation, this has 2,640 MJ/m², while the SH with insulation is 2,580 MJ/m². The dwelling built in Cuenca has an EE_T of 3,806 MJ/m².

According to what has been presented, it is seen that the most significant difference is manifested in the housing built in Cuenca (1,671 MJ/m²), which features concrete block walls that greatly increase its EE_T. In contrast, the houses of Quito show a difference of 505 MJ/m² with the ones devoid of insulation and 445 MJ/m² with those which have insulation.

These data show that housing without insulation has a higher EE_T than housing with insulation because the former has a system built of concrete walls, which significantly raises its EE_T. It should be mentioned that in these homes the doors, floors, or windows have not been considered for the calculation.

This comparative analysis shows the high impact that the use of insulating and industrialized materials has in increasing the EE_T. In the proposed prototype, poly-aluminum is the material with the greatest impact, even when it is recycled. This implies that its excessive use is counterproductive. However, it is chosen for its easy maintenance and durability under the region's climatic conditions.

CONCLUSION

From this study, it can be concluded that the passive strategies proposed, namely, direct solar gains, thermal mass, compactness, and the use of internal gains, are effective for an EH to reach comfort on both an Average (23.5°C) and Extreme (21.8°C) Day in the Andean climate. Both the results obtained and the minimum temperature (approx. 18°C) highlight that the use of insulation in this climate is not necessary, as it can be replaced by an air chamber.

On the other hand, it is possible to determine that the EE_T of the proposed construction system is lower than that recorded in other social prototypes with energy efficiency standards. This model represents 60% of social housing in Ecuador.

The poly-aluminum boards used in the model, although they are manufactured from recycled material, have high levels of embodied energy since the percentage that is recycled is not high and, in addition, the reused polyethylene and aluminum require a large amount of energy for their production. This opens a line of research on the effectiveness of recycling these and other materials in construction systems.

Finally, this research highlights that the use of passive strategies in the Andean region of Ecuador may be sufficient to achieve thermal habitability, reduce environmental impact and, more importantly, reduce both the use of unnecessary materials and the economic value of the prototype. The results of this study can be put into practice and promote the collaboration of local labor for their construction since it integrates vernacular construction systems and others that are easy to install.

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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

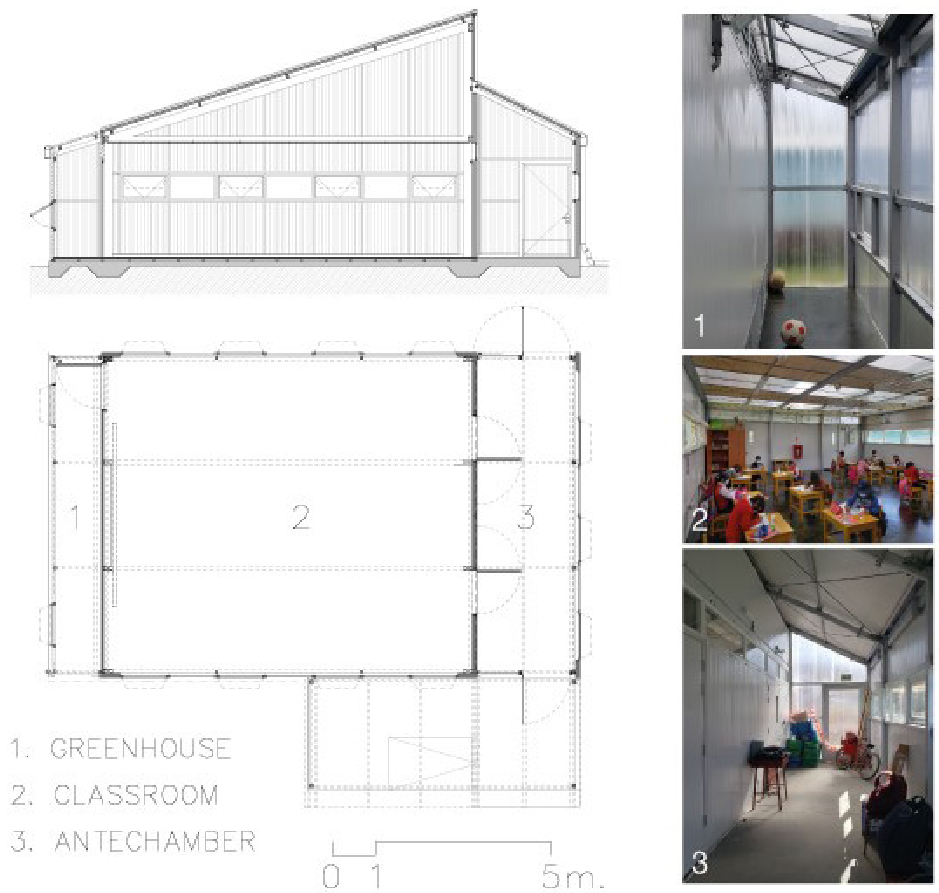

Figure 1: Plan, section, and photos of the "Plan Heladas" module (Second version, 2020). Source: Specifications Report, National Program for Educational Infrastructure (PRONIED, 2021). Photos by the authors.

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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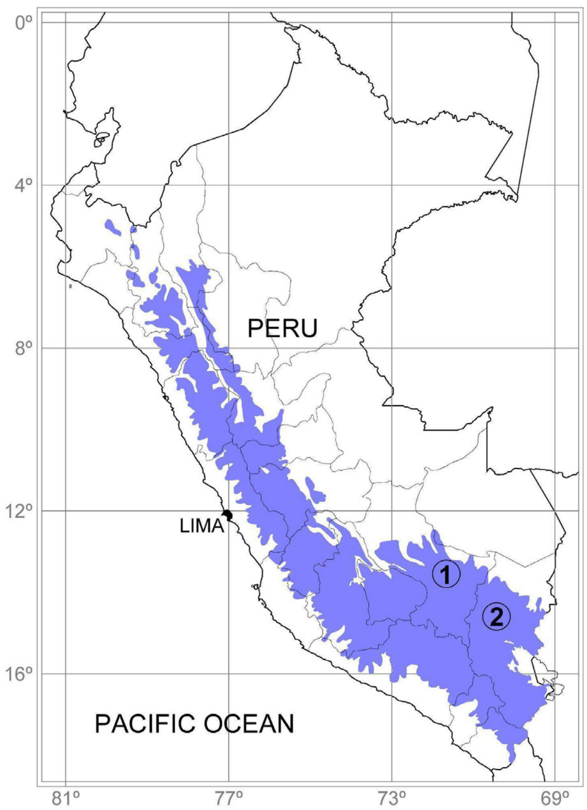

Figure 2: High Andean region of Peru, altitude equal to or greater than 3,500 m.a.s.l. and the location of the schools monitored for this study: (1) EI 50425, Cusco, latitude -13.42°, longitude -71.65°, altitude 3,737 m.a.s.l. and (2) EI 72073, Puno, latitude -14.68°, longitude -70.35°, altitude 3,913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

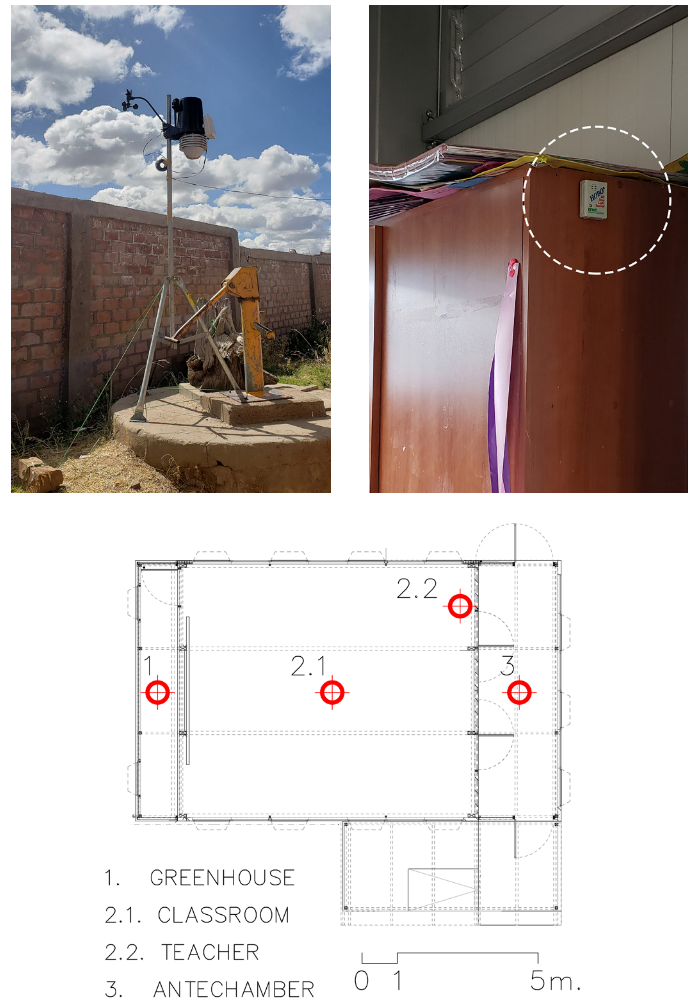

Figure 3: Mounting of meteorological station (left), view of indoor datalogger located in the classroom (center), and location of all data loggers within the module (right). Source: Prepared by the authors

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.

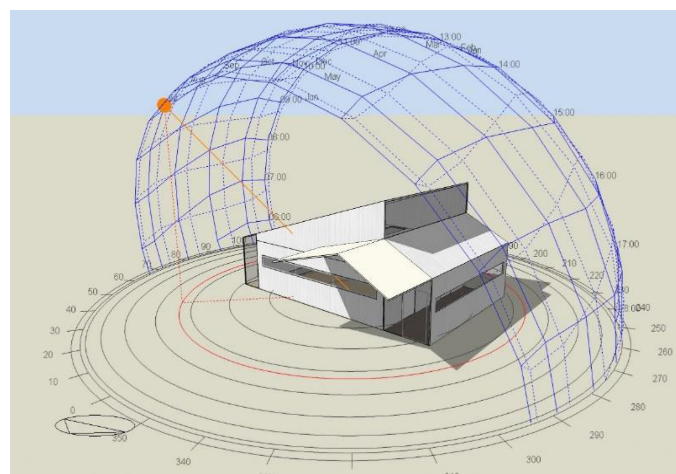

Figure 5: Screenshot of the model in the DesignBuilder software. Source: Prepared by the authors

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/

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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.

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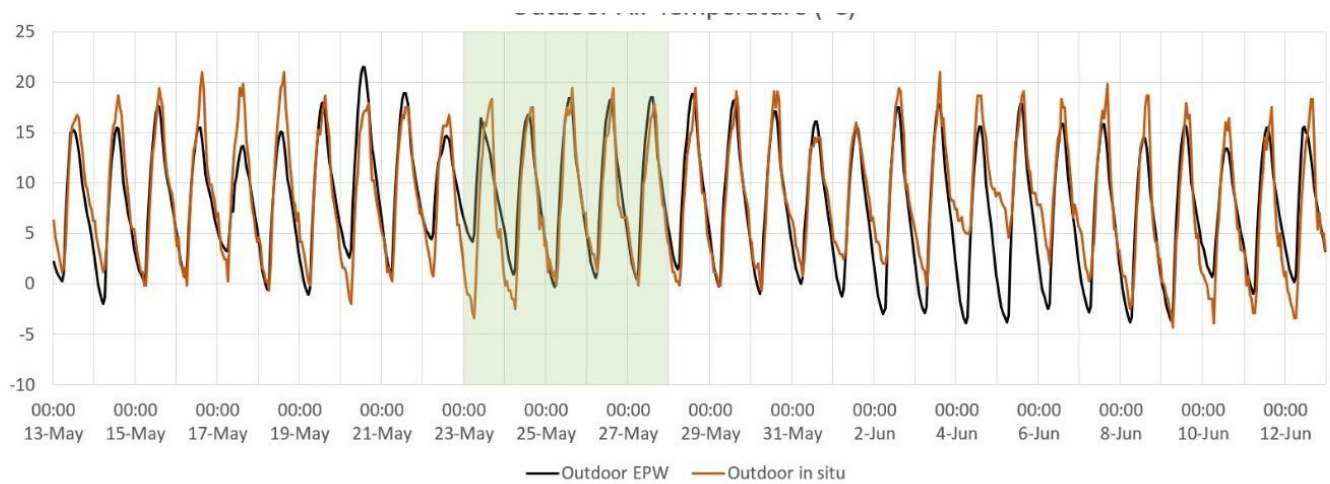

Figure 6: Comparison between the outdoor temperatures of the representative week based on on-site measurements and the outdoor temperatures based on the .epw file. Source: Prepared by the authors

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

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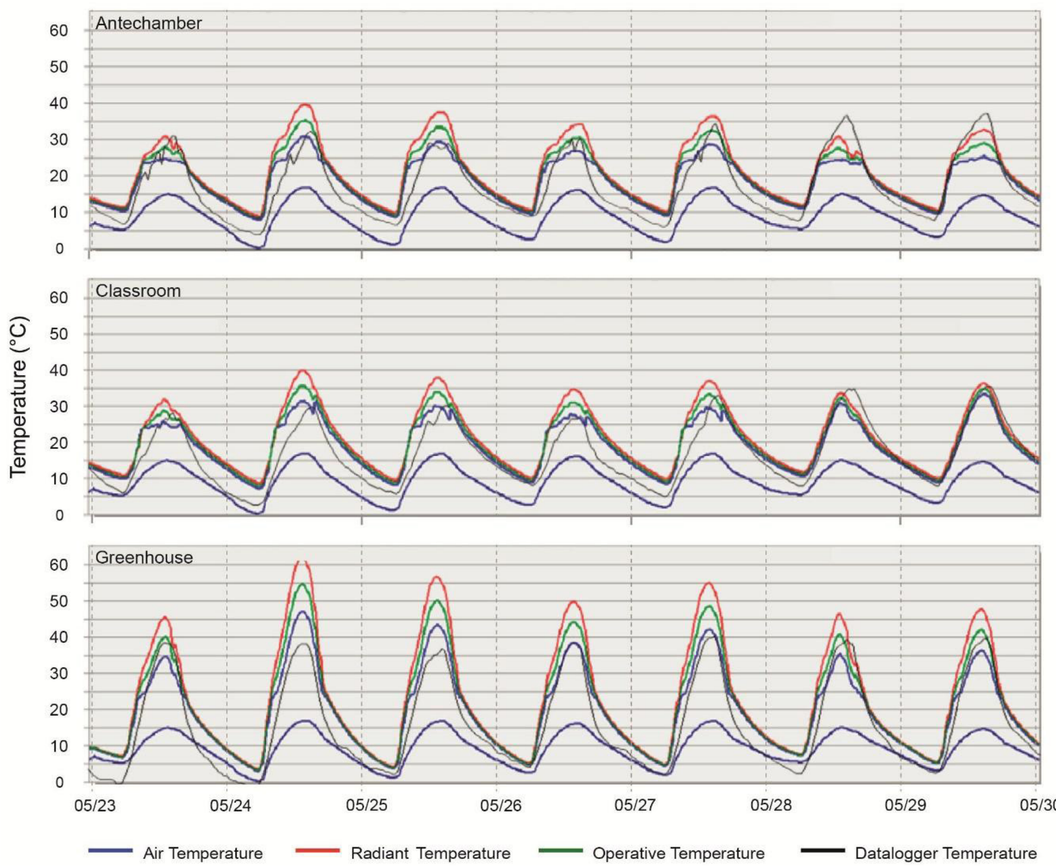

Figure 7: Calibration of antechamber (top), classroom (center), and greenhouse (bottom) with radiant temperatures (red), operative temperatures (green), simulated external air temperature (blue) and on-site measured external air temperature (grey). Source: Prepared by the authors

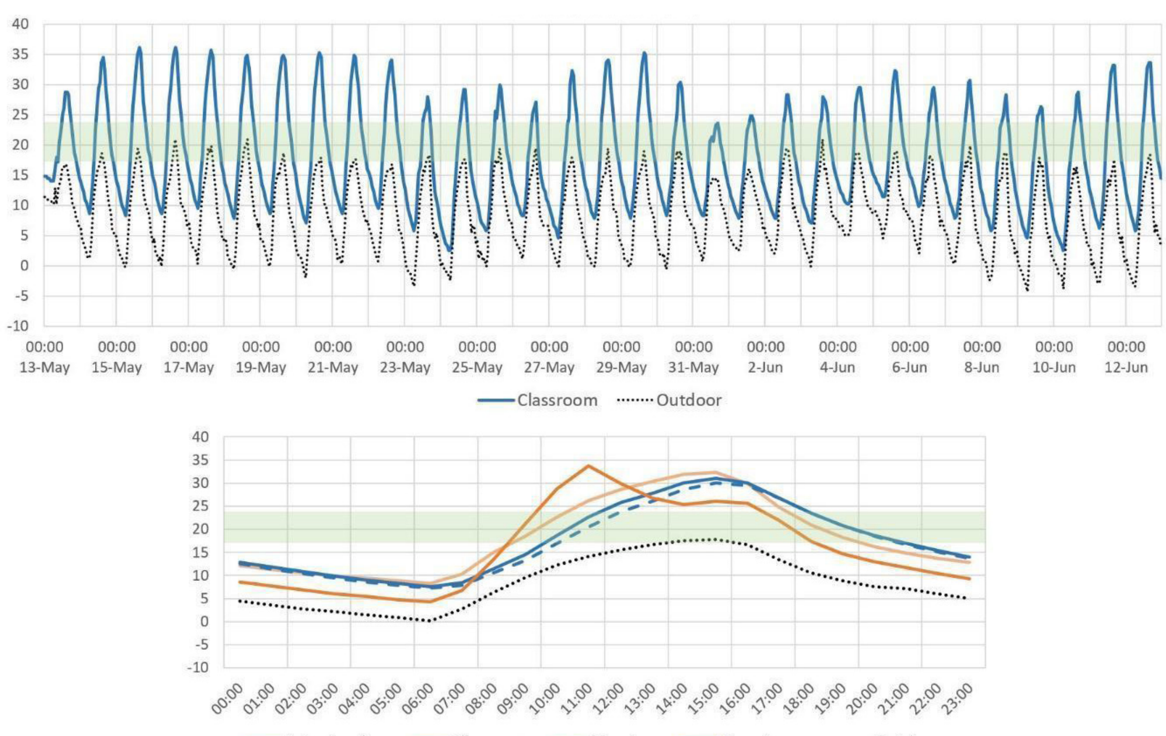

Figure 8: Classroom and outdoor air temperature (above); average hourly temperatures of all module rooms (below). The green zone indicates the comfort limits. Source: Prepared by the authors

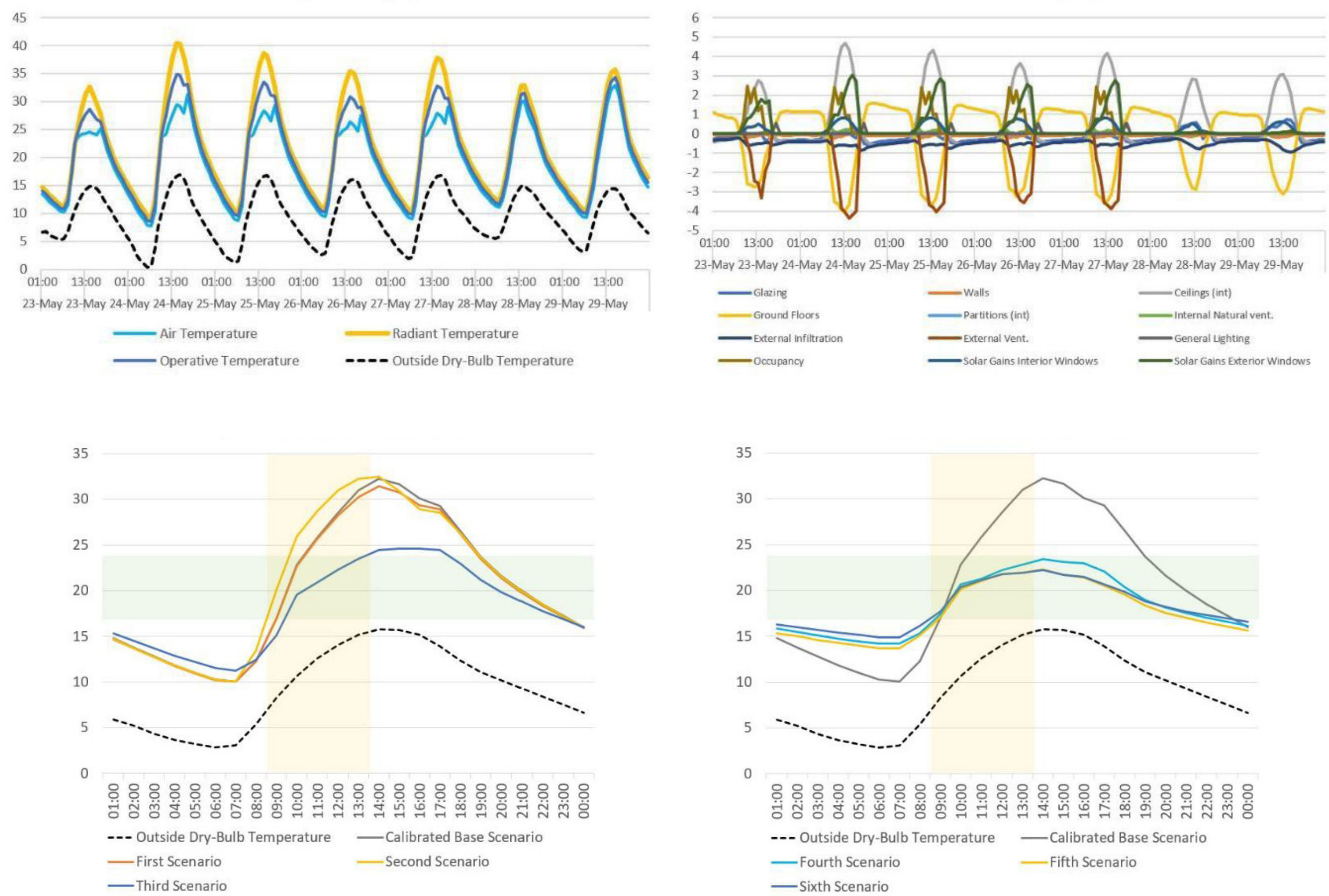

Figure 9: Temperature simulations and thermal balance of the base proposal (above) and temperature simulations of the base proposal with the 6 proposed scenarios (below). The green bar is the comfort zone and the yellow one is the hours of use of the classroom. Source: Prepared by the authors

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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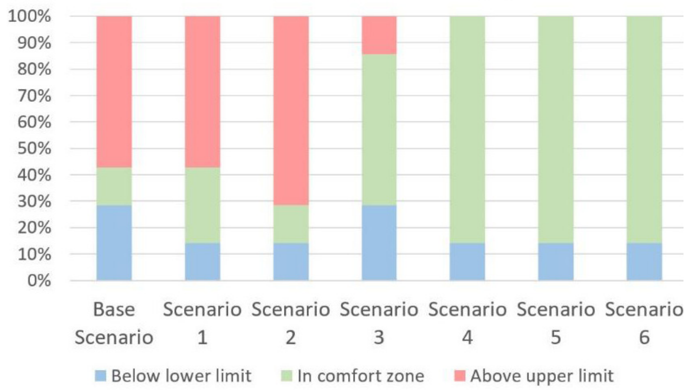

Figure 10: Percentage of time in thermal comfort during class hours in each scenario. Source: Prepared by the authors

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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CLIMATE CHANGE AND THERMAL COMFORT IN COLOMBIAN SOCIAL HOUSING

CAMBIO CLIMÁTICO Y CONFORT TÉRMICO EN LA VIVIENDA DE INTERÉS SOCIAL COLOMBIANA

MUDANÇA CLIMÁTICA E CONFORTO TÉRMICO EM HABITAÇÕES SOCIAIS COLOMBIANAS

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RESUMEN

El cambio climático es una de las problemáticas más relevantes del siglo XXI a nivel mundial y, a pesar del desarrollo de estrategias que buscan minimizar sus consecuencias, es una realidad irreversible. Por consiguiente, es pertinente analizar su impacto sobre la arquitectura colombiana, específicamente en la Vivienda de Interés Social (VIS), tipo de edificación que más se construye en el país. El objetivo de esta investigación fue conocer el desempeño térmico de la VIS actual, en relación con el cambio climático, a partir de un modelo tipo para las ciudades más pobladas de Colombia Bogotá, Medellín y Cali. Dicho modelo se realizó a través de simulaciones computacionales en tres escenarios futuros (2030/2050/2080), los que permitieron diagnosticar cómo el cambio climático tendrá efecto en el confort térmico de sus ocupantes. Dentro de los resultados se demuestra que, del total de los escenarios evaluados (576), tan sólo el 18,9% se encuentra en un rango aceptable de tiempo en confort térmico (>70%). Esto que indica que la mayor parte de la VIS actualmente construida en Colombia no brinda condiciones de confort térmico tanto en un escenario de cambio climático como en el escenario actual, pues en ambas situaciones los casos favorables representan un bajo porcentaje respecto del total de los casos evaluados.

Palabras clave
cambio climático, viviendas de interés social, confort térmico.

ABSTRACT

Climate change is globally one of the most relevant problems of the 21st century and despite strategies that seek to minimize its consequences, it is an irreversible reality. Therefore, it is pertinent to analyze its impact on Colombian architecture, specifically on Social Housing (SH), the type of building most frequently built in the country. The purpose of this research was to get to know the thermal performance of current SH, in relation to climate change, based on a standard model for the most populated cities in Colombia, namely Bogotá, Medellín, and Cali. This model was made using computer simulations in three future scenarios (2030/2050/2080), which allowed diagnosing how climate change will affect the thermal comfort of the occupants. The results show that, of the total number of scenarios evaluated (576), only 18.9% are in an acceptable range of time in thermal comfort (>70%). This indicates that most of the SH currently built in Colombia do not provide thermal comfort conditions either under a climate change scenario or in the current scenario, since in both situations the favorable cases represent a low percentage with respect to the total number of cases evaluated.

Keywords
climate change, social housing, thermal comfort.

RESUMO

As mudanças climáticas são uma das questões mais relevantes do século XXI em nível global e, apesar do desenvolvimento de estratégias para minimizar suas consequências, é uma realidade irreversível. Portanto, é pertinente analisar seu impacto na arquitetura colombiana, especificamente na Habitação de Interesse Social (HIS), o tipo de construção mais comum no país. O objetivo desta pesquisa foi conhecer o desempenho térmico da HIS atual em relação às mudanças climáticas, com base em um modelo padrão para as cidades mais populosas da Colômbia: Bogotá, Medellín e Cali. Esse modelo foi criado por meio de simulações computacionais em três cenários futuros (2030/2050/2080), que permitiram diagnosticar como as mudanças climáticas afetarão o conforto térmico dos ocupantes. Os resultados mostram que, dos cenários avaliados (576) apenas 18,9% estão em uma faixa aceitável de conforto térmico (>70%). Isso indica que a maior parte da HIS atualmente construída na Colômbia não oferece condições de conforto térmico tanto em um cenário de mudanças climáticas quanto no cenário atual, pois em ambas as situações os casos favoráveis representam uma porcentagem baixa em relação ao total de casos avaliados.

Palavras-chave
mudanças climáticas, habitação de interesse social, conforto térmico.

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INTRODUCTION

Climate change is globally one of the 21st century's most relevant environmental problems. Today, it is the 13th Sustainable Development Goal proposed by the United Nations, and despite strategies that seek to combat it and minimize its consequences, it is an irreversible reality (IPCC, 2007). In the specific case of Colombia, phenomena such as El Niño and La Niña are typical examples of how interannual climate variability has been changing (Pabón & Montealegre, 2017). For this reason, it is important to analyze its impact on Colombian architecture, specifically in Social Housing (hereinafter, SH), and reflect on its resilience capacity, since its construction comprises one of the highest indexes in the country.

Colombia is located on the equatorial line in the tropical zone of South America; as a result, it receives a high contribution of annual solar radiation. This specific location means that its climate is determined by its topography, namely that meteorological changes fluctuate depending on the geographical position of the cities (IDEAM & UNAL, 2018). Due to this aspect, the country cannot be categorized within a single specific climate, so sometimes the consequences that climate change has in the national territory are not obvious. Faced with this situation, Pabón (2012) argues that the overwhelming expression of global warming and climate change in Colombia is the shrinking of mountain glaciers and the rising of the average sea level on the Colombian coasts. For this reason, Colombian architecture should consider an adaptation process that prioritizes the country's current and future environmental dynamics.

Colombia has been showing a clear pattern of growth in urban centers since the mid-20th century, in that the country's regional capitals exceed 90% urbanization, while smaller cities show much higher growth compared to rurality (National Administrative Department of Statistics, 2021b). This shows the need to start evaluating the criteria that are currently considered for building design.

According to the intergovernmental panel on climate change, building operation and construction produce 38% of all energy-related CO_2 emissions, so these must be halved by 2030 if the construction sector is to move towards climate neutrality by 2050 (IPCC, 2020).

Among the strategies proposed in international studies to address climate change, two possibilities stand out. On one hand, Aleksić et al. (2016) propose "mitigation and adaptation", both applicable to any sector of society. According to the authors, from the architectural point of view, mitigation is addressed through the creation of energy-efficient buildings, the use of renewable energies, and an appropriate selection of materials; meanwhile, climate change adaptation seeks to build energy-efficient buildings that also adapt to the natural conditions of their context. Thus, it is proposed that attention so far in the architectural field has focused on mitigation measures, which has meant that the priority is not implementing strategies that help existing buildings to be resilient to their environment.

