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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.

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).

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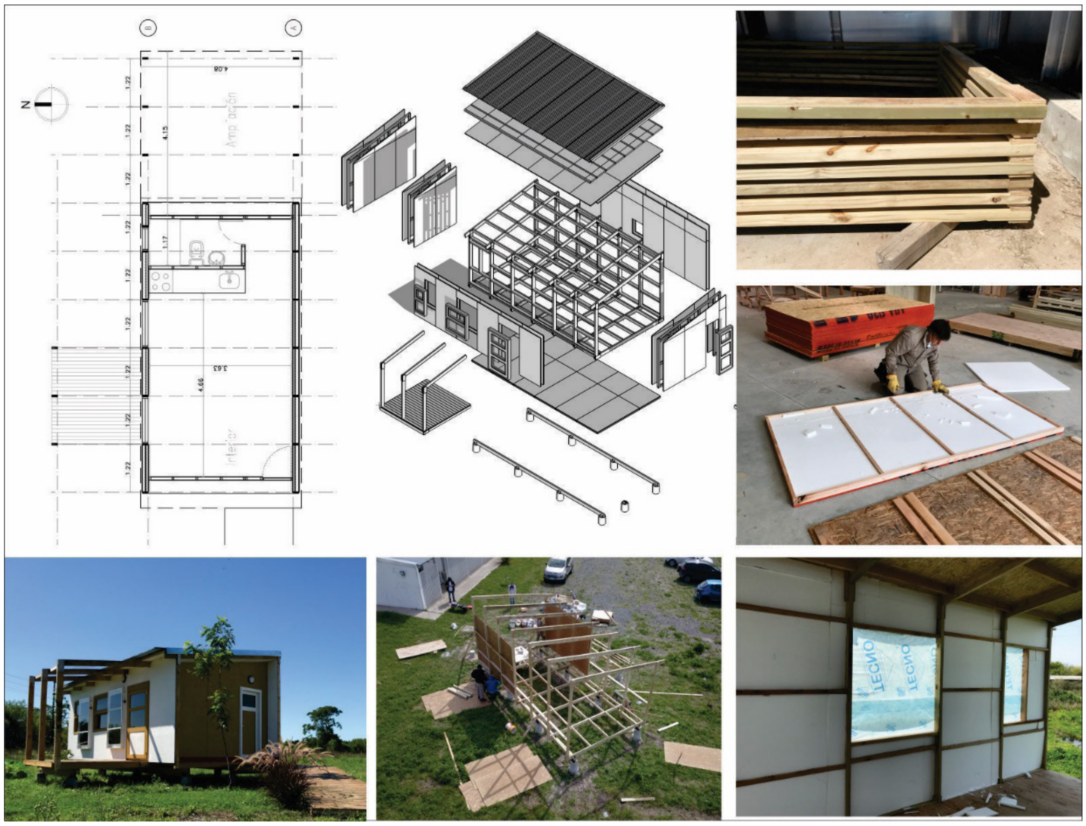

Figure 1. Documentation of the housing solution, parts, images of the process, and final result (clockwise from top left). Source: Preparation by the authors

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/m^2°C)	Roof K W/m^2°C)	Floor K (W/m^2°C)	G (W/°C m^3)
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]

