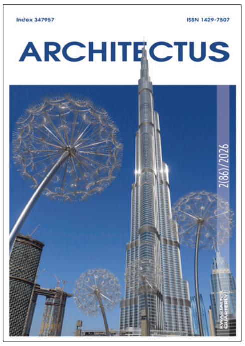

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Adaptation and reuse of buildings: how do traditional and contemporary buildings perform thermally under real-world operating conditions?

Abstract

Promoting resilience in the built environment increasingly relies on the refurbishment and reuse of existing buildings to meet contemporary performance and sustainability standards. Traditional buildings have character and strategic importance; however, they are often considered poorly performing, though their inherent qualities can contribute to extending their lifespan. This study examines whether notable differences exist between traditional and contemporary construction systems in terms of thermal performance under real-world operating conditions. Continuous temperature data were collected over a three-year period from two indoor spaces – one built using traditional techniques and the other employing contemporary systems – both monitored under occupied and unoccupied conditions. The analysis included air temperature and radiant temperature of interior surfaces to evaluate the combined influence of building characteristics and occupancy patterns. The findings indicate that differences between the two construction systems are relatively minor, with occupancy exerting the dominant effect, bringing the thermal performance of both buildings closer together. These results suggest that traditional architecture can achieve thermal performance comparable to that of modern constructions in Mediterranean climate, highlighting its value as a resilient and sustainable component of the existing building stock through targeted building refurbishment.

Key words: traditional buildings, monitoring, thermal performance, radiant temperature, building refurbishment

Introduction

Traditional buildings in European countries constitute a substantial portion of the existing building stock. The expansion of most cities and towns during the late 19th and early 20th centuries resulted in an architectural legacy predominantly constructed using traditional techniques, prior to the widespread adoption of more technologically advanced construction systems. This legacy is not confined to major cities but is equally present in small towns and rural areas, making traditional architecture both widespread and territorially significant.

From both cultural and environmental perspectives, traditional buildings possess inherent values that merit preservation (Webb 2017; Galatioto, Ciulla and Ricciu 2017). They stand as tangible evidence of historical construction practices and are deeply intertwined with local cultural identity (Akkurt et al. 2020; Mariani, Rosso and Ferrero 2018) offering a stark contrast to the homogenization and placelessness often associated with the contemporary international style.

From an environmental standpoint, extending the lifespan of existing buildings is a key strategy for reducing the embodied energy associated with construction and lifecycle processes. This can be achieved through regular maintenance and context-sensitive updates, not only in traditional structures but also across the broader stock of existing buildings. Additionally, the reuse of buildings contributes to the revitalization of depopulated urban centres (Caro, Sendra 2020), curbs land consumption linked to suburban sprawl, and helps counteract territorial depopulation (Martín, Ma-

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zarrón and Cañas 2010). This latter aspect is essential for promoting a more balanced and sustainable spatial distribution of population, thereby reducing the pressure on large urban agglomerations.

Traditional architecture reflects a symbiotic relationship with climate and local environmental conditions. Building dimensions, forms, and materials were historically adapted to the availability of local resources and climatic needs. In contrast, contemporary construction is increasingly shaped by global market forces, prevailing trends, and standardized regulations, especially those concerning thermal performance. Traditional buildings are often perceived as thermally inefficient, prompting owners to pursue major retrofits or even demolition (Ding 2013).

Policies often assume that traditional buildings are thermally underperforming, directing subsidies toward HVAC (Heating, Ventilation, Air Conditioning) replacement and thermal insulation addition (Stéphan et al. 2014; de la Flor et al. 2021; Timur, Başaran and İpekoğlu 2022; Dervishi et al. 2022). However, the thermal behaviour of traditional buildings is more nuanced and cannot be fully captured by simplified metrics. For instance, traditional buildings often achieved insulation through thick, massive walls, unlike modern buildings that rely on lightweight envelope systems with added insulation. These differences affect the buildings' dynamic thermal behaviour, with implications for thermal inertia, comfort, and energy use (Gagliano et al. 2014; Avendaño-Vera, Martinez-Soto and Marincioni 2020; Stazi et al. 2014; 2015; Slee, Parkinson and Hyde 2013).

However, numerous studies have highlighted a persistent discrepancy between predicted and actual energy performance in buildings, both existing and newly constructed (Sunnika-Blank, Galvin 2012; van den Brom, Meijer and Visscher 2019). This phenomenon, known as the Energy Performance Gap (EPG) (De Wilde 2014; Shi et al. 2019) is frequently associated with two widely discussed effects in the field of energy policy: the prebound effect, which stems from overestimating the energy demand of existing buildings based on the assumption of poor construction quality, and the rebound effect, where high-performing buildings consume more energy than expected due to user behaviour and other real-life variables (Galvin 2014; Hoffmann, Geissler 2017). Incorporating more realistic input data into thermal simulations could help reduce this theoretical performance gap and challenge assumptions about the relative inefficiency of traditional construction.

Most studies on the thermal performance of existing buildings rely on either simulations or environmental monitoring (Martín, Mazarrón and Cañas 2010; Callegaro et al. 2023). A common approach involves the use of software such as *DesignBuilder*, built on the *EnergyPlus* simulation engine, to develop calibrated digital models (Aste, Angelotti and Buzzetti 2009). Accurate model calibration requires assigning thermal properties (e.g., *U*-values, mass, air tightness) to building components, often approximations in the context of existing structures. These models are typically created using environmental data collected over a specified period and then used to test various retrofitting scenarios (Giuliani, Henze and Florita 2016; Mousa, Lang and Yousef 2017; Aste et al. 2015; Evola et al. 2017; di Perna et al. 2011; Gagliano et al. 2016). However, variables such as solar shading, ventilation, and internal loads are heavily influenced by occupant behaviour, which is difficult to replicate with precision (Delzendeh et al. 2017; Ascione et al. 2020; Stazi, Naspi 2019). Although standard occupancy schedules can be used, real patterns are inherently variable. Additionally, climatic data employed in simulations are derived from statistical models that, while generally reliable, may not capture the full variability of actual conditions. Therefore, although simulations offer valuable insights into the comparative performance of different design strategies, their reliability in predicting real-world thermal behaviour, particularly in traditional buildings, remains limited due to uncertainties in input data (Malik, Bardhan and Banerji 2020).

Environmental monitoring serves both as a tool to calibrate simulations and as a means of empirical investigation, particularly in experimental setups such as test cells or mock-ups (Lindberg, Binamu and Teikari 2004). These studies often aim to compare the thermal behaviour of different materials and envelope configurations. Nonetheless, they frequently omit the role of human occupants, whose interactions with buildings are crucial to understanding actual thermal performance.

Collecting data from real, inhabited spaces presents both logistical and methodological challenges. Short-term monitoring allows for greater control and observation of user behaviour, whereas long-term monitoring introduces complexity but provides more representative data regarding seasonal patterns and occupant interaction. Despite these challenges, long-term monitoring in occupied buildings yields valuable insights that are often missing from simulations and lab-based studies.

In light of these complexities, a deeper understanding of the thermal characteristics of both traditional and contemporary buildings is essential to inform effective and context-sensitive interventions (Costa-Carrapiço et al. 2022; Calcerano, Cecchini and Martinelli 2017; Martínez-Molina et al. 2016; Martín, Cañas and González 2004). To this end, the present study offers a comparative analysis of two construction typologies – traditional and contemporary – based on long-term environmental monitoring. Conducted outside a controlled laboratory setting, this empirical research captures the variability and complexity of real-life conditions in Mediterranean climate. The methodology provides a more accurate picture of building performance in use and contributes to refining the understanding of the Energy Performance Gap. Ultimately, the findings aim to support more informed decision-making in both policy and practice for the sustainable management of the built environment.

Methodology

To assess and compare the thermal performance of two building systems under real-life operating conditions, air temperature and relative humidity were monitored in two comparable spaces, one in a traditional building and the other in a contemporary structure. These indoor measurements were complemented by outdoor meteorological data (air temperature, relative humidity, and solar radiation), to contextualize insight into the observed indoor thermal behaviour.

The monitoring campaign lasted three years, allowing for a comprehensive and longitudinal assessment that accounted for interannual climatic variability and ensured a representative range of environmental conditions.

The collected data were analysed across four complementary levels:

– Annual trends. Annual datasets were examined to identify general temperature trends and assess the typical thermal behaviour associated with each construction system. Specific timeframes were also selected for more detailed investigation. One such analysis focused on thermal amplitude, comparing a winter and a summer week in both buildings during free-running operation and in the absence of occupancy. This approach enabled an evaluation of the thermal response of the envelope alone, isolating it from user behaviour and mechanical conditioning.

– Summer results. Occupant influence was assessed by comparing summer weeks with and without occupancy. This comparison highlighted the role of user interaction, specifically in terms of natural ventilation, solar shading strategies, and internal heat gains, and revealed the resulting differences in thermal performance between the two case studies.

– Thermal decay and winter heat loss. A winter week was analysed to calculate and compare the theoretical and observed time constants. These findings were further supported by steady-state heat loss calculations, providing additional insight into the passive thermal performance of each envelope system.

– Air and radiant temperature. Simultaneous measurements of air and radiant temperatures were conducted over a weekend in both summer and winter of 2023. The inclusion of radiant temperature provided a more complete and comprehensive understanding of indoor thermal conditions, more accurately reflecting the actual thermal sensation experienced by occupants. This final stage of analysis enhanced the comparative assessment of the two construction systems by incorporating comfort-related parameters beyond air temperature alone.