Considering this, the authors present several examples of houses that are resilient to extreme climatic conditions such as hurricanes, floods, or unstable terrains, which, through adaptability, resist these situations. By analyzing this in the Colombian context, the need to propose houses and spaces resilient to context-related climatic conditions is ratified and, in this way, apart from responding to climatic adversities, it can contribute to improving people's quality of life. As Eckardt (2011) explains, "resilience enables the coexistence of communities with the risk conditions of a given territory."

Likewise, within the climate change adaptation process, the relevance of thermal comfort to people's health has also been demonstrated, which happens due to long periods spent in enclosed spaces. Gamble et al. (2009) show that a person can spend more than 90% of their life inside a building, demonstrating the impact that its design has on their health. For this reason, the explanations of Soto-Estrada et al. (2016) and Januszkiewicz (2017) are relevant at this point since, despite researching in separate parts of the world, Colombia and Poland, they agree on the importance that the envelope's design has in a building.

In their studies, both mention that resilient buildings, apart from generating thermally comfortable spaces, help people's physical and mental health not to be harmed, ratifying the direct relationship there is between architecture, health, and climate change. Thus, the two studies show that the type of architecture currently being developed in the two contexts analyzed does not respond to its immediate environment, and with this, it is concluded that the architecture we live in is not resilient to climate change. Understanding it as such, it is crucial to start developing homes that guarantee their occupants' well-being from their design, both from their conception and for future scenarios.

Additionally, from the urban point of view, talks have also begun about the importance of

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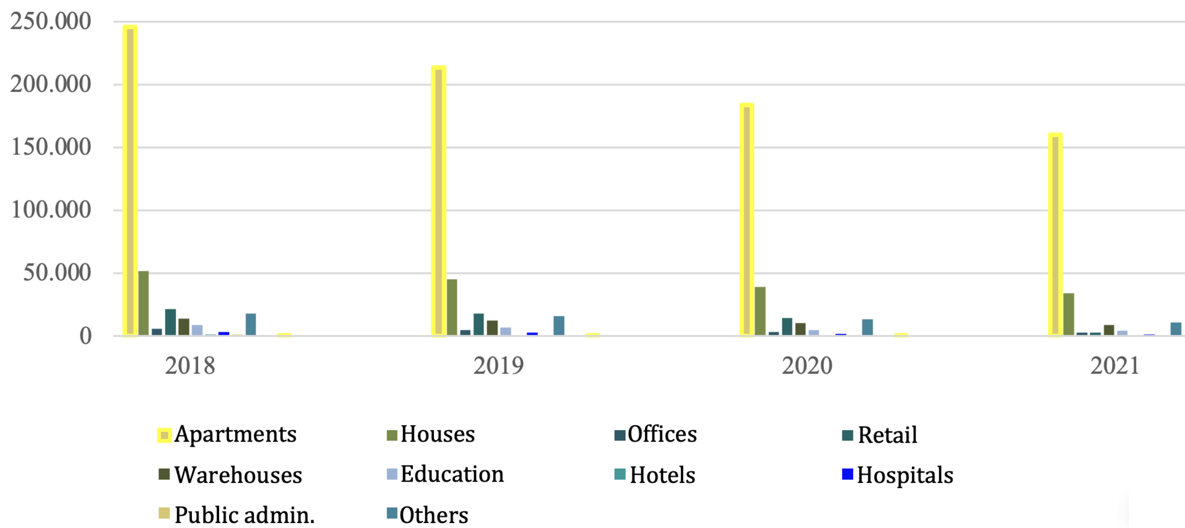

Figure 1. Annual average of the new area by purpose, 2018-2021. Source: Preparation by the authors based on the Buildings Census (CEED).

resilience to climate change and its relationship with sustainability. Alavsi et al. (2021) mention that climate adaptation is one of the most relevant criteria for sustainability and gives, as an example, cities in Asia where they have managed to find harmony between architecture and the environment based on the experience and culture of the local community. Likewise, Gifreu (2018) dares to rethink the definition of sustainable development, stating that it must be "timely to prevent and mitigate the effects of climate change".

In this way, it is essential to understand that climate change is real, as is the need to investigate not only mitigation but also adaptation measures, as the scenario described reaffirms the need to consolidate buildings that are resilient to future climatic conditions.

Bearing this in mind, the main objective of this research was to study the thermal behavior of SH in the face of climate change, located in the three most populated cities of Colombia: Bogotá, Medellín, and Cali, using computer simulations to observe their behavior in three future scenarios (2030/2050/2080).

HOUSING IN COLOMBIA

Between 2018 and 2021, multifamily housing was the most built construction type in Colombia, accounting for around 68% of the new builds according to a 2021 study conducted by the National Administrative Department of Statistics (2021a), whose data can be seen in Figure 1. This was the main reason why this research focused on Colombian multifamily housing because, by being the most representative, it can lead to a greater social impact. Likewise, within the cited document, SH represented the largest area in the multifamily housing sector, thus further narrowing down the case study.

SH in Colombia is defined by the Ministry of Housing, City, and Territory (2020) as "one that has the elements that ensure its habitability, with quality standards in urban, architectural, and construction design and whose maximum value is 150 current legal minimum monthly salaries (150 SMLMV)".

For 2021, SH has become one of the main strategies to provide a home for Colombian families. However, these houses are not built taking into account environmental conditions or sustainability parameters that guarantee low energy consumption.

Giraldo & Herrera (2017) and Giraldo et al. (2015) explain that passive air conditioning strategies are not implemented in Colombian SH, but mechanical ventilation systems are usually used to help improve the building's feeling of internal comfort, which generates greater energy consumption. Hence, SH in Colombia is not designed to face the context's current or future climatic conditions o without using active strategies that help to improve comfort conditions. Giraldo & Herrera (2017) argue that the scientific management of comfort through passive strategies is disregarded when designing these homes, which consequently, generates decontextualized buildings that do not guarantee the well-being of their inhabitants.

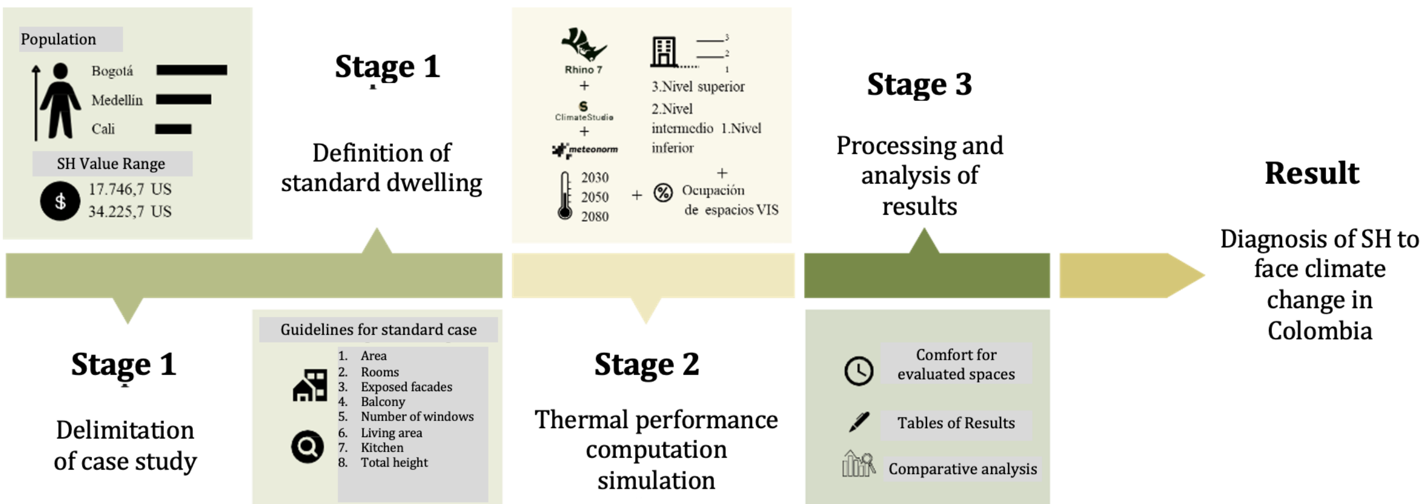

Figure 2. Graphic summary of the methodology implemented for the research. Source: Preparation by the authors.

Table 1. Relative humidity and average temperature for the evaluated cities. Current scenario and future scenarios. Source: Preparation by the authors.

City	Year	Average temperature* (°C)	Relative humidity (%)	Average Temperature* coldest day (°C)	Average Temperature* hottest day (°C)	Temperature* range in comfort (ASHRAE 55, Comfort 90)
Bogota	Current	13.2	81.7	11.9	13.8	24.4 - 19.4
	2030	14.4	80.8	12.3	15.6	24.8 - 19.8
	2050	15	80.6	12.6	16.6	25 - 20
	2080	16.3	80.4	14.1	17.3	25.4 - 20.4
Data taken from the Bogotá/Eldorado weather station, Latitude: 4.717° Longitude: -74.15°, Altitude: 2,548 masl						
Medellín	Current	21.8	70.8	21.4	26.3	27.1 - 22.1
	2030	22.1	77.2	22.7	26.2	27.2 - 22.2
	2050	22.6	77.3	23	26.4	27.3 - 22.3
	2080	23.8	77.4	23	26.9	27.7 - 22.7
Data taken from the Medellín/Olaya Herrera weather station, Latitude: 6.217° Longitude: -75.6°, Altitude: 1,499 masl						
Cali	Current	23.4	76.3	21.8	25.6	27.6 - 22.6
	2030	24.8	74.9	22.3	28.4	28 - 23
	2050	25.3	74.9	23.1	28.8	28.1 - 23.1
	2080	26.4	75.1	24.2	29	28.5 - 23.5
Data taken from Cali CO weather station, Latitude: 3.4°, Longitude: -76.5°, Altitude: 944 masl						

*Dry bulb temperature

METHODOLOGY

This research implemented an experimental and quantitative methodology that allowed diagnosing the climate change adaptation capacity of SH in Colombia. The methodology included three stages: a first stage to delimit the case study and define the type of housing to be evaluated. A second one, where thermal performance computer simulations were run for standard houses in the three selected cities (Bogotá, Medellín, and Cali), considering future climate projections (2030/2050/2080). Finally, a third stage, which included processing the results obtained and making a comparative analysis, that considers the relationship between time and place.

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Table 2. Occupancy patterns and artificial lighting. Source: Preparation by the authors.

Schedule	Occupation patterns		Artificial lighting patterns (DPI) (5w/m²)	
	Rooms (%)	Living Room/Kitchen (%)	Rooms (%)	Living Room/Kitchen (%)
00:00 - 00:59	100	0	0	0
01:00 - 01:59	100	0	0	0
02:00 - 02:59	100	0	0	0
03:00 - 03:59	100	0	0	0
04:00 - 04:59	100	0	0	0
05:00 - 05:59	100	0	0	0
06:00 - 06:59	100	0	100	0
07:00 - 07:59	100	0	100	0
08:00 - 08:59	0	0	0	0
09:00 - 09:59	0	0	0	0
10:00 - 10:59	0	0	0	0
11:00 - 11:59	0	0	0	0
12:00 - 12:59	0	0	0	0
13:00 - 13:59	0	0	0	0
14:00 - 14:59	0	50	0	0
15:00 - 15:59	0	50	0	0
16:00 - 16:59	0	50	0	100
17:00 - 17:59	0	50	0	100
18:00 - 18:59	0	100	0	100
19:00 - 19:59	0	100	0	100
20:00 - 20:59	0	100	0	100
21:00 - 21:59	0	100	0	100
22:00 - 22:59	100	0	100	0

Figure 2 outlines and describes in detail the methodological process of the research.

To delimit the case study, the SH located in the country's three most populous cities was considered, which, according to the latest population and housing census of 2018, are Bogotá, Medellín, and Cali (National Administrative Department of Statistics, 2018). Then, the commercial value range defined for SH in the country was identified, which for 2022 ranges from US $17,746.7 (70 SMLMV) to US $34,225.7 (150 SMLMV).

After defining the range and location, data on the current offer in the real estate sector was collated using websites, to determine a typified housing model in each of the cities being studied. In this phase, 20 recently completed multifamily SH projects, or ones under construction, were considered. Of these, eight aspects of the evaluated housing typologies were identified: apartment area, number of rooms, number of exposed facades, the inclusion of a balcony, number of windows per room, living area and kitchen, and total height of the building.

Once each standard dwelling was established, thermal performance computational simulations were run in the Rhinoceros 3D software with the ClimateStudio plug-in, which is supported by the EnergyPlus calculation engine for its thermal performance simulations (Solemma, 2020). This allows making simulations for energy efficiency, daylight access, artificial light performance, and aspects of thermal and visual comfort.

To run the simulations, climate files were taken from the main weather stations for each of the selected cities. Subsequently, these files were processed through the Meteonorm climate projection software

Table 3. Metabolic rate and internal loads established by city. Source: Preparation by the authors.

Standard apartment - Bogota					
Space	Area (m²)	Num. of people	People/m²	Metabolic rate	Equipment (kW)
Kitchen / Living Room	15.8	4	0.25	1.8	7.59
Master bedroom	8.25	2	0.24	0.7	n/a
Room 1	4.97	1	0.2	0.7	n/a
Room 2	6.61	1	0.15	0.7	n/a
Standard apartment - Medellin					
Kitchen / Living Room	18.03	4	0.22	1.8	6.66
Master bedroom	12.08	2	0.17	0.7	n/a
Room 1	5.96	1	0.17	0.7	n/a
Room 2	5.96	1	0.17	0.7	n/a
Standard apartment - Cali					
Kitchen / Living Room	17.92	4	0.22	1.8	6.7
Master bedroom	9.52	2	0.21	0.7	n/a
Room 1	4.95	1	0.2	0.7	n/a
Room 2	6.17	1	0.16	0.7	n/a

to generate climate files in three future scenarios (2030/2050/2080). The most relevant climate data of the cities evaluated for the current and future scenarios are presented in Table 1.

Along with the analysis of the climatic data, four annual simulations were run (current, 2030, 2050, and 2080) for spaces mainly occupied by the standard housing of each city, varying the orientation of their main facade. The results showed the hourly operating temperature in a given period as the most relevant data, according to the use of the evaluated spaces. Additionally, the variable of dwelling location in relation to the building was considered. Thus, three situations were simulated for each type of house: the first on the first floor, the second on an intermediate floor, and the third on the top floor.

To define occupancy schedules, artificial lighting patterns, the number of people, and the thermal load of equipment, the regulations established by the Brazilian Association of Technical Standards (ABNT) (2013), which manage clear and consistent standards with the Colombian reality, were taken into account (Table 2). Regarding the metabolic rate, the figures determined by the CBE thermal comfort tool were used, which has specific standards for each activity (Table 3). Natural ventilation, as it is a passive space, is considered through the openings, which were assigned an operating temperature, an opening percentage, and a given schedule (Table 4).

On the other hand, for a while now climate change projection scenarios have been created as a tool for research and assessment of the impact and mitigation of climate change. These are defined as "[...] alternatives based on assumptions, of how the world will evolve, so they are not forecasts, since they are not associated with probabilities" (Escoto et al., 2017) and are published by the Intergovernmental Panel on Climate Change (IPCC).

The main objective of these scenarios is to facilitate the research and evaluation of climate change, reducing the range of uncertainty in the efforts made for its mitigation and adaptation (O'Neill et al., 2014). This is why authors such as Kebede et al. (2018) and O'Neill et al. (2014) recommend that the scientific community considers a set of common scenarios.

Notwithstanding this, for this research, it was only possible to generate scenario A2 of the SRES scenarios for the climate files considered, which represents one of the least optimistic scenarios of this set. According to what has been proposed in

Table 4. Temperature, percentage, and time enabled for window opening. Source: Preparation by the authors.

City	Year	Operating temperature that enables the opening of a window	Percentage of effective window opening	Schedule enabled for window operation
Bogota	Current	21.9	50% (sliding opening system)	Hours of occupancy determined for each space. See Table X
	2030	22.3		
	2050	22.5		
	2080	22.9		
Medellín	Current	24.6		
	2030	24.7		
	2050	24.8		
	2080	25.2		
Cali	Current	25.1		
	2030	25.5		
	2050	25.6		
	2080	26		
Infiltrations considered		Infiltration renewal rate: 0.5 air changes per hour		

Table 5. Characteristics of SRES scenarios. Source: Preparation by the authors based on the translation and adaptation of Quante & Bjørnæs (2016) made by Pereira Ruchansky (2019).

Scenario	Description
A1	Very fast world economic growth, reaching the maximum world population by mid-century, alternative development of energy technologies. It is divided into three groups, which reflect technological change alternatives: intensive in fossil fuels (A1FI), energies of non-fossil origin (A1T), and balance between the different sources (A1B)
A2	Very heterogeneous world with strong population growth, slow economic development, and slow technological change
B1	Scenario with the same world population as A1, but with a faster evolution of economic structures towards a service and information economy.

the academic literature, this scenario is equivalent to a midpoint between CPR scenarios 6 and 8.5 (Pereira Ruchansky, 2019). On the other hand, regarding the cumulative total of CO_2 emissions between 1990 and 2100 for different scenario groups, it is established that scenario A2 could be close to SSP3 and SSP4 (Pedersen et al., 2021). The scenario considered is described in Table 5.

Next, the results obtained from the described simulations were analyzed, considering the ASHRAE 55:2020 Adaptive Comfort Standard for naturally ventilated buildings. This allowed identifying the thermal comfort level for each of the spaces evaluated in the homes using the percentage of time in comfort established by said standard.

To evaluate thermal performance, multiple standards and norms have been created worldwide, such as the Building Thermal Installations Regulation (RITE), the ISO 7730:2005 Standard, ASHRAE 55:2020, and the UNE-EN 16798-1:2020 Standard. However, within Colombian regulations, there is no national standard that allows objectively evaluating comfort.

Table 6. Constructive characteristics of standard housing for each city. Source: Preparation by the authors.

City/characteristic	Cali	Medellín	Bogota
Area (m^2 - by ranges)	$50m^2$ - $60m^2$	$50m^2$ - $60m^2$	$50m^2$ - $60m^2$
Number of rooms	2 rooms	3 rooms	2 rooms
Exposed facades	1 exposed facade	1 exposed facade	1 exposed facade
Existence of balcony	With balcony	With balcony	Without balcony
Bedroom windows	1 window	1 window	1 window
Kitchen windows	without windows	1 window	1 window
Living room windows	1 window	1 window	1 window
Number of floors	8 floors	23 floors	12 floors
Indoor ceiling height	2.24m	2.20m	2.30m
Interior floor finishing	Exposed concrete (without leveling mortar)	Exposed concrete (with leveling mortar)	Exposed concrete (without leveling mortar)
Materiality interior walls	Brick partition walls with an average thickness of 12cm		
Materiality external walls	Exterior walls in reinforced concrete with light colored finish (e.g., white, yellow, light blue)		Exterior walls in reinforced concrete finished in dark colors (e.g., Dark gray, dark brown)
Slab materiality and finish	10cm thick solid slab. Finished on the underside with white textured paint		
Materiality of the roof	10cm thick solid slab. Finished on the underside with white textured paint. Finished on the upper side with waterproofing and 5cm mortar		
Window installation	3mm natural aluminum and clear glass window		
Thermal transmittance of opaque materials			
City	Constructive element	U-Value [W/m²K]	Heat Capacity [[k]/m²k]
Bogota - Cali - Medellin	Roof	3.696	272.32
	Walls facades	3.911	367.92
	Interior walls	2.861	227.52
	Mezzanine slab	4.444	229.575
	Subfloor slab	3.39	570
Characteristics of translucent elements			
City	U-Value [W/m²K]	SHGC	Tvis
Bogota - Cali - Medellin	5.82	0.818	0.877
Fixed and mobile protective elements			
In no case were protective elements considered on the windows, either fixed or mobile (ex: eaves, curtains)			

This research considered the ASHRAE 55:2020 Standard for data processing, as it has been widely cited in related regulations and green building certification systems, in addition to being considered as one of the most appropriate to evaluate the thermal performance of free-running homes (Rubio et al., 2017). This is based on the predicted percentage of dissatisfied people (PPD) and predicted mean vote (PMV) as most of the cited standards. This standard proposes a model to determine the thermal comfort requirements in naturally ventilated buildings and is only applicable when the occupants perform a sedentary activity, with a metabolic rate of between 1 and 1.3 met. It also contemplates two upper and two lower operating temperature limits, which are for an acceptability index of 80% and 90% respectively, by which the comfort range for a certain space is defined (Godoy, 2012). The comfort ranges of 90% acceptability for each evaluated scenario are presented in Table 6.

Regarding the definition of standard housing, based on the search carried out in the real estate sector, the characteristics were defined to establish one for each study city. The aspects evaluated are presented in

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Figure 3. Architectural floorplans of standard housing for Cali, indicating the location of openings and obstructions. Source: Preparation by the authors.

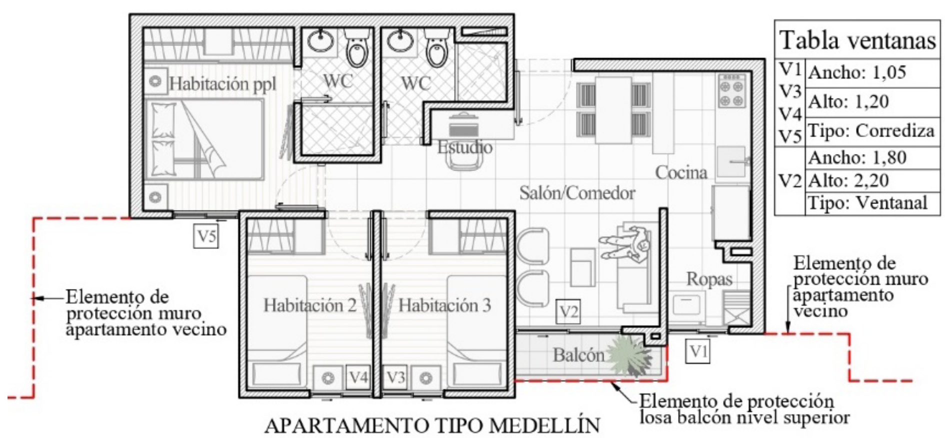

Figure 4. Architectural floorplans of standard housing for Medellin, indicating the location of openings and obstructions. Source: Preparation by the authors.

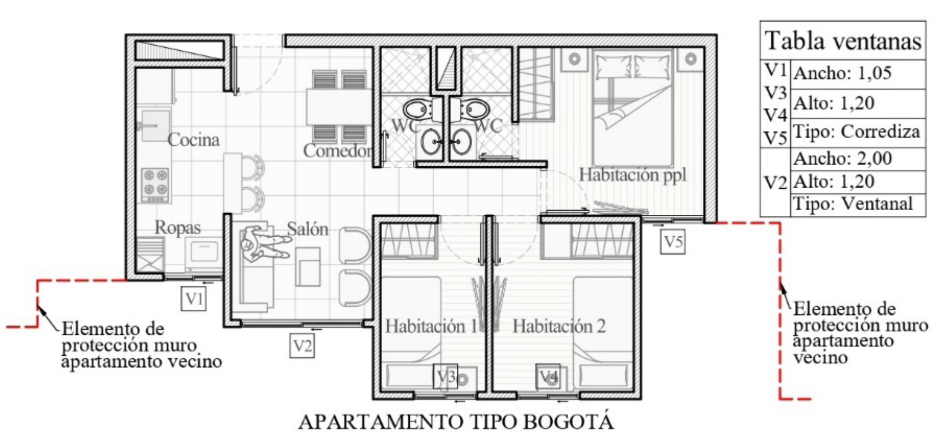

Figure 5. Architectural floorplans of standard housing for Bogota, indicating the location of openings and obstructions. Source: Preparation by the authors.

Table 7. Summary of the results obtained by percentage of favorable scenarios. Source: Preparation by the authors.

City	Floor	Year	Kitchen and living room	Master bedroom	Bed. 1	Bed. 2	Percentage of favorable scenarios by city	Percentage of total favorable scenarios
Cali	First floor	Current	100%	25%	100%	50%	26%	18.92%
		2030	100%	25%	100%	100%		
		2050	100%	25%	100%	100%		
		2080	100%	25%	100%	100%		
	Intermediate floor	Current	0%	0%	0%	0%		
		2030	0%	0%	0%	0%		
		2050	0%	0%	0%	0%		
		2080	0%	0%	0%	0%		
	Top floor	Current	0%	0%	0%	0%		
		2030	0%	0%	0%	0%		
		2050	0%	0%	0%	0%		
		2080	0%	0%	0%	0%		
	Percentage of favorable scenarios by space		33.33%	8.33%	33.33%	29.17%		
Medellín	First floor	Current	50%	0%	0%	0%	14%	
		2030	50%	0%	0%	50%		
		2050	75%	25%	25%	50%		
		2080	100%	50%	100%	100%		
	Intermediate floor	Current	0%	0%	0%	0%		
		2030	0%	0%	0%	0%		
		2050	0%	0%	0%	0%		
		2080	0%	0%	0%	0%		
	Top floor	Current	0%	0%	0%	0%		
		2030	0%	0%	0%	0%		
		2050	0%	0%	0%	0%		
		2080	0%	0%	0%	0%		
	Percentage of favorable scenarios by space		22.92%	6.25%	10.42%	16.67%		
Bogota	First floor	Current	50%	25%	0%	0%	17%	
		2030	50%	25%	0%	0%		
		2050	0%	0%	0%	0%		
		2080	25%	0%	0%	0%		
	Intermediate floor	Current	75%	100%	0%	0%		
		2030	75%	100%	0%	0%		
		2050	25%	50%	0%	0%		
		2080	75%	100%	25%	0%		
	Top floor	Current	0%	0%	0%	0%		
		2030	0%	0%	0%	0%		
		2050	0%	0%	0%	0%		
		2080	0%	0%	0%	0%		
	Percentage of favorable scenarios by space		31.25%	33.33%	2.08%	0.00%		

Table 8. Consolidated percentage of scenarios where 70% or more of the time in thermal comfort is achieved. Source: Preparation by the authors.

City	Cali	Medellín	Bogota	Total scenarios
Current	12%	2%	9%	22%
2030	12%	4%	10%	25%
2050	12%	6%	3%	20%
2080	12%	12%	9%	33%

Table 6 and the most representative characteristics are identified for each of them. On the other hand, Figure 3, Figure 4 and Figure 5 represent their architectural floorplans.

RESULTS AND DISCUSSION

To process and analyze the results, the starting point was to define a minimum unit of analysis, i.e., one scenario. In total, 576 scenarios were analyzed, which comprise the following analysis parameters: a city, a space, a year, a location in relation to the building, and an orientation. The results of the operating temperatures in the occupancy schedules for each scenario were compared to the comfort range determined for each case, to identify the time that scenario is within thermal comfort.

Subsequently, a minimum value was defined that establishes a scenario as "acceptable" in terms of thermal comfort. Within the academic literature, the limits of acceptability for the predicted mean vote index (PMV) have been investigated, considering variables such as fluctuations in outdoor temperature during the day or year (Lenzuni, 2021), as well as in the validation of indicators to evaluate indoor thermal comfort, such as, for example, the percentage of time a space is within the thermal comfort range (Rueda et al., 2023). However, minimum acceptability related to a space's time in thermal comfort was not found.

Consequently, for the analysis of the obtained results, it was considered that the scenarios with 70% or more of the time within the thermal comfort range would be spaces with an "acceptable" thermal performance. This value is defined by considering that the evaluated scenarios are free running, a condition that makes it difficult to achieve 100% of the time in thermal comfort.

A summary table was obtained (Table 7) with the information obtained, on one hand, that identifies the percentage of scenarios by space, by city, and totals found within that acceptable range of time in comfort. On the other hand, the percentage of favorable scenarios for each year, by city and total scenarios, was summarized in Table 8, identifying the variations between years.

Additionally, the most favorable and unfavorable scenarios for each city are identified in Figure 6, considering the combination of the analysis parameters that yielded the longest and shortest time in comfort.

From the results obtained, particular behaviors by city, and also general trends, are observed. From a general perspective, for Cali and Medellín a differentiated behavior appears between the first, intermediate, and top floors. For the first floor, a higher percentage of time in thermal comfort is seen in most of the analyzed spaces, regardless of orientation or year evaluated. In contrast, for these same cities, apartments on intermediate and upper floors have a higher percentage of time above thermal comfort in the evaluated scenarios, indicating high thermal gains, a situation also found by Murillo et al. (2022) for existing SH in the city of Medellín.

Also, a pattern is observed concerning the times of thermal discomfort. In Medellín and Cali, for most of these scenarios, the main cause is high temperatures. On the other hand, in Bogotá, there are only situations with low temperatures (Table 9). This condition could be evaluated according to research such as that of Pérez-Fargallo et al. (2018), where specific comfort standards are proposed for each case. It is also assumed that the situation described considers the specific climatic conditions of each city.

From analysis by city, it is seen that Cali has only 26% of the scenarios evaluated within an acceptable time in comfort range. However, the variations in the resulting percentages for these do not occur between each year evaluated. This indicates that, for this context, the comfort deficit does not seem to be a consequence of climate change, but rather the current design of SH for Cali. Given this, ensuring a thermally comfortable home for the current scenario should be the priority, which in turn would mean that it would be prepared for the future climate change scenario.