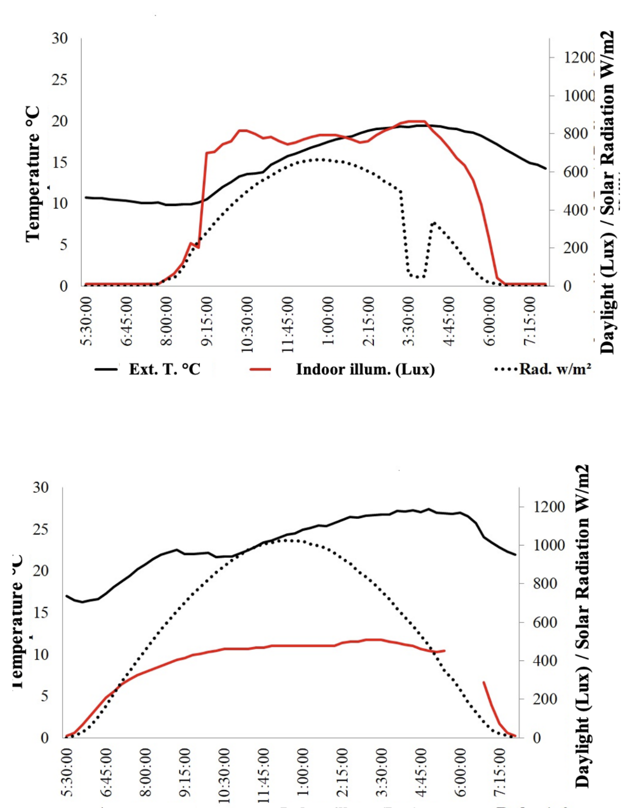

Figure 3. Specific measurement (located on the red star of the floorplan in Figure 3) of the daylight in the main room in August (left) and November (right). Source: Preparation by the authors

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.

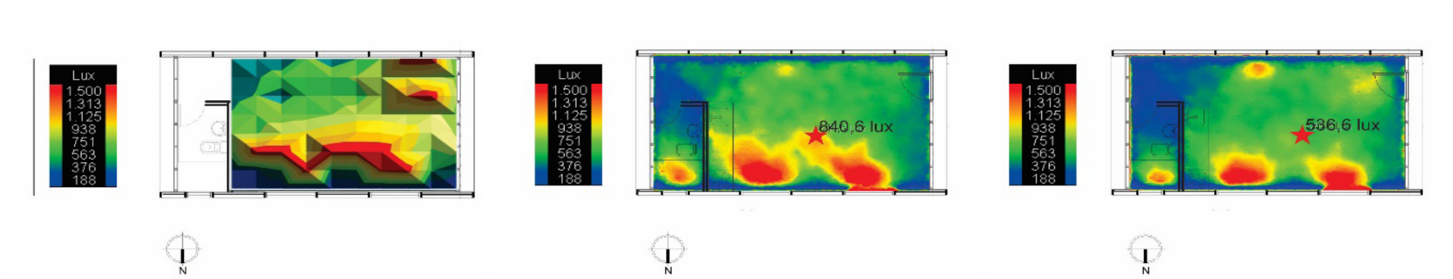

Figure 4. Point-to-point measurements for August 24th at 3 pm (left), daylight simulation on a sunny day at 3 pm in August (center), and November (right). Source: Preparation by the authors

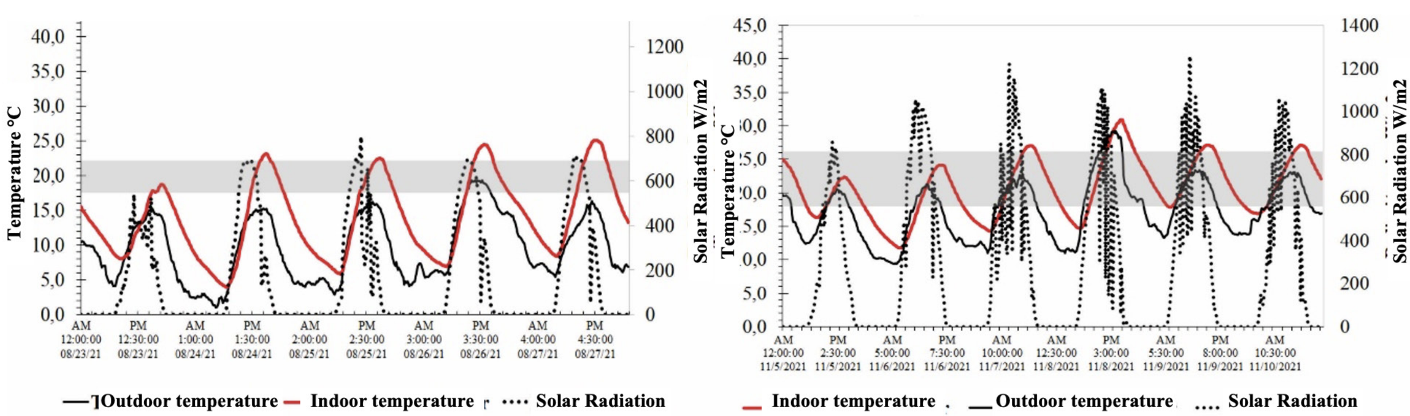

Figure 5. Thermal behavior in August (left) and November (right). Source: Preparation by the authors.