Case study

The study was conducted in two adjacent houses located in a small town within the coastal mountain range of Catalonia, Spain (40°N17'N, 1°1'E). Despite being built a century apart, the two dwellings are comparable in size, form and orientation, making them suitable for a comparative analysis of different construction systems. The town (Capafonts), situated at an altitude of 750 m above sea level, has approximately 100 inhabitants. According to Köppen's climate classification, the area has a Mediterranean climate with warm summers (Csb), characterized by an average annual temperature of 13.3 °C and a seasonal amplitude of 17.9 °C between the coldest and the warmest periods. The average daily temperature fluctuation is 10 °C. Relative humidity averages 70.3% annually, and total yearly precipitation amounts to 525 mm/year, with spring and autumn being the rainiest seasons.

The town is located atop a hill in the centre of a valley, with its built fabric arranged concentrically along the slope. The two houses selected for the study are located at the western edge of the town, with open views to the west and facing the town to the east. They are attached to adjacent buildings on their northern and southern façades. For clarity, House 1 is the traditional dwelling situated on the northern side, and House 2 is the contemporary dwelling on the southern side (Fig. 1).

Access to both dwellings is through the east façade at street level. Each house has three above-ground floors (ground, first, and second) and two semi-basement levels oriented westward due to the sloped terrain. The ground floor of the traditional house (House 1) comprises a lobby, a living room with an open kitchen, and a staircase connecting all levels. The contemporary house (House 2) has the same arrangement but also features an additional bedroom and bathroom on this level. Both dwellings open to balconies or terraces on the west façade.

The first floor in each dwelling contains three bedrooms and one bathroom, with House 2 also incorporating a laundry room. The second floor occupies a smaller footprint in both cases, being set back from the west façade in the traditional house and from the east and west façades in the contemporary.

On the first semi-basement level the traditional house accommodates two bedrooms, a bathroom and a storage area, while the contemporary house is designed as a garage. The second semi-basement level is smaller in area and is not conditioned for occupancy in either dwelling.

The traditional house was constructed around the early 20th century, although the exact date is unknown. It has

Fig. 1. West façade of the houses. At left, House 1; at right, House 2 (photo by J. Lopez-Besora)

Il. 1. Zachodnia fasada domów. Po lewej dom 1; po prawej dom 2 (fot. J. Lopez-Besora)

Table 1. Constructive elements of House 1 and House 2, and their physical characteristics (elaborated by J. Lopez-Besora)
Tabela 1. Elementy konstrukcyjne i detal architektoniczny w domach 1 i 2 oraz ich specyfikacja (oprac. J. Lopez-Besora)

	Code*	S [m^2]	*U*-value [W/m^{2}K]	M [kg]	M′ [kg]
House 1	F1	10.5	1.91	13192	6596
	W1	3.1	4.30	77	77
	PW1	7.2	–	6057	3028
	PW2	14.8	–	14322	12454
	P1	11.2	–	558	279
	D1	2.8	–	–	–
	FL1	8.3	–	2543	1271
	FL2	28.1	–	8605	1652
	C1	36.4	–	11148	5574
	TOTAL	122.4	–	56500	33581
House 2	F2	13.0	0.45	2493	849
	W2	8.2	2.70	286	286
	PW2	10.2	–	9830	1282
	PW3	12.8	–	6438	1609
	P2	14.2	–	926	463
	D1	6.8	–	–	–
	FL3	34.6	–	10585	5292
	C2	34.6	–	10585	5292
	TOTAL	134.4	–	41142	15075

* Key in the text and Figure 2.

undergone various renovations throughout its lifespan. Its construction system is traditional with load-bearing stone masonry walls approximately 60 cm thick, supporting one-way structural slabs composed of wooden joists and ceramic vaults. Exterior joinery consists of wooden frames with single glazing and high air permeability, complemented by internal shutters. The calculated *U*-values of the façade and windows are 1.91 and 4.30 W/m^{2}K, respectively (Table 1). This typology is representative of vernacular construction across the region and other areas with similar climatic and geographic conditions. It remained prevalent until the emergence of modern systems, such as brick load-bearing walls with concrete slabs and, later, reinforced concrete structures.

The contemporary house, by contrast, was built in 2015 based on a technical design project. Its structural system consists of reinforced concrete columns and one-way concrete slabs. The envelope comprises multilayer façades with exterior and interior brickwork (14 cm and 7 cm thick, respectively), a ventilated cavity, and 5 cm of thermal insulation (expanded polystyrene). Openings consist of high-performance windows with aluminium-clad exteriors and wooden interiors, and double glazing; one of the windows includes interior shutters. The *U*-values of the façade and windows are 0.45 and 2.70 W/m^{2}K, respectively.

Both dwellings are equipped with heating systems consisting of oil-fired boilers connected to aluminium radiators. Neither house has mechanical cooling systems for the summer season.

The study was conducted in the living room of both houses, which have nearly identical dimensions. The floor areas measure 36.4 m^2 in House 1 and 34.5 m^2 in House 2, while the corresponding volumes are 92.2 m^3 and 91.7 m^3. All surfaces, except for the west façade, are considered adiabatic. Table 1 and Figure 2 present a detailed breakdown of the envelope elements of each monitored space. Each component is coded (F for façades, W for windows, PW for party walls, P for partitions, D for doors, FL for floors and C for ceilings), along with their area (S, in m^2), *U*-value (W/m^{2}K) total mass (M, in kg) and effective mass (M′, in kg). The total mass (M) refers to the full material thickness, while the effective mass (M′) accounts for only half the thickness for non-insulated elements, or the mass from the insulation layer inward for insulated assemblies.

Methods

Air temperature and relative humidity were continuously monitored in the living rooms of both houses over a three-year period, from 27 September 2019 to 26 September 2022. Data acquisition was uninterrupted except for brief pauses required for battery replacement. Two TESTO 175H1 data loggers were employed, one in each dwelling, placed in the north-west corner of the living room (Fig. 2). Measurements were recorded every 20 min starting on the hour. For clarity, the air temperature in House 1 and House 2 is denoted as T_H1 and T_H2, respectively.

In addition to the long-term monitoring, a short-term measurement campaign was carried out in 2023 to capture both air temperature and radiant temperature in the same rooms. These measurements were conducted over two weekend periods, one in winter (10–12 February 2023) and one in summer (30 June–2 July 2023). The same TESTO data loggers used in the long-term monitoring were deployed in identical locations. Radiant temperature was recorded using a FLIR TG267 thermal imaging camera. Air temperature and relative humidity were logged at 20-minute intervals.

Thermal images were captured at multiple times throughout each weekend at predefined and equivalent points in both living rooms, including the floor, ceiling, west façade, party wall, and the north wall of the traditional house. In the winter campaign, thermal imaging was performed on Friday upon arrival, immediately before activating the heating system (Table 2).

Climate data (outdoor air temperature, relative humidity, and solar radiation) were obtained from a weather station located 40 m from the monitored houses (764 m altitude, UTM coordinates E 334739, N 4573418). This station is operated by Meteoprades (meteoprades.net), a non-profit organization that collects meteorological data from several sites in the region. All meteorological variables were recorded in synchrony with the indoor monitoring intervals.

No behavioural guidelines were provided to the occupants during the monitoring period; they were instructed to go about their daily routines without modification. Both houses are used intermittently, primarily on weekends and during holidays. The traditional house is typically occupied by 2 to 6 people, while the contemporary is occupied by 2 to 4. As both are second residences, occupancy may fluc-

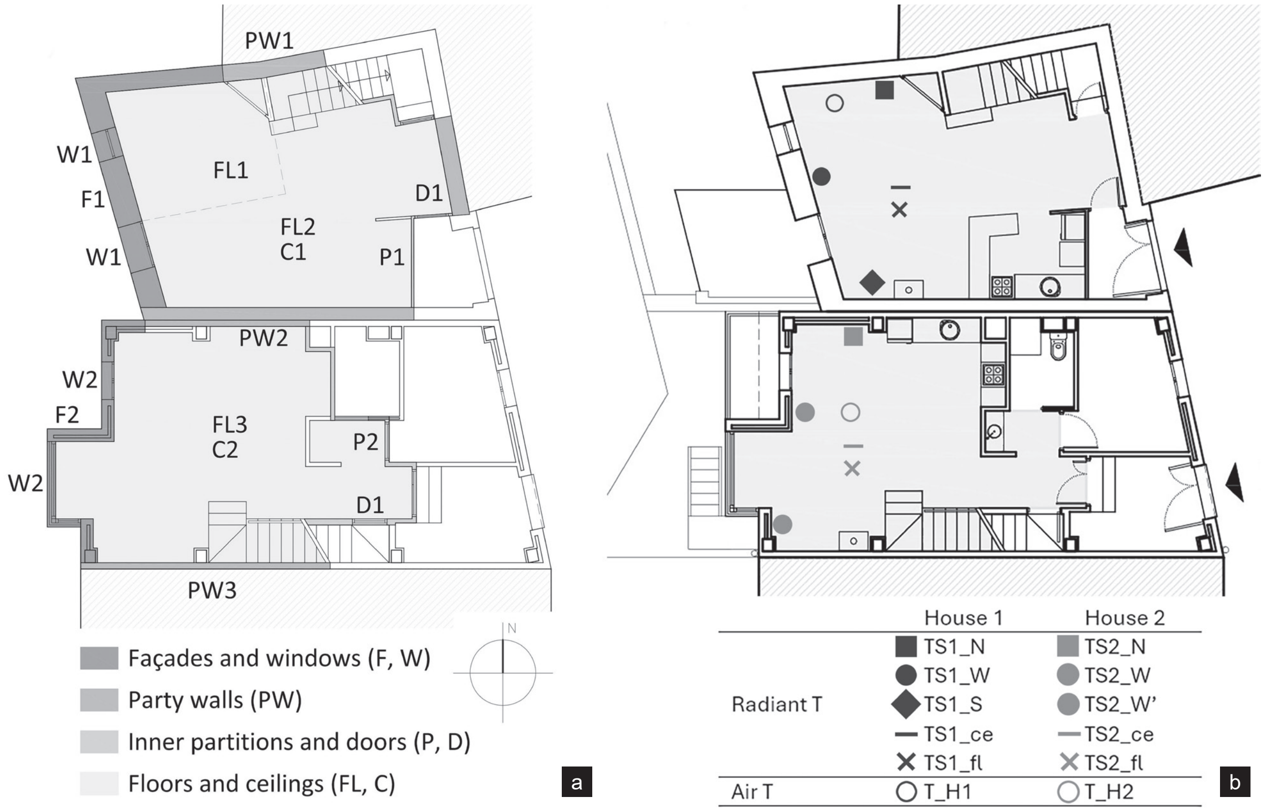

Fig. 2. Floor plan: a) codes of constructive elements, b) location of the measurement points for air temperature and radiant temperature (elaborated by J. Lopez-Besora)