On the other hand, in Bogotá there is a longer time in thermal comfort when the exposed facade faces east and west, compared to the north and south orientation, which do not have a direct solar incidence due to the behavior of the sun in Colombia.

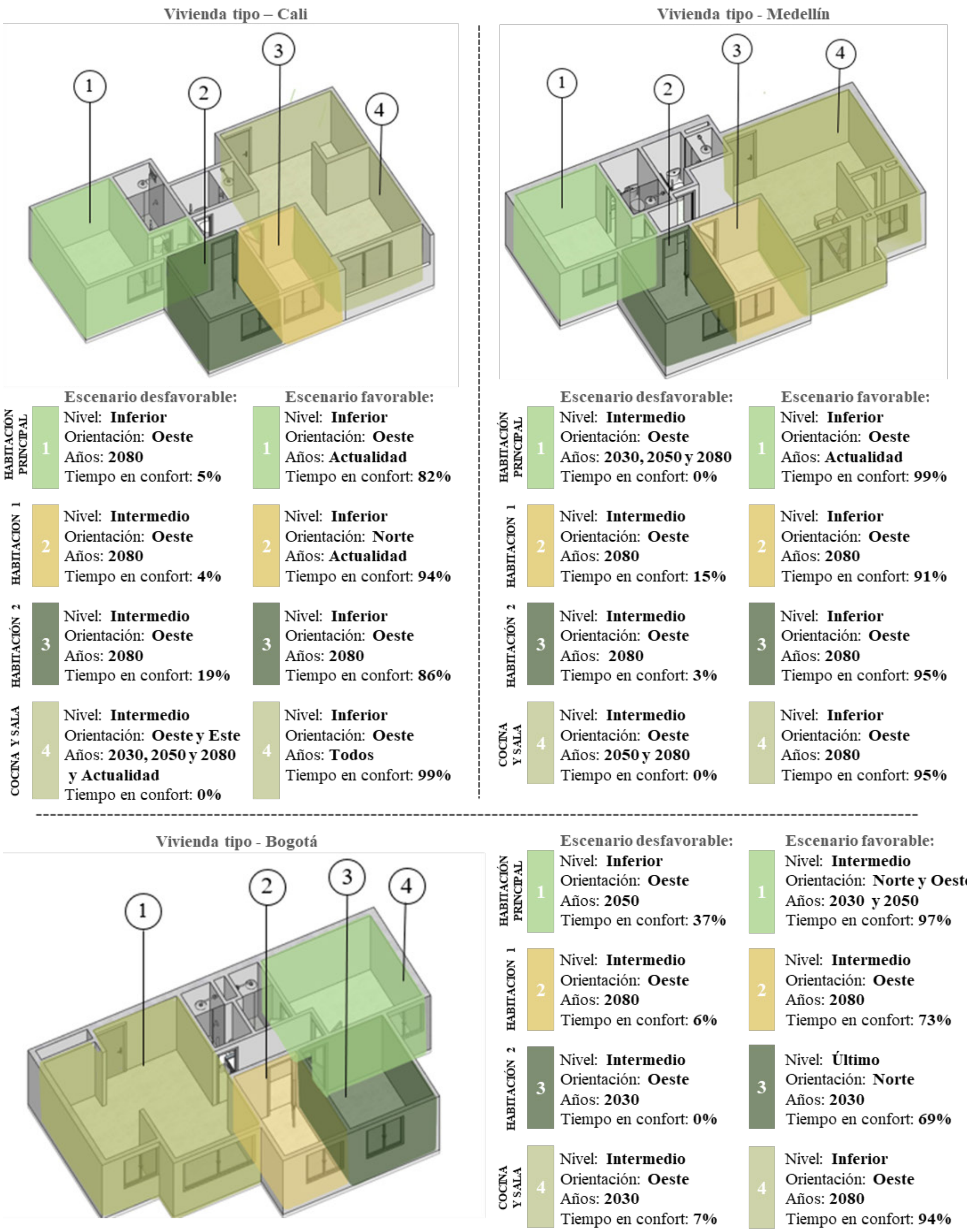

Figure 6. The most unfavorable and favorable scenarios for each analyzed city and space. Source: Preparation by the authors.

Table 9. Percentage of scenarios in discomfort by city and totals by location within the comfort range. Source: Preparation by the authors.

City	Space	A higher percentage of time above the comfort range	A higher percentage of time below the comfort range
Cali	Kitchen and living room	67%	0%
	Master bedroom	67%	25%
	Bedroom 1	67%	0%
	Bedroom 2	67%	0%
	Percentage of all scenarios for Cali	67%	6%
Medellín	Kitchen and living room	67%	10%
	Master bedroom	67%	27%
	Bedroom 1	67%	23%
	Bedroom 2	67%	17%
	Percentage of all scenarios for Medellin	67%	19%
Bogota	Kitchen and living room	0%	65%
	Master bedroom	0%	67%
	Bedroom 1	0%	98%
	Bedroom 2	0%	100%
	Percentage of all scenarios for Bogota	0%	82%
Percentage of all scenarios evaluated		44%	36%

Finally, the space with the greatest impact on climate change is the bedrooms, where the differences in comfort time between the years evaluated are more marked, different from the kitchen where the variations are between 1%-2%.

CONCLUSIONS

From all the scenarios evaluated (576), only 18.9% are within an acceptable range of time in thermal comfort. Within this figure, Cali is the city where higher percentages of time in thermal comfort are observed, both currently and in the climate change projection, where 26% of the scenarios evaluated for this city are within the comfort temperature range, a low percentage nonetheless. Additionally, it is surprising that, for all the cases evaluated in the three cities, there is a favorable trend over time. For example, by 2080 the percentage of favorable scenarios increases by 11%, compared to the percentage of favorable scenarios for the current climate, for which 78% of the cases evaluated are outside the range in thermal comfort.

This indicates that most of the SH currently built in Colombia do not provide thermal comfort conditions either in a climate change scenario or in the current scenario, because in both situations the favorable cases represent a low percentage of all the cases evaluated. This situation is aggravated by the similarity found between the architectural designs of apartments in different cities, as it evidences a disconnect with the climatic context, which could be one of the main reasons why situations such as those reflected in the results obtained are presented.

For future research, it is urgent to investigate design strategies that respond to climate change for new homes, as well as climate change adaptation strategies for existing homes, considering in both scenarios, as a first measure, satisfying the thermal comfort of the current context. The particular analyses by city, as well as the identification of some trends described in the previous section, can serve as a starting point.

It should also be noted that considerations such as not including pre-existences or neighbors were taken into account within the simulations, since there was no estimated environment because these were hypothetical situations. Additionally, the routines for the user considered are those established by international standards, meaning that they do not adhere to the Colombian sociocultural reality. This is because, at present, there is no profile created that can be studied in this type of specific analysis.

Finally, on being research that does not consider real measurements of the spaces, its conclusions, although they may give indications of possible situations, should be corroborated in future research with on-site measurements and thermal comfort perception surveys.

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THERMAL, LIGHT, AND THERMOGRAPHIC EVALUATION OF A WOODEN HOUSING SOLUTION IN A WARM TEMPERATE CLIMATE FOR LOW-INCOME HOUSING

EVALUACIÓN TÉRMICA, LUMÍNICA Y TERMOGRÁFICA DE UNA SOLUCIÓN HABITACIONAL DE MADERA EN CLIMA TEMPLADO CÁLIDO PARA EL HÁBITAT POPULAR

AVALIAÇÃO TÉRMICA, LUMÍNICA E TERMOGRÁFICA DE UMA SOLUÇÃO HABITACIONAL DE MADEIRA EM CLIMA TEMPERADO QUENTE PARA O HABITAT POPULAR

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RESUMEN

El acceso a la vivienda en los sectores sociales de bajos ingresos plantea la necesidad de una reflexión relevante para América Latina. En este contexto, se ha desarrollado una Solución Habitacional Modular (SHM) de madera en un barrio de la periferia de CABA llamado el Partido de La Plata, orientada a la mejora habitacional de sectores populares y gestionada por una cooperativa de trabajo, la universidad y el sector científico-técnico. Se tiene por objetivo evaluar el comportamiento térmico, lumínico y las condiciones de estanqueidad en la envolvente edilicia de una SHM de madera del sector Partido de la Plata en un clima templado-cálido. Para ello, en primer lugar, se realizó un monitoreo interior y exterior (temperatura, humedad relativa e iluminación natural), luego se evaluaron los calefactores solares de aire y finalmente se realizó termografía digital nocturna. Los resultados muestran desempeños favorables en el aspecto lumínico diurno y una buena respuesta térmica diurna en épocas frías. No obstante, también se encontraron fenómenos por mejorar, como la necesidad de acondicionamiento térmico nocturno, de mejora de la estanqueidad de la envolvente, de ventilación nocturna en épocas cálidas de refuerzo del sombreo y del aislamiento térmico.

Palabras clave
hábitat, madera, sistemas modulares, evaluación.

ABSTRACT

Access to housing in low-income sectors brings up the need for a relevant reflection on Latin America. In this context, a wood-based Modular Housing Solution (MHS) has been developed in a neighborhood on the outskirts of CABA called La Plata, oriented to a housing improvement for working-class sectors, and managed by a labor cooperative, the university, and the scientific-technical sector. The objective is to evaluate the thermal and light behavior and the airtightness conditions of the building envelope of a wooden MHS in the La Plata district in a warm-temperate climate. For this purpose, first, indoor and outdoor monitoring (temperature, relative humidity, and natural lighting) was carried out, then the solar air heaters were evaluated, and finally, digital thermography was performed at night. The results show favorable daytime lighting performance and good daytime thermal response in cold weather. However, there was also room for improvement, such as the need for thermal conditioning at night, improvement of the airtightness of the envelope, night ventilation in warm seasons, reinforcement of shading, and thermal insulation.

Keywords
habitat, wood, modular systems, evaluation.

RESUMO

O acesso à moradia nas camadas sociais de baixa renda levanta a necessidade de uma reflexão relevante para a América Latina. Nesse contexto, foi desenvolvida uma Solução Habitacional Modular (SHM) de madeira em um bairro da periferia da CABA (Cidade Autônoma de Buenos Aires) chamado Partido de La Plata, com foco na melhoria habitacional das camadas populares e gerenciada por uma cooperativa de trabalho, a universidade e o setor científico-tecnológico. O objetivo é avaliar o desempenho térmico, lumínico e as condições de estanqueidade do envelope construtivo de uma SHM de madeira na região do Partido de La Plata em um clima temperado-quente. Para isso, em primeiro lugar, foi realizado um monitoramento interno e externo (temperatura, umidade relativa e iluminação natural), em seguida, foram avaliados os aquecedores solares de ar e, por fim, foi realizada termografia digital noturna. Os resultados mostram desempenhos favoráveis na iluminação diurna e uma boa resposta térmica diurna durante períodos frios. No entanto, também foram encontrados aspectos a serem melhorados, como a necessidade de condicionamento térmico noturno, melhoria na estanqueidade do envelope, ventilação noturna em períodos quentes, reforço do sombreamento e isolamento térmico.

Palavras-chave
habitat, madeira, sistemas modulares, avaliação.

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INTRODUCTION

The habitat is a symbolic-imaginary reference to human existence where dimensions such as the political, economic-social, aesthetic-cultural, ethical, and environmental intervene. Within this framework, suitable housing raises both the need for land tenure security and the availability of services and infrastructure (drinking water, sanitation, accessibility, and culture) and is understood as a multidimensional process that contemplates the right to a dignified and healthy "living", and to the enjoyment of the city and public spaces, under the principle of social justice.

At the same time, the Working-Class Habitat is developed as a progressive and spontaneous response to inequalities between the most vulnerable and those who have the most (Miranda-Gassull, 2017), without the collaboration of technicians or professionals, but with limited economic resources and great effort, under what is known as Social Production of Habitat, hereinafter SPH (Migueltorena, 2020; San Juan et al., 2023). SPH generates urban and rural habitable spaces, controlled by self-producers and other social agents operating on a non-profit basis (Enet et al., 2008; Pirez, 2016; Romero-Fernández, 2002, cited in Miranda-Gassull, 2017). It is also a culture of solidarity and complementarity with other social actors, with transformative political, economic, and social implications of power relations. It is understood that SPH is associated with Technologies for Social Inclusion (TSI) through technological solutions for housing. In this regard, Thomas & Becerra (2014) define this as the ways of designing, developing, implementing, and managing technologies aimed at solving social and environmental problems, generating social and economic dynamics of social inclusion and sustainable development, where the main actors are social organizations.

Thus, it is understood that, from the perspective of SPH and TSI, the search for effective and sustainable solutions that collaborate to improve the working-class habitat and the design of suitable housing, must overcome state assistance and produce proposals that strengthen the inhabitants' abilities to overcome their problems based on their own cultural and political guidelines (Pelli, 2007).

A Modular Housing Solution, hereinafter MHS, was born within this context, resulting from social interaction to define responses to build public/social policies for vulnerable sectors. Within this framework, the design of a housing unit is proposed, based on establishing project logics for emergency housing situations, which incorporate knowledge, improve the quality of life, train, encourage habitat self-organization and co-management, foster production and work, and generate spaces for integration and exchange.

For materials, it uses wood for its structure and enclosure. Therefore, it is considered that MHS has become an accessible, reliable, and sustainable option compared to traditional building materials since it provides a better thermal quality than traditional masonry construction.

Although there is a high consensus regarding the potential of wood construction due to its energy efficiency and low environmental impact, there are few studies on its thermal, energy, and environmental comfort behavior. It is considered that, faced with the current environmental, climatic, and energy crisis conditions, knowing the thermal behavior of wooden buildings could promote their use.

At an international level, Viholainen et al. (2021) highlight that wood construction can reduce embodied carbon in construction and focus analysis on the perception of European citizens about its use to improve its social acceptance. On the other hand, energy rehabilitation assessments do not consider using wood for possible improvements (Pérez Fargallo et al., 2016), evading the important building market that combines wood and construction (Iglesias Gutiérrez del Álamo & Lasheras Merino, 2020; De Aráujo, et al., 2019). However, there are efforts to promote the use of wood, as in Muñiz, et al. (2022), who develop a simplified and flexible system entirely using wood that makes involves more complex work in the workshop to reduce onsite times and processes. In the Latin American sphere, diverse research has demonstrated the benefits of this type of construction (Filio Reynoso et al., 2017; Silva et al., 2023). Garay Moena et al. (2022), for example, highlight the advantages of wood such as its low carbon footprint, industrialization capacity, adoption of domestic and international standards, and its seismic, thermal, and acoustic efficiency. However, its promotion use as a constructive material is needed. Similarly, they highlight that negative perceptions persist in Chile regarding the material's combustibility, its fragility, and its relationship with precarious construction, while the population considers that it does not provide durability or safety (Salazar, 2008). Although it has been used to build working-class housing (Jiménez, 2020), only 14% of constructions use wood (in contrast, in Nordic countries, this index is above 90%), despite having in 2008, the largest forestry industry in Latin America with 2,110,000 ha.

Another example is Uruguay, which has 1,000,000 ha of fast-growing tree species. However, the resource is being wasted due to limited investment in this industry (Dieste et al., 2019). The potential of adding value to the country's forest production is analyzed in this sense, and highlighting the importance of promoting this renewable industry to reduce the environmental impacts of construction. Its greatest impacts take place in the use, maintenance, repair, and replacement phase (in terms of the paint, varnishes, other elements, new parts, etc.), while energy conditioning through construction is significantly lower. Although there have been no studies on the impacts on the habitability of wooden houses, work is currently been done on methodologies that assess their potential from the point of view of the life cycle (Soust-Verdaguer, 2022).

In Argentina, wood construction is considered an important alternative to drive the forestry industry. According to Vogel (2020), as of 2019, the country had 1,300,000 ha of cultivated forests, with suitable species for structural components. According to that author, several companies build approximately 3,500 wooden houses a year, just 3% of all the houses built annually with a building permit. Of these, more than 70% use a structural framing system (platform system or continuous system).

In this regard, it is important to mention the existence of the Center for Training, Technology Transfer, Production and Services in Wood (CTM-FCAyF- UNLP), in the city of La Plata, whose objective is to promote sustainable development and competitiveness of the region's forestry-industrial sector, while producing specialized goods and services. The study presented here appears in this last line, where the UNLP is central in the co-management of this housing.

The proposal for this work is located on the urban periphery of the district of La Plata, the capital of the Province of Buenos Aires, Argentina. This town has 772,618 inhabitants and 260 working-class neighborhoods with more than 50,000 families. Most of the homes are irregular, precarious, and have little or no accessibility to infrastructure, paving, or lighting services (UCALP, 2021). The growth of socioeconomic inequalities is visualized in this way, in the reproduction of an unequal, fragmented, and disputed territory (Dammer Guardia et al., 2019), a situation that has worsened with the COVID-19 pandemic.

In this context, this article presents the progress of two research projects (San Juan, 2018-2021; Viegas, 2021-2024), and in particular, looks to evaluate the thermal behavior, lighting, temperature, and airtightness conditions of the building envelope of a wooden MHS in the district of La Plata, characterized by its temperate-warm-humid climate. The idea is to establish the base behavior, highlight its sustainable aspects, and formulate possible improvements for its replicability in other contexts.

METHODOLOGY

The district of La Plata, Buenos Aires (- 34° 56 00; -57° 57 00) is located on a high plain (23msnm.) on the banks of the La Plata River. Its warm temperate climate with thermal amplitudes of less than 14°C (Argentine bioenvironmental zone III-b) has two marked seasons, winter and summer, with the former prevailing. The average temperature is 15.8°C and the average rainfall is 1007 mm/year. In winter, the average temperature is 9.7°C; RH: 82%; HeatingDD $_{20}$: 1668°C. On the other hand, the average summer temperature is 21.7 °C; RH: 70% (IRAM, 2012).

The HS was built seeking to respond to typological, functional, constructive, and productive flexibility criteria and proposes a linear base module of 30 m^2 with a living-dining room, kitchen, and bathroom, which is expandable to 1 or 2 bedrooms (Figure 1). It can be assembled individually or paired on a plot. It is north-facing and has a semi-covered gallery. Its main components (wooden rings and modulated panels of 1.22 m x 2.44m) are made systematically in a workshop (CTM-UNLP), which allows production in large quantities, as well as reducing waste, economizing materials, providing flexibility in terms of enclosures and the use of recycled materials, and improving the working conditions of builders (Figure 1). Regarding the thermal insulation, it has 0.02 m of EPS in the walls, 0.04 m of EPS in the roof, and 0.04 m of EPS in the floors with a density of 20 kg/m^3. Finally, the total surface area of the windows (bathroom, south-facing, dining room) and doors (sliding door and access door), made of wood with single glazing, is 8.62 m^2.

Its air conditioning system has two solar air heaters in a wooden box (1.22 m x 2.00 m x 0.10 m) that has side holes, with a matt black galvanized corrugated sheet as an absorbing surface (0.5 mm thick), separated 0.03 m from the box on its back, and plain glass as a transparent cover. They are connected to the inside with an upper and lower 110 mm diameter PVC duct with a cover. Table 1 shows the indicators[1] of the housing solution.
For data collection, the process involves the following:

1 Admissible G for residential buildings of 80 m3 and winter DD between 1500 and 2000: 2.15 (IRAM, 2000). K Admissible Level B (recommended). Winter (Outdoor design temp. greater than or equal to 0 °C). Walls 1 W/m2 °C; Roofs 0.83 W/m2 °C. Summer (bioenvironmental zone IIIb). Walls 1.25 W/m2 °C; roofs 0.48 W/m2 °C (IRAM, 1996).

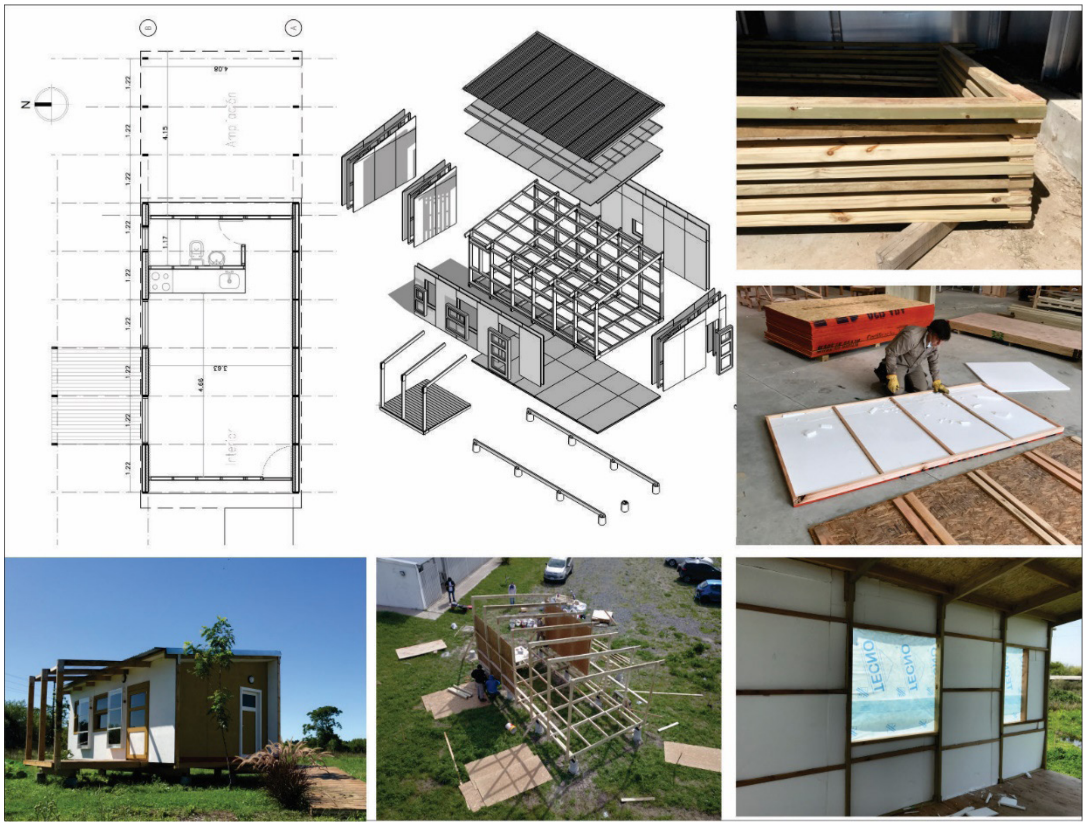

Figure 1. Documentation of the housing solution, parts, images of the process, and final result (clockwise from top left). Source: Preparation by the authors

Table 1. Dimensional, morphological, and energy indicators. References: Ci - Compactness index; FF - Form factor; K - thermal transmittance; G - Global loss coefficient. Source: Preparation by the authors

Indoor perimeter (m)	Useable area (m^2)	Indoor Surface area (m^3)	Total surface area of windows and doors (m^2)	Surface area of north windows and doors (m^2)	Surface area of south window (m^2)	Surface area of west door (m^2)	Indoor envelope (m^2)	Ci (%)	FF	Wall K (W/m²°C)	Roof K W/m²°C)	Floor K (W/m²°C)	G (W/°C m³)
21,0	25	80,8	8,62	6,73	0,25	1,64	106,3	1,18	1,5	0,8	0,4	0,7	2

I. HS measurements without occupancy, which include: temperature (°C), relative humidity (%), and illuminance (Lux) between August and November 2021. This was done in discrete 15-minute periods using HOBO UX100-003 micro-data loggers, suspended at 1.2m, two placed in the living/sleeping areas and two supported on the ducts of the solar air heaters (one at the cold air inlet and the other at the hot air outlet) and an outdoor sensor placed suspended under the floor of the overhang (Figure 2);
II. Point-to-point illuminance measurement at a specific time and day using a 20,000 Lutron LUX LT-YK10LX digital light meter;
III. Collection of hourly climate data from the La Plata Observatory (OALP, in Spanish) weather station;
IV. Temperature measurements in °C (similar conditions as step i) to evaluate the potentialities/difficulties of a cross and selective ventilation in an extremely warm period (which was representative of the region's hottest summer days) in December 2022;
V. Evaluation of the temperatures and airtightness of the envelope and its joints (Figure 2) with digital night thermography (21hs), using a Testo 865

Figure 2. Placement of data loggers and thermographic imaging. Source: Preparation by the authors

thermal imaging camera (standard lens FOV 31o x 23o – IFOV 3.4 mrad. 3.5" TFT screen – 320 x 240 pixels) at the beginning of 2022's cold period, and incorporating auxiliary energy inside through a 2000 Wh electric radiator.

The light simulation methodology makes daylight simulations using the *Velux Daylight Visualizer* software for two sunny days with low and high illuminance respectively (August and November)[2]

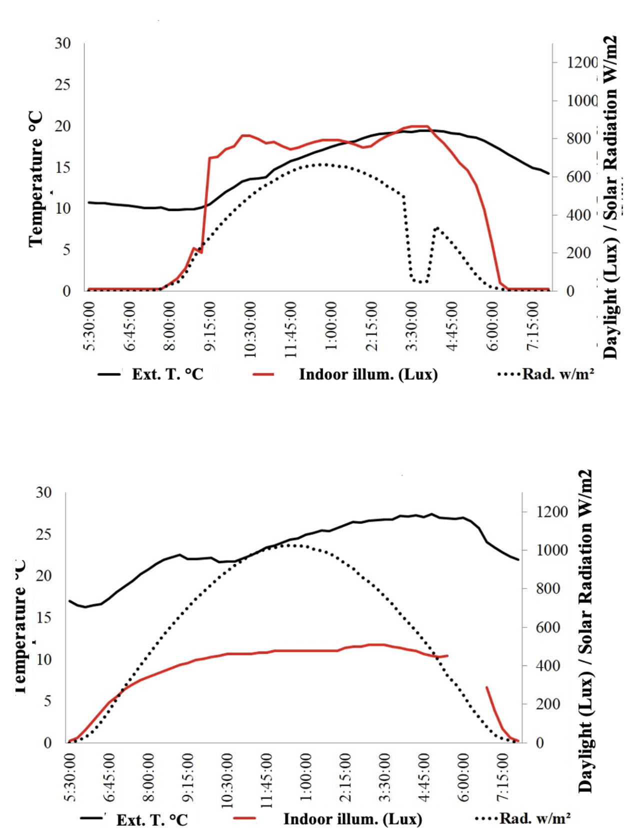

Figure 3. Specific measurement (located on the red star of the floorplan in Figure 3) of the daylight in the main room in August (left) and November (right). Source: Preparation by the authors

RESULTS

INDOOR DAYLIGHT

The specific measurements were analyzed on an August day when a maximum of 800 lux was recorded (coinciding with the entry of the sun's rays), and in November, recording a maximum of 500 lux, as the sun's entry is reduced due to the design and orientation (Figure 3). Considering the measured point as an average, it is observed that for a sunny August day (representative of 35% of the month's days)[3], auxiliary lighting is not required between 9 am and 6 pm, as stated by IRAM (1969)[4].

Next, point-to-point measurements in the main room were compared (Figure 3) with simulations for two sunny days with low and high horizontal global

2 The measurement months were validated based on the standard design days for the La Plata region. The measurement day in August has average (solar midday) values of 670 W/m2 for global solar radiation and 77,000 Lux for global illuminance (the most unfavorable condition is in June with 560 W/m2 and 55,440 Lux). The day in November has an average (solar midday) global solar radiation value of 1070 W/m2 and an illuminance of 107,000 Lux (the most unfavorable condition is December with 1100 W/m2 and 110,000 Lux).

3 On overcast days (35% of the month's days have relative heliophania between 20% and 70%), the global horizontal illuminance is reduced to 40,000 lux.

