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THERMAL PERFORMANCE OF WOOD-FRAME VS. TRADITIONAL HOUSING: A FIELD MEASUREMENT APPROACH

Gabriel Pena-Vergara
Pedro Galione-Klot
Fedrico Favre
Universidad de la República, Department of Applied Thermodynamics, Montevideo, Uruguay
gabpena@fing.edu.uy, pgalione@fing.edu.uy, ffavre@fing.edu.uy

Juan Rodriguez
Gunnar Gil
Universidad de la República, North Coast Physics Department, Salto, Uruguay
jrodigue@fing.edu.uy, gunnargm@gmail.com

María Noel López
Universidad de la República, Institute of Technologies, Climate and Comfort in Architecture, Faculty of Architecture, Design and Urban Planning, Montevideo, Uruguay
marialop@farq.edu.uy

Abstract. *The energy demand in the residential sector stems from heating, cooling, cooking, water heating, appliances, and lighting. Energy usage in homes is influenced by climate, architectural design, energy systems, and economic status. In socioeconomically vulnerable areas, restricted access to heating and cooling systems and inadequate housing design can lead to indoor discomfort, affecting quality of life. This study analyzes the energy performance of single-family social housing using two construction methods: wood frame and traditional (heavy system). Monitored houses were built in nearby rural/suburban areas, with measurements taken in two and three-bedroom homes during winter and summer. Data collected included indoor and outdoor temperatures, relative humidity, air permeability.Local microclimate conditions were characterized using nearby meteorological station data. Both construction methods showed good thermal performance, enhancing indoor thermal comfort compared to outdoor conditions. The traditional method outperformed the wood frame, with fewer thermal discomfort hours and better dampening of outdoor conditions, leading to a smaller thermal amplitude indoors. During warm periods, traditional housing maintained lower indoor temperatures at daily peaks. All houses had wood stoves in the living room, effectively heating the entire house in winter. The primary energy consumption was for hot water systems and outdated refrigerators, as the houses had minimal electrical appliances.*

Keywords: *Thermal Comfort, Social Interest Household, Experimental Assessment, Materials Influence*

1. INTRODUCTION

Social housing plans are a crucial tool for providing access to quality housing solutions for vulnerable, low-income populations. The social housing examined in this study consists of homes partially constructed with labor provided by the recipient families, while the State contributes additional labor, design, and other necessary resources. A fundamental aspect of these homes is the thermal comfort they offer to their inhabitants. In this context, approaches such as numerical simulations and on-site measurements are essential for improving the design, usage, and performance of housing, particularly in the case of social housing.

Several studies have addressed the comparison of different construction techniques. For instance, Gazquez *et al.* (2022) compare two social housing units in Argentina, one with a traditional construction system (ancient system, built by self-construction) and another with a contemporary system (based on the International Style), evaluating the embodied energy of materials and energy consumption through a life cycle analysis. Triana *et al.* (2023) investigate energy efficiency strategies in social housing in Brazil. Dalbem *et al.* (2019), also in Brazil, use numerical simulations to evaluate the potential for social housing to meet minimum national regulatory standards and even achieve the Passive House standard. Hermawan *et al.* (2015) compare eight heavy construction houses with eight wood-frame houses through on-site measurements in a warm and tropical region, finding greater comfort in the wood-frame houses. Mendon *et al.* (2017) use EnergyPlus to compare heavy construction houses, wood-frame houses, and steel-frame houses in moderate and warm climates, showing that heavy construction houses have greater efficiency and highlighting the importance of thermal insulation. Lastly, Nässén *et al.* (2012) conduct a life cycle analysis comparing concrete and wooden buildings, though without considering differences in energy performance during use.

In this work, we compare the thermal performance of social housing with different construction solutions based on on-site measurements. These houses are built using par. Two types of construction are evaluated: one of heavy construction ("Traditional") and one of light construction ("Wood Frame"). The results were obtained through collaboration with two public institutions in Uruguay: the National Energy Directorate and MEVIR (Movement for the Eradication of Rural Unhealthy Housing), focused on analyzing construction typologies implemented in Uruguay. Previous studies compared these houses using computational simulations with EnergyPlus as in Favre *et al.* (2023) and Galione *et al.* (2023).