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

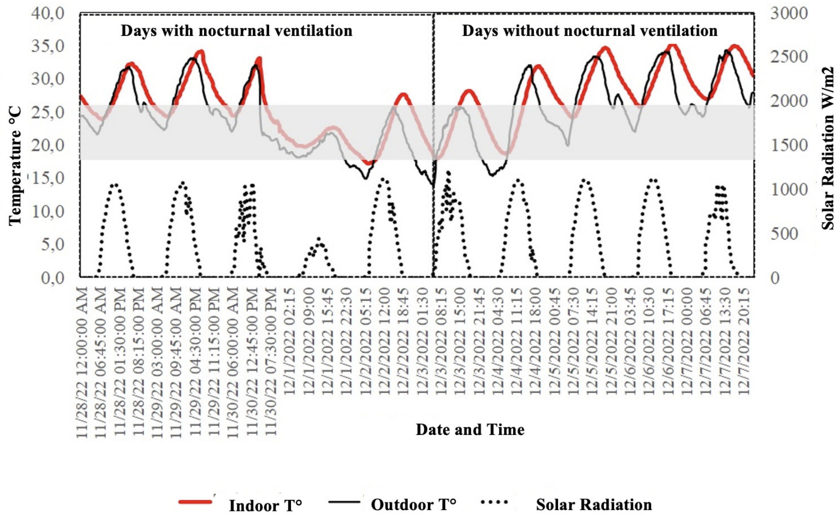

Figure 6. Behavior on warm days with and without nocturnal ventilation (gray indicates the summer comfort level of 18°C to 26°C). Source: Preparation by the authors.

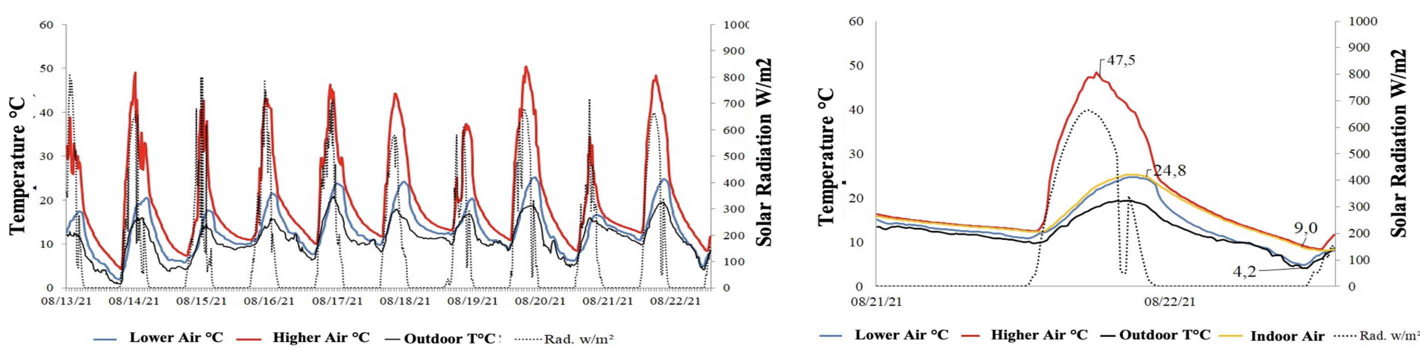

Figure 7. Thermal response of the solar air heater in the cool period. Source: Preparation by the authors.