4 In the dining room/living room, the general illuminance level is 50 lux and the specific one is up to 150 lux.

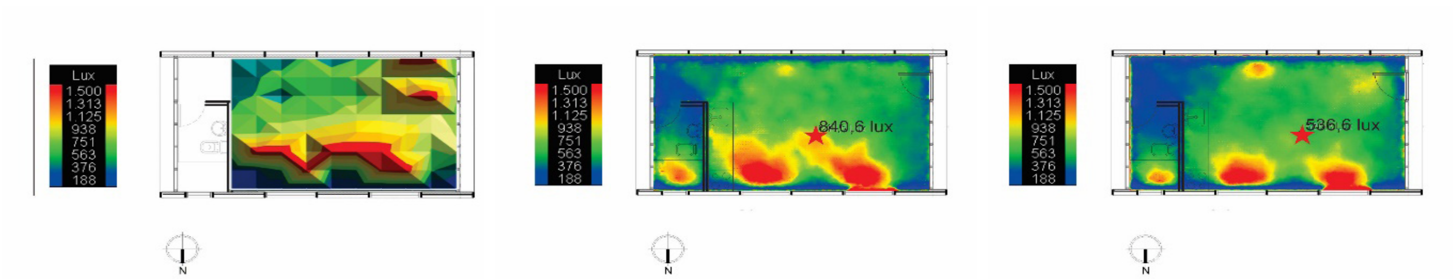

Figure 4. Point-to-point measurements for August 24th at 3 pm (left), daylight simulation on a sunny day at 3 pm in August (center), and November (right). Source: Preparation by the authors

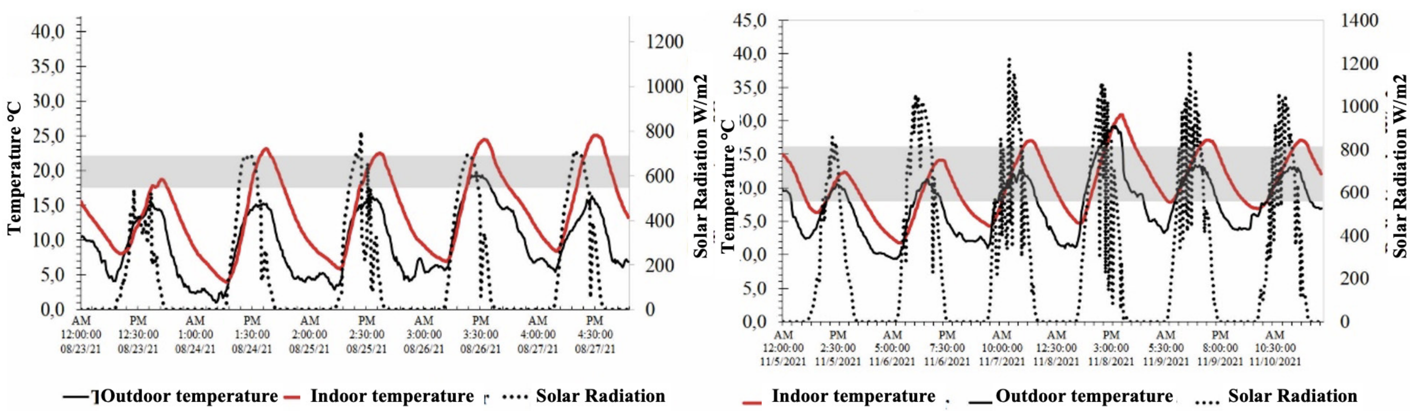

Figure 5. Thermal behavior in August (left) and November (right). Source: Preparation by the authors.

illuminance, respectively, to check the distribution of the illuminance E (Lux) at a given point and time of measurement (Figure 4)

The *in-situ* point-to-point measurements in August show a greater uniformity in space (with minimum values of 500 lux). Alongside this, they highlight the light contribution of the window located in the access door and show the fit of the simulations. From the fit, the light simulations recorded average values between 500 and 700 lux, in both August and November.

In the location near the window, records of 1500 lux were observed in both months. According to the simulation, 81% of the surface had more than 300 lux in August, 86% of the surface had more than 300 lux in November, and according to the measurements, 97% had more than 300 lux on the surface.

THERMAL BEHAVIOR

Figure 5 shows the MHS's thermal behavior for 5 days in August and November, as well as a thermal comfort level between 18 and 22 °C in winter and extended to 26 °C in summer (Givoni, 1969).

In the graphs, it can be seen that in the cool period, the HS is kept 4°C above the minimum outdoor temperature and 7°C above the maximum outdoor temperature, the latter due to the entry of solar radiation. This condition is verified during days with relative heliophania higher than 70% (08/24 at noon 22.3 °C indoors, 15 °C outdoors). It is also possible to confirm direct solar gain, as well as the heat input provided by solar air heaters. Considering the period within thermal comfort, it is observed that the day-night oscillation is caused by the HS's lack of thermal inertia, for which auxiliary energy would be required between 11.45 PM and 10 AM.

As for the warm period, it can be seen in the graph that the house's behavior is impaired by the absence of vegetation in the pergola and cross ventilation. In this sense, it is seen that with maximum outdoor temperatures of 30°C, the HS raises its maximum temperature by two degrees more than outside. It was then proposed to evaluate the internal conditions

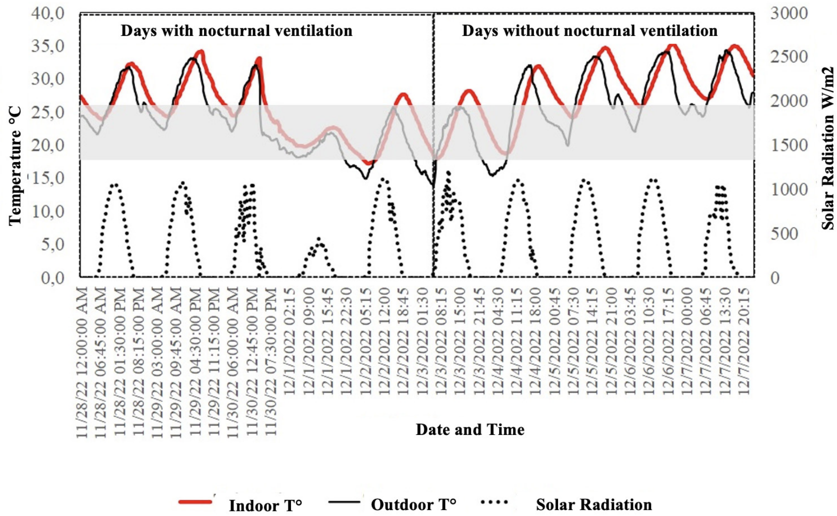

Figure 6. Behavior on warm days with and without nocturnal ventilation (gray indicates the summer comfort level of 18°C to 26°C). Source: Preparation by the authors.

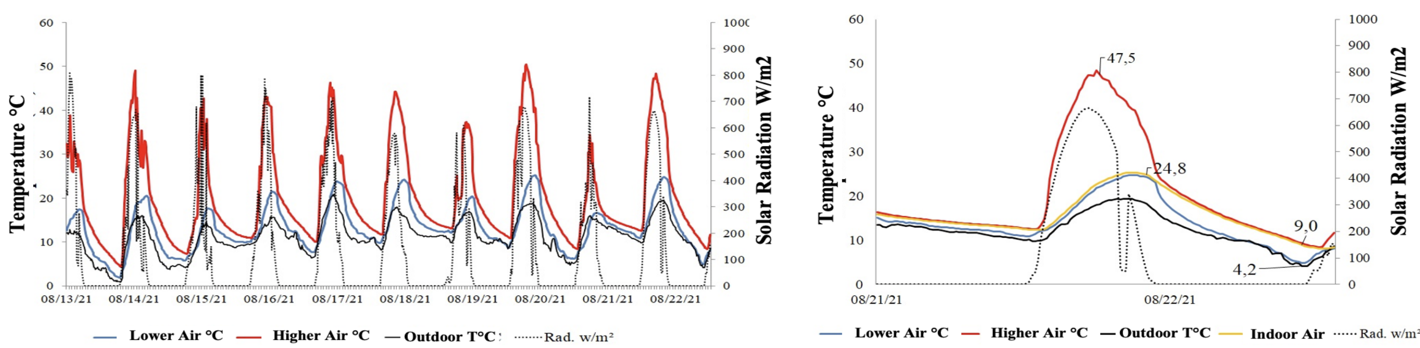

Figure 7. Thermal response of the solar air heater in the cool period. Source: Preparation by the authors.

by recreating actions that are similar to the pergola's vegetation protection, with nocturnal cross ventilation, and blocking the solar heater, in a representative period of very warm days in 2022.

THERMAL BEHAVIOR ON WARM DAYS BY APPLYING NOCTURNAL VENTILATION

For this analysis, cross ventilation (north and south window) was used by opening the south and north windows (crossed) after 5 pm and closing them at 8.30 am to avoid the entry of daytime heat.

The image shows that, on very warm days, similar to summer conditions (average maximum temperature of 35.2 °C in February 2023 heat wave, according to SMN[5]), although indoor temperatures are high (Figure 6) and above the comfort level during the day, the HS allows the temperature to dissipate thanks to its good nocturnal ventilation by opening the lower south (0.4 m x 0.4 m) and north windows (1.2 m x 1.2 m). In the evenings, the temperatures drop to the comfort level. It is considered that the levels are acceptable and could be improved by shading the envelope with surrounding vegetation and improving thermal inertia, possibly incorporated into the HS floors, and reinforcing thermal insulation.

SOLAR AIR HEATERS FOR AIR CONDITIONING

Solar air heaters for the main indoor environment were evaluated in winter as a heat input (Figure 7).
On evaluating 10 consecutive days with good heliophany, the heater registers maximum temperatures between 40 and 50 °C. On a day with good heliophany (700 W/m^2 of maximum solar radiation), the heater reaches 47.5 °C at the hot air outlet, while inside the

5 National Meteorological Service of Argentina (https://www.smn.gob.ar/estadisticas)

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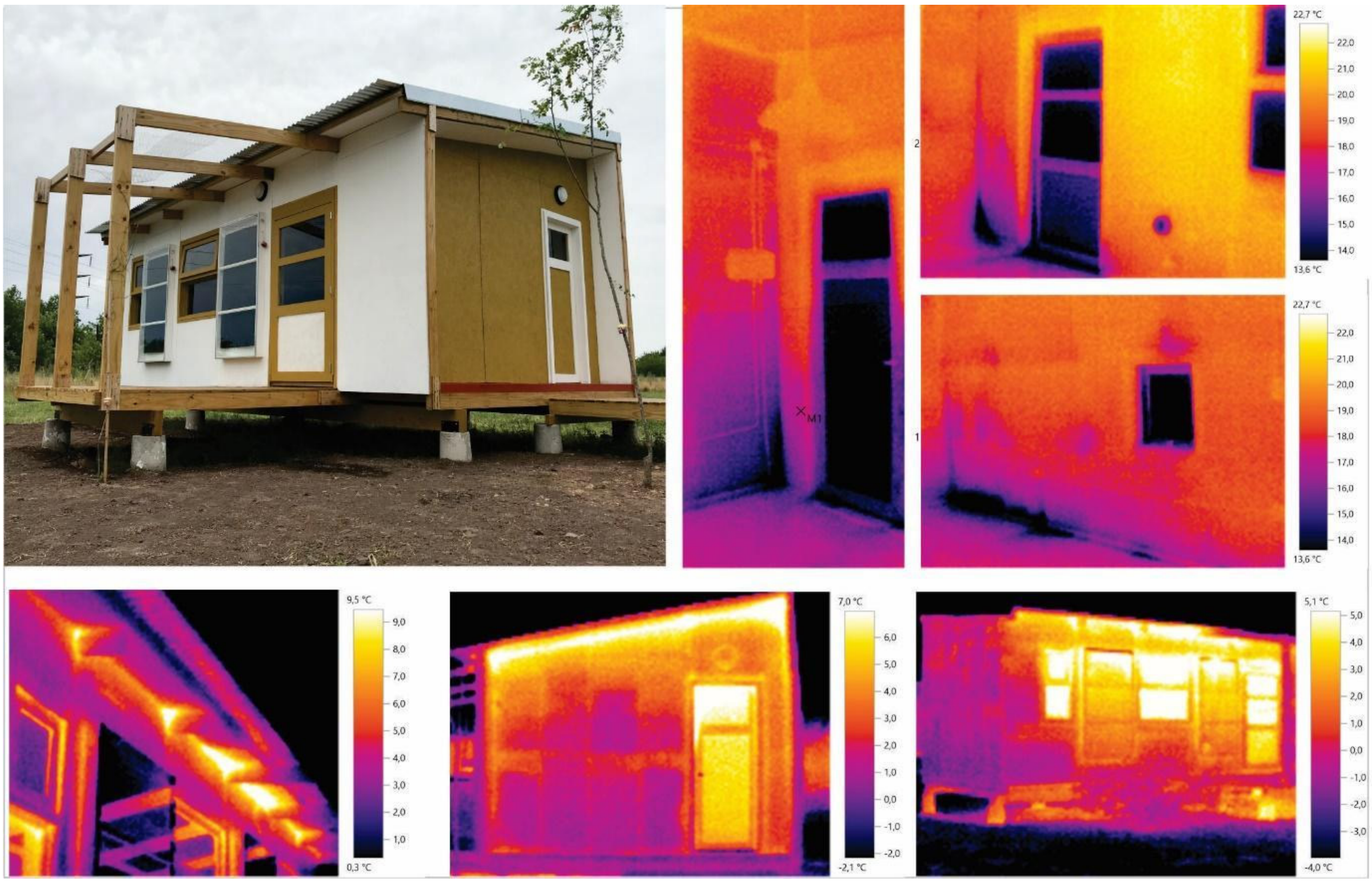

Figure 8. Thermal imaging images taken on 05/27/2022 between 8 and 10 pm. Source: Preparation by the authors.

HS, the maximum is 24.8 °C, almost 5 °C above the maximum temperature. On the other hand, when the sun goes down, the temperatures of the solar system drop because it has no thermal mass. Thus, indoor temperatures are kept at almost 5°C above (9°C) the outdoor temperature (4.2°C). In short, the system has a good thermal response and contributes to indoor conditioning. However, an improvement in thermal inertia made by incorporating mass in floors or using heavy solar-based systems such as a Wall Heat Accumulator (WHA), could reduce the drop in nighttime temperature.

ASSESSMENT OF THE BUILDING ENVELOPE'S TEMPERATURE AND AIRTIGHTNESS

Figure 8 summarizes the evaluation of the thermal envelope's temperatures and airtightness, whose thermal jump between indoor and outdoor temperatures was 10°C. Similarly, it can be seen that indoor wall temperatures are as expected (between 17 and 22°C), as opposed to the low temperatures of the outside walls (less than 6°C). With these figures, it is confirmed that the wooden envelope and its interior thermal insulation do not produce substantial thermal losses. As expected, simple wooden doors and plain glass windows, which are the design conditions of an economic housing solution, are the causes of the greatest losses. In this sense, the use of wooden shutters and reinforcing doors could reduce the aforementioned heat loss. On the other hand, the study allows verifying that the wooden rib structure with internal insulation does not produce considerable thermal bridges. Although critical points are detected (wall and floor joints), where heat leakage is observed with values below 14°C, it should also be noted that no heat losses were detected by wall-roof joints.

Critical points are seen with the exterior. On one hand, in the roof-wall joint and, on the other, in the extension of the wooden braces from the inside to the outside. These sectors would require sealing with suitable elements to avoid thermal losses.

Finally, if this analysis is linked to the HS' behavior on very hot days, the infiltration would cause heat entry in summer, whereby it will be essential to improve the room's airtightness, reinforce thermal insulation, and provide vegetation protection to improve indoor comfort conditions.

CONCLUSIONS

Access to housing in the most vulnerable sectors is self-managed, where housing self-production and self-construction processes become the only way to access land in the dynamics of the working-class habitat. A wooden modular housing solution (MHS) was developed, designed, built in this context, and managed by all the social actors involved, to seek technological developments for social inclusion, which promote self-determination, self-management, and independence from the social groups involved, coinciding with what was stated by Pelli (2007), Thomas & Becerra (2014), Enet et al. (2008), and Pirez (2016). As in Muñiz et al. (2022), intense workshop work was encouraged to reduce construction work and improve the working conditions of cooperative groups.

The analysis of the HS' thermal, light, and airtightness behavior allows supporting the benefits of this type of construction. little analyzed in the international literature (Pérez Fargallo et al., 2016; Iglesias Gutiérrez del Álamo & Lasheras Merino, 2020; De Aráujo et al., 2019), and encourage wood construction (Muñiz et al., 2022; Filio Reynoso et al., 2017; Silva et al., 2023; Garay Moena et al., 2022), which, in line with what was proposed by Dieste et al. (2019), would also add value to the local forest resource through a local production center.

For the daylight analysis in August (on sunny days), considering the value recorded in the center of the space as an average, it could be concluded that, between 9 am and 6 pm, no auxiliary lighting would be required according to IRAM (1969).

As for thermal analysis, it is concluded that it has a good response in cool months since it is conditioned during the day with solar energy. However, the absence of thermal mass means auxiliary energy is needed at night. Solar air heaters contribute well to daytime conditioning. On the other hand, the building envelope registers some critical points with airtightness that require improvement, but in general, it retains heat inside while the external faces of the walls are cold (without heat loss).

Finally, for summer, it is concluded that it is essential to activate nighttime cooling mechanisms to lower the daytime thermal load, along with the need to improve the shading of the exterior envelope and improve airtightness and thermal insulation, given that the level in the climatic conditions evaluated is not sufficient to face excess temperature, unlike in winter.

To conclude, it is essential that in future research, thermal simulations are run to evaluate the improvements needed for summer conditions and under climate change scenarios, and in the same way, evaluate the thermal response of new modular housing solutions that incorporate thermal mass on the floor's surface in warm seasons.

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CONTRIBUTIONS OF THE INVERTED CLASSROOM METHODOLOGY IN THE TEACHING-LEARNING PROCESS OF BIOCLIMATIC ARCHITECTURE

APORTES DE LA METODOLOGÍA DE AULA INVERTIDA EN EL PROCESO DE ENSEÑANZA-APRENDIZAJE DE LA ARQUITECTURA BIOCLIMÁTICA

CONTRIBUIÇÕES DA METODOLOGIA DA SALA DE AULA INVERTIDA NO PROCESSO DE ENSINO-APRENDIZAGEM DA ARQUITETURA BIOCLIMÁTICA

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RESUMEN

La educación se ha transformado debido a las tecnologías. Por lo cual, más que compartir el conocimiento, se busca promover la creatividad desde herramientas y métodos. El objetivo del presente documento es analizar la idoneidad del aula invertida en el proceso de enseñanza-aprendizaje de la arquitectura bioclimática en contexto de pandemia o enseñanza tradicional presencial. La metodología tiene un enfoque cualitativo, diseño no experimental, y estudio exploratorio. Los resultados confirman que los alumnos dedujeron los conocimientos teóricos y las competencias que habrían recibido de manera lineal en el aula tradicional. Como conclusión, se plantea que la diferencia de esta práctica docente respecto a la tradicional estuvo en hacer que lo teórico deviniera de lo práctico, accionando un proceso de transposición didáctica que no sólo simplificó los saberes, sino que se apoyó en generar transversalidades desde las variables que integran el proceso de aprendizaje.

Palabras clave
arquitectura bioclimática, educación, aula invertida, proyectos, arquitectura vernácula, arquitectura sustentable

ABSTRACT

Education has changed thanks to technology. Therefore, more than sharing knowledge, the aim is to promote creativity through tools and methods. This paper aims at analyzing the suitability of the inverted classroom in the teaching-learning process of bioclimatic architecture in the context of a pandemic or traditional classroom teaching. The methodology has a qualitative approach, a non-experimental design, and an exploratory study. The results confirm that the students deduced the theoretical knowledge and competencies they would have received in a linear way in the traditional classroom. In conclusion, it is suggested that the difference between this teaching practice and a traditional one was in making the theoretical derive from the practical, activating a didactic transposition process that not only simplified knowledge but was based on generating transversalities from the variables involved in the learning process.

Keywords
bioclimatic architecture, education, inverted classroom, projects, vernacular architecture, sustainable architecture.

RESUMO

A educação tem passado por transformações devido às tecnologias. Mais do que compartilhar conhecimento, busca-se promover a criatividade por meio de ferramentas e métodos. O objetivo deste documento é analisar a adequação da sala de aula invertida no processo de ensino-aprendizagem da arquitetura bioclimática em contexto de pandemia ou ensino tradicional presencial. A metodologia adotada possui abordagem qualitativa, design não experimental e estudo exploratório. Os resultados confirmam que os alunos assimilaram os conhecimentos teóricos e habilidades que teriam adquirido de forma linear na sala de aula tradicional. Como conclusão, argumenta-se que a diferença dessa prática docente em relação à tradicional está em fazer com que o teórico se torne prático, ativando um processo de transposição didática que não apenas simplificou os saberes, mas também se apoiou na geração de interdisciplinaridade a partir das variáveis que compõem o processo de aprendizagem.

Palavras-chave
arquitetura bioclimática, educação, sala de aula invertida, projetos, arquitetura tradicional, arquitetura sustentável.

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INTRODUCTION

Young university students no longer see technological advances as novelties, but as part of their daily life, now inhabited by digital tools that allow them to access and share information all the time, rethinking the modern concepts of time and space (Albarello, 2016). Daura and Barney (2016) state that teachers should identify activities that promote greater creativity and give students greater autonomy to learn (UNESCO, 2019).

This paradigm shift requires a change in teaching-learning strategies, because, as Soriano and Aguilar (2018) well reference, students are now "digital natives". In this regard, Perilla (2018) mentions that today's students need to find challenges and a sense of usefulness to the contents.

In this sense, the flipped classroom is a teaching method whose objective is to give the student a more active role in their learning process (Berenguer, 2016). Its dynamics lead to students studying the theoretical concepts provided by the teacher on their own. In this way, "learning by doing" is applied (González & Yanacallo, 2020) as a principle that, translated into instructional design, leads to a conversion of the units and contents of the subject around statements, which, as hypotheses, must be verified or refuted by the student through research and exemplification.

However, architecture teaching is traditionally structured around the "process of acquiring knowledge to understand and solve certain types of problems or situations" (Saldarriaga, 1996, p. 70), which comprises the epistemological space of architecture, namely, specific knowledge of the area and diverse knowledge produced in the heteronomy of its practice (Campo, 2018).

This has become a problem capable of transversally articulating the teaching-learning process of architecture at an undergraduate and postgraduate level, approaching the architectural project from the environmental conditions (Restrepo, 2013). Most architecture schools have included the relationship between architecture and the environment in their academic curricula to "promote knowledge and skills in sustainable environmental design, with the aim of achieving comfort, pleasure, well-being, and energy efficiency in new and existing buildings" (Almonte *et al.*, 2012, p. 3). In this way, the purpose of this article is to analyze the suitability of a flipped classroom in the bioclimatic architecture teaching-learning process in the context of the pandemic or traditional face-to-face teaching.

METHODOLOGY

This qualitative research was based on the flipped classroom model (Berenguer, 2016), to achieve a deeper perspective that would allow contextualizing the reality of the teaching-learning process of bioclimatic architecture in the context of the pandemic or traditional face-to-face teaching in the Master's Degree in Architecture and Urbanism (MAU) at the Universidad del Valle. A non-experimental-based research and exploratory study design were used in this research.

To carry out the research, the subject was divided into four workshops that would become modules for discovery and experimentation.

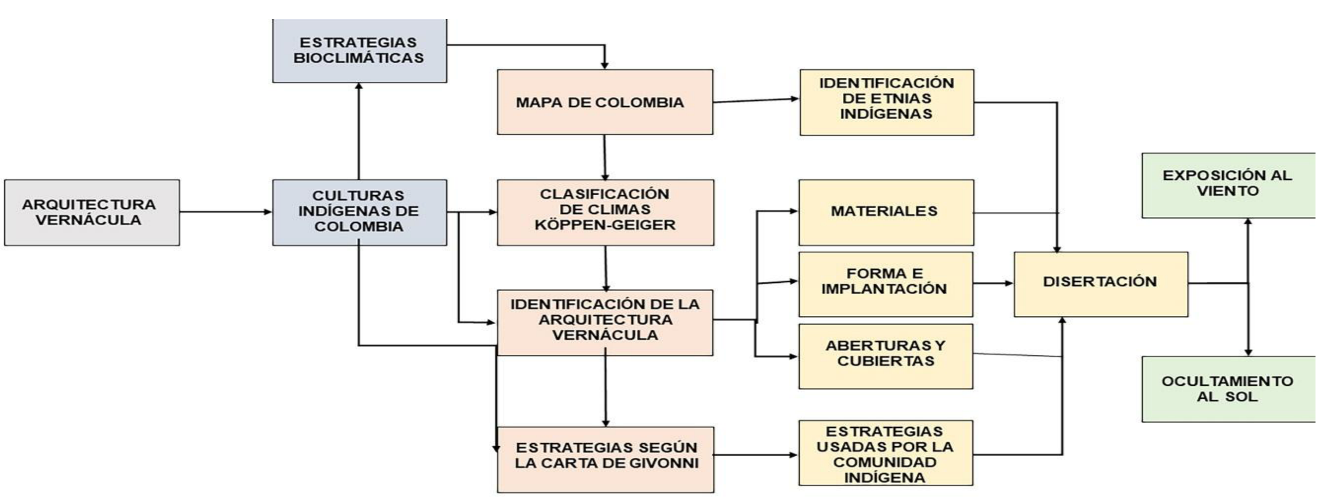

Figure 1. Diagram of Workshop 1. Source: Preparation by the authors

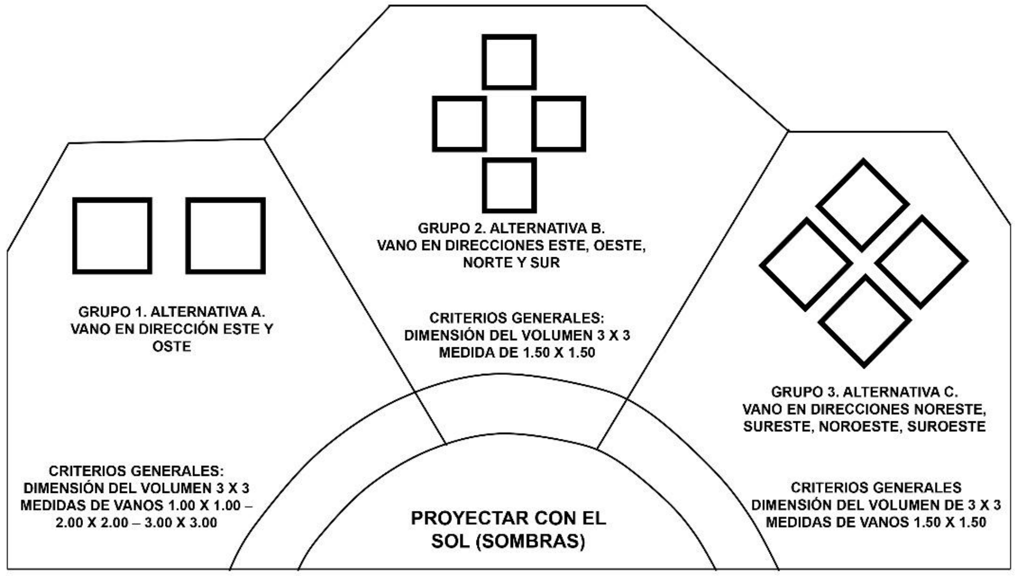

Figure 2. Diagram of Workshop 2. Source: Preparation by the authors

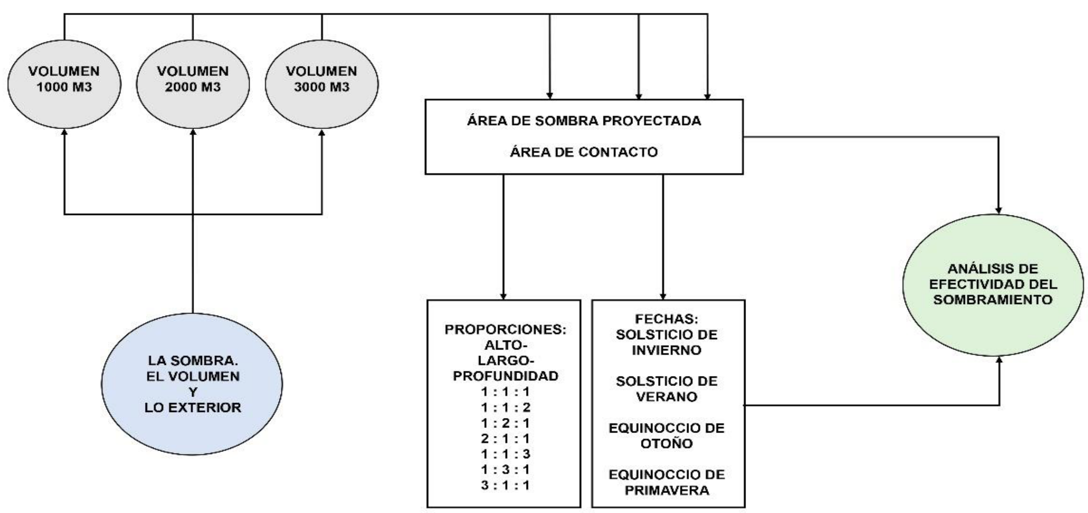

Figure 3. Diagram of Workshop 2.1. Source: Preparation by the authors

WORKSHOP 1: VERNACULAR ARCHITECTURE

The analysis of another country's vernacular architecture was put forward, in this case, Venezuela. With this reference, it was shown, first of all, how the forms of construction of each of the ethnic groups studied in this territory, had an architecture that is related to the environmental conditions (Philokyprou, 2011). Subsequently, it was demonstrated how these aspects were considered in their buildings (Figure 1).

WORKSHOP 2: SUN

This began by exchanging knowledge on topics such as the translational and rotational movement of the Earth and its relationship with building envelopes. Subsequently, a first task was assigned to the students, which consisted of defining a form of solar protection for a window with a specific orientation (Figure 2). In the second part of this workshop, emphasis was placed on shading projection in outdoor spaces through built volumes (Figure 3).

WORKSHOP 3: WIND

This began with an explanation of the principles that produce air movement and how some building examples manage to take advantage of it. The models used in the study of shading were used for calculations and simulations, whereby the students were able to analyze the behavior of airflow and air movement considering the location and size of the window (Figure 4).