Il. 2. Rzut: a) oznaczenia elementów konstrukcyjnych, b) lokalizacja punktów pomiarowych temperatury powietrza i temperatury promieniowania (oprac. J. Lopez-Besora)

tuate, especially during leisure periods or visits. The living rooms in both houses feature an integrated open-plan kitchen, which is regularly used when the dwellings are occupied. It is important to note that the monitoring period includes the nationwide lockdown imposed in Spain due to the SARS-CoV-2 pandemic, which began in the third week of March 2020 and lasted through the end of May 2020.

Results and discussion

Yearly thermal behaviour

The initial results present the complete dataset of indoor air temperatures measurements from both houses, along with the corresponding outdoor temperature data obtained from the nearby weather station (https://dataverse.csuc.cat/dataset.xhtml?persistentId=doi:10.34810/data1479). Figure 3 illustrates the temporal evolution of indoor and outdoor temperatures over three annual periods, each spanning from October to September, for the years 2019, 2020, 2021, and 2022.

The difference in mean annual indoor temperature between the two dwellings ranges from 0.68 °C to 2.07 °C, with House 2 consistently registering higher average temperatures than the traditional house. The largest temperature gap was recorded during the 2021–2022 period, which also coincided with the highest average outdoor temperature across the study duration. On average, the indoor temperature in

Table 2. Day and time of thermographic imaging for each house (elaborated by J. Lopez-Besora)

Tabela 2. Dzień i czas obrazowania termograficznego dla każdego z obiektów (oprac. J. Lopez-Besora)

	House 1		House 2	
	Day	Time	Day	Time
Winter	10/02/2023	22:20	10/02/2023	22:20
	11/02/2023	01:20	11/02/2023	01:20
		11:40		
		15:40		15:40
		17:40		
		22:20		22:20
	12/02/2023	10:00	12/02/2023	
		14:00		14:00
		15:40		15:40
Summer	30/06/2023	21:40	30/06/2023	21:40
	01/07/2023	00:40	01/07/2023	00:40
		10:00		10:00
		13:20		13:20
		16:40		16:40
		20:20		20:20
		22:40		
	02/07/2023	10:40	02/07/2023	10:40
		16:00		16:00
		19:20		19:20

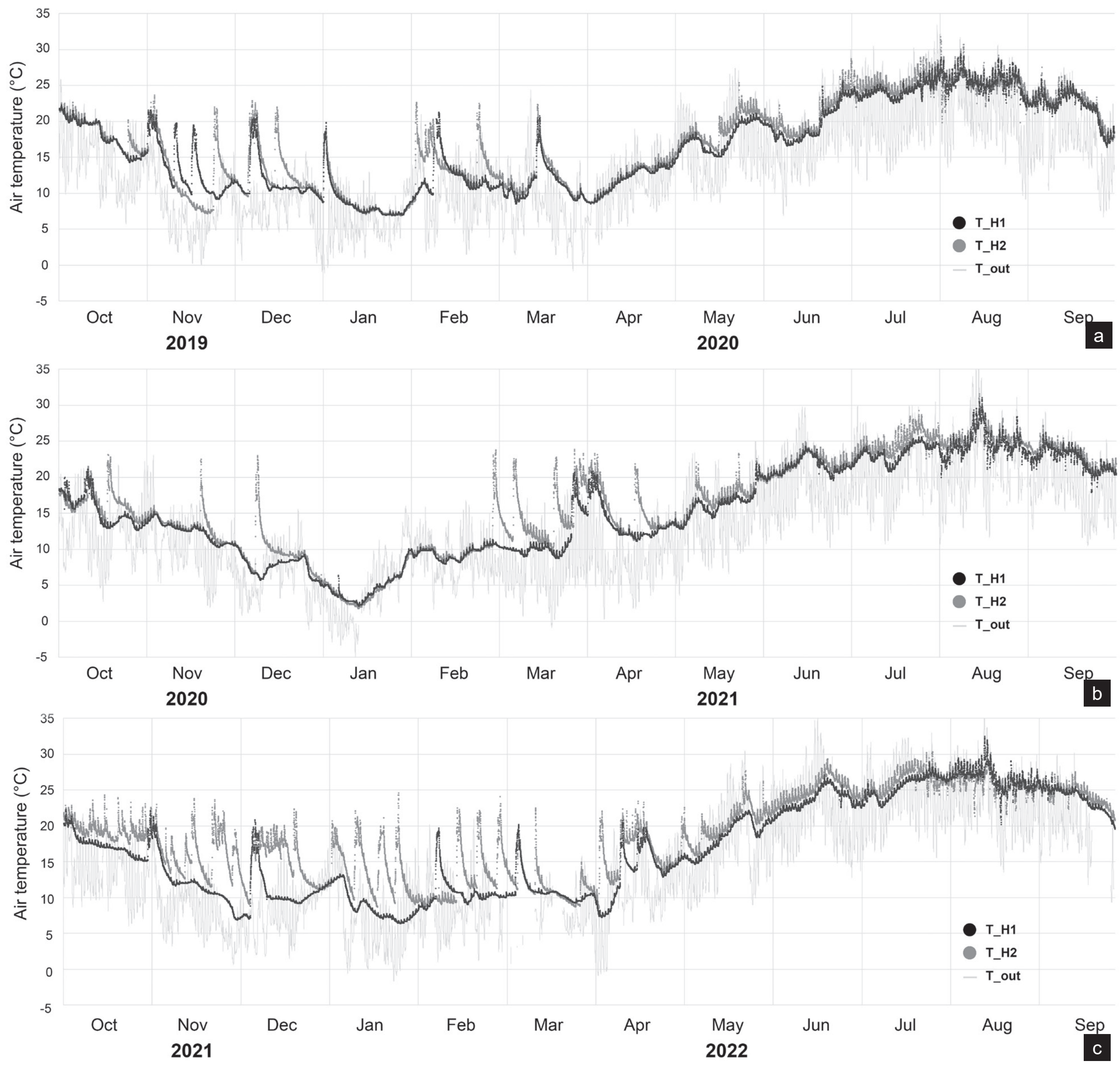

Fig. 3. Yearly results of air temperature in House 1, House 2, and outdoor:
a) October 2019–September 2020, b) October 2020–September 2021, c) October 2021–September 2022
(elaborated by J. Lopez-Besora)

Il. 3. Temperatura powietrza w domu 1 i 2 oraz temperatura zewnętrzna w ciągu roku: a) październik 2019–wrzesień 2020,
b) październik 2020–wrzesień 2021, c) październik 2021–wrzesień 2022 (oprac. J. Lopez-Besora)

House 1 exceeded the outdoor temperature by 2.35–2.94 °C, while in the contemporary house the difference was greater, ranging from 3.62–4.42 °C. These measurements reflect real-life operating conditions, as both homes were occupied for a comparable, though not identical, number of days.

The annual temperature curves in Figure 3 capture typical occupancy rhythms, for instance, brief peaks during winter weekends associated with heating system activation upon arrival, and heightened temperature variability during the summer, especially in August, corresponding to increased household activity.

To explore this in greater detail, a focused analysis was conducted on two one-week periods under free-running conditions and in the absence of occupants: one in winter and one in summer (Fig. 4). The winter week analysed spans from 10 to 17 January 2020. During this period, both houses exhibited similar thermal behaviour, with average indoor temperatures of 7.75 °C in the traditional house, 7.78 °C in the contemporary, and 6.48 °C outdoors. Daily thermal amplitude was below 1 °C in the traditional house and slightly above 1 °C in the contemporary one, indicating stable indoor conditions in both dwellings under winter free-running scenarios (Lopez-Besora et al. 2022).