The structure of this work is as follows: Section 2 describes the analyzed typologies and their construction characteristics, as well as the on-site measurements. Section 3 presents and analyzes the results obtained, comparing the thermal performance and energy consumption of the houses. Finally, the conclusions are detailed in Chapter 4.

2. METHODOLOGY

2.1 Typology design

The case study focuses on analyzing two- and three-bedroom houses of the same typology, constructed using two different building solutions. The spatial distribution and the geometry of the rooms are very similar for both construction solutions, with some differences that will be detailed later. The two construction solutions are referred to as "traditional" and "wood frame". Figure 1 shows the floor plan for the two- and three-bedroom houses. Both types of houses are located in rural or suburban areas with very low surrounding population density, and they are 110 km apart.

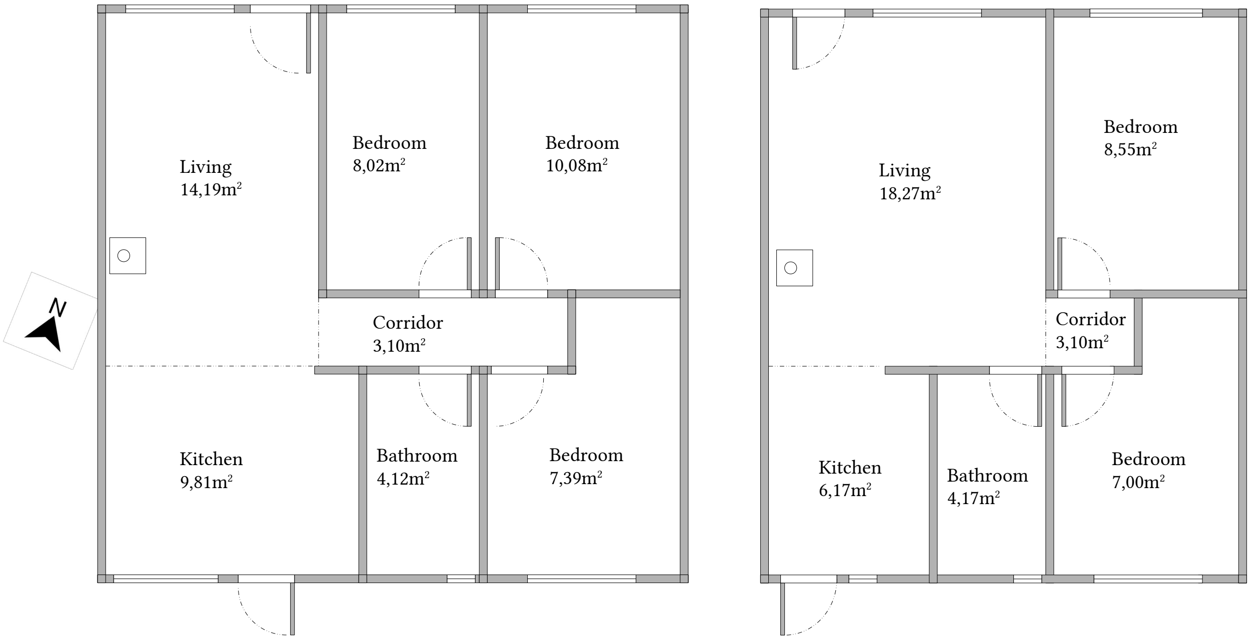


Figure 1: Floor plan for 2D and 3D typology

2.1.1 "Traditional"

The building envelope comprises an exterior vertical enclosure of a 22 cm double wall, consisting of an interior layer of 12 cm field brick, a moisture barrier layer, a 1 cm sand and Portland cement layer with waterproofing and asphalt emulsion, 3 cm expanded polystyrene thermal insulation, a 1 cm air cavity, and an exterior layer of 5.5 cm field brick. The interior walls are made of 12 cm field brick, with both faces roughcast. The upper enclosures consist of eucalyptus beams measuring 2”×6”, an OSB phenolic ceiling of 15 mm, a 200 μm vapor barrier above, 50 mm glass wool thermal insulation with aluminum foil facing the interior space, 2”x2” wooden battens, and an exterior finish of trapezoidal galvanized sheet metal. According to the roof details, the thermal insulation is interrupted by the battens. The windows are made of natural anodized aluminum, series 20 (in bedrooms, bathroom, kitchen, and living room). Additionally, the bedrooms have PVC roller shutters. The main and secondary doors are made of natural anodized aluminum, both with a glazed section. Consequently, the overall heat transfer coefficient (U) is 0.738 $W/(m^2.K)$ for the exterior walls and

$0.761\ W/(m^2.K)$ for the roof.