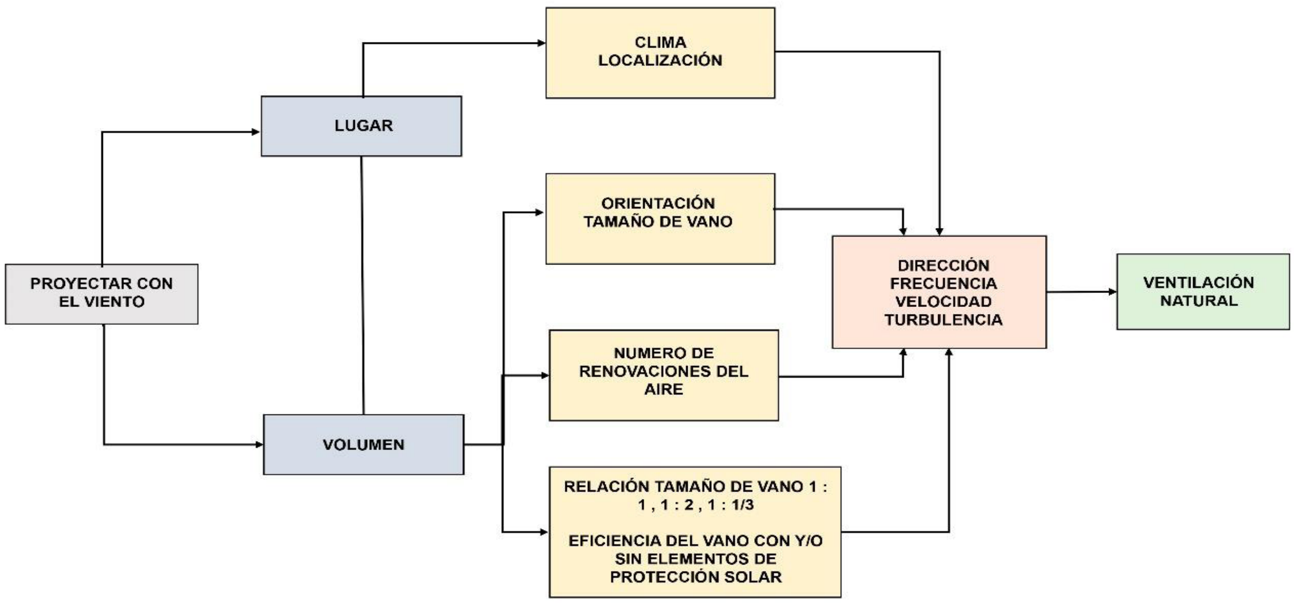

Figure 4. Diagram of Workshop 3. Source: Preparation by the authors

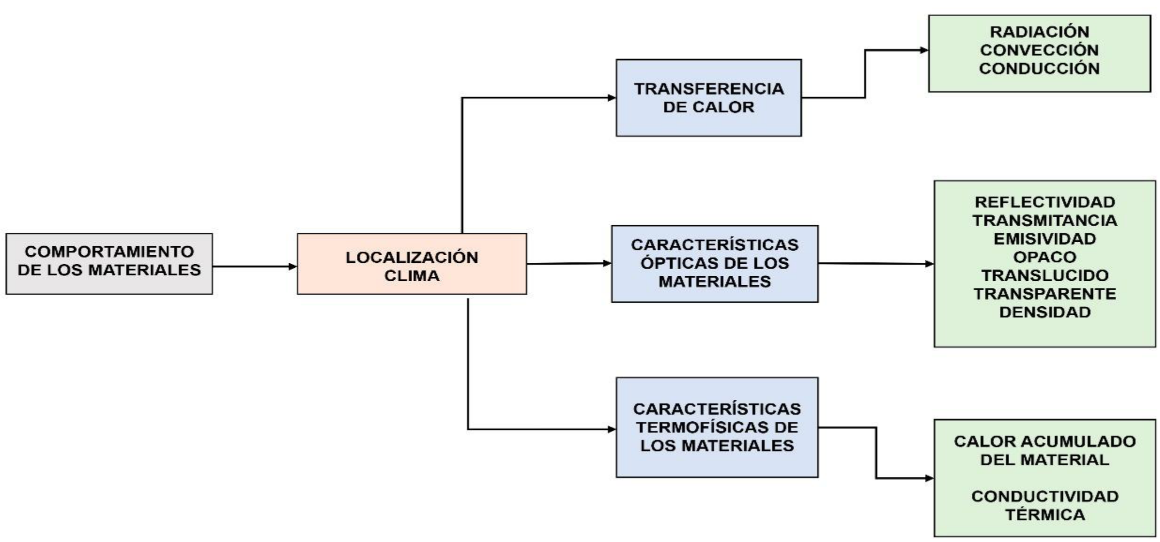

Figure 5. Diagram of Workshop 4. Source: Preparation by the authors

WORKSHOP 4: THERMODYNAMICS OF MATERIALS

This workshop was mediated by the concepts that define the physical and thermal properties of materials. Hence, it was proposed to analyze the behavior of the indoor hourly temperature using high, medium, and low-density materials, with and without insulating material (Givoni, 1969). For this, a database programmed in Excel was used (Neila, 1997) that allowed making analyses, which later the students had to use to interpret the temperature and time values (Figure 5).

EVALUATION OF THE METHOD AND ANALYSIS OF THE RESULTS

To evaluate the performance and quality of the didactics in the workshops taught, three techniques were used: the first, a peer evaluation of the process, which was done at the end of the workshops (providing a meta-evaluation and a hetero-evaluation of the experience); the second, was a semi-structured interview made individually to the students.

The peer evaluation was done internally and externally using the 2 teachers who taught the subject as an internal jury and, as an invited jury, 4 external teachers were included in MAU. They attended as evaluators at the end of each workshop, and alongside presenting their feedback to the participants once the activity had finished, shared their assessments through a semi-structured interview.

The second strategy used, the semi-structured interview, was applied to the 8 students enrolled in the subject, as a structured survey, through a census sampling. In it, each of the suitability indicators was evaluated in simplified and general terms through a conversation, to capture a general appreciation that allowed the student to share the elements that had been most relevant within the process without being led by a pre-established script.

Finally, to define the adequacy in the other five indicators, once the subject was completed, an online questionnaire was applied with a Likert grading scale. Five levels were established from lowest to highest, using a numerical scale to measure attitudes: 1 (strongly disagree), 2 (disagree), 3 (neither agree nor disagree), 4 (agree), and 5 (strongly agree). The average is taken from this scale as a reference value since consistent levels were expected in the participants' assessment.

As mentioned previously, a census sample was made that covered all the students in the course, so this figure is simultaneously for the universe, sample, and population.

In these instruments, six didactic suitability dimensions were evaluated using the components proposed by Godino, 2017 and Godino, 2013:

- Epistemic suitability: Estimates the learning achieved compared to traditional models.
- Cognitive suitability: Evaluates whether the objectives set were achievable compared to the students' previous knowledge and if they were achieved at the end of the course.
- Interactional suitability: Establishes whether the interactions with the teacher are solving the students' doubts and difficulties and are favoring the learning process.
- Mediational suitability: Analyzes the adequacy of the resources used in the pedagogical process, involving time, technologies, and materials.
- Affective suitability: Evaluates the student's interest, motivation, involvement, and participation during the learning process.
- Ecological suitability: This was useful to estimate the adequacy of the educational process in the institution's educational project, the study curriculum, and the social and professional environment.

Semi-structured interviews were used to process the experience assessment instruments, as inputs to evaluate and design the aforementioned questionnaire. In addition, the assessments made by peer reviewers and the individual students allowed making a qualitative assessment of the experience in broader terms, particularly regarding epistemic and ecological suitability.

TEACHING-LEARNING OF BIOCLIMATIC ARCHITECTURE AT THE SCHOOL OF ARCHITECTURE OF THE UNIVERSIDAD DEL VALLE

MAU offers an architecture and bioclimatic urbanism line of work where the thermal comfort of users and the use of climatic conditions of the place are studied (Olgyay, 1963). The teaching-learning process in the Architecture and Bioclimatic Urbanism course at MAU has been oriented towards competence-learning, which dictates that to achieve the performance levels of a given competence, a set of evidence and indicators of achievements must be met.

In this sense, the achievements in the subject's teaching-learning process are translated into generating different experiences so that the student becomes the protagonist of their educational process through the transformation of didactical strategies, which targets a resignification of the processes inherent to the classroom. By getting students to become protagonists of their learning, the pace of the process takes on a personal dimension, and a personal learning environment (PLE) is generated (Vidal, 2015). Thus, students with functional diversity can take advantage of the possibility of developing certain aspects or repeating content at certain times.

Aguilera-Ruiz et al. (2017) take stock of this and refer, in addition to the advantages already mentioned, to the drawback in that this modality involves an additional effort for the teacher than the traditional method, as well as point out the resistance that students can express to it.

To materialize this modality, the course is structured under the following premise: the theoretical becomes practical. That is, during the subject, a process of didactic transposition is activated as a strategy that not only simplifies the assimilation of knowledge for the student, but also relies on the generation of transversalities from the elements involved in the learning processes: actors, channels, means, and didactic sequences (López-Gutiérrez & Pérez-Ones, 2022).

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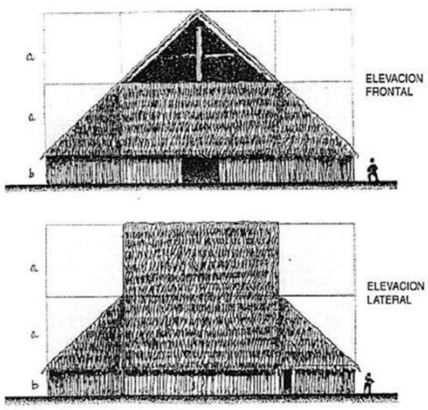
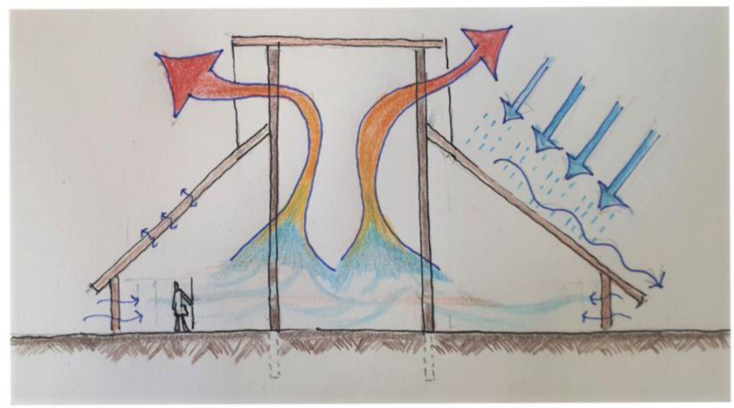
TALLER 1





TALLER 2

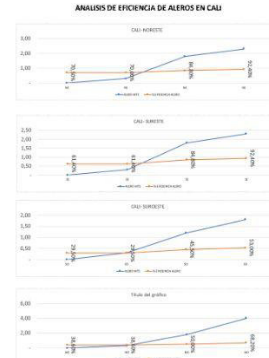
ANALISIS EFICIENCIA DE ALEROS Y PARTESOLES SEGÚN ORIENTACION

BUENOS AIRES								
ORIENTACION	ALERO MTS	EFICIENCIA ALERO	ANGULO INCLINACION GRADOS	PARTESOL		EFICIENCIA PARTESOL	ANGULO GRADOS PARTESOLES	
	MAXIMO/ MINIMO			IZQ	DER		IZQ	DER
TODAS	0,3	34% A 66%	81	0,3	0,3	32% al 59%	9	7
TODAS	1,8	42% A 60%	45	1,8	1,8	21% al 46%	45	38

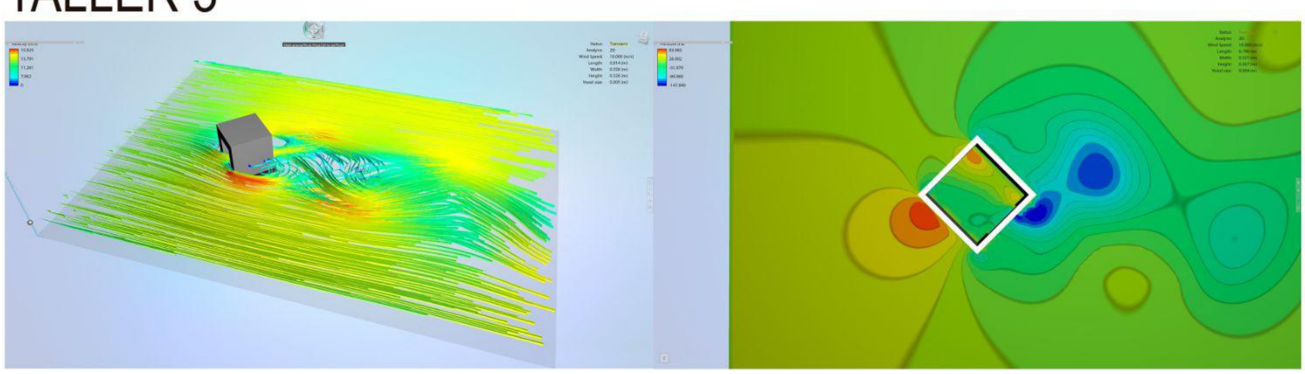
BUENOS AIRES

ORIENTACION	ALERO MTS	% EFICIENCIA ALERO	ANGULO INCLINACION GRADOS	PARTESOL		EFICIENCIA PARTESOL
NE	-	66,00%	90	-	-	37,20
	0,30	66,00%	81	0,30	0,30	37,20
	1,80	60,30%	45	1,80	1,80	37,20
SE	-	60,90%	90	-	-	60,90
	0,30	60,90%	81	0,30	0,30	59,00
	1,00	65,40%	61	-	-	60,90
	1,80	60,30%	45	1,80	1,80	36,50
SO	-	34,00%	90	-	-	34,00
	0,30	34,00%	81	0,30	0,30	32,00
	1,20	41,00%	56	-	1,00	32,10
	1,80	42,30%	45	1,80	1,80	21,80
NO	-	45,50%	90	-	-	37,20
	0,30	45,50%	81	0,30	0,30	37,20
	1,80	42,30%	45	1,80	1,80	37,20

ANALISIS DE EFICIENCIA DE ALEROS EN CALI

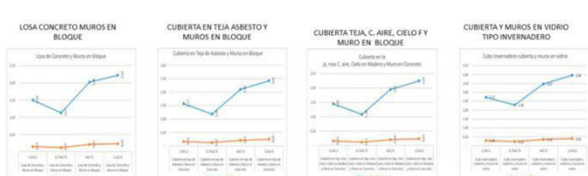


TALLER 3



TALLER 4

COMPARACION CET- APERTURAS Y MATERIALES



ANALIZANDO LA VARIACION CET (PROMEDIOS TEMPERATURA INTERIOR CON RESPECTO A LOS PROMEDIOS DE TEMPERATURA EXTERIOR), CON RESPECTO A LA ABERTURAS DE VENTILACION Y LOS MATERIALES

SE OBSERVA COMO INFLUYE EL TAMANO DE LAS VENTANAS. PARA NUESTRO CLIMA TROPICAL ES INDISPENSABLE QUE LAS VENTANAS SEAN DE TAMANOS OPTIMOS PARA GENERAR CONFORT AL INTERIOR DE LA EDIFICACION.

DESCRIPCION MATERIALES	APERTURAS	T MAX	T MININA	VAR T.I	CET
Losa de Concreto y Muros en Bloque	1,5X1,5	24,77	23,26	1,5	0,15
Cubierta en taja de Asbesto y Muro en Concreto	1,5X1,5	24,81	23,24	1,57	0,16
Cubierta en taja, mas Caire, Cielo en Madera y Muro en Concreto	1,5X1,5	24,73	23,28	1,45	0,15
Cubo Invernadero cubierta y muros en vidrio	1,5X1,5	25,57	22,86	2,72	0,28
Cubo en Zinc (cambuches)	1,5x1,5	25,21	23,04	2,17	0,22

EN ESTE GRAFICO SE EVIDENCIA COMO LOS DEFERENTES MATERIALES USADOS AFECTA LA TEMPERATURA EXTERIOR AL INTERIOR DEL VOLUMEN.
EL VIDRIO USADO PARA INVERNADEROS ES MUY UTIL PARA CLIMAS FRIOS Y TEMPLADOS, PERO PARA CLIMAS TROPICALES REQUIERE DE UN DISENO AYUDADO CON VEGETACION, MEJORES APERTURAS Y ELEMENTOS ADICIONALES QUE LE DEN CONFOTR AL ESPACIO.

EL ZINC, MUY USADO EN LAS CONSTRUCCIONES IMPROVISADAS, GENERA ESPACIOS INCONFORTABLES PARA TODO TIPO DE CLIMAS, DADO EL MATERIAL QUE ES ALTAMENTE CONDUCTIVO.

Figure 6. Processes and results of the workshops. Source: Preparation by the authors

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In the application of this model during the global health crisis caused by Covid-19, the flipped classroom (Janssen, 2020) became an approach to be considered, as Williner (2021) and Cornelis (2020) confirm, as it does not require the physical presence of the teacher. However, although this methodology is an opportunity for the student to assume the limelight, it also entails that both the institution and the professors assume a greater burden.

RESULTS AND DISCUSSION

ASSESSMENT OF DIDACTIC SUITABILITY

The flipped classroom was proposed during the health contingency to take advantage of the context to generate a resignification of learning. Based on the investment this change of approach implies, the student must independently work, study, and analyze the theoretical concepts that the teachers provide.

By structuring the course into workshops and not programmatic content, so that the learning of bioclimatic architecture was generated from the real to the abstract, it was considered that it was not so necessary for students to have specific prior knowledge to understand the exercises and, in addition, the possibility of grouping students beyond their level of studies was opened. This new organization meant a strengthening and creation of new synergies between undergraduate and postgraduate students, through the promotion of collaborative work, the construction of critical knowledge, exchange, and discussion within the group, between groups, and with teachers; the demonstration of knowledge taken on board by the student, theoretical speculation from practice and, finally, the validation of competencies achieved as the course progresses (Figure 6).

EPISTEMIC SUITABILITY

From the indicators addressed during the study, this was the only one evaluated beyond the students, since it determines that the ownership of the contents should be reviewed by academic and expert peers. To this end, the end of each workshop was accompanied by a jury to whom the students presented their findings, followed by a question and answer session. No errors or epistemological inconsistencies were found in the concepts or contents taught and handled by the participants, on the contrary, thanks to these interventions it was demonstrated that the studied statements were reaffirmed by the students, who found conceptual interrelationships and an appropriation of the concepts, being able to generate demonstrations and explanations of these in their own words. This shows the ability to build arguments, solve problems, and suggest connections between knowledge.

COGNITIVE SUITABILITY

When designing the workshops, the competencies acquired in the preliminary curricular units were reviewed and considered, so the level of difficulty handled was appropriate for a course that aimed to generate the appropriate theoretical framework for understanding the principles of bioclimatic architecture. In this way, as a complement, advisory sessions were included to expand upon and reinforce knowledge, where the students were able to clarify doubts and dialog in depth with the teacher on aspects that they had researched following the flipped classroom model. In addition, diverse modes of assessment were proposed that aimed to activate different relevant cognitive and metacognitive processes such as generalization, connections, and conjectures, among others.

To achieve cognitive suitability, it became necessary to monitor the students' performance individually throughout each workshop, because, at first, the changes from the traditional model to the flipped classroom approach generated some resistance. This was manifested in the individual interviews, although in the didactic suitability survey, an average of 4.61 was reached. At this particular point, it was found that about 50% expressed feeling a degree of disorientation or confusion in terms of understanding the statements of the first workshop.

INTERACTIONAL SUITABILITY

The way the teacher conducted the exercise was measured, as were the presentation of the topic and the exercises, the interaction between the teacher and the student, and the spaces offered for dialog. Although a systematic observation of the students' cognitive processes was used in this phase and the dialog and communication between and with the students were observed, the instruments applied highlighted that the levels of interaction could be improved for these.

In the survey results in items 13 and 14 (Table 1) it can be seen that, although more than 60% said they completely agreed with the communication, dialog, and interaction with the teacher, the remaining 40% only agreed or had a neutral opinion, which shows

Table 1. Didactic suitability survey results. Source: Preparation by the authors

	ITEM OF DIDACTIC SUITABILITY	MEAN	STANDARD DEVIATION
1	I clearly understood the ideas and objectives of the exercises from the beginning	4.61	0.61
2	I clearly and precisely understood the relationship between the objectives of the workshops and the subject	4.61	0.47
3	I consider that it improved my ability to analyze and interpret the architectural solutions projected from the climate	4.73	0.44
4	I can recognize values and technological solutions in architectural references that allow me to take advantage of or protect the building from sunlight	4.60	0.48
5	I think that the course enriched my training as an architect	4.86	0.33
6	I consider that the workshops expanded my understanding of architectural actions	4.60	0.37
7	I consider that the exercise improved my appreciation of tropical architecture	4.70	0.45
8	I consider that the workshop provided me with knowledge and processes to project bioclimatic design considerations	4.73	0.37
9	I remained motivated throughout the preparation of the exercises	4.82	0.38
10	The subject allowed me to understand the importance of researching and exploring with an open vision and critical thinking	4.81	0.39
11	I consider that with the workshops I exercised my ability to infer conclusions from premises and evidence that were presented to me in the process	4.60	0.61
12	I consider that the subject led me to reflect and generate new ideas and concepts to find design solutions	4.46	0.61
13	I believe that there was a relevant, effective, and timely dialog with the teacher	4.53	0.61
14	The communication with the teacher throughout the subject was clear and assertive	4.33	0.69
15	The approach of the exercise, the instructions, and the didactic material were sufficient to understand the objectives and scope of the exercise	4.62	0.48
16	I think that the course allowed me to develop my critical thinking	4.60	0.61
17	I consider that throughout the subject I improved my abilities and aptitudes to carry out research regarding collecting information, processing it, and generating conclusions from them	4.66	0.47
18	I think that this course improved my understanding of architecture	4.73	0.44
19	I consider that the course was planned with optimal timing to fulfill its objectives	4.40	0.48
20	I believe that the necessary resources were available at a technical and didactic level to achieve the objectives	4.33	0.86
21	The platforms and means used were the most suitable	4.40	0.48
22	I believe that what I have learned can be used in my work as an architect	4.93	0.24

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that the students perceived that they were not fully integrated into the educational process.

MEDIATIONAL SUITABILITY

The use of technologies and support material was evaluated, as well as all aspects related to the environment where the teaching-learning process took place. Given that the approach adopted during this experience was framed under distance learning, it is evident that the use of communication and information technologies became more relevant, which, in this case, were evaluated from the experience perceived by the students through the aforementioned questionnaire. A positive assessment of this instrument was obtained from all the students. However, at a technical level, 14% of the sample expressed neutrality in the statement that the strategies provided had been sufficient, a figure that was observed in the items related to communication with the teacher and the means used, as can be seen in Table 1 in items 19, 20, and 21. From this, it can be inferred that, for the preparation of the workshops, it is necessary to evaluate the items, times, and didactic material provided to the students.

AFFECTIVE SUITABILITY

For this point, the students' interest in the tasks arranged was evaluated. Based on the evidence from the surveys, the assessment was again indisputably positive. This section specifically highlights that, at first, the items that assessed student motivation were estimated with the highest grade and remained constant throughout the exercise, an aspect that was confirmed by the high participation and willingness of the students in the advisory sessions and the interviews conducted individually.

ECOLOGICAL SUITABILITY

Ecological suitability refers to the relationships of the contents taught with the guidelines, objectives, strategies, and contents of the structures that form the context of the curricular unit. In this case, this section saw the best grades from the surveyed students, achieving unanimity in the statements that referred to the contribution of the exercises in their training as architects, the stimulation of critical thinking, the development of research competencies, and the integration of knowledge within the curriculum.

SUMMARY OF DIDACTIC SUITABILITY

The levels of internalization and competencies experienced, according to the teaching-learning processes and from the dimensions of didactic suitability, evidence an acceptance of the flipped classroom strategies in the Architecture and Bioclimatic Urbanism course. In the affective, ecological, epistemic, and cognitive suitability, a strengthening of learning is seen as the cognitive inference processes encompassing implication, reflection, and reasoning operations. However, the mediational and interactional dimensions provide average indices of competition, since distance learning does not favor such interaction. This, although predictable, highlights the didactic potential of the flipped classroom to consolidate achievement indicators in the cognitive, procedural, and, attitudinal aspects, although it is only a small sample of how this modality has an impact on the student's experience at an emotional level. It should be said that, despite the multiple means and strategies applied, the interactional levels were lower.

Similarly, these results show that, in the mediational dimension of the didactic experience, the assessment of students was lower, a fact that can be attributed to the nature of instructional and distance learning means, whose rigidity in planning can be understood as a distancing in the teacher/student relationship.

CONCLUSION

The implementation of these workshops in the Architecture and Bioclimatic Urbanism course shows that inductive learning from practical experience generates an immersion in the knowledge that the student can use as a basis for their project design. This does not mean that the student is a mere receiver, but, on the contrary, behaves as the main agent of the learning process, generating the bases of their knowledge through experience, encouraging their creativity, and stimulating the search. This is in line with the forms of knowledge of Latin American cultures and with architectural learning, as "learning by doing".

Taking the didactic suitability indicators as a starting point to evaluate the teaching, was an enriching strategy. The analysis of the experience around the 6 indicators allowed detecting that the proposed approach of learning by doing had a positive impact on the student, beyond that evidenced in the evaluations. It was possible to interpret through the different items that the process was enjoyable and stimulating for the participants and that the greatest opportunity to improve this methodology was found in the evaluation planning and the didactic means. In addition, in both cases, it was possible to suggest the construction of a collaborative curriculum and the application of other formats and strategies for the theoretical lessons in future tests, which inevitably form part of the contents described in the program.

Finally, this experience showed that the limitations imposed by the pandemic and distance learning resulted in an opportunity to generate transformations. Although architecture and bioclimatic urbanism learning would have been conventionally structured around the ratification of affirmations, rethinking the academic space for the organization and empowerment of the student gives the conditions to achieve significant learning from the reinterpretation of everyday life. The principles of architecture and bioclimatic urbanism affect our way of experiencing the environment from key concepts such as sensation and thermal quality. That is why embodied thinking through digital tools and teaching advice allows for consolidating and stimulating critical thinking and the fulfillment of competencies.

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El tapanco en viviendas vernáculas de querétaro, México. Uso y eficiencia higrotérmica
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TAPANCO IN VERNACULAR HOUSES IN QUERÉTARO, MEXICO. USE AND HYGROTHERMAL EFFICIENCY

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EL TAPANCO EN VIVIENDAS VERNÁCULAS DE QUERÉTARO, MÉXICO. USO Y EFICIENCIA HIGROTÉRMICA

O “TAPANCO” NAS MORADIAS VERNACULARES DE QUERÉTARO, MÉXICO. USO E EFICIÊNCIA HIGROTÉRMICA.

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RESUMEN

Hoy día son evidentes las consecuencias climáticas provocadas por las emisiones de gases de efecto invernadero (GEI) que encaminan a alcanzar 2.7 °C de calentamiento global hacia 2100. La dependencia energética de las edificaciones es una de las causas principales, pues demandaron solo para calefacción el 50% del consumo de energía global en 2021, siendo necesario implementar sistemas bioclimáticos pasivos de climatización. Este trabajo documenta la utilización en viviendas vernáculas de Querétaro, México, de un eficiente sistema pasivo tipo ático, denominado "tapanco", consistente en una cámara de aire inerte que funciona como amortiguador térmico. Se evaluó un caso aplicando metodologías de medición con termo-higrómetros, complementando con termografía y simulación termo-eólica. Los hallazgos de índices higrométricos adecuados, propiciados por el sistema, lo convierten en alternativa relevante de solución pasiva en el diseño arquitectónico bioclimático futuro, para abatir los índices energéticos y climáticos adversos.

Palabras clave
arquitectura vernácula, arquitectura bioclimática, calentamiento global, eficiencia energética.

ABSTRACT

Today, the climatic consequences caused by greenhouse gas (GHG) emissions are evident and are on track to see global warming of 2.7 °C by the end of the century. The energy dependence of buildings is one of the main causes, since they required 50% of global energy consumption in 2021 just for heating, making it necessary to implement passive bioclimatic air conditioning systems. This work documents the use in vernacular dwellings in Queretaro, Mexico, of an efficient attic-type passive system, called "tapanco", consisting of an inert air chamber that functions as a thermal buffer. A case was evaluated by applying measurement methodologies with thermo-hygrometers, complemented with thermography and thermo-wind simulation. The findings of adequate hygrometric indices, fostered by the system, make it a relevant alternative for a passive solution in future bioclimatic architectural design, to reduce adverse energy and climatic indices.

Keywords
vernacular architecture, bioclimatic architecture, global warming, energy efficiency.

RESUMO

Hoje, as consequências climáticas das emissões de gases de efeito estufa (GEE) são evidentes e estamos a caminho de atingir 2,7°C de aquecimento global até 2100. A dependência energética das edificações é uma das principais causas, pois elas representaram 50% do consumo global de energia apenas para aquecimento em 2021, tornando-se necessário implementar sistemas passivos bioclimáticos de climatização. Este trabalho documenta a utilização de um eficiente sistema passivo tipo sótão, chamado "tapanco", em moradias tradicionais de Querétaro, México. O sistema consiste em uma câmara de ar inerte que atua como amortecedor térmico. Foi avaliado um caso utilizando metodologias de medição com termo-higrômetros, complementadas por termografia e simulação termo-eólica. Os resultados dos índices higrométricos adequados proporcionados pelo sistema fazem dele uma solução passiva alternativa relevante como solução passiva no futuro projeto arquitetônico bioclimático, visando reduzir os índices energéticos e climáticos adversos.

Palavras-chave
arquitetura tradicional, arquitetura bioclimática, aquecimento global, eficiência energética.