In contrast, the summer week analysed, from 8 to 15 July 2020, revealed more significant differences. The average indoor temperature in the traditional house was 24.10 °C, while in the contemporary it reached 25.04 °C; both were significantly higher than the average outdoor temperature, which was 20.41 °C. The daily peak temperatures were also higher in the contemporary house than in the traditional,

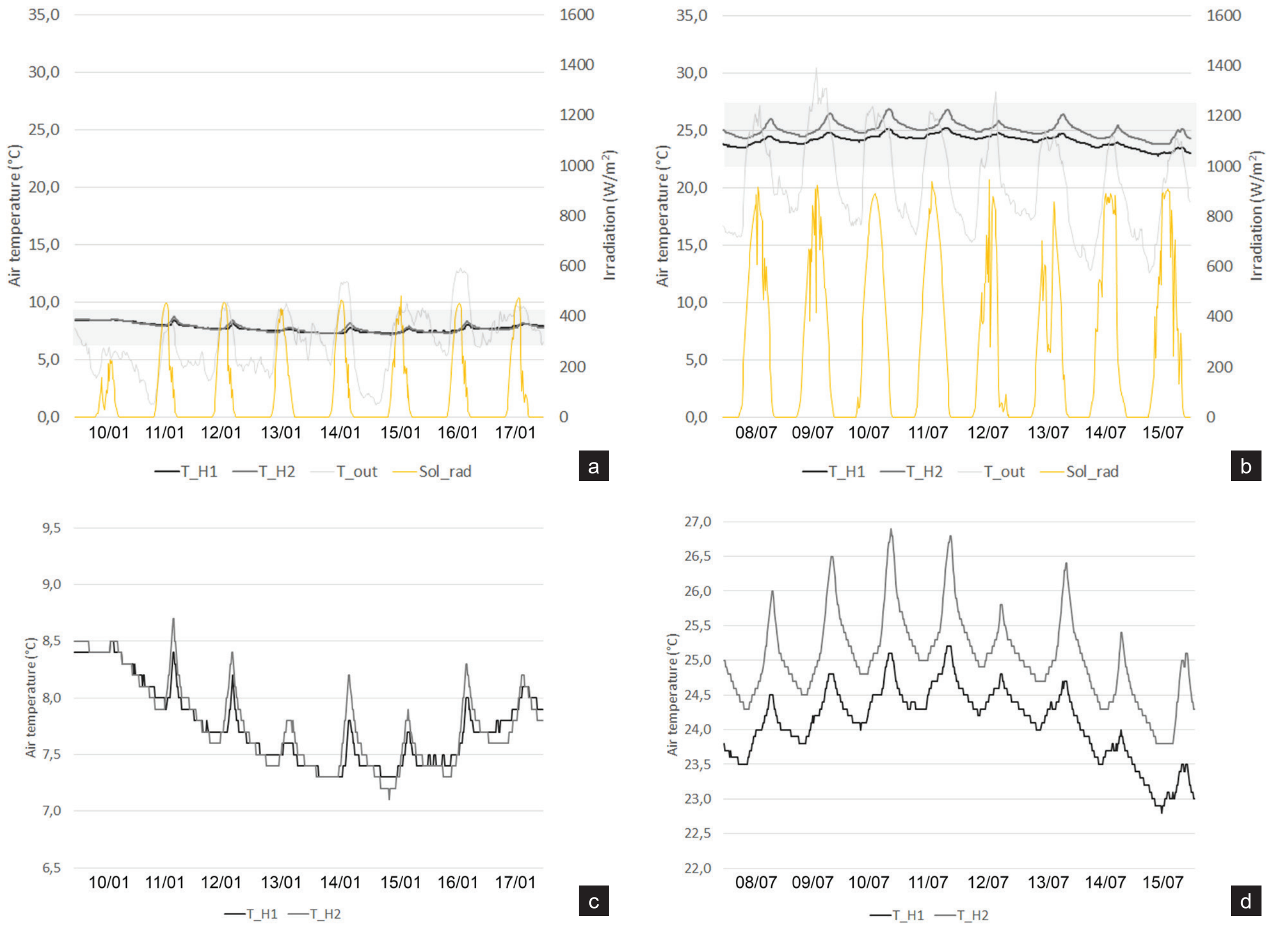

Fig. 4. Air temperature in House 1 (T_H1), House 2 (T_H2), outdoor air temperature (T_out), and solar radiation (Sol_rad): a) week of 10–17 January 2020, b) week of 8–15 July 2020, c) detail of T_H1 and T_H2 in the winter week, d) detail of T_H1 and T_H2 in the summer week (elaborated by J. Lopez-Besora)

Il. 4. Temperatura powietrza w domu nr 1 (TH_1), domu nr 2 (TH_2), temperatura powietrza na zewnątrz (T_out) i promieniowanie słoneczne (Sol_rad): a) 10–17 stycznia 2020, b) 8–17 lipca 2020, c) szczegółowy rozkład temperatury TH_1 i TH_2 w tygodniu zimowym, d) szczegółowy rozkład temperatury TH_1 i TH_2 w tygodniu letnim (oprac. J. Lopez-Besora)

and this difference was more pronounced than in the winter analysis. These findings suggest that the traditional house is less responsive to solar radiation gains, particularly from the west.

Moreover, the indoor air temperature in the traditional house consistently remained lower than in the contemporary throughout the summer week. On some days, the maximum temperature in the traditional house was even lower than the minimum temperature recorded in the other, underscoring the superior thermal buffering capacity of the traditional envelope.

These results highlight the greater sensitivity of the contemporary house to external climatic conditions and solar heat gains, while the traditional house exhibits greater thermal inertia and indoor temperature stability in both summer and winter. It is important to note that these findings correspond to periods with no internal heat loads or user interactions, thus offering a clearer view of the intrinsic thermal performance of each construction system.

The following sections build upon this foundation by analysing how occupancy and daily routines influence indoor thermal conditions, specifically on summer and winter periods.

Summer results with and without occupants

The summer week in Figure 4 shows a regular thermal pattern driven by outdoor temperature and solar radiation. In contrast, the annual curves in Figure 3 become less distinct and begin to overlap from late July through August, making it difficult to discern clear trends. This period coincides with the summer holiday season when both dwellings are regularly occupied.

To assess thermal variability in this period, four representative summer weeks were analysed: two unoccupied (6–12 July 2020 and 12–18 July 2022), and two occupied (9–15 August 2021 and 1–7 August 2022). The results are shown in Figures 5 and 6.

During the unoccupied weeks (Fig. 5), the indoor temperature profiles remained consistent and showed predictable patterns, minimally influenced by internal gains. In the week of 6–12 July 2020, the contemporary house recorded the highest average indoor temperature (25.1 °C), exceeding both the traditional (24.2 °C) and the outdoor temperature (21.3 °C). A similar trend was observed during the week of 12–18 July 2022, when the contemporary reached an

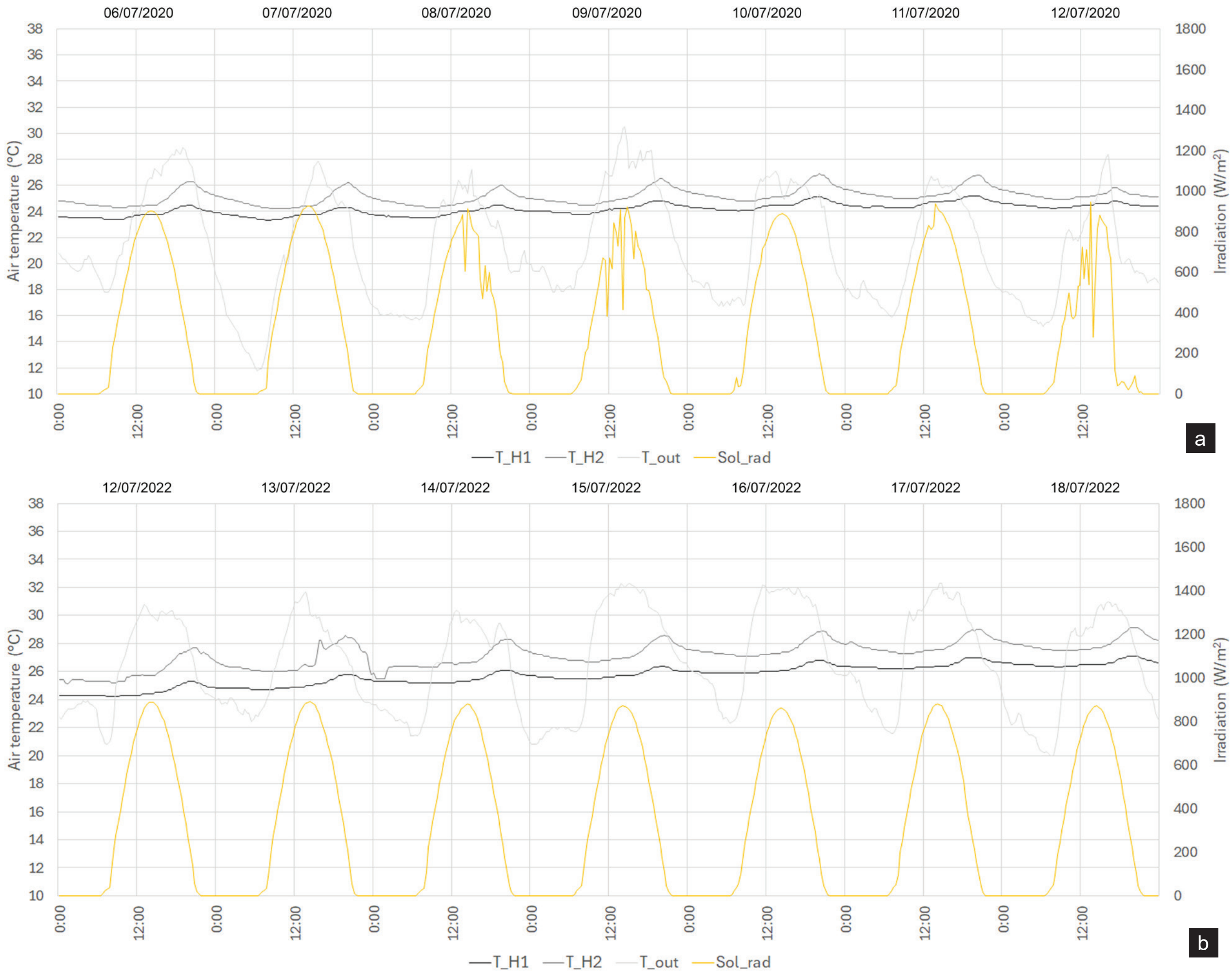

Fig. 5. Air temperature in House 1 (T_H1), House 2 (T_H2), outdoor air temperature (T_out), and solar radiation (Sol_rad), during two weeks without occupancy: a) 6–12 July 2020, b) 12–18 July 2022 (elaborated by J. Lopez-Besora)