2.1.2 "Wood frame"

This system is designed based on structural panels made of wooden frames (Eucalyptus grandis), manufactured in a carpentry workshop and assembled on site. The three-bedroom typology has some minor variations in measurements compared to the traditional system. One difference is the location of the partitions that form the bedroom closets. Although the usable floor area is the same for both construction solutions, the interior volume of the houses differs, which is smaller in the wooden house ($148.8\ m^3$) compared to the traditional one ($161.9\ m^3$) due to the horizontal ceiling.

The foundation system of the wooden house is superficial, based on a $12\ cm$ reinforced concrete slab. The vertical enclosures are made of multi-layer wooden panels ("sandwich"), prefabricated in a carpentry workshop. The panels have a standard module of 1.22×2.44 m and a "half panel" of 0.61 x 2.44 m. They are composed (from interior to exterior) of $12.5\ mm$ gypsum board, 150μ polyethylene, $12\ mm$ plywood as the interior layer of the panel, a frame made of planed wooden slats measuring $89 \times 36.5\ mm$, $50\ mm$ glass wool, $12\ mm$ plywood, Tyvek wall barrier, and finally, Superboard Siding ($8\ mm$ fiber cement boards imitating wood). According to the panel details, the thermal insulation is interrupted by the wooden structure. Therefore the overall heat transfer coefficient (U) is $0.60\ W/(m^2.K)$ for the exterior walls.

The interior partitions have a standard module of 1.22×2.44 m and a "half panel" of $0.61 \times 2.44\ m$ and are composed of $12.5\ mm$ gypsum board, plastered and painted on both sides. In the bathroom and kitchen, moisture-resistant $12.5\ mm$ cement boards are used, along with 12 mm plywood, a frame made of planed wooden slats measuring $89 \times 36.5\ mm$, $50\ mm$ glass wool, and $12\ mm$ plywood as the exterior layer of the panel.

The ceiling frame is made of planed wooden slats measuring $89 \times 36.5\ mm$ and its layers are, from interior to exterior: $12\ mm$ plywood in bedrooms and hallways, fire-resistant gypsum boards of $12.5\ mm$ in the kitchen, and moisture-resistant boards of $12.5\ mm$ in the bathrooms. Above this layer, there is a 150μ polyethylene, $50\ mm$ glass wool with aluminum foil facing the exterior, and a Tyvek membrane. The thermal insulation, according to the plans, covers the ceiling structure, thus eliminating thermal bridges. In that way, the celing overall heat transfer coefficient (U) is $0.72\ W/(m^2.K)$.

Above the horizontal ceiling, there is a ventilated air chamber and a gable roof made of pre-painted self-supporting sheet metal. The windows are made of natural anodized aluminum, series 20 (in bedrooms, bathroom, kitchen, and living room). Additionally, the bedrooms have PVC roller shutters. The main door is a frame type with a structure of eucalyptus wood, veneered with virola plywood, and externally clad with tongue-and-groove wooden boards. The secondary door is made of natural anodized aluminum with a glazed section.

2.2 Climate Data Compilation

Two climate files were generated for each of the four locations by integrating data from four different sources, which include ambient temperature, relative humidity, wind speed (magnitude and direction), global and diffuse solar irradiance on a horizontal plane. For the city of Tacuarembó, ambient temperature, relative humidity, and wind speed data were sourced from the La Magnolia measurement station of the National Institute for Agricultural Research (INIA). Solar irradiance measurements were obtained from the Solar Energy Laboratory (LES, UdelaR), also located at La Magnolia, INIA. The LES data series was incomplete, so it was supplemented with global solar irradiance measurements from INIA. Diffuse solar irradiance was generated using an empirical model. The INIA irradiance data were adjusted against the LES data due to discrepancies between the two measurements. The LES instruments are calibrated every two years against a secondary standard, ensuring high quality. Therefore, they were considered as a reference. For the city of Rivera, ambient temperature, relative humidity, and wind speed data were obtained from the OGIMET website, originating from a meteorological station located in Santana do Livramento, Brazil. Solar irradiance estimates were derived from satellite data processed by the LES. All data were graphically inspected and averaged on an hourly scale. Missing data were linearly interpolated, and the consistency of the resulting time series was visually verified.

