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Thermal behaviour optimization in thick bricks wall of architectural heritage

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A R T I C L E I N F O

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A B S T R A C T

The thermal envelope of a building plays a key role in its energy efficiency; therefore, accurately characterizing its behaviour is essential to reliably estimate energy consumption. In historic buildings, errors in these estimations can compromise the rehabilitation process and lead to ineffective interventions. Understanding the thermal behaviour of traditional construction systems allows for the establishment of realistic and non-invasive in situ assessment methods, which are crucial for appropriate energy retrofitting. This study evaluates the applicability of the Heat Flow Meter (HFM) method in thick brick masonry walls of historic buildings, by installing heat flux sensors on both sides of the wall. The analysis was carried out on a landmark 20th-century building over a 45-day winter monitoring period, assessing the thermal performance of the wall to validate the method's effectiveness in heritage contexts, while identifying the advantages and limitations of the efficiency of its heating system. The results were compared with the theoretical model based on Fourier's law, revealing notable discrepancies: daily periods were observed during which the wall simultaneously received heat from both the interior and exterior environments, contradicting the assumption of unidirectional heat transfer. This phenomenon highlights the potential of massive walls to act as dynamic thermal regulators. The study demonstrates the value of harnessing these ambient thermal gains as a passive strategy to improve energy efficiency without compromising indoor comfort established in regulations, and reinforces the relevance of traditional construction solutions in the sustainable conservation of built heritage.

1. Introduction

The growing concern about environmental degradation and anthropogenic global warming has led the European Union to set ambitious emission reduction targets. In this context, a goal has been set to reduce greenhouse gas emissions by 80 % by the year 2050, compared to levels at the end of the last century [1].

The construction sector represents a considerable challenge due to its high energy consumption. This sector accounts for 40 % of final energy use in Europe, surpassing the industrial and transport sectors [2]. To meet climate targets, it is essential to reduce greenhouse gas emissions by 90 % [3]. Existing buildings are a fundamental component of total energy use. [3–5]. Heating, in particular, is the largest energy consumer in existing buildings and contributes approximately 40 % of total greenhouse gas emissions [6–8]. Although most available studies focus on the residential sector, recent data indicate that energy consumption for heating accounts for 39 % of total energy consumption in Spain, compared to 1 % for air conditioning [9], highlighting the pre-eminence of heating in the energy demand of existing buildings [7,8].

In recent years, the construction industry has adopted new energy conservation regulations, driven by various European directives [10–12]. The efficient renovation of the existing building stock is paramount and requires a comprehensive understanding of construction elements and their performance [13–15]. The built heritage, particularly historic buildings, represents a significant portion of the European urban landscape, and its conservation is essential. Approximately one quarter of the current building stock in Europe was constructed before the mid-20th century [16]. Beyond their cultural and historical

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significance, historic buildings serve essential functions by housing dwellings, public buildings, and services. Therefore, energy retrofit strategies and compatible solutions for such buildings have been identified as priorities in the EeB PPP roadmap [17]. Numerous studies have explored energy-saving strategies in historic buildings [18–22], highlighting the use of passive solutions [23,24]. These solutions have significant potential to improve energy efficiency without compromising the original structure.

Over the past decade, efforts to reduce the energy consumption of buildings have gained importance [25]. However, multiple factors influence energy performance, such as climate zone, HVAC systems, and renewable energy production. The building envelope plays a fundamental role in energy efficiency, as heating and cooling account for between 35 % and 70 % of the building's total energy use [10,26]. Thermal resistance (R-value) is a critical parameter in evaluating energy efficiency, and accurate measurement is essential to avoid deviations in theoretical calculations. The thermophysical properties of the building envelope have been identified as key variables in predicting energy consumption [27–29]. Nonetheless, a performance gap persists between expected and measured consumption [30–32], attributed to factors such as occupant behaviour, construction defects, and material degradation [33–35]. Discrepancies between expected and actual performance of construction elements have been shown to lead to inefficiencies [20,22]. In situ measurement of the R-value enables more accurate assessments by considering real environmental conditions and the state of material conservation, including moisture accumulation [36,37].