Il. 5. Temperatura powietrza w domu nr 1 (TH_1), domu nr 2 (TH_2), temperatura powietrza na zewnątrz (T_out) i promieniowanie słoneczne (Sol_rad) w trakcie dwóch tygodni braku użytkowania domów przez mieszkańców: a) 6–12 lipca 2020, b) 12–18 lipca 2022 (oprac. J. Lopez-Besora)

average of 27.2 °C, while the traditional maintained a lower average (25.7 °C) than the outdoor environment (26.6 °C). It is noteworthy that the 2022 week experienced significantly higher solar radiation levels than the corresponding period in 2020, likely contributing to the overall temperature increase.

Figure 7 illustrates that during these unoccupied periods, traditional house consistently exhibited a narrower temperature range (lower diurnal thermal amplitude) compared to the contemporary one, which also maintained higher peak temperatures throughout. This suggests that the traditional building envelope provides greater thermal buffering capacity under passive conditions.

In contrast, the occupied weeks (Fig. 8), reveal marked differences in thermal behaviour. The temperature curves become less regular due to the influence of occupant activity. Since no behavioural protocols were imposed, users were free to manage ventilation, shading, and cooking practices according to their needs. During the week of 9–15 August 2021, the average indoor temperature was identical in both houses (26.4 °C), slightly above the outdoor average of 25.5 °C. However, during the week of August 2022, indoor temperatures in both the traditional and the contemporary houses exceeded the outdoor average by 2.2 °C and 1.3 °C, respectively. Unlike in 2021, the 2022 period was characterised by sustained high outdoor temperatures with minimal daily variation, which contributed to heat accumulation, particularly in the traditional, where dissipation appeared less effective.

Figures 7 and 8 confirm that the regular thermal fluctuation patterns observed during unoccupied weeks are disrupted during occupancy Both houses exhibited increased temperature variability, with wider ranges between maximum and minimum values. The expansion of the interquartile range (IQR) boxes also indicates greater dispersion in the indoor thermal data, reflecting the heterogeneity of occupant-driven events.

These variations underscore the impact of occupant presence on thermal dynamics. For instance, in the contemporary house, morning ventilation commonly produced a temperature drop of approximately 1 °C. In contrast, limited early-morning activity was observed in the traditional during the week of 1–7 August 2022, which diminished the effectiveness of ventilation as a cooling strategy during that period. Around midday, occupancy and cooking activities in both

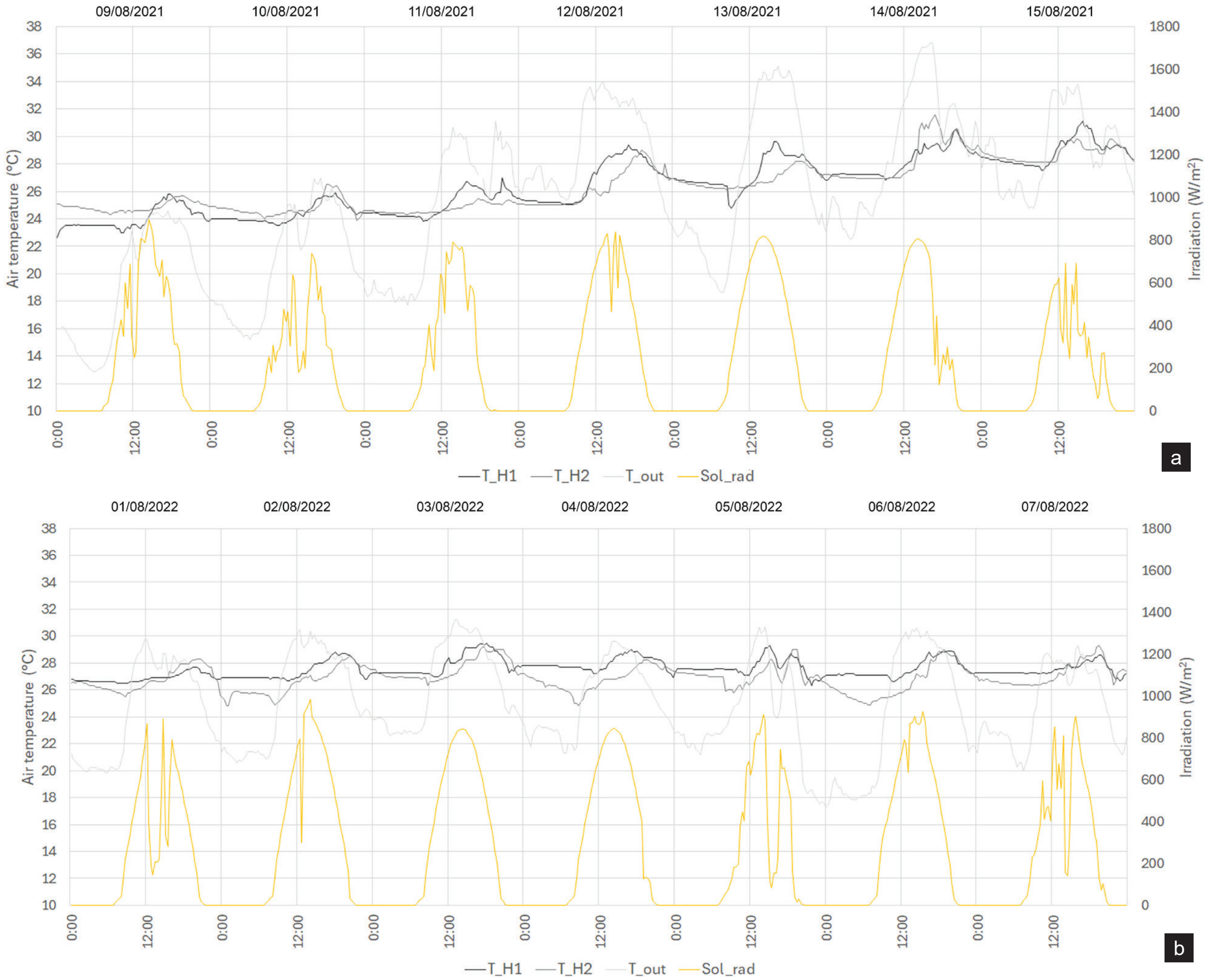

Fig. 6. Air temperature in House 1 (T_H1), House 2 (T_H2), outdoor air temperature (T_out), and solar radiation (Sol_rad), during two weeks with occupancy: a) 9–15 August 2021, b) 1–7 August 2022 (elaborated by J. Lopez-Besora)

Il. 6. Temperatura powietrza w domu nr 1 (TH_1), domu nr 2 (TH_2), temperatura powietrza na zewnątrz (T_out) i promieniowanie słoneczne (Sol_rad) w trakcie dwóch tygodni użytkowania obiektów przez mieszkańców: a) 9–15 sierpnia 2021, b) 11–7 sierpnia 2022 (oprac J. Lopez-Besora)

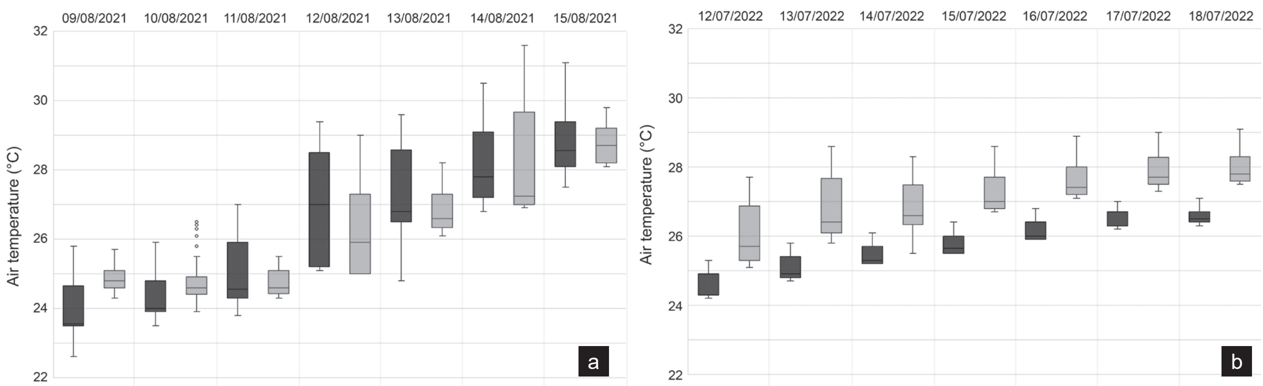

Fig. 7. Daily maximum and minimum temperatures in House 1 (dark grey) and House 2 (light grey) for the summer weeks without occupancy: a) 6–12 July 2020, b) 12–18 July 2022 (elaborated by J. Lopez-Besora)

Il. 7. Maksymalna i minimalna dzienna temperatura powietrza w domu nr 1 (ciemnoszary), domu nr 2 (jasnoszary) w trakcie tygodni letnich bez użytkowników: a) 6–12 lipca 2020, b) 12–18 lipca 2022 (oprac. J. Lopez-Besora)

houses caused temperature peaks exceeding 1 °C, relative to adjacent periods. Although such fluctuations were observed in both dwellings, the traditional house tended to retain heat for longer durations, indicating higher thermal inertia.