INTRODUCTION

The current serious climatic effects can be significantly reduced by reducing Greenhouse Gas emissions (hereinafter, GHG), which, due to human energy dependence, are the cause of global warming. These should be kept at 1.5 °C or below to avoid the climate debacle by 2100 (United Nations Environment Programme, 2021).

Many buildings have high energy demands in their lifecycle and are not thermally functional. This is mainly due to their materials' terrible thermal properties and inadequate architectural design and insulation. The reason for this is that construction is globally standardized, and disregards local climates or energy implications (Intergovernmental Panel on Climate Change, 2022). This leads to electro-mechanical air conditioning being the most sought-after solution in the residential sector (Aguilera et al., 2018). A noteworthy fact is that, in 2021, heating alone accounted for 50% of global energy consumption (Global Crisis Response Group, 2022). At present, the energy efficiency of buildings is the main problem to be solved in this sector, because indoor air conditioning is the world's highest energy consumer. Hence, proposing a passive bioclimatic system solution is the central theme of this study.

If we want to reach a goal where energy efficiency is the key principle governing the construction of residential buildings, this should be done through ways of building that avoid mechanical air conditioning. This can be achieved through improved designs that consider the local climate. It is also necessary to propose the use of low-embodied energy materials, as well as to include passive bioclimatic strategies and nature-based solutions that allow buildings to adapt to the future climate. The implementation of these proposals looks to decrease energy requirements (Intergovernmental Panel on Climate Change, 2022), while allowing comfort and ensuring human well-being.

On the other hand, it is evident that current architectural paradigms are obsolete and, for the same reason, must be questioned to make a turn toward other types of already proven solutions, such as vernacular architecture. These, based on the ancestral knowledge product of centuries of observation and experimentation, have historically demonstrated efficiency in their physical adaptability, through natural materials and bioclimatic strategies, and they represent a powerful alternative for energy efficiency (hereinafter, EE).

Vernacular houses use passive strategies to guarantee hygrothermal comfort with almost zero energy demand because they do not use electro-mechanical systems, even when they lack electricity. They are built through shortage and meticulous resource management, representing a sustainable environmental heritage at the service of the current building. Developing countries preserve samples of these habitats that may represent model systems of adaptability (Rapoport, 2003).

In Querétaro, vernacular constructions have been documented in several climatic regions (Figure 1), such as those that use the passive bioclimatic system called "tapanco", which consists of an inert air chamber that functions as a thermo-acoustic buffer, fostering suitable indoor hygrothermal conditions, in diverse climates.

Hence, the objective of this work consists of documenting the use of the tapanco passive bioclimatic system in the vernacular dwellings of Querétaro and evaluating their hygrothermal efficiency by analyzing a case located in an extreme temperate climate zone, using internal-external parameter measurement methodologies for this. First, measurements were made with hygrometers; second, an analysis was made with thermographic photographs, and finally, thermo-wind modeling and simulation were made. This starts from the hypothesis of associating internal comfort with thermal regulation and relative humidity, extrapolating thermal performance to extreme conditions through simulation considering the design and materials.

Figure 1. Rural and urban vernacular housing of Querétaro. Source: Preparation by the authors.

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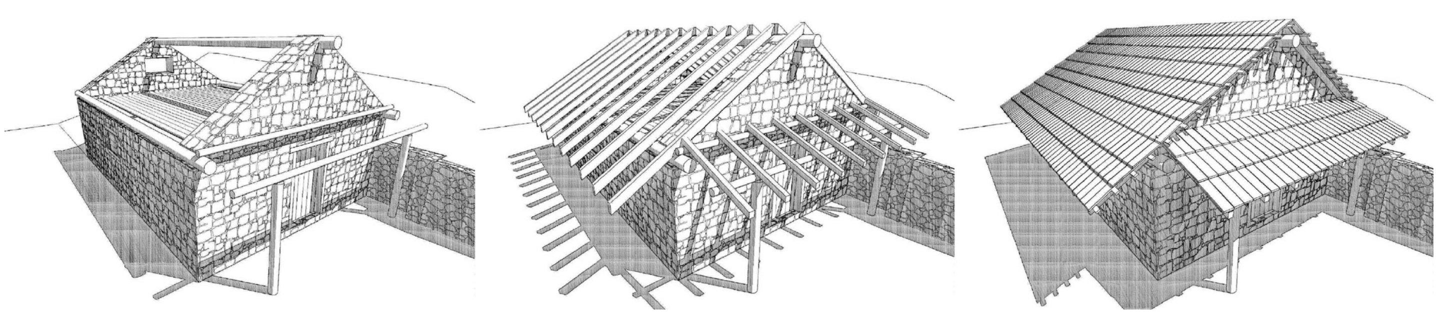

Figure 2. Wood and tejamanil tapanco structure. Source: Preparation by the authors.

The results allow verifying the suitability of tapanco to produce indoor hygrometric comfort, considering it as a design alternative for architectural models that are thermally and energy efficient. Once this knowledge has been scientifically translated to current architectural requirements, it will be very useful to face future climates.

The purpose of this study is not to specify the rates of decrease in energy expenditure with the use of the system. However, it can be confirmed that according to the works of Martín-Consuegra et al. (2014) and Suárez et al. (2018), both the implementation of passive bioclimatic strategies, as well as uninhabitable attics or "cool ventilated roofs", mainly on sloping roofs, have a significant impact on the improvement of EE.

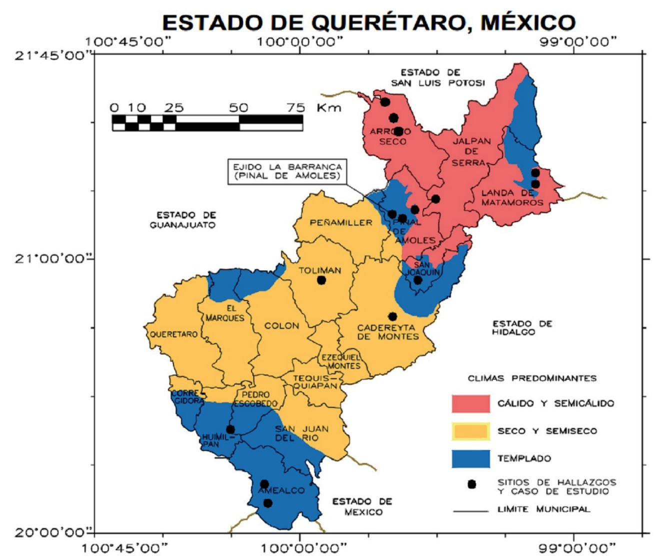

Figure 3. Political and climatic division of Querétaro. Location of sites with findings and case study. Source: Prepared by the authors with data from INEGI, 2017.

BACKGROUND

Vernacular tapanco in querétaro

The attic has been a passive bioclimatic strategy used for centuries, which consists of a thermal insulation chamber. A similar element has been used in the vernacular architecture of Queretaro, namely the "tapanco", whose name comes from the Nahuatl "tapantli" (roof) and the suffix "co" (in). This is a type of attic used to store objects and dry seeds or plants. It consists of a height division in a room using a horizontal board, forming a mezzanine that has no habitable function, unlike the attic (Figure 2).

This mezzanine works as a thermo-acoustic buffer by optimizing the thermal transmittance values of the roof "delaying" the passage of the outdoor temperature, for long enough to keep the interior stable until restarting the thermal cycle, also reducing the noises due to rain or hail. It is useful in temperate or warm weather, using a vent in the tympanum to remove inert air. Fifteen sites with evidence of this element have been documented in Querétaro, in diverse climatic regions, highlighting the locality of extreme temperate climate, "La Barranca" in the municipality of Pinal de Amoles, where the measurements were made (Figure 3).

The architectural conformation of the rural vernacular tapanco, completely covers the bay, based on a truss and strut type structure, made with small beams, bars, and rafters, and is covered with small wooden tiles called "tejamanil", which are manually made locally (Figure 4).

In the traditional houses of more urban areas, there are large tapancos (Figure 5) that also use a larger-scale truss-type structure, covered with a clay roof, which rests on one-rod thick masonry walls (80 cm).

These vernacular constructions have other passive strategies that contribute to their thermal efficiency, which are not the subject of analysis in this study, but are interesting to mention, such as a wise combination of local materials with good thermal inertia; the use of semi-buried "thermal walls"; the frank east-west orientation of the bays; and the use of endemic vegetation to reduce sunlight and humidify, etc.

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Figure 4. Tapancos in rural areas of Querétaro. Source: Preparation by the authors.

Figure 5. Tapancos in urban areas of Querétaro. Source: Preparation by the authors.

With the decay of vernacular housing to make way for new ways of living with current notions of "evolution" (Juárez, 2022), in Querétaro, the tapanco has almost completely fallen into disuse, even the existing one collapsing, due to ignorance about its hygrothermal benefits and by allowing entry to industrial materials, with documentation on this strategy being a pressing matter.

STATE-OF-THE-ART

The current serious environmental problems have forced the establishment of EE policies in many countries, related to energy measurements and certifications as tools to minimize energy consumption and GHG emissions (Fernandez et al., 2020). This policy has established minimum requirements for envelopes and mechanical systems for thermal comfort. There are many energy standards, however, these are not applied in all countries, so many constructions consider them as a "voluntary" guideline. More than 80% of the initiatives proposed globally consist of methods focused only on the demand-consumption relationship and not on EE (Reus-Netto et al., 2019).

Reducing energy consumption without affecting comfort requires the implementation of bioclimatic architectural systems, mainly in residential buildings (Manzano et al., 2015, cited in Fernandez et al., 2020), which should be hygrothermally evaluated and monitored. The 2030 Agenda of the United Nations disseminates principles of bioclimatic architecture, energy efficiency, and the use of low-impact materials to achieve these goals.

There are works related to energy assessment, insulation requirements, implementation of passive strategies, and their relevance in EE, such as those developed by Aguilera et al. (2018), Mercado et al. (2018), Reus-Netto et al. (2019), and Fernández et al. (2020). Reference is specially made to studies by Martín-Consuegra et al. (2014), Suárez et al. (2018), and Calderon (2019), about the analysis of the thermal and energy efficiency of roof air chambers.

For sustainability, thermal functionality, and the use of passive strategies in vernacular housing, there are studies such as those by Herrera and Medina (2018), Mandrini (2022), and Juárez (2022). Also, the works of Mercado et al. (2018), Ganem-Karlen (2018), and Alamino and Kuchen (2021) refer to the importance of thermo-energetic simulation tools, infrared thermography, and others, as instruments for hygrothermal assessment. In Querétaro, practically no vernacular housing technical-architectural studies have been made under scientific methodologies, but serious research with an anthropological approach has been done, which helps to understand the phenomenon of vernacular environments.

THEORETICAL FRAMEWORK

VERNACULAR HOUSING, SUSTAINABILITY, AND ENERGY EFFICIENCY

Vernacular architecture, whose thermal behavior is achieved without resorting to electro-mechanical systems and almost zero energy demand, contributes to the environmental, economic, and quality of life aspects, in line with integral sustainability (Mandrini, 2022). This way of building is born from ancestral knowledge and the accumulation of climate adaptability experiences, with sustainable empirical references such as the conservation of knowledge; use of local materials; community participation; and diversity of solutions (Larraga et al., 2014). This appears among indigenous peoples as a response to their living needs, taking advantage of their local environment and climate, and achieving self-sufficiency and comfort. Limited resources and technologies allowed them to attain efficient solutions, harmonizing the work-family life link in interaction with the environment (Juárez, 2022).

These vernacular environments are rationally ecological and agricultural small habitats, almost self-sufficient in the production, management, and consumption of resources, which contribute to community identity and socio-cultural values, thus playing an important role in the economy, society, and environmental management (Herrera & Medina, 2018). The buildings these comprise are energy efficient throughout their entire life cycle, with almost zero demand for the extraction, production, and transfer of local, natural materials with excellent thermal properties. When they are demolished, these buildings are completely reintegrated into the natural environment or recycled. In addition, they use bioclimatic strategies that do not require electricity for air conditioning or lighting and have little electrical equipment.

COMFORT, PASSIVE BIOCLIMATIC STRATEGIES, AND HYGROTHERMAL ASSESSMENT

Comfort is a fundamental condition of habitat and architectural sustainability since it responds to the need for shelter. Incorporating sustainable constructive solutions fosters indoor thermal comfort with few energy implications, and is pertinent for analyzing traditional lifestyles that seek bioclimatic solutions (Calderon, 2019).

Thermal comfort not only depends on environmental parameters but also on other elements of the environment and the perception of the subject, in addition to sociocultural aspects (Mandrini, 2022). When interacting with electro-mechanical systems, user behavior affects the performance of buildings, and the use of energy (Mercado et al., 2018). The physical sensation of the subjects influences their well-being, efficiency, and comfort. With continuous variations of the environment, they take conscious or unconscious actions to recover the thermal balance and be comfortable (Rincón-Martínez et al., 2022), using mechanical systems that involve high energy consumption, and variables depending on the climate and the envelope (Reus-Netto et al., 2019).

The passive strategies incorporated into the architectural design (hereinafter, EPDA) contribute to energy efficiency and adapt the building to environmental conditions, improving hygrothermal comfort and reducing energy demand. The weighting of these strategies depends on the local climate, being able to resort to diverse solutions, such as the thermal insulation of roofs, walls, and floors; external colors; shading and window proportion; passive solar systems; heights and level of airtightness among others. These are implemented to reduce energy demand, and some studies demonstrate this (Aguilera et al., 2018; Instituto Nacional de Estadística y Geografía, 2017, p. 2; Martín-Consuegra et al., 2014; Mercado et al., 2018; cited in Fernández et al., 2020).

EE measures in buildings include regulations, monitoring, and evaluation, considering new buildings, energy-efficient buildings, and existing buildings (Schneider, 2015, cited in Ganem-Karlen, 2018). They also require reliable and fast diagnostic techniques. Before building, it is advisable to make a thermal simulation that emulates the comfort conditions, considering materials and climate, taking into account, for relative humidity (RH), the following relationship for non-extreme climates: at high temperatures, low relative humidities, and vice versa, (Ceja, 2012).

In vernacular architecture, forms are given in response to the combined effect between temperature, humidity, and air (Atmaca & Gedik, 2019; Bassoud et al., 2021; Chang et al., 2021; Manavvi & Rajasekar, 2020; 2021; Yan et al., 2020; Zhang et al., 2018; cited in Rincón-Martínez, 2022). The geometry is also conditioned by the materials and the need to implement passive bioclimatic strategies to achieve comfort, as will be observed in the case analyzed.

METHODOLOGY

Due to the little existing evidence, the case was chosen because it is located in an area of extreme temperate climate and because of the almost complete conservation of materials, design, and tapanco. Three types of analytical measurements are

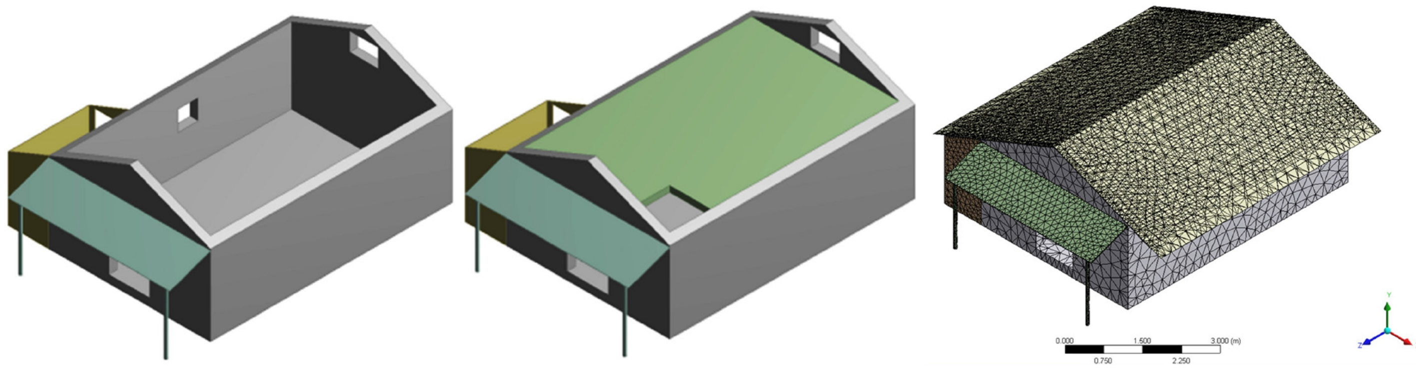

Figure 6. Model and mesh for ANSYS. Source: Preparation by the authors.

included: thermographic inspection; measurement of internal-external parameters using thermo-hygrometers; thermal and wind simulation, with which complementarity is sought and a comparison is made to obtain more reliable results.

THERMOGRAPHIC INSPECTION

The exterior mapping was done using thermographic inspection, to differentiate the qualitative behavior of the materials and contrast them with the simulation, to observe surface thermal variations and identify defects, such as structural failures, moisture, lack of insulation, and thermal bridges. Images were taken at a distance of 4 to 5 m, on November 5, 2011, around 12:00 pm, using a *Flir Systems ThermaCAM E45* camera, and *QuickReport* software from the same firm. To make quantitative thermography that would yield more reliable data, an emissivity value of 0.85 was introduced, which is around the average presented by the materials typically used in construction.

MEASUREMENTS WITH THERMO-HYGROMETERS

Internal-external measurements of temperature and relative humidity (RH) were made, using *Thermotracker* thermo-hygrometers, with continuous monitoring *in situ* for three months, from July to September, reporting data every fifteen minutes to obtain daily behavior averages. The internal sensors were installed in the following locations: one in the middle of the living space, between the tapanco and floor, away from the window; and the other, in the spatial middle of the tapanco, between the flooring and the ceiling. An external reference sensor was placed halfway between the wing (protruding part of the roof) and the floor, to protect the device from the weather and direct solar radiation. Data from the quarterly cycle were recorded and interpreted with the *Thermotracker Pro* software.

THERMO-WIND SIMULATIONS

The simulation was done using the finite element technique with the *ANSYS* program, to validate the thermographic information obtained. The model was made in *Solid Works*, considering the constituent elements: materials, tapanco, porch, and window. This model was exported to *Design Geometry* making the meshing of the control volume for the *ANSYS* analysis (Figure 6).

The materials' thermal conductivity data input into the *ANSYS* program, were: 0.28 W/m °C for wood, 0.72 W/m °C for stone, and 60.5 W/m °C for steel sheet. The finite element values were transposed to extreme situations, with a winter temperature of 5 °C, summer of 50 °C, and solar radiation of 1,050 W/m^2, registered by the weather station for the study area, on the chosen date and time.

One of the factors for heat transfer is convection, which depends on airspeed, hence a wind simulation was made in *ANSYS*. Starting from the thermal model, with a CFD meshing, a speed of 5.8 m/s was introduced, which was the average found.

On the other hand, it is relevant to note that users emphatically stated that the house is cool in summer and, mainly warm in extreme winters, not requiring tools for indoor comfort.

RESULTS AND DISCUSSION

HYGROTHERMAL ANALYSIS OF THE CASE STUDY: LA BARRANCA, MUNICIPALITY OF PINAL DE AMOLES

The geographical coordinates of La Barranca are 21° 07'36.2" N, 99° 41'08.3" W. It has a temperate sub-humid climate with summer rains, high humidity, and very low temperatures (average 14°C), even below zero at around

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Figure 7. Evaluated bay. Habitable exterior and interior and tapanco. Source: Preparation by the authors.

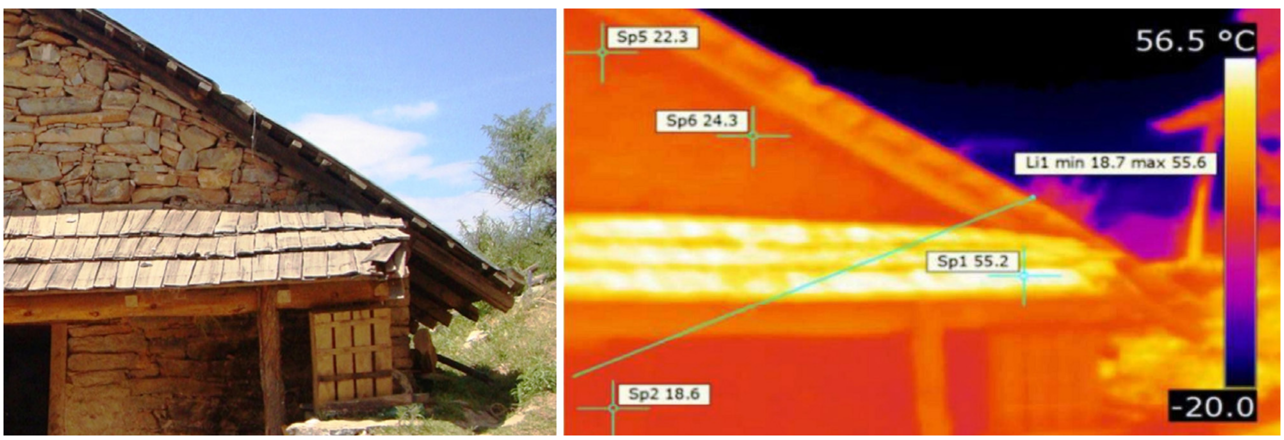

Figure 8. Thermal map - front of the house. Source: Preparation by the authors.

3,000 meters above sea level, and is one of the highest localities in the country.

Its constructions wisely combine design and endemic materials, wood and stone, with clay 55 cm thick walls that support the "gabled" truss roof and the low height boarding (1.85 m). The tapanco is formed in a triangular shape with an approximate slope of 60%, necessary to clear rain and sleet. The roof originally covered with "tejamanil", due to forest restrictions and with more than 75 years of useful life, has been coated with a galvanized sheet, without affecting its thermicity. The bay is multifunctional with dimensions of 5x7 m (Figure 7).

THERMOGRAPHIC INSPECTION

Figure 8 shows that the frontal thermal map; Sp1, which is the roof of the porch, registers the highest value with 55.2 °C. The stone tympanum, corresponding to Sp5, registers 22.3 °C. On the other hand, Sp2, located under the porch, has the lowest value, with 18.6 °C. This reflects that the thermal conditions are suitable for that space, which acts as a thermal buffer.

In Figure 9, the roof of the porch, that is, point Sp2, presents 53.6°C, which is the highest value. On the other hand, the lowest value is the floor, Sp8, with 14.3°C. Finally, Sp5, which is the wooden bench exposed to the sun, has 41.5°C.

The top of the roof is seen in Figure 10a and Figure 10b. In this, the ridge or Sp1 has 51.6°C, which is the highest value. At Sp4, which is the wooden structure, 27.5 °C is recorded. In the case of the shaded stone wall, which is Sp5, a temperature of 12.7 °C is recorded, which is the lowest value, which confirms the thermal efficiency of the wings. This becomes more noticeable in Figure 10c which shows the thermal difference between the sunny part of the tympanum and the one shaded by the wing.

Figure 11 shows the interior ceiling as seen from the tapanco. The highest temperature of 40.8°C is from a gap (thermal bridge). The running boards, Sp2, register 27.4°C; one beam, Sp5, has 22.9°C; the stone wall registers a minimum of 14.7°C.

MEASUREMENT OF INTERNAL PARAMETERS WITH HYGROMETERS

In Figure 12, the bay's internal behavior can be seen in black, which maintained a temperature between 13 and 16°C. Meanwhile, in gray, its external behavior is

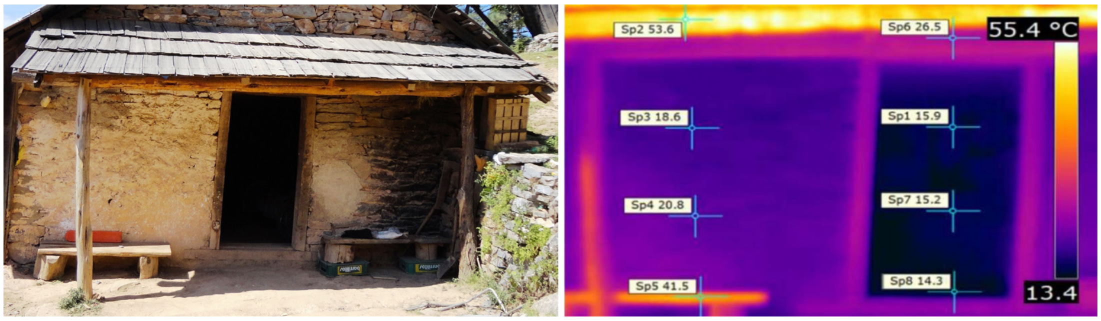

Figure 9. Thermal map - access porch of the house. Source: Preparation by the authors.

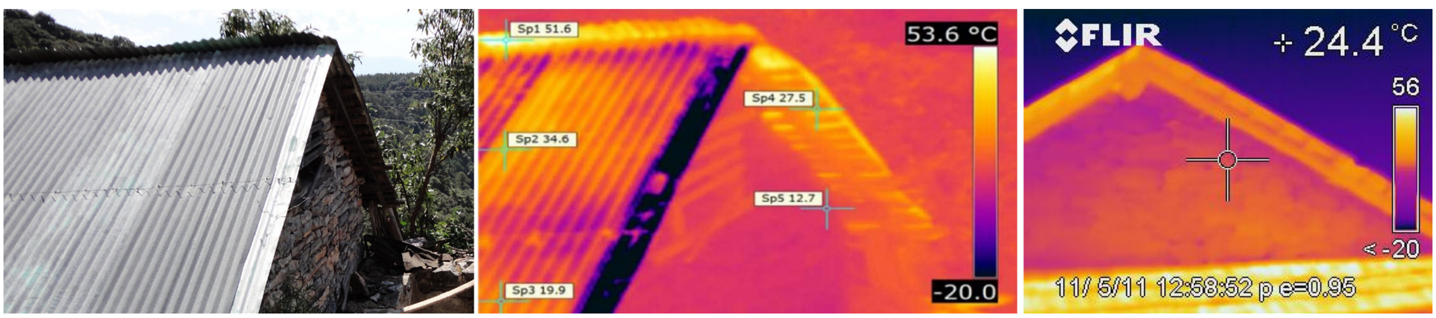

Figure 10. Thermal map – the exterior roof of the house and gable. Source: Preparation by the authors.

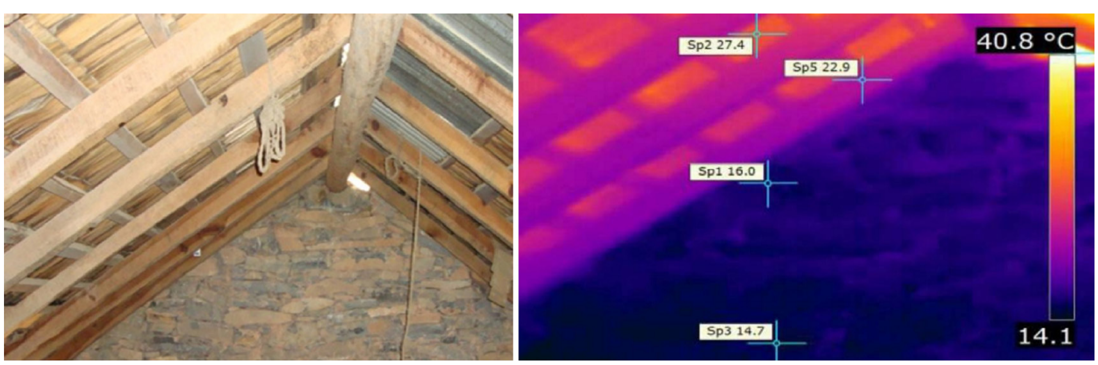

Figure 11. Interior thermal map of the tapanco. Source: Preparation by the authors.

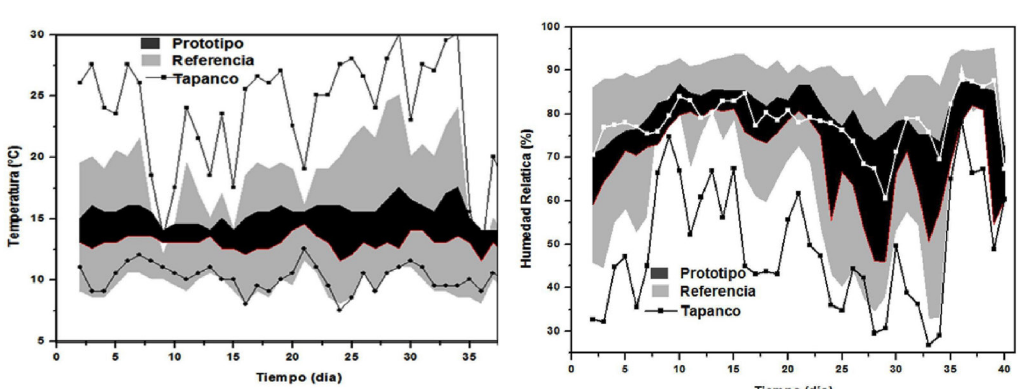

Figure 12. Indoor hygrothermal behavior. Source: Preparation by the authors.