2.3 Temperature

Dry bulb temperature and relative humidity measurements were conducted using HOBO UX100-003, HOBO UX100-011 loggers, all configured for data recording at 15-minute intervals, within $\pm 0.21C$ and 3.5% accuracy. The habitable rooms within the residences were monitored, ensuring at least one sensor was placed in each room (kitchen/living room and three bedrooms). The sensors were strategically placed in the rooms to avoid direct solar radiation and, when possible, near the barycenter of the space. Measurements for the hot period will be analyzed from February 10 to March 9 (summer), and for the cold period from July 10 to July 29 (winter).

Based on meteorological data, the adaptive comfort range was determined ANSI/ASHRAE (2017). Once the minimum and maximum comfort temperatures for each day were established, the degree hours of discomfort for each room were calculated from the temperatures measurements. This calculation involved summing the degrees of discomfort for each hour (Dh), as detailed below.

- If $T_{In} > T_{Max} \rightarrow Dh = T_{In} - T_{Max}$
- If $T_{In} < T_{Min} \rightarrow Dh = T_{Min} - T_{In}$
- If $T_{Min} < T_{In} < T_{Max} \rightarrow Dh = 0$

Where T_{Int}, T_{Min}, and T_{Max} correspond to the indoor temperature, minimum comfort temperature, and maximum comfort temperature, respectively. Since the measurement periods were not the same for all houses or for both periods, the daily average of degree hours of discomfort was calculated to enable comparison between the different houses.

Additionally, the average damping factor of each room in the houses was determined for both summer and winter. The damping factor (DF) is the ratio of the indoor thermal amplitude to the outdoor thermal amplitude, as described in Eq. (1)

$$DF = \frac{T_{In,Max} - T_{In,Min}}{T_{Out,Max} - T_{Out,Min}} \tag{1}$$

2.4 Air permeability

The air permeability of the two houses was characterized using a Blower Door equipment, specifically the Minneapolis Blower Door System: 2 Fan System from the U.S. company The Energy Conservatory. The test was conducted according to Method 1 of ISO 9972:2015, with all interior doors open and exterior doors closed. The volumetric flow through the building was measured for indoor-outdoor pressure differentials ranging from 10 to 100 Pa, in 10 Pa increments.

The data were then used to adjust the characteristic parameters of the mathematical model suggested by the standard (flow and pressure coefficients). Subsequently, using this model, the air change rate at a pressure difference of 50 Pa (n_{50}) was estimated within an accuracy of 10%.

3. RESULTS

3.1 Indoor temperature

3.1.1 Performance during the warm period

One of the main differences between the two construction systems is the thermal inertia of the exterior and interior walls, which leads to differences in the indoor temperature behavior when exposed to similar environmental conditions. The thermal inertia of a building envelope stabilizes the indoor temperature, reducing variability caused by external weather conditions. In Fig. 2, the temperature evolution of one bedroom (southeast-oriented to minimize the impact of direct radiation) for both construction solutions during the warm period is presented. During the measurement period, the lower comfort temperature ranged between $18.8°C$ and $20.2°C$, while the upper comfort temperature ranged between $25.8°C$ and $27.2°C$.