In summary, the summer data reveal that while both houses are sensitive to internal gains during occupancy, the traditional construction system exhibits greater thermal stability during unoccupied periods, and higher heat retention

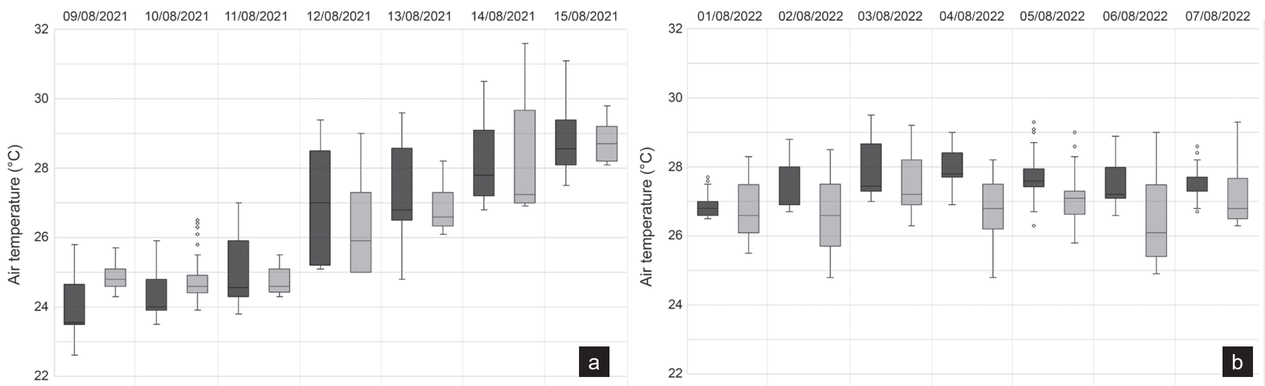

Fig. 8. Daily maximum and minimum temperatures in House 1 (dark grey) and House 2 (light grey) for the summer weeks with occupancy: a) 9–15 August 2021, b) 1–7 August 2022 (elaborated by J. Lopez-Besora)

Il. 8. Maksymalna i minimalna dzienna temperatura powietrza w domu nr 1 (ciemnoszary), domu nr 2 (jasnoszary) w trakcie tygodni letnich z użytkownikami: a) 9–15 sierpnia 2021, b) 1–7 sierpnia 2022 (oprac. J. Lopez-Besora)

once internal gains are introduced. These findings illustrate the combined influence of construction system and user behaviour on summer indoor thermal performance.

Winter results: stationary heat loss and time constant

To evaluate and compare the thermal behaviour of both dwellings in winter conditions, a twofold approach was adopted: first, we conducted theoretical calculations of stationary heat losses, and second, we validated these results with empirical data from monitored winter periods.

• Stationary heat loss analysis

The heat loss through transmission and ventilation in each living room was estimated under static, free-running conditions, using the parameters outlined in Table 1. The calculation of total heat losses followed Equation (1), while the thermal time constant was derived using Equation (2).

$$\text{Transm.loss} = (U\,\text{window} * S\,\text{window}) + (U\,\text{wall} * S\,\text{wall}) \quad (1)$$
$$\text{Vent.loss} = Cp\ \text{air} * \rho\ \text{air} * V\,air * \text{ach}/3600$$
$$\text{Total loss} = \text{Transm.loss} + \text{Vent.loss}$$

$$\text{Time constant} = \frac{M'}{\text{Total loss}} \quad (2)$$

where:

Transm.loss – Transmission loss [W/K],
U window – *U* thermal transmittance [W/m^{2}K],
S window – *S* surface [m^2],
Vent.loss – Ventilation loss [W/K],
Cp air – *Cp* heat capacity [J/kg K],
ρ air – ρ density [kg/m^3],
V air – *V* volume [m^3],
ach – *ach* air changes per hour,
Total loss – total loss [W/K],
Time constant – time constant [h],
M' – M' effective mass [kg]

Transmission heat losses were obtained by multiplying *U*-values with the surface areas of the building envelope components. The results indicate a transmission heat loss of 33.38 W/K for the traditional house and 27.99 W/K for the contemporary one, which represents only a 19% higher value for the traditional house despite its less thermally efficient construction system.

Ventilation heat losses were calculated based on assumed air change rates. For House 2, we considered 0.7 ACH, in accordance with the Spanish building code (RITE), whereas for House 1, the infiltration rate was doubled to 1.4 ACH due to lower airtightness and older window systems. Assuming an air density of 1.1 kg/m^3 (for 10 °C at 751 m altitude) and a specific heat capacity of 1030 J/kg·K, the ventilation losses were 40.6 W/K for House 1 and 20.2 W/K for House 2. In this case, the traditional house doubles the value of the contemporary one.

Summing both components, the total heat loss amounts to 74.0 W/K in the traditional house and 48.2 W/K in the contemporary, implying that the traditional house exhibits approximately 53% greater thermal losses. Notably, the ventilation component is the most critical contributor to this difference.

A hypothetical retrofit scenario (RI1) in which the windows of the traditional house were replaced with those from the contemporary would reduce transmission losses to 28.42 W/K, and ventilation losses to 20.3 W/K, thereby aligning total thermal losses (48.7 W/K) closely with those of the contemporary house (Table 3). A more comprehensive intervention (RI2), involving both window replacement and external insulation to match the *U*-values of the contemporary, would result in 44% lower heat loss than in the contemporary house. Nevertheless, adding thermal insulation may not be viable due to heritage conservation constraints and limited interior space, in addition to hindering heat dissipation during the summer.

• Thermal mass and dynamic behaviour

Beyond steady-state conditions, thermal mass significantly influences the dynamic thermal response of a building, particularly during unheated periods. Following occupant departure, the decay in indoor temperature is governed by the building's effective thermal mass (M'), which, when combined with heat loss values, defines the thermal time constant (τ), a measure of the time required for indoor temperature to stabilise in the absence of heat gains. The coeffi-

Table 3. Transmission, ventilation and total thermal losses in House 1 and House 2. In the case of House 1, two retrofit scenarios have been considered: RI1 corresponds to window replacement, and RI2 corresponds to window replacement and addition of thermal insulation (elaborated by J. Lopez-Besora)

Tabela 3. Przenikanie, wentylacja oraz całkowite straty ciepła w domu nr 1 i domu nr 2. W przypadku domu nr 1 były rozważane dwa scenariusze modernizacji: RI1 – wymiana okien, RI2 – wymiana okien z dodaną izolacją termiczną (oprac. J. Lopez-Besora)

	Transm. loss [W/K]	Vent. loss [W/K]	Total loss [W/K]
House 1	33.38	40.6	74.0
RI1 (window)	28.42	20.3	48.7
RI2 (window+thermal insulation)	13.095	20.3	33.4
House 2	27.99	20.2	48.2

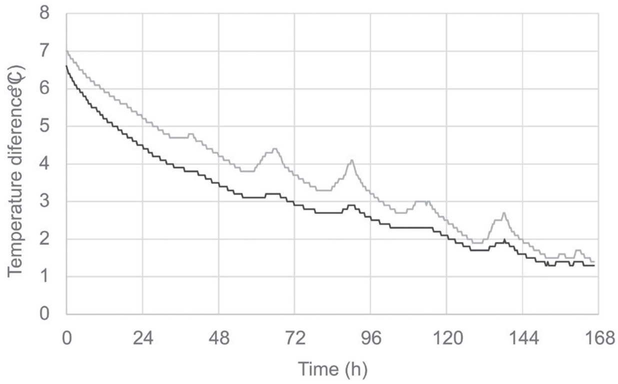

Fig. 9. Air temperature in House 1 and House 2 from 16 to 23 March 2020 (elaborated by J. Lopez-Besora)

Il. 9. Temperatura powietrza w domu 1 i domu 2 od 16 do 23 marca 2020 (oprac. J. Lopez-Besora)

cient τ is calculated by dividing thermal mass by the thermal loss coefficient (Equation 2).

Using the effective thermal mass values from Table 1 and a specific heat of 1000 J/kg·K, House 1 and House 2 present 33.6 MJ/K and 15.1 MJ/K, respectively. As such, the traditional house has more than double the thermal mass of the contemporary one. Calculated time constants τ are 126.1 h for House 1 and 87.0 h for House 2, indicating that the traditional house takes 39 hours more to stabilise, reflecting greater thermal inertia.

• Empirical validation

These theoretical results were then compared with monitored data during a selected winter week (16–23 March 2020), which captures a full heating cycle: activation of heating from Friday to Sunday (during occupancy), followed by five days of unheated operation after the occupants' departure on Sunday evening.

As shown in Figure 9, both houses exhibit a temperature decay pattern after heating is turned off, with distinct behaviours. The contemporary house shows higher afternoon temperature peaks due to greater exposure to solar gains, while the traditional one maintains a more gradual and consistent temperature decline, likely due to reduced glazing and the presence of shutters.