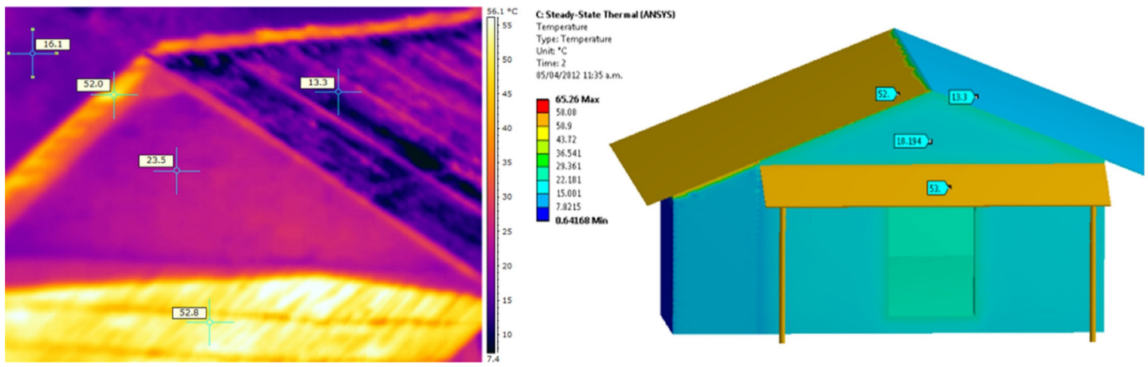

Figure 13. Exterior comparative thermography and ANSYS simulation. Source: Preparation by the authors.

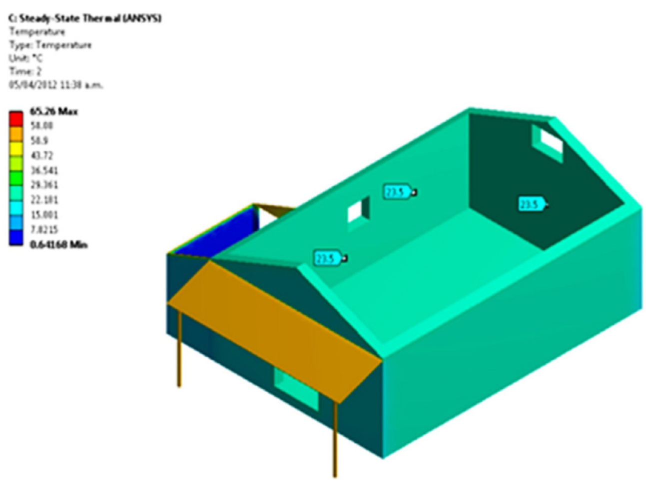
Figure 14. Simulation of indoor thermal behavior. Source: Preparation by the authors.

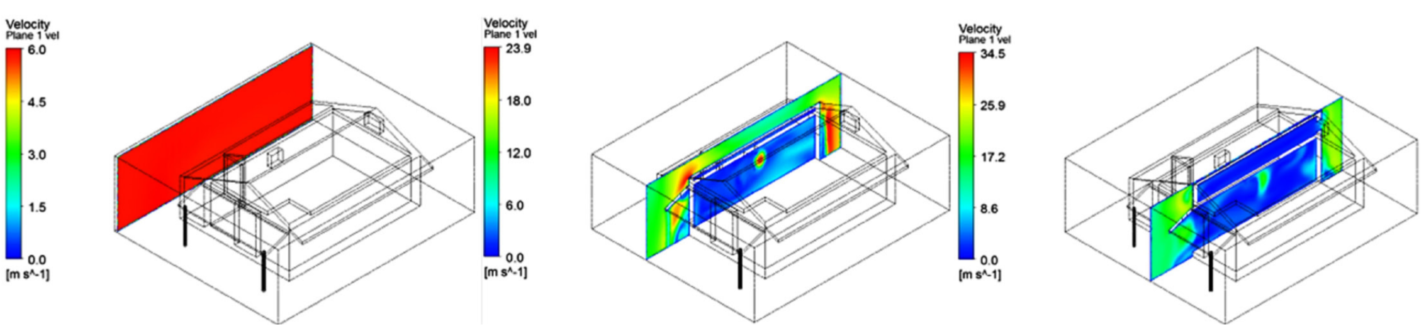

Figure 15. Simulation of airspeed behavior. Source: Preparation by the authors.

observed, with a temperature between 8 and 24 °C. The dotted line indicates the behavior of the tapanco with maximum temperatures of 30°C and minimums of 7.5°C, demonstrating that it works as a heat island by maintaining stable temperatures under this element, i.e., as a thermal buffer. The interior had between 45 and 85% RH, while, at the same time, the external device registered between 30 and 95% RH. According to these data, it is observed that the tapanco shows expected data: HR decreases when concentrating heat, because, except for tropical climates, these variables play an inversely proportional role.

FINITE ELEMENT THERMAL AND WIND SIMULATION

Once the transpolation to extreme situations is done, the results in *ANSYS* show agreement with those of the thermography (Figure 13), since both techniques have similar outdoor temperatures: about 52°C on the sunny roofs, 13°C on the shaded ones, and 18-23°C on the shaded tympanum.

The indoor measurements, which result from the finite element technique, yielded a temperature of 22.5°C ±

7.3°C, considered comfort (Figure 14), and similar to that of the analysis with thermo-hygrometers.

The wind simulation, shown in Figure 15, demonstrates that when the maximum outdoor speed is reached, the indoor one is low. This result is considered a preliminary result relative to the airtightness of the construction and should be verified later by a more detailed analysis.

The air is directed by the sides and by the top of the house as shown in the "*streamline*" from Figure 16.

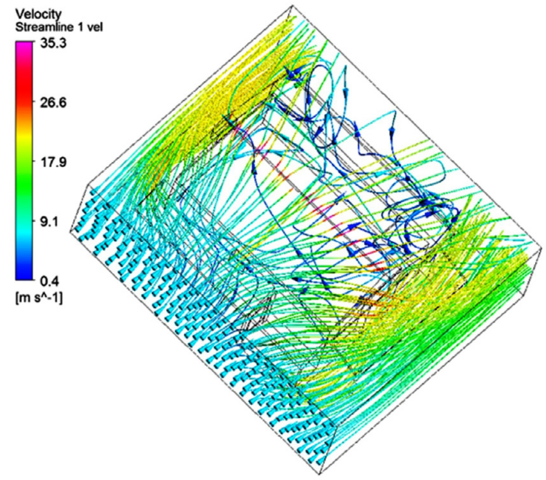

Figure 16. Streamline of the wind. Source: Preparation by the authors.

CONCLUSION

The thermography allowed observing the thermal behavior of the materials and elements with which the house is made. Wood and stone conserve low temperatures, between 12 and 16°C, while roofing has indices above 50°C. The behavior of other elements not proposed as objects of the study were also identified, such as the wings, which, although they are used for rain removal, also play a thermal role, since they cover a large part of the walls from radiation, keeping them at a low temperature that will be projected inside (Figure 8 and Figure 10).

Another thermal element is the porch, which keeps temperatures below 20°C when its roof is over 50°C. This forms a comfortable space since it buffers the direct radiation on the door, which, in turn, acts as a thermal bridge (Figure 9). The open O-P orientation of the bay combined with the inclined roof keeps half of it without solarization, with temperatures that are around 30°C, while the exposed one has values above 50°C (Figure 10), confirming the suitability of using this geometry.

The application of the three measurement techniques (thermographic inspection, thermo-hygrometric measurements, and thermo-wind simulation) allowed having a broader vision of the behavior of the prototype, concluding that the design-materials-tapanco group contributes significantly to indoor comfort. The comparison of the results reflects a good match between the hygrometric indices of the techniques, by showing averages in the habitable area of 20°C for the temperature and 65% RH.

The authors consider then the hypothesis raised is proven, as the tapanco indisputably represents the main passive bioclimatic design element in the analyzed case. It significantly regulates the hygrothermal factors and, given the indices obtained in this study, it fosters ideal conditions for human comfort, matching the parameters indicated by Olgyay (1998). In fact, there are comfort conditions even in extreme situations such as those the model has been subjected to in the simulation and which are presented on the site. Comparatively, industrialized buildings rarely present these comfortable and healthy conditions due to the inadequate thermal index of the materials, along with a design that does not consider the local climate or insulate the envelope, for which the use of mechanical air conditioning is necessary, which implies high energy demand and GHG emissions (Intergovernmental Panel on Climate Change, 2022).

On the other hand, the wind simulation allowed obtaining preliminary findings of the airtightness of the bay, which is due to an aerodynamic design that deflects the direct impact of the wind (Figure 16), as well as by the materials and the joint of the stone with clay. However, it is felt that this phenomenon should be studied in greater depth in subsequent research.

In conclusion, the authors feel that it is essential to consider the properties and behavior of materials, solarization, and the implementation of passive bioclimatic strategies in architectural design since they are fundamental elements that influence the conditions of hygrothermal comfort. It is also necessary to carry out, as far as possible, previous hygrothermal simulations that take into account the particular conditions of each project. All the aforementioned variables, when analyzed scientifically, will allow achieving indoor environmental quality that exerts influence on human health, attitudes, and performance, and understanding the problems of spatial design (Alamino & Kuchen, 2021).

The analysis of the tapanco and other vernacular architecture bioclimatic strategies, as well as their sustainability, are inescapable topics in the research. Under scientific approaches, it represents a very practical theoretical basis for rethinking paradigms and conceptual models of present and future architecture, which should be eminently passive and contribute to EE.

In light of the results obtained in this work, in-depth scientific analysis of these vernacular manifestations that are a source of millenary architectural knowledge and that today entail a solution that if not unique, is very efficient and relevant, is imperative. The authors consider that this topic should urgently be promoted as a systematic and constant line of research in Academia, due to the rapid extinction of many of these living samples of ancestral knowledge.

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FEASIBILITY OF THE ADAPTIVE THERMAL COMFORT MODEL UNDER WARM SUB-HUMID CLIMATE CONDITIONS: COOLING ENERGY SAVINGS IN CAMPECHE, MEXICO

VIABILIDAD DEL MODELO DE CONFORT TÉRMICO ADAPTATIVO BAJO CONDICIONES DE CLIMA CÁLIDO SUBHÚMEDO: AHORRO ENERGÉTICO EN REFRIGERACIÓN EN CAMPECHE, MÉXICO

VIABILIDADE DO MODELO DE CONFORTO TÉRMICO ADAPTATIVO EM CONDIÇÕES DE CLIMA QUENTE SUBÚMIDO: ECONOMIA DE ENERGIA NA REFRIGERAÇÃO EM CAMPECHE, MÉXICO

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RESUMEN

El enfoque convencional para alcanzar el confort térmico generalmente se centra en modificar la temperatura de consigna en edificios totalmente climatizados. Sin embargo, el enfoque del confort térmico adaptativo es una alternativa que considera la interacción entre los edificios, el clima local y los usuarios para permitir mejoras significativas en el ahorro de energía. El trabajo analiza la viabilidad de implementar estrategias de confort térmico adaptativo, comparando modelos adaptativos basados en la norma ASHRAE 55-2020 y un modelo regional para la tipología climática tropical de México, contrastando los resultados respecto del enfoque estático. Se analizó térmicamente 13 locaciones del Estado de Campeche obteniendo que las estrategias de ventilación son aplicables en todo el Estado y que ambos modelos aseguran mejoras en el consumo de energía. Además, los resultaron siguieren que es necesario desarrollar más modelos adaptativos locales para proponer estrategias con mejor potencial de impacto en la región.

Palabras clave
confort térmico adaptativo, clima cálido subhúmedo, ahorro energético

ABSTRACT

The conventional approach to achieve thermal comfort generally focuses on modifying the setpoint temperature in fully air-conditioned buildings. However, the adaptive thermal comfort approach is an alternative that considers the interaction between buildings, the local climate, and the users to allow significant improvements in energy savings. This paper analyzes the feasibility of implementing adaptive thermal comfort strategies, comparing adaptive models based on the ASHRAE 55-2020 Standard and a regional model for the tropical climate typology of Mexico, and contrasting the results with the static approach. Thirteen locations in the State of Campeche were thermally analyzed, seeing that the ventilation strategies are applicable throughout the State and that both models ensure improvements in energy consumption. In addition, the results suggest that it is necessary to develop more local adaptive models to propose strategies with better potential impact in the region.

Keywords
adaptive thermal comfort, hot sub-humid climate, energy savings.

RESUMO

A abordagem convencional para alcançar o conforto térmico geralmente se concentra em modificar a temperatura de referência em edifícios totalmente climatizados. No entanto, a abordagem do conforto térmico adaptativo é uma alternativa que considera a interação entre os edifícios, o clima local e os usuários, a fim de permitir melhorias significativas na economia de energia. Este trabalho analisa a viabilidade de implementar estratégias de conforto térmico adaptativo, comparando modelos adaptativos baseados na norma ASHRAE 55-2020 e um modelo regional para a tipologia climática tropical do México, contrastando os resultados com a abordagem estática. Foram analisados termicamente 13 locais no estado de Campeche, concluindo-se que as estratégias de ventilação são aplicáveis em todo o estado e que ambos os modelos garantem melhorias no consumo de energia. Além disso, os resultados sugerem a necessidade de desenvolver mais modelos adaptativos locais para propor estratégias com maior potencial de impacto na região.

Palavras-chave
conforto térmico adaptativo, clima quente subúmido, economia de energia.

INTRODUCTION

Currently, the building sector is the second largest energy consumer in the world, covering about 40% of energy consumption and generating just over 30% of global emissions (Pérez-Fargallo et al., 2020). One of the main reasons behind this is the high rates of indoor thermal discomfort, meaning that 50% of the energy in buildings is destined to satisfy air conditioning needs (Jimenez-Torres et al., 2023). These patterns increase in cities with hot or tropical climates, which, in the last decade, have seen a constant increase in their population, leading, consequently, to a greater demand for air conditioning.

Under this scenario, the setpoint temperature in air conditioning equipment plays an important role in thermal comfort and high energy consumption. On one hand, this temperature is usually set at a fixed value (sometimes restricted), which means there is not adequate thermal satisfaction for all the occupants of the enclosures. In addition, the greater the difference between the setpoint temperature and the ambient temperature, the more electric power consumption increases. Based on this situation, several studies have shown that by increasing the setpoint or target temperature it is possible to reduce energy consumption by up to 30%. Even in tropical climate regions by setting a temperature above 25.5°C, significant reductions in energy use have been observed (Hoyt et al., 2015). However, it is important to emphasize that these studies have been made under what is currently known as the traditional approach, based on the Predicted Mean Vote (PMV) index, which is also known as the thermal balance model or static model (Sala et al., 1999), which has among its main drawbacks, limiting the interaction of users with the environment.

In the last decade, a new approach to the search for occupant comfort called adaptive thermal comfort (ATC), has become increasingly relevant. Its main idea is to replicate the natural behavior of humans, which is capable of adapting physiologically and psychologically to the increase in temperature to a given point. The adaptive model is based on diverse research regarding the relationships between acceptable indoor air temperature and outdoor air temperature, establishing that the comfort temperature depends on environmental conditions (Tsolkas et al., 2023). Several studies have been carried out under this approach to analyze the potential energy savings, even considering climate change scenarios. Salcido et al. (2016) demonstrated a savings potential of between 50 – 60% when using adaptive strategies. Other researchers (Sánchez-García et al., 2019; Sánchez-García et al., 2023) have established in different studies that, by implementing the adaptive comfort strategy, energy savings of more than 30% are achieved even under climate change scenarios.

However, the adaptive approach has also been the subject of debate in recent years since, although it presents important advances by incorporating adaptation variables, the model's formulation has bias. Among them is its inaccuracy when implemented in different constructions on having been designed based on data from office buildings (Yau & Chew, 2012). In addition, the ATC models promoted most internationally lack analysis in tropical climate regions, leaving doubts about their viability in Latin American locations (Rodriguez & D'Alessandro, 2019). This has led to questioning whether these models can promote a more intensive use of energy instead of reducing it, with one of the most recommended alternatives being the development of local adaptive models that fit the needs of the population where an impact is desired.

Therefore, this work addresses the possibility of reducing the demand for air conditioning equipment in communities with a hot-humid climate, located in the south of Mexico, using the adaptive comfort approach. The case of Mexico is interesting because the residential sector is one of the main energy consumers, allocating more than 20% to air conditioning processes (SENER, 2021). In addition, the locations where the hot-humid climate predominates represent 30% of the country's homes and the records indicate that energy requirements double there, so the analysis and search for energy efficiency techniques are imperative.

The research takes the State of Campeche, Mexico as a case study, analyzing the implementation of the ATC model promoted by the ASHRAE 55-2020 regulations (ASHRAE, 2020) and an adjusted regional model for the tropical climate of Mexico (Oropeza-Perez et al., 2017).

CHARACTERISTICS OF THE REGION OF CAMPECHE

The State of Campeche, Mexico, is one of three states of the country located in the southeast peninsular region. It is bordered to the north by the Gulf of Mexico, to the east by Quintana Roo, Yucatan, and Belize, to the west by Tabasco, and to the south by Guatemala. Its territorial extension is 57,484.9 km^2 with a population of just under 1 million inhabitants spread across 13 municipalities (Figure 1). 99.95% of the territory has a hot humid climate with rains in summer. On the energy issue, it is listed among the states with an electricity tariff for temperatures between 30°C and 31°C during the summer.

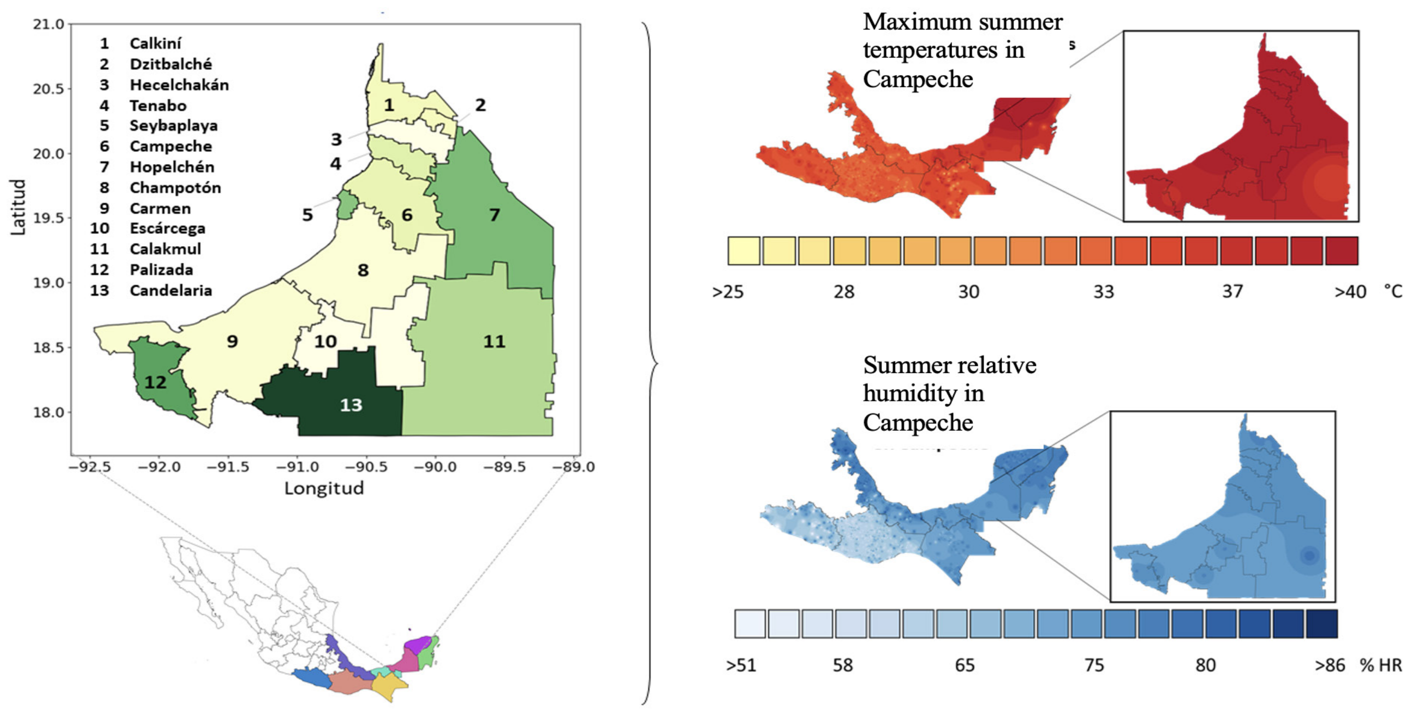

Figure 1. Geographical distribution and climatic characteristics of the State of Campeche, Mexico. Source: Preparation by the authors.

However, the latest weather station records indicate that temperatures inland exceed 37°C (INEGI, 2022), leading to high electricity consumption to satisfy the need for thermal comfort in homes. This is indicative that this region can potentially be benefited both from energy savings and thermal comfort by applying an adaptive approach.

METHODOLOGY

The study was divided into three stages: (i) obtaining the climatic and geostatistical information of the State of Campeche; (ii) applying the ATC models in the State's municipalities to obtain their comfort temperatures; (iii) calculating the potential cooling and heating hours for each municipality, as well as the feasibility of the ATC approach compared to the static model.

CLIMATIC AND GEOSTATISTICAL DATA

The meteorological information was obtained using the Meteonorm V7 software, downloading 13 climatic files of the State of Campeche for 2022, with one-hour intervals. The geostatistical data of population and territorial extension, as well as the entity's maps, come from the last population census made in 2020, whose information is freely accessible on the portal of the National Statistics and Geography System.

ADAPTIVE THERMAL COMFORT APPROACH

The ATC is based on the idea that the temperature inside a building (T_c) can be estimated from the outside ambient temperature (T_{out}).

This relationship is expressed by a linear regression using data collected in field studies both in the official updates of diverse international regulations and in regional adaptations of the approach (Carlucci et al., 2018):

$$T_c = mT_{out} + b \qquad \text{(Equation 1)}$$

where the slope *m* is a value proportional to the degree of adaptation of the region's climatic conditions and the abscissa *b* is the theoretical comfort value (based on measurements) at an outdoor temperature of 0°C (Equation 1).

The paper aims to analyze two ATC models for Campeche. The first is the model promoted by the ASHRAE 55-2020 regulations (ASHRAE, 2020), which, although it does not follow an international standard, is one adopted most around the world. This ATC model was generated from data measured on 160 buildings located in countries on four continents, which has promoted its use as a standard in much of the world. The regulations indicate that a comfort temperature threshold at 80% reliability is obtained from the following linear equations (Equation 2 and Equation 3) (Carlucci et al., 2018):

Upper limit (acceptability 80%) =
$$0.31\,\overline{T}_{pma(out)} + 21.3\ °C \quad (10 \leq \overline{T}_{pma(out)} \leq 33.5) \qquad \text{(Equation 2)}$$

Limit to infer (acceptability 80%) =
$$0.31\,\overline{T}_{pma(out)} + 14.3\ °C \quad (10 \leq \overline{T}_{pma(out)} \leq 33.5) \qquad \text{(Equation 3)}$$

Where $\overline{T}_{pma(out)}$ represents the prevailing average outdoor temperature. When $\overline{T}_{pma(out)}$ is above or below this threshold, it is necessary to implement cooling or heating strategies inside the building to achieve occupant comfort.

The second ATC model evaluated is the one developed by Oropeza-Perez et al. (2017). This is distinguished by being the first regional ATC model designed for Mexico, which divides the country into four types of climate (arid, temperate, hot dry, and hot humid). The model was developed from 74 surveys distributed proportionally in the four climatic zones. The entire territory of the State of Campeche is classified as a hot humid climate. According to this, the ATC is given by equation 4:

$$T_c = 0.38\,\overline{T}_{pma(out)} + 15.7\ °C \qquad \text{(Equation 4)}$$

To homogenize the description of this model with what is expressed by the ASHRAE 55-2020 standard, the upper (Equation 5) and lower (Equation 6) limits were defined by adding ± 3.5°C:

Upper limit (acceptability 80%) =
$$0.38\,\overline{T}_{pma(out)} + 18.2\ °C \quad (10 \leq \overline{T}_{pma(out)} \leq 33.5) \qquad \text{(Equation 5)}$$

Limit to infer (acceptability 80%) =
$$0.38\,\overline{T}_{pma(out)} + 13.2\ °C \quad (10 \leq \overline{T}_{pma(out)} \leq 33.5) \qquad \text{(Equation 6)}$$

For both approaches, it highlights the concept of $\overline{T}_{pma(out)}$. Its importance lies in the fact that the ATC is based on the premise that the temperature inside buildings does not depend exclusively on the current day, but is influenced by the ambient temperature of the previous days; where $\overline{T}_{pma(out)}$ represents these effects. In previous versions of ASHRAE regulation 55-2017, $\overline{T}_{pma(out)}$ was considered as a value obtained through monthly averages. From the last two modifications, this is linked to the days before the day of interest, whose equation is given by equation 7:

$$\overline{T}_{pma(out)} = (1-\alpha)[T_{e(d-1)} + \alpha T_{e(d-2)} + \alpha^2 T_{e(d-3)} + \alpha^3 T_{e(d-4)} + \cdots] \qquad \text{(Equation 7)}$$

Where α is a weighted value that varies between 0 and 1, while $T_{e(d-1)}$ represents the number of previous days to consider that may impact the internal temperature of the building. For this work, seven previous days were used, as well as an α of 0.8 which is for regions with a tropical climate as is the case of the State of Campeche considering the ASHRAE 55-2020 regulations.

COOLING AND HEATING HOURS POTENTIAL

The Cooling Degree Hours (CDH) (Equation 8) and Heating Degree Hours (HDH) (Equation 9) methods were used to identify the cooling and heating potential during the ATC's implementation. Both measure the influence of temperature changes on the energy performance of the building. The CDH is defined as the cumulative sum of subtracting a setpoint temperature (T_T) from the average ambient temperature of each hour (T_a). Where h indicates the total number of hours analyzed and the apostrophe (+) indicates that only positive results are effective during the summation. Similarly, the HDH indicates the cumulative sum of subtracting the average ambient temperature of each hour (T_a) from the setpoint temperature (T_T), (Jimenez-Torres et al., 2023):

$$CDH = \begin{cases} \sum_{h}^{8760} (T_a - T_{T,EC})^+ & \text{enfoque estático} \\ \sum_{h}^{8760} (T_a - T_{T,DC})^+ & \text{enfoque dinámico} \end{cases} \qquad \text{(Equation 8)}$$

$$HDH = \begin{cases} \sum_{h}^{8760} (T_{T,EH} + T_a)^+ & \text{enfoque estático} \\ \sum_{h}^{8760} (T_{T,DH} + T_a)^+ & \text{enfoque dinámico} \end{cases} \qquad \text{(Equation 9)}$$

Conventionally, the setpoint temperature is assigned to a static value. For CDH, it is given by the static cooling temperature (=25°C), and for HDH is given by

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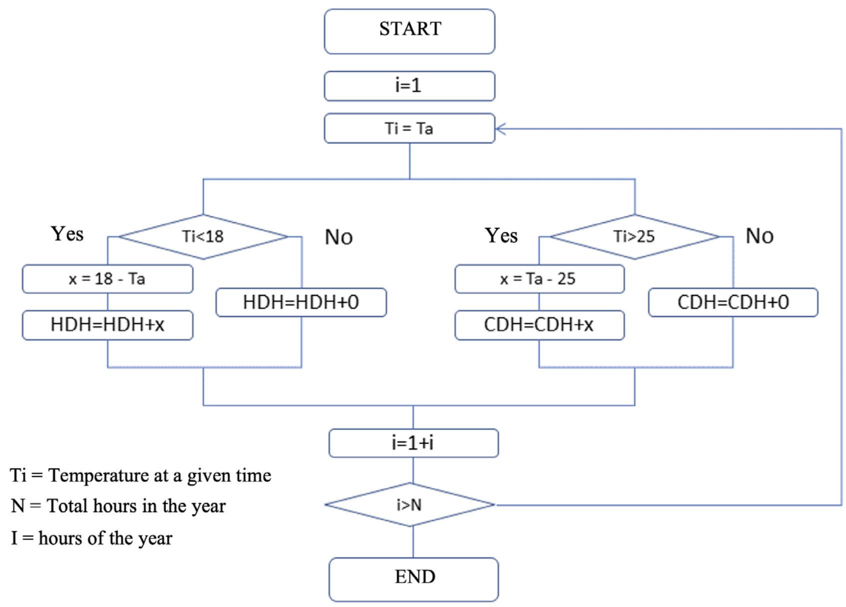

Figure 2. Flow diagram to obtain the static CDH and HDH. Source: Preparation by the authors.

the static heating temperature (= 18°C). Both values are within the range historically described in several regulations, such as the case of ANSI/ASHRAE 169-2020 (ANSI/ASHRAE, 2021). Figure 2 illustrates the algorithm used to calculate the static CDH and HDH.

For the adaptive approach, the setpoint temperature is considered dynamic and is given by the value of the comfort temperature at the 80% upper limit of acceptability (and the 80% lower limit of acceptability for the CDH and HDH, respectively. In this work, it is intended to compare both the adaptive model of the ASHRAE 55-2020 regulation and the regional model developed by Oropeza-Perez et al. (2017) compared to the static model to determine the viability of the adaptive approach.