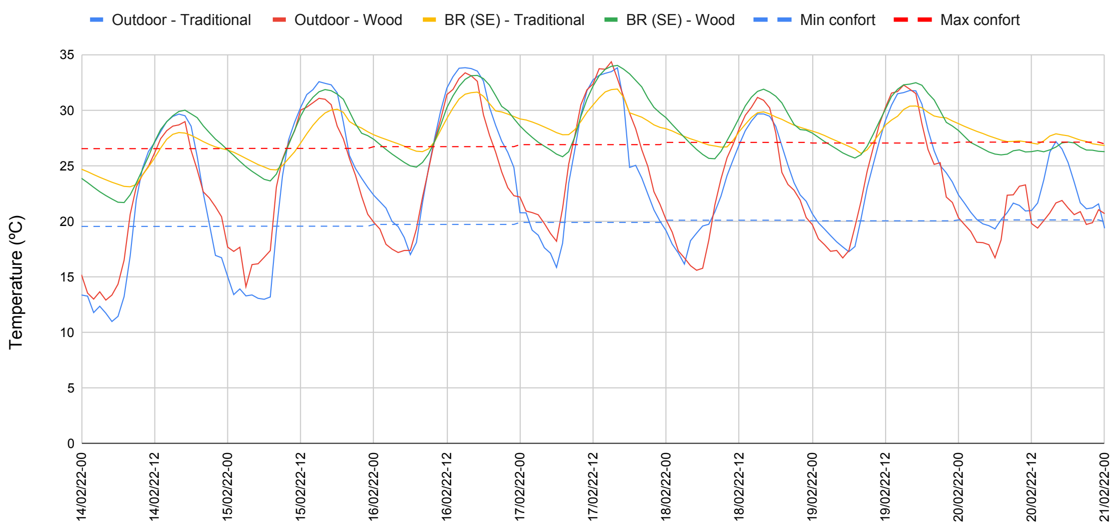


Figure 2: Temperatures during the warm period for both construction solutions. BR (SE) stands for Southeast-oriented bedroom. 00 and 12 indicate midnight and midday hours.

Despite differences in external temperatures between the two locations and varying occupant behaviors regarding the use of ventilation and solar protection, it is evident that the traditionally constructed house exhibits a lower thermal amplitude. Additionally, in the wooden house's bedroom, higher-than-ambient temperatures occur in the afternoon, indicating the impact of solar radiation. The graph also highlights the contribution of the traditional system's thermal inertia, which results in a greater delay in the occurrence of interior temperature peaks relative to the exterior, with a lag of approximately 1.5 hours.

Table 1 summarizes the average thermal amplitude and damping factor of all rooms in the three-bedroom houses monitored during the warm period. It is observed that for external thermal amplitudes of around $12°C$, the traditionally constructed house reduces the interior thermal amplitude by between 63 % and 75 %, while the wood-constructed house achieves a reduction of between 50 % and 60 %, with fluctuations close to $6°C$.

Table 1: Average daily thermal amplitude in three-bedroom houses during the warm period. K: kitchen; LR: living room; BR: bedroom.

		Outdoor	K (SE)	LR (NW)	BR-3 (SE)	BR-2 (NW)	BR-1 (NW)
Traditional 3BR	**Amplitude (ºC)**	12,3	3,5	4,7	3,3	3,8	3,8
	DF		0,29	0,38	0,27	0,31	0,31
Traditional 2BR	**Amplitude (ºC)**	12,3	3,9	4,2	3,4	3,1	-
	DF		0,32	0,34	0,28	0,25	-
Wood frame 3BR	**Amplitude (ºC)**	12,4	-	6,3	5,7	5,7	4,8
	DF		-	0,51	0,46	0,46	0,39
Wood frame 2BR	**Amplitude (ºC)**	12,4	5,2	5,5	6,0	5,4	-
	DF		0,42	0,44	0,48	0,43	-

This damping of temperatures during the warm period represents significant benefits in reducing daily maximum peaks, especially in houses without cooling systems. As can be seen in Fig. 2, the traditional construction maintains lower daily maximum temperatures, which are below external temperatures, whereas the wooden house experiences higher indoor maxima that exceed the recorded outdoor temperatures.

This results in a lower number of degree hours of discomfort in the traditionally constructed house. As shown in Tab. 2, the traditionally constructed presented, on average, between 16 and 33 degree hours per day of discomfort due to high temperatures, while for the wooden house, these ranged from 37 to 52.

Table 2: Average daily degree hours of discomfort for three-bedroom houses during the warm period. K: kitchen; LR: living room; BR: bedroom.

		Outdoor	K (SE)	LR (NW)	BR-3 (SE)	BR-2 (NW)	BR-1 (NW)
Traditional 3BR	**<Min**	18,5	0	0	0	0	0
	>Max	15,9	16,5	27,3	21,7	32,9	26,9
Traditional 2BR	**<Min**	18,5	0	0	0	0	-
	>Max	15,9	28,3	26,4	20,8	29,1	-
Wood frame 3BR	**<Min**	15,5	-	0	0	0	0
	>Max	17,7	-	44,5	37,8	52,2	39,8
Wood frame 2BR	**<Min**	15,5	0	0	0	0	-
	>Max	17,7	53,9	36,8	45,0	41,2	-

The average temperatures in both houses were higher than the average outdoor temperatures, resulting in a high percentage of time during which the indoor temperature exceeded the upper comfort limit. The rooms in the traditionally constructed house experienced discomfort due to high temperatures between 51 % and 75 % of the time, whereas the wooden house experienced discomfort between 61 % and 78 % of the time. In contrast, outdoor conditions only exceeded the comfort limit for a fifth to a quarter of the hours in a day.