To model this decay, we fitted the indoor temperature curves to an exponential decay function. The resulting curves displayed strong correlation, with R^2 values of 0.974 (House 1) and 0.965 (House 2). From these fits, we derived empirical time constants of 115 h for House 1 and 116 h for House 2. While the fitted value for House 1 closely matches the theoretical estimate (difference of 11 h), House 2 exhibits a notable discrepancy of 29 h, potentially due to greater exposure to solar radiation, which compensates for some of the cooling and prolongs the effective decay (Marincic 1999; Isalgue et al. 1980).

Despite the fundamental differences in construction, insulation, exposure, and thermal mass, the overall cooling behaviour of both dwellings is remarkably similar in practice. The traditional house's higher mass and reduced exposure to solar gains offset its inferior insulation and greater heat loss, while the contemporary house benefits from superior envelope performance but is more sensitive to external conditions.

Summer and winter air and radiant temperature

This phase of the study involved measuring and comparing the air temperature and radiant temperature of the living room interior surfaces during a winter weekend (10–12 February 2023) and a summer weekend (30 June – 2 July 2023) (Figs. 10–13) (Lopez-Besora, Isalgue and Coch 2024).

Winter measurements began on Friday evening and concluded on Sunday afternoon (Figs. 10, 12). These measurements were taken under real-use conditions, with occupants present and the heating system in operation. Results indicate that radiant temperatures in the traditional house remained below the air temperature until Sunday. Thereafter, some surfaces, particularly the ceiling and floor, exhibited slightly higher radiant temperatures than the air. The lowest radiant temperature values were consistently recorded on the façade surfaces (TS1_W and TS1_N). In contrast, the contemporary house exhibited a more rapid thermal response. Several surfaces reached radiant temperatures exceeding the air temperature within just a few hours of activating the heating. Notably, the façade in the contemporary showed elevated radiant temperatures (TS2_W and TS2_W′) due to direct solar radiation.

During the summer period, the air temperature in the traditional house remained approximately 1 °C lower than that of the contemporary for most of the time (Figs. 11, 13). Radiant temperatures closely tracked air temperatures in both dwellings, although they were slightly higher, particularly in the contemporary house. Compared to winter, the amplitude of radiant temperature fluctuations was significantly reduced in both houses. As observed in winter, the ceiling and floor tended to register the highest radiant temperatures.

Thermal sensation is influenced by both air temperature and radiant temperature. In summer, the convergence of these two variables implies that air temperature largely governs thermal perception. In winter, however (especially under intermittent occupancy) radiant temperature becomes a critical

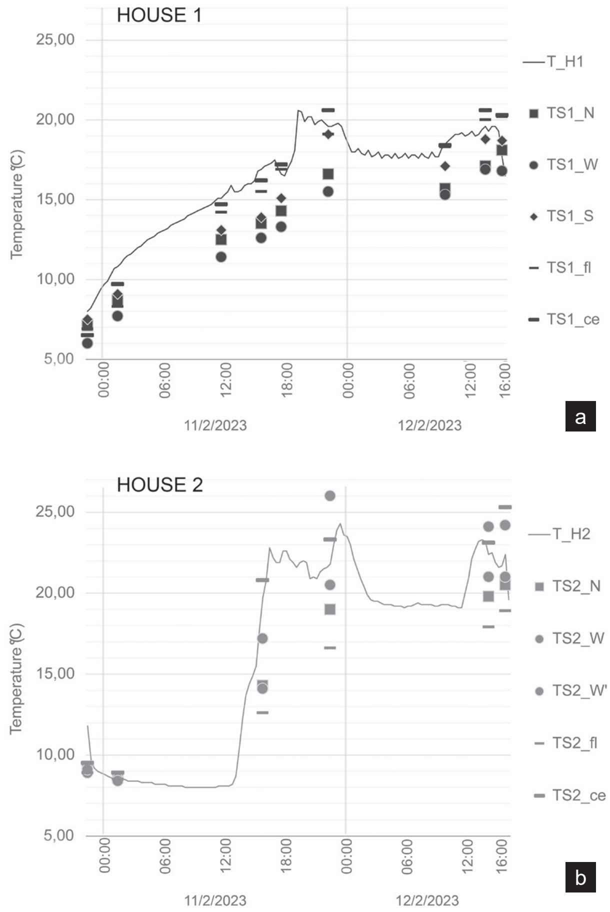

Fig. 10. Measurements of air temperature and radiant temperature from 10 to 12 February 2023: a) House 1, b) House 2; the codes for the measured points are listed in Figure 2 (elaborated by J. Lopez-Besora)

Il. 10. Pomiary temperatury powietrza i temperatury promieniowania w okresie 10–12 lutego 2023: a) dom nr 1, b) dom nr 2, opis oznaczeń zgodny z il. 2 (oprac. J. Lopez-Besora)

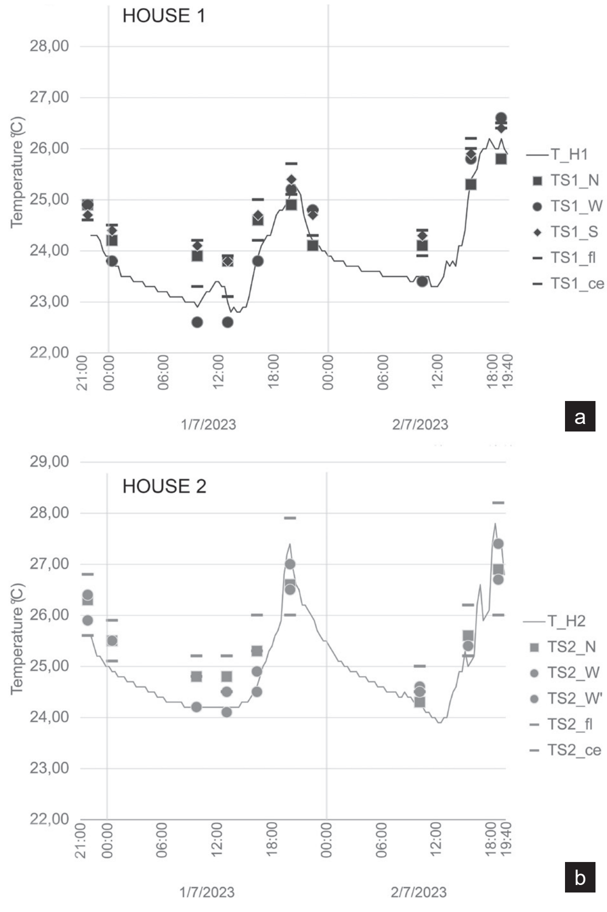

Fig. 11. Measurements of air temperature and radiant temperature from 30 June to 2 July 2023: a) House 1, b) House 2; the codes for the measured points are listed in Figure 2 (elaborated by J. Lopez-Besora)

Il. 11. Pomiary temperatury powietrza i temperatury promieniowania w okresie 30 czerwca – 2 lipca 2023: a) dom nr 1, b) dom nr 2, opis oznaczeń zgodny z il. 2 (oprac. J. Lopez-Besora)

parameter. When comparing buildings with markedly different thermal mass, radiant temperature plays a decisive role. The traditional house, with its higher thermal mass, demonstrates less favourable performance under winter conditions but offers potential benefits for thermal comfort in summer, particularly during the early part of the season.

Conclusions

The reuse of traditional architecture plays a pivotal role in enhancing urban resilience and preserving cultural heritage. This study contributes to that goal by expanding the understanding of thermal performance in traditional buildings compared to contemporary counterparts of similar morphology in a specific climate. The methodology, based on long-term in situ monitoring of occupied dwellings, provides valuable insights into real-life thermal dynamics under typical use conditions.

In a context where existing buildings, particularly traditional ones, often face intensive retrofitting or demolition due to economic pressures, this research underscores the continued relevance and functional viability of traditional architecture when addressed through well-founded, context-sensitive interventions. The findings support the idea, aligned with theories such as the rebound and prebound effects, that the thermal performance gap between traditional and contemporary buildings may be narrower than often assumed. The climatic context is fundamental, as the climate under study is a temperate one, in which conditions are favourable for living for much of the year. Therefore, the potential for architecture reuse in this specific case is a relevant factor.