VIABILITY INDICATORS OF THE ADAPTIVE APPROACH

The viability of the ATC for the region is measured by comparing the annual hours (h_i) when each of the municipalities is within the comfort threshold at an acceptability of 80%. This is known as the annual percentage of the potential application of natural ventilation (PNV) and is given by Bienvenido-Huertas et al. (2021):

$$PNV = \frac{100\sum_{h}^{8760} h_i}{8760} \quad \text{(Equation 10)}$$

RESULTS AND DISCUSSIO

ANALYSIS OF COOLING DEGREE HOURS

Figure 3 illustrates the spatial representation throughout Campeche on the demand for annual cooling hours considering the static approach (Figure 3a), the dynamic approach developed by Oropeza-Perez et al. (2017) (Figure 3b), and the dynamic approach based on the ASHRAE 55-2020 standard (Figure 3c). For all three cases, it is clear that the municipalities located in the north of the state are the ones that require the highest demand for cooling, even though the entire entity has the same type of climate. This can be explained because the State's northern municipalities have the lowest rainfall levels throughout the year, between 700 and 800 mm, while the southern municipalities see rainfall levels of 1500 to 2000 mm (INEGI, 2022). In addition, although INEGI data report that more than 77% of the state is covered by forest and grassland, the soil type is variable in the region. The areas where higher levels of CDH are reported are located in karstic soils with an abundance of rocky surfaces. As one heads south, the dominant physiography is hills, which coincides with the reduction in the demand for cooling. Finally, the lowest latitudes, with the lowest demand for CDH, are the State's swampy area.

From Figure 3, it is inferred that the static approach is the one that homogeneously demonstrates the highest demand for CDH in the year, in most of

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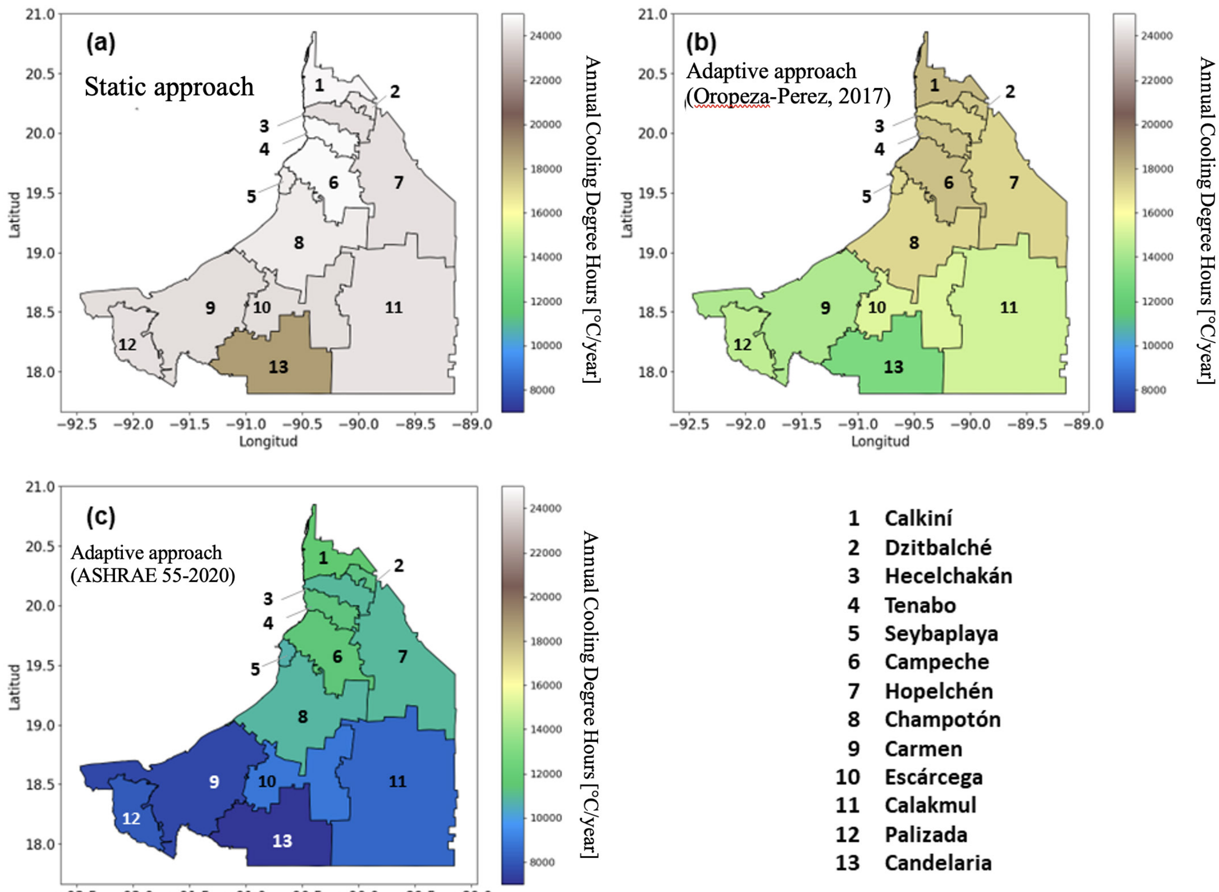

Figure 3. Cooling degree hours for the municipalities of Campeche: (a) static model; (b) regional adaptive model; (c) ASHRAE 55-2020 adaptive model. Source: Preparation by the authors.

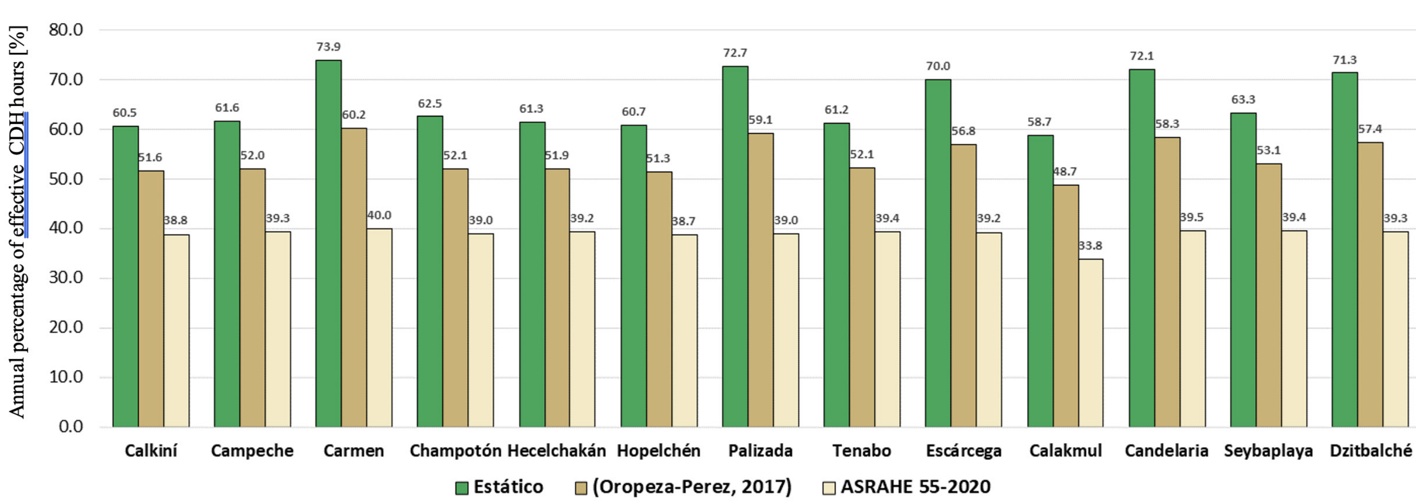

Figure 4. Annual comparison for the municipalities of Campeche on the percentage of cooling hours-year required using the static approach and the adaptive comfort approach. Source: Preparation by the authors.

the territory. Except for the municipality of Candelaria, the entire State has an almost constant CDH ranging from 24,000 to 24,800°C/hour-year. Comparing these values with those of Figure 3b and Figure 3c, it is seen that the adaptive approach leads to less energy use for cooling in all the entity's municipalities. However, there are notable differences between the two ATC models. The ASHRAE model indicates that it is possible to reduce the CDH index by between 53 and 62%, while the regional model, although exhibiting benefits, reduces these by half, decreasing between 28 and 31%, compared to the static approach. This may be because the ASHRAE 55-2020 model is designed under analysis in less hot climates, implying a less drastic reason to change for the occupants (m=0.31). This may lead to a critical limit in tropical climate regions, such as Campeche, to comply in theory with the model, but in practice, it increases occupant discomfort. On the other hand, the regional model indicates that populations in hot climates do not have a broad tolerance to heat (b=18.3), as well as a lower climatic adaptation to sudden temperature changes that occur in the region.

Another important point to analyze is how the integration of the adaptive approach impacts the operation hours of air conditioning equipment. Figure 4 presents the annual percentage of hours air conditioning equipment is used to cool rooms. The static approach shows a 60% use of air conditioning during the year, with the southern municipalities (Carmen, Palizada, Escárcega, and Candelaria) being the ones that use air conditioning the most. This implies that, despite their annual consumption being lower than the northern municipalities, they are the ones with the longest time outside their comfort zone. On the other hand, by using the regional adaptive model, it is possible to reduce effective CDH hours by between 10% and 8%; reducing operating hours in most municipalities to below 55%, while the ASHRAE model suggests that it is possible to reduce annual CDH hours to below 40%. However, it is important to consider what was discussed above, since, according to Humphreys et al. (2007) a poor implementation of the adaptive approach can be counterproductive as it would encourage occupants to use more energy to relieve heat stress. This demonstrates the value of the regional model by more clearly representing the characteristics of the State, while at the same time indicating that the adaptive approach is an appropriate option for reducing the energy consumption of air conditioning.

ANALYSIS OF HEATING DEGREE HOURS

For HDH, its analysis does not imply the need for heating actions in the State (temperatures in the

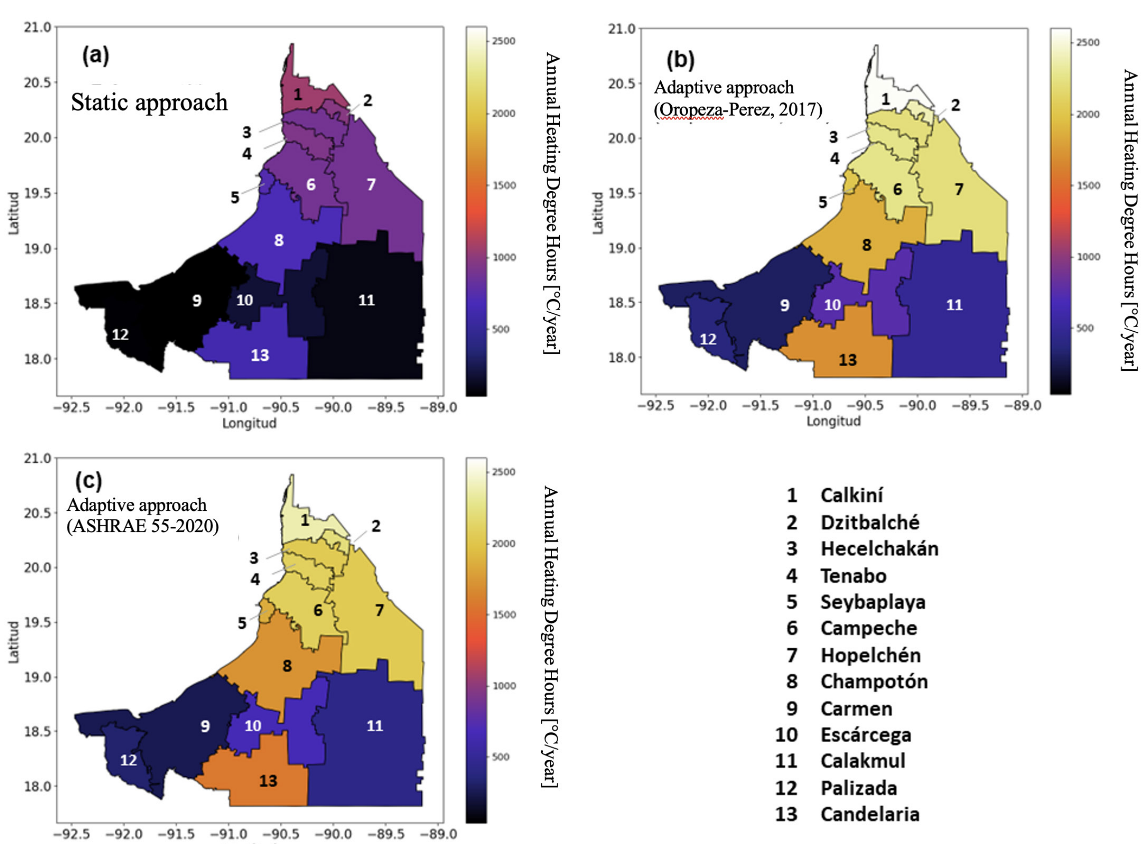

Figure 5. Heating degree hours for the municipalities of Campeche: (a) static model; (b) regional adaptive model; (c) ASHRAE 55-2020 adaptive model. Source: Preparation by the authors.

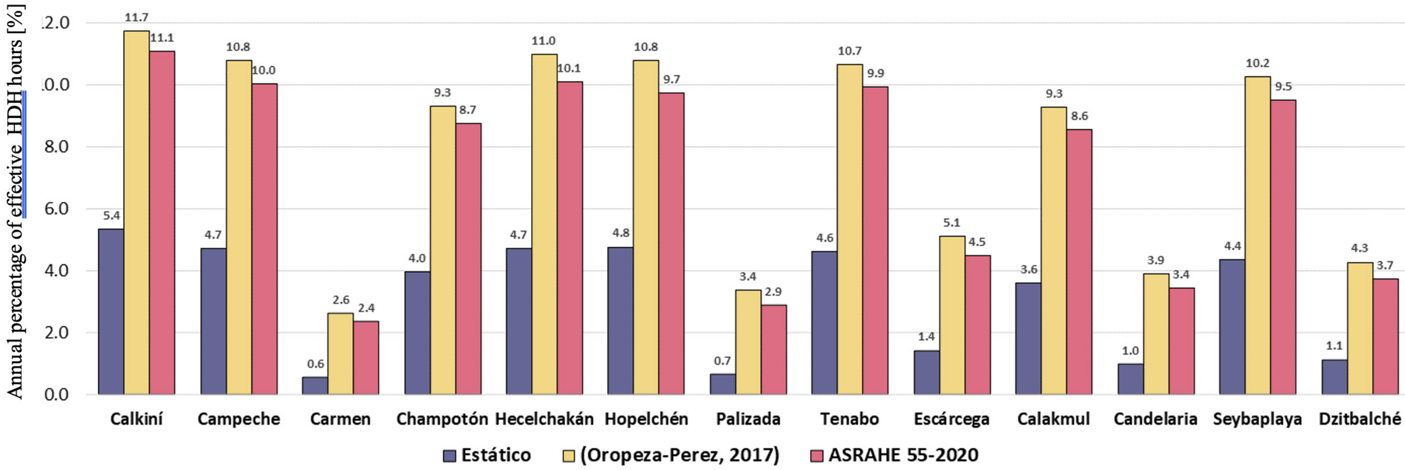

Figure 6. Annual comparison for the municipalities of Campeche of the percentage of heating hours-year required using the static approach and adaptive comfort approach. Source: Preparation by the authors.

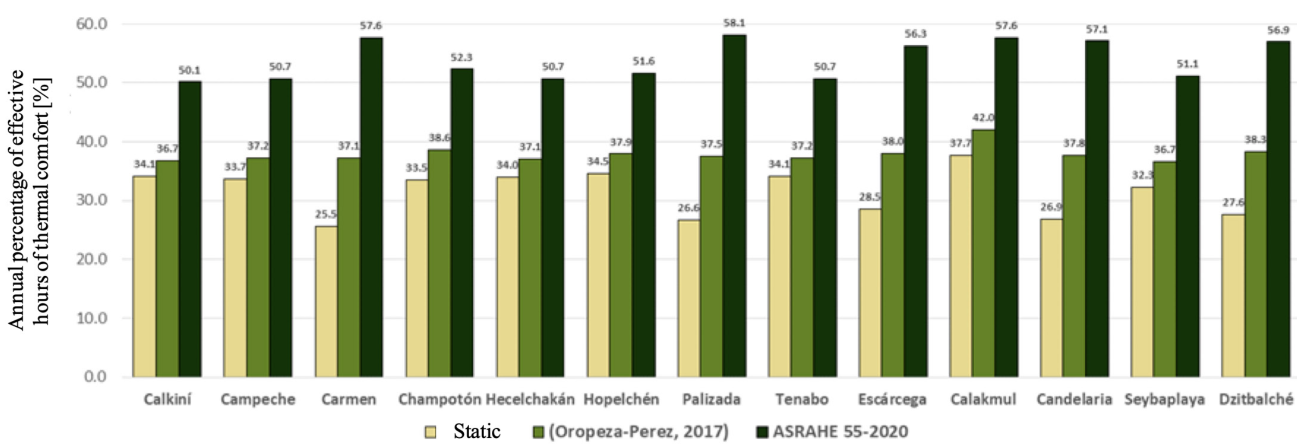

Figure 7. Annual comparison for the municipalities of Campeche of the percentage of heating hours-year required using the static approach and the adaptive comfort approach. Source: Preparation by the authors.

region are hardly ever lower than 18°C), but it is an indication of the time when the population may be in temperatures below the comfort zone.

According to Figure 5, there is a phenomenon similar to the case of the CDH where the municipalities of Carmen, Palizada, Candelaria, and Escárcega (located to the south) have the lowest discomfort rates during the year. The results of the static approach show that the HDH requirements for the State are minimal, coinciding with the tropical climate conditions of Campeche. However, remembering that here the HDH indicates the level of occupant discomfort, it is necessary to compare these with the adaptive results. Based on Figures 5b and 5c, the adaptive approach infers that HDH needs are higher. It is important to note that in comparison to the CDH case where the ASHRAE model varies by up to 20% from the regional model, the HDH difference between the two is minimal, which can be corroborated in the color scale of Figure 5. On average, the models differ by 9.8%, so in this case, they do agree on the heating estimate. It should be noted that this difference may be due to the perception of cold in tropical climate regions, where the population begins to feel discomfort at higher temperatures than in temperate regions.

On the other hand, the analysis was made regarding the annual hours that the population is below the comfort zone (Figure 6). The difference between the effective hours for both adaptive models only varies between 0.2% and 0.9%, with the municipalities with the lowest percentage of HDH being the ones where the smallest differences were found. In all cases, the adaptive model barely exceeded 10% of annual hours,

Table 1. Differences in the percentage of hours of CDH, HDH, and annual thermal comfort of each adaptive model compared to the static approach for the State of Campeche. Source: Preparation by the authors.

Municipality	Model (Oropeza-Perez et al., 2017)			ASHRAE 55-2020 Model		
	CDH	HDH	Comfort	CDH	HDH	Comfort
Calkiní	9.0	6.4	2.6	21.7	5.7	16.0
Campeche	9.6	6.1	3.5	22.2	5.3	16.9
Carmen	13.7	2.1	11.6	33.9	1.8	32.1
Champotón	10.4	5.3	5.1	23.6	4.8	18.8
Hecelchakán	9.4	6.3	3.1	22.1	5.4	16.7
Hopelchén	9.4	6.0	3.4	22.0	5.0	17.0
Palizada	13.6	2.7	10.9	33.7	2.2	31.5
Tenabo	9.1	6.0	3.1	21.8	5.3	16.5
Escárcega	13.2	3.7	9.5	30.8	3.1	27.8
Calakmul	10.0	5.7	4.3	24.8	5.0	19.9
Candelaria	13.8	2.9	10.8	32.6	2.5	30.2
Seybaplaya	10.2	5.9	4.3	23.9	5.1	18.8
Dzitbalché	13.9	3.1	10.8	32.0	2.6	29.4
Average	11.2	4.8	6.4	26.5	4.1	22.4
Standard Deviation	2.1	1.6	3.6	5.1	1.4	6.5

which translates into just under 40 days of the year, with most of that time being at night.

POTENTIAL NATURAL VENTILATION APPLICATION

The ultimate purpose of the analysis is to identify the level of positive impact that the implementation of adaptive strategies has in the 13 municipalities of Campeche. According to what was presented in Figure 7, the implementation of both adaptive models demonstrates advantages over the static approach. In the case of the ASHRAE 55-2020 model, it was identified that its use would be associated with the possibility of applying natural ventilation for at least 50% of the year in all municipalities of the State, with the possibility of being used in up to more than 57% in municipalities such as Palizada, Carmen, and Calakmul. In the case of the regional model, there are moderate benefits with an average percentage of natural ventilation use of 38% throughout the territory.

Table 1 shows that the adaptive regulatory approach and the regional approach improve the perspective of natural ventilation application by 16% and 6.4%, respectively. It is interesting to analyze the effects of the regional model. On one hand, the municipalities in the north of the state (Campeche, Calkiní, Hecelchakán, and Tenabo) have improvements of barely 2.4 and 3.5% compared to the traditional model. On the other hand, the best results occur in the southern municipalities.

In the case of the ASHRAE model, similar results can be found as indicated in the previous paragraph, which makes it clear that natural ventilation strategies based on the adaptive approach do not benefit the entire federal entity in the same way. In the case of the ASHRAE model, its effectiveness remains in doubt, specifically in the case of CDH, considering that it may be overestimating the population's tolerance to the region's extreme heat conditions. On the other hand, the regional model showed that, although it can be adjusted to climate conditions, it also makes clear the need to develop local comfort models that take into account the regional subdivision of the country's entities to propose strategies considering the reality of the Mexican southeast.

The results can be used to make other analyses such as identifying the percentage and degree of impact on the population when implementing natural ventilation strategies using the adaptive approach (Figure 8). In the case of the ASHRAE model, it is appreciated that the impact range is between 50% and 60%. In this case, the data can be divided into four strata, where the case of 54-56% was omitted due to the lack of values. According to the population data of each municipality, 48% of the inhabitants of Campeche have the possibility of applying natural ventilation strategies, just under 52% of the year. These results coincide with the fact that the most densely populated area is the municipalities of Campeche and Seybaplaya. On the other hand, 43% of the population has the possibility

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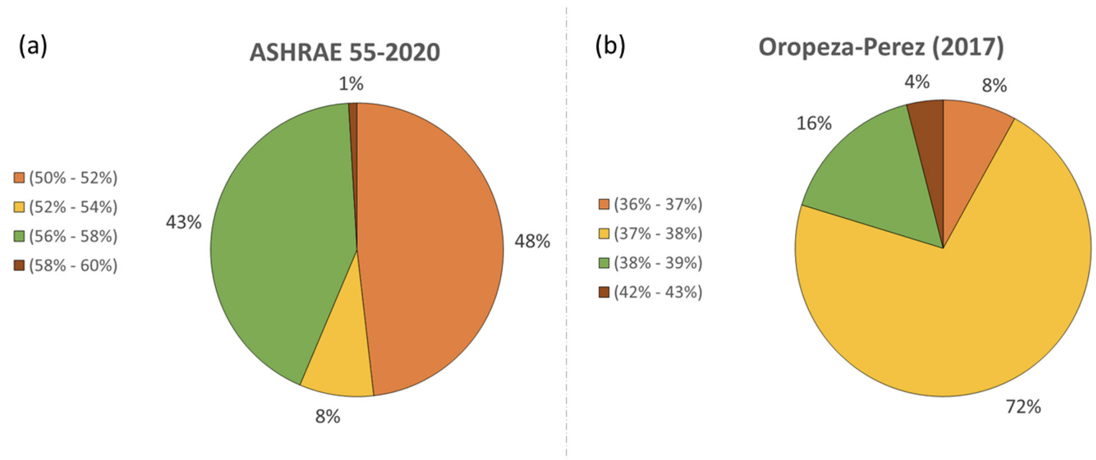

Figure 8. Population in the State of Campeche that the percentage of effective hours of ATC impacts (a) analysis based on ASHRAE 55-2020 model; (b) analysis based on regional model. Source: Preparation by the authors.

of implementing the adaptive approach to achieve thermal comfort levels between 56% and 58% per year. This is due to the greater demographic distribution in the southern municipalities where thermal stability is greater. In the case of the local model, the results are more concentrated. In this case, to provide a better appreciation, it was divided into four strata with 1% intervals. According to the results of this model, 88% of the population is in a range between 37 and 39% possibility of natural ventilation. This indicates that the model impacts a large percentage of the inhabitants. In addition, these values are above what can be achieved with the static approach. In this way, the regional model shows that, although to a lesser extent, the adaptive approach does favor the reduction of energy consumption for the State's inhabitants and questions the viability of implementing the conventional ASHRAE model in the region.

Finally, the adaptive approach has advantages both from the perspective of comfort and energy savings. In the case of Campeche, which is a young federal entity with a small and growing population, this type of approach offers the possibility of urban growth with better design and approach strategies. However, it is imperative to run more focused studies in the different municipalities to be able to make more specific estimates that fit the reality of the region.

CONCLUSION

This study focused on analyzing the implementation of the adaptive thermal comfort approach as a strategy to improve thermal sensation and energy savings in buildings in the state of Campeche. By reviewing the 13 climate files of each of the State's municipalities, the potential cooling and heating hours, and feasibility of the adaptive approach for the region were determined. For this purpose, the model of the ASHRAE 55-2020 regulation and a regional model developed for tropical climates in Mexico were analyzed. These models were compared with the conventional static thermal comfort approach to determine the advantages and differences between the two.

The results showed that both adaptive models can contribute to reducing the use of air conditioning equipment in the State's 13 municipalities. However, significant differences were found in the potential of both models, which were attributed to the fact that the model based on the ASHRAE 55-2020 standard, although widely used, may have biases as it is not designed with variables typical of a tropical climate. According to the results, the regional model averaged an 11.2% reduction in annual air conditioning hours while the regulatory-based approach obtained 15.4% and 16.0% respectively.

Regarding the feasibility of implementation, the regional adaptive approach demonstrated the ability to improve thermal comfort inside buildings by 2.6% to 11.6%, while the ASHRAE approach indicated improvements between 16% and 32%. On the other hand, the results of the regional model show that, although to a lesser extent, the adaptive approach does favor the reduction of energy consumption among the State's inhabitants, and opens the question about the feasibility of implementing the conventional ASHRAE model in the region.

Finally, the work gives rise to developing further studies focused on: (i) generating specific models for the different municipalities or subregions of the state to make estimates that fit the context of the country's southeast, (ii) studying adaptive behavior in the different building types n the region.

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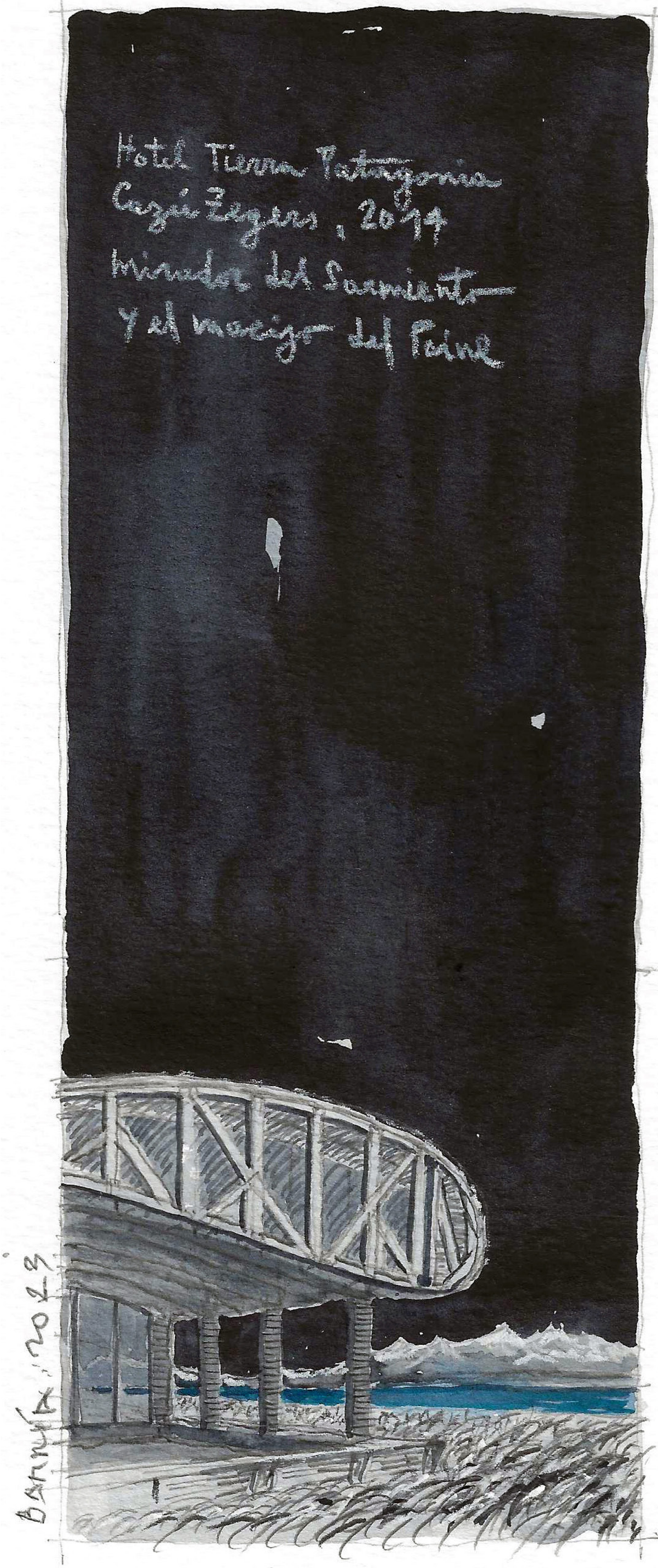
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Cazú Zegers, 2011
Mirador del Sarmiento
y el macizo del Paine
BARRÍA, 2023