Concerning minimum temperatures, the traditional system sustains higher temperatures compared to the wood frame system. Neither house recorded temperatures below the minimum comfort limit. The graph in Fig. 2 shows that both houses have potential for cooling during the night until the early morning hours. However, this natural ventilation resource during favorable periods was underutilized, especially at night when the potential is greatest.

3.1.2 Performance during the cold period

The houses are equipped with a heating system using a wood stove, which strongly influences the analysis of the evaluation of indoor temperatures. The stove is located in the living room and is the only heating system. It uses wood as an energy source and is manually fed, leading to reductions in indoor temperatures during the night when the stove runs out of fuel due to the interruption in feeding.

Analogous to the previous section, Fig. 3 presents the temperature evolution of a bedroom in each house during the cold period. During this period, the lower limit of adaptive comfort was between $16.7°$ and $19.1°C$, while the upper limit was between $23.7°$ and $26.1°C$. Although the temperature evolution is affected by the use of the heating system on some days, it is generally observed that the wooden house experiences faster increases and decreases in temperature compared to the traditional one. This phenomenon can be attributed to differences in the thermal inertia of the two construction systems, which is also evident when analyzing the average indoor and outdoor thermal amplitudes of both houses, as shown in Tab. 3, where a greater damping effect is observed in the traditionally constructed house.

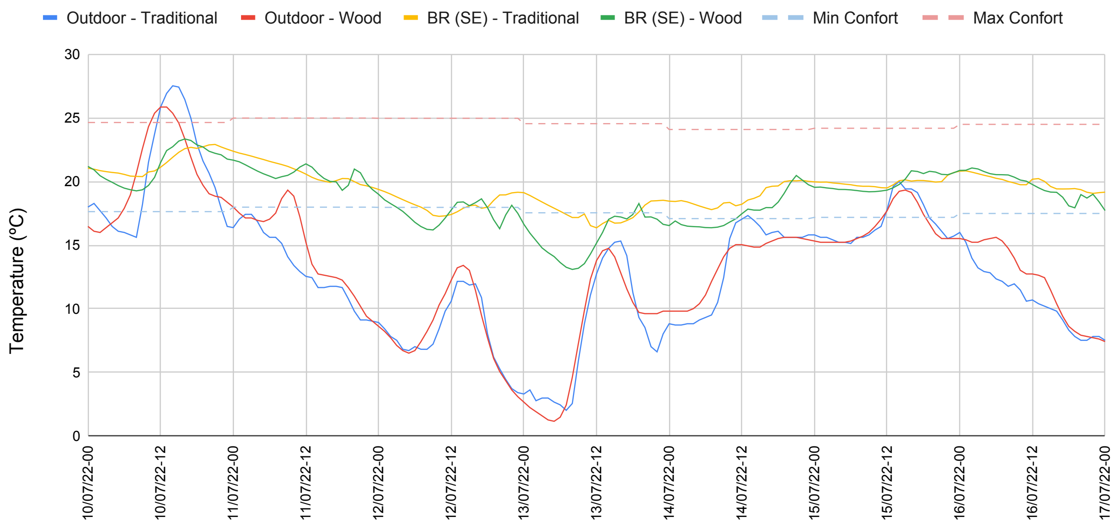


Figure 3: Temperatures during the cold period for both construction solutions. BR (SE) stands for Southeast-oriented bedroom. 00 and 12 indicate midnight and midday hours.

Table 3: Average daily thermal amplitude in three-bedroom houses during the cold period. K: kitchen; LR: living room; BR: bedroom.