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/m² 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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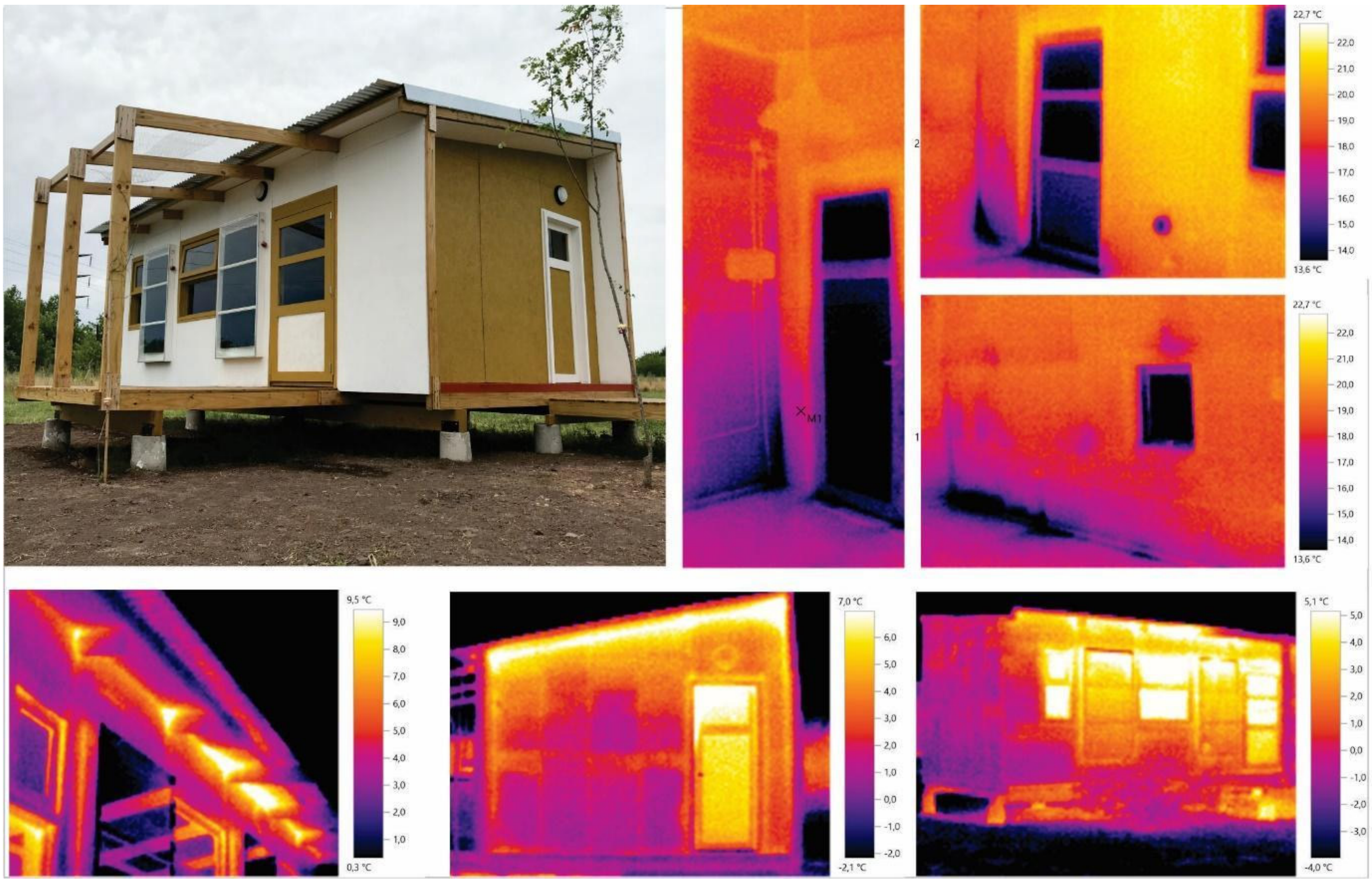

Figure 8. Thermal imaging images taken on 05/27/2022 between 8 and 10 pm. Source: Preparation by the authors.

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

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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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