Throughout the monitoring period, both houses exhibited remarkably similar annual average indoor temperatures. However, under unoccupied conditions, the contemporary house proved more sensitive to external climatic variations, with sharper thermal fluctuations. In contrast, the traditional house demonstrated greater thermal stability, attributed to its higher thermal mass. Under occupied conditions, both houses were strongly influenced by user behaviour, including ventilation practices, internal heat gains, and solar shading. In this context, the differences between the two construction systems are less pronounced. These finding emphasize

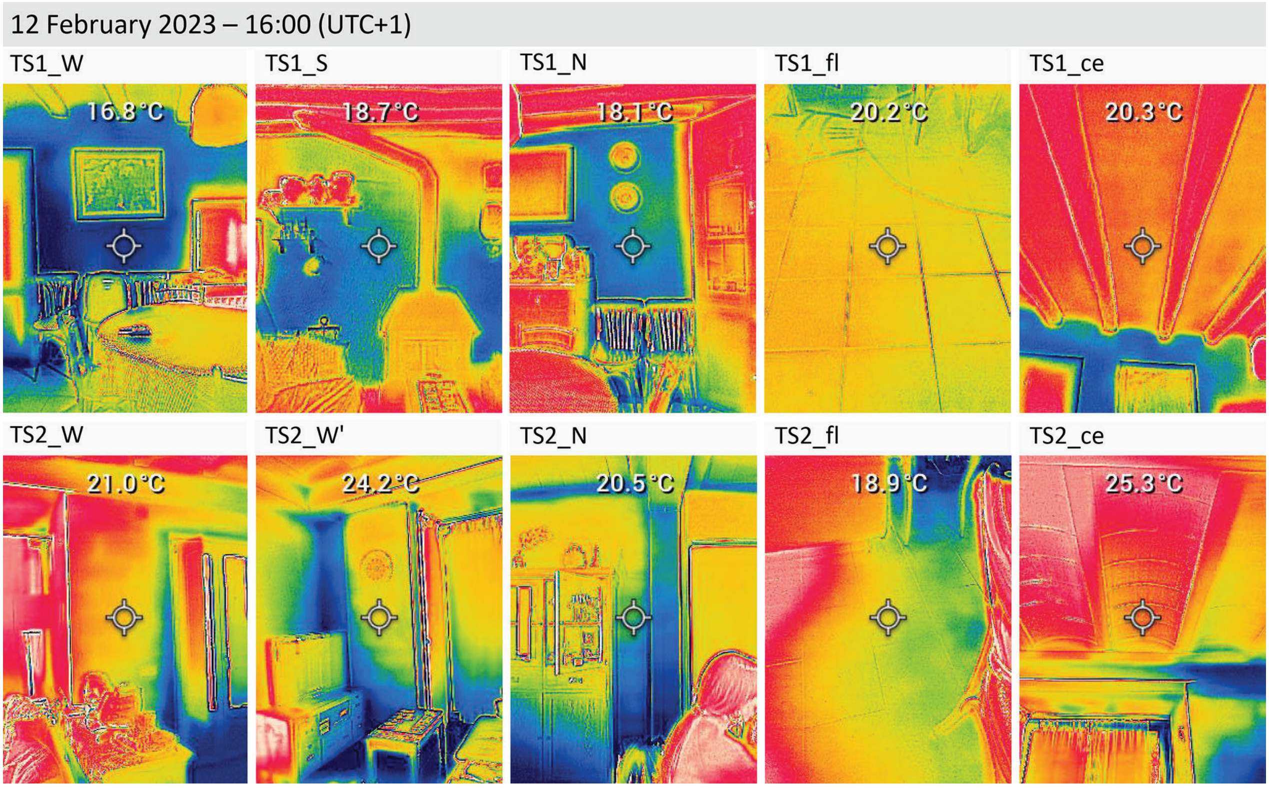

Fig. 12. Thermal images with the radiant temperature in the specified points of House 1 and House 2. Data acquisition: 12 February 2023 (elaborated by J. Lopez-Besora)

Il. 12. Obrazy termiczne z temperaturą promieniowania w określonych punktach domu nr 1 i domu nr 2. Data badania: 12 lutego 2023 (oprac. J. Lopez-Besora)

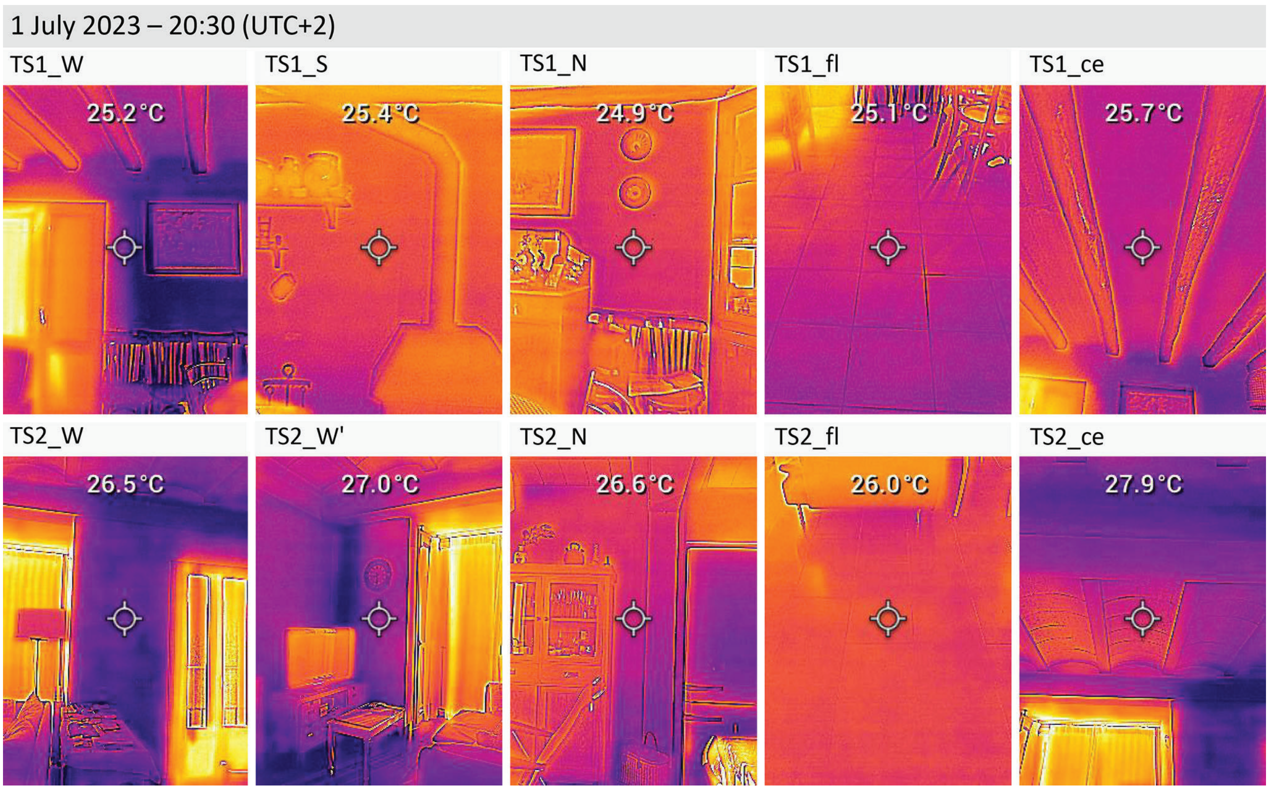

Fig. 13. Thermal images with the radiant temperature in the specified points of House 1 and House 2. Data acquisition: 1 July 2023 (elaborated by J. Lopez-Besora)

Il. 13. Obrazy termiczne z temperaturą promieniowania w określonych punktach domu nr 1 i domu nr 2. Data badania: 1 lipca 2023 (oprac. J. Lopez-Besora) the decisive role of occupants in shaping thermal performance in architecture, reaffirming that user behaviour is as critical as construction quality in determining real-world outcomes. In fact, the study reveals the character of both buildings: holiday residences with a social function and a strong mediterranean character, which shape their behaviour, as observed in the monitoring results.

Beyond user influence, construction systems and building typology also played a key role. Despite the contemporary house having components with lower thermal transmittance (*U*-values), the overall transmission heat losses were comparable between the two dwellings. The traditional house compensates for a less insulated envelope with smaller windows and compact design, whereas the contemporary house, with larger glazed areas and greater façade exposure, experiences higher heat losses. This contrast embodies divergent design philosophies and reveals the distinct aesthetic character of each architectural approach: traditional architecture emphasizes thermal performance through mass and compactness, while contemporary architecture often prioritizes formal expression and spatial openness achieved through the use of thermally efficient materials.

Ultimately, this study contributes to the scientific understanding of thermal behaviour in traditional buildings in Mediterranean context and highlights the importance of retrofit strategies that respect and leverage the intrinsic characteristics of existing structures. Rather than applying standard solutions, adaptive reuse should be guided by real-life data and contextual sensitivity to ensure both energy performance and building preservation.

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Streszczenie

Adaptacje i nowe funkcje użytkowe budynków: jak tradycyjne i współczesne budynki zachowują współczynniki termiczne w warunkach rzeczywistych?

W przypadku zachowania odporności na zmiany klimatu w środowisku zurbanizowanym istotnym elementem jest znacząco zwiększający się udział obiektów poddawanych adaptacjom i zmianom sposobów użytkowania w celu osiągnięcia współczesnych wymagań i standardów. Budynki tradycyjne mają odpowiednie znaczenie strategiczne i charakter, jednakże często nie odpowiadają współczesnym wymaganiom, chociaż ich nieodłączne cechy mogą przyczynić się do przedłużenia ich okresu funkcjonowania. W przedstawionym badaniu zajęto się szczególnymi różnicami pomiędzy tradycyjnymi i współczesnymi rozwiązaniami konstrukcyjno-architektonicznymi związanymi z termiką obiektu w bieżących, realnych warunkach. Ciągłość badań temperatur została zebrana w ciągu trzech lat w dwóch wnętrzach budynków – jednego zbudowanego w tradycyjny sposób, a drugiego zgodnie ze współczesnymi technikami budowlanymi – zarówno w okresach użytkowania, jak i braku tegoż i obejmowała badania temperatur powietrza, promieniowania etc. Otrzymane rezultaty świadczą o tym, że różnice wynikające z systemów konstrukcyjnych są relatywnie małe, z użytkowaniem jako dominującym czynnikiem, z niemal ujednoliconym zachowaniem termicznym obu obiektów. Potwierdza to, że w klimacie śródziemnomorskim obiekty tradycyjnej architektury mogą osiągnąć wydajność cieplną porównywalną z wydajnością współczesnych konstrukcji, i podkreśla ich wartość jako elementu zachowującego zrównoważenie energetyczne.

Słowa kluczowe: budynki tradycyjne, monitoring, wydajność cieplna, temperatura promieniowania, modernizacja budynków