		Outdoor	**K (SE)**	**LR (NW)**	**BR-3 (SE)**	**BR-2 (NW)**	**BR-1 (NW)**
Traditional 3BR	**Amplitude (ºC)**	10,3	3,4	5,9	2,4	3,2	3,3
	DF		0,33	0,57	0,23	0,31	0,32
Traditional 2BR	**Amplitude (ºC)**	10,3	-	5,8	2,4	3,2	
	DF		-	0,56	0,23	0,31	-
Wood frame 3BR	**Amplitude (ºC)**	9,7	5,1	5,8	3,5	3,9	3,3
	DF		0,52	0,60	0,36	0,40	0,34
Wood frame 3BR	**Amplitude (ºC)**	9,7	-	4,7	4,2	3,7	-
	DF		-	0,49	0,43	0,38	-

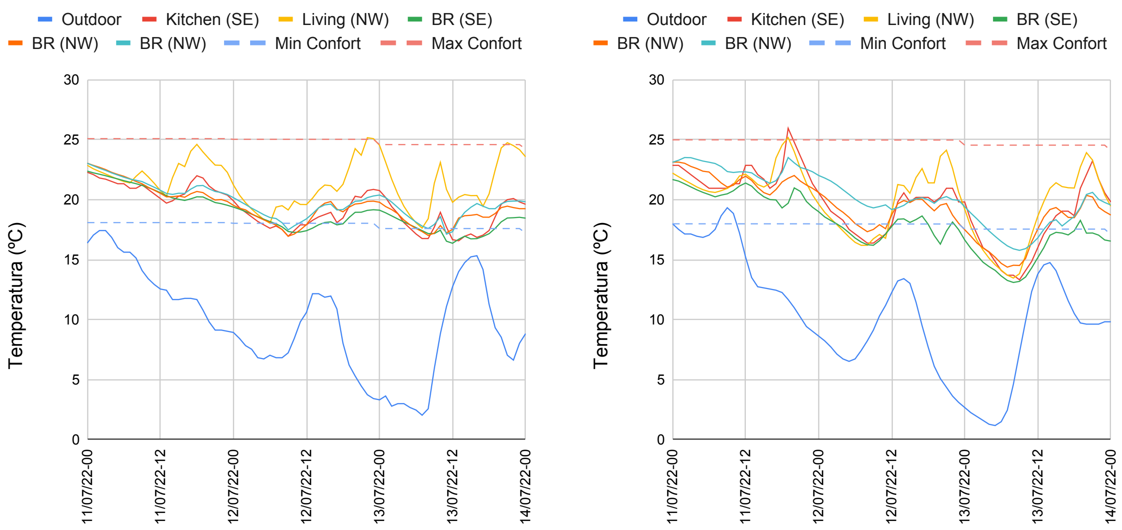
Despite the low outdoor temperatures, both houses achieved comfort levels most of the time, primarily due to the use of the heating system and the good thermal insulation of the houses. As shown in Tab. 4, the amount of heating degree hours required inside both houses is significantly lower than that outside. It is also noted that the wooden house required more heating degree hours compared to the traditionally constructed house.

Figure 4 shows the temperature evolution of all rooms in both three bedroom houses during a week of the cold period. The graphs clearly illustrates the use of the wood stove, which is the only heating source, as indicated by the deviation of the yellow curve corresponding to the Living Room (NW) from the rest of the records. The occupants report that they turn on the stove from 7 AM to 10 AM, which is evident in the graph showing several increases in indoor temperature coinciding with these times. This pattern repeats in the afternoon, with heating usage from 5 PM to 11 PM. The use of the stove, as well as other thermal loads, positively affects the other rooms, although with notable differences. While the temperature in the living room is significantly higher than in the bedrooms during the periods when the stove is on, the heat reaches the bedrooms, allowing them to exceed the lower comfort limit for most of the time. After the stove is no longer fed (during the night and early morning), the indoor temperature decreases. This decrease is significantly less than that of the outdoor temperature (which reached 1°C on some days), indicating that the insulation and thermal inertia of

Table 4: Average daily degree hours of discomfort for three-bedroom houses during the cold period. K: kitchen; LR: living room; BR: bedroom.

		Outdoor	**K (SE)**	**LR (NW)**	**BR-3 (SE)**	**BR-2 (NW)**	**BR-1 (NW)**
Traditional 3BR	**<Min**	99,2	1,9	0,3	2,8	1,3	1,1
	>Max	1,9	0	0	0	0	0
Traditional 2BR	**<Min**	99,2	-	3,4	2,8	1,3	-
	>Max	1,9	-	0,7	0	0,2	-
Wood frame 3BR	**<Min**	87,5	3,2	3,2	6,5	2,5	0,6
	>Max	0,8	2,0	1,7	0,04	0,9	0,9
Wood frame 2BR	**<Min**	87,5	-	29,6	29,7	27,0	-
	>Max	0,8	-	0	0	0	-

the house are acceptable. However, during the coldest early mornings, it is necessary to supplement with external energy to maintain comfort conditions in the bedrooms.



(a) House with traditional construction

(b) House with Wood frame construction

Figure 4: Three-bedroom during the cold period. BR (SE) stands for Southeast-oriented bedroom. 00 and 12 indicate midnight and midday hours.

The first premise of passive design to maintain indoor thermal comfort conditions in winter is to prevent energy loss, making the proper management of natural ventilation crucial. The temperature graph shows that the occupant of this house ventilates the kitchen, living room, and bedrooms when the outdoor temperature is at its maximum, i.e., they open the windows at noon. The graphs align with the behavior reported by the residents regarding window opening. The second premise of design is to gain energy. This is observed in the rooms with windows oriented to the northwest, which present higher indoor temperatures. It is also noted that the bedroom oriented to the southeast is always at a lower temperature due to lower solar gains. This behavior is because the total daily solar radiation gains in the cold period for the NW orientation are significantly greater than for the SE orientation. Similar results are observed for the house constructed with wood, where supplemental heat input would have been necessary to maintain thermal comfort.

3.2 Air permeability

In Tab. 5, a summary of the results from the permeability tests is presented, including interior volume, airflow (C_L) and pressure (n) coefficients, airflow rate (q_{50}), and air changes per hour (n_{50}) both at a pressure difference of 50 Pa. The latter parameter has an uncertainty of approximately 10 $\%$.

The air changes per hour at 50 Pa for the four surveyed houses ranged between 9.54 and 11.88, representing a variability of 20 $\%$ relative to the mean value. It is noteworthy that the difference between the three-bedroom houses is less than 1 $\%$.

The main points of permeability identified were:

- Kitchen door threshold

Table 5: Main points of air permeability of four houses

	Units	3BR - Traditional	3BR - Wood	2BR - Traditional	2BR - Wood
Volum	m^3	159,8	150,0	131,8	121,6
C_L	$m^3/h.Pa^n$	187	140	170	138
n	-	0,557	0,616	0,568	0,544
q50	m^3/h	1652	1558	1565	1160
n50	ACH	10,34	10,39	11,88	9,54

- Roller shutter drawers
- Bathroom window
- Air intake for the wood stove
- Ceiling hatch (wooden house)

Regarding the window and door frames, although air ingress was observed, it is considered within the usual range for the quality of the profiles. Given the uncertainty inherent in the testing method and the fact that the main sources of air ingress do not directly depend on the construction system, it is concluded that there are no significant differences between the two solutions (traditional and wood).

4. CONCLUSIONS

After monitoring four residences constructed with two different building systems throughout both warm and cold seasons of the year, several pertinent outcomes are underscored. It is crucial to note that the thermal performance of these residences is intricately tied to user behavior, which varies among houses.

The environmental parameters (comprising temperature, radiation, wind speed, and direction) in both locations exhibited minor discrepancies, ensuring relatively homogeneous conditions for the residences during the observation periods.

Although both building solutions exhibited commendable thermal performance, improving indoor thermal comfort compared to outdoor conditions, the traditional construction method surpassed its wooden counterpart, resulting in fewer degree hours of thermal discomfort, particularly during the warm season.

The traditional houses exhibited superior damping and lag in response to outdoor conditions, leading to a reduction in indoor temperature amplitude across all rooms. This phenomenon can be attributed to the heightened thermal inertia inherent in this building system. Furthermore, during warmer periods, these houses effectively maintained indoor temperatures below their outdoor peaks.

The utilization of a wood stove as the heating equipment, complemented by the house' low thermal transmittance, is enough to heat the entire house while operational. Nevertheless, nocturnal temperatures intermittently dipped below the lower comfort threshold, particularly in wooden-built ones.

Both building solutions, equipped solely with wood stoves for heating, evidenced superior performance during winter compared to summer. This discrepancy is appreciated in the degree hours of discomfort for each season, registering low values (almost negligible) in winter but ascending to considerable magnitudes in summer.

Regarding envelope permeability, given the inherent uncertainties of the testing methodology and the fact that the principal sources of air infiltration are not directly contingent on the building system, it is deduced that no substantive discrepancies exist between the traditional and wooden solutions.

5. ACKNOWLEDGEMENTS

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