Moreover, such measurement facilitates the assessment of construction quality when material properties and stratigraphy are uncertain [38,39]. The thermal properties of the envelope directly impact the annual energy demand of buildings [28,29,40], with walls being the element responsible for the highest energy loss [31,32,41]. The thermal transmittance of walls is a key factor in energy performance, influencing heat transfer and HVAC system requirements [42–47]. The use of imprecise thermophysical characteristics can affect heating strategies, the cost-effectiveness of energy-saving measures, and the effectiveness of retrofit interventions in historic buildings. Thus, the use of monitored data is considered a fundamental tool for reducing the performance gap and improving the quality of construction processes [37,48,49]. The energy balance of walls impacts thermal comfort, energy consumption, and pollutant dispersion [50–52], as well as urban ventilation [53–55]. Accurate characterization of energy performance is essential for planning retrofits, quality control in new construction, and the development of urban policies based on real data. Incorrect estimations of energy consumption in historic buildings can jeopardize retrofit processes, promoting ineffective approaches. Therefore, in situ measurement of the R-value is key to reducing errors and informing improvement strategies [26,56,57].

Although there is extensive literature on materials and techniques in historic buildings, information on the thermal characterization of their envelopes remains limited [20]. Theoretical studies often present uncertainties due to the diversity of materials and construction methods [22,58]. The use of indoor and outdoor heat flux measurements allows inference of the thermal structure of building elements and their response to heat flow, minimizing errors in theoretical estimates. The most commonly used methods include quasi-steady-state approaches such as the average method [59] and linear regression models [5,60], enabling accurate evaluation of energy performance [61,62]. A thorough analysis of the thermophysical properties of buildings will allow the development of effective energy efficiency strategies, contributing to sustainability and the optimization of the building stock.

The energy efficiency of historic buildings depends largely on the thermal envelope, so accurate characterisation of the building envelope is essential to guide effective renovation strategies. Conventional methods based on Fourier's law have limitations in thick walls, underestimating the complex dynamics of actual heat flow. This study focuses exclusively on the winter period and applies the SHB-HFM method to a 63 cm thick historic pressed brick wall located on the north-west façade of the school Nuestra Señora de Lourdes in Valladolid, comparing in situ measurements with theoretical results. The daily periods in which the wall simultaneously receives heat inputs from both environments are identified, revealing thermal dynamics that are not captured by traditional models.

The main objective of the research is to characterize the most efficient winter time periods of the wall, validating the applicability of the HFM method and providing accurate indicators of the thermal behaviour of historic building envelopes. The results enable the optimisation of heating systems and refurbishment strategies, highlighting the contribution of walls to passive thermal regulation and extending the applicability of the findings beyond the case studied.

The present study aims to contribute to the thermal characterization of traditional construction solutions by providing accurate indicators of thermal behaviour and establishing feasible methods for in situ evaluation. For this purpose, the applicability and precision of the SHB-HFM method are analysed, assessing its ability to generate representative data in historic buildings, along with a comparative analysis of Fourier's method in thermal modelling, contrasting its estimates with in situ measurements to identify advantages and limitations. This study builds on the evidence that certain wall types can release part of the accumulated heat into the indoor environment, contributing to the passive thermal regulation of the space in winter. In this context, the main objective of the research is to identify and characterize the time periods during which such thermal transfer is most efficient, in order to optimize heating systems by studying the thermal performance of these construction elements and enhance their contribution to the building's energy performance. This approach seeks to optimize climate control and sustainability strategies by minimizing the energy performance gap through a more precise characterization of historic materials and structures.

2. Materials and methods

2.1. Case of study

The building selected as the case study is the school Nuestra Señora de Lourdes, located at Calle Paulina Harriet No. 22 in Valladolid (Spain). It is an emblematic construction dating back to the early 20th century (built in 1900), according to the cadastral records, and features characteristics typical of significant architecture from that period. The building stands on a 12,667 m^2 plot and is strategically located near the historic centre of Valladolid, in an area that blends architectural heritage with natural surroundings. The building is used for teaching purposes and is therefore only occupied from Monday to Friday, 8:00 a.m. to 4:30 p.m., coinciding with the hours when the radiant heating is turned on. It does not have any air conditioning system in summer.

Due to both its educational function and architectural value, this building is recognized as a representative example of public heritage buildings. However, like many other publicly used properties, it faces an urgent need to improve its energy efficiency. The age of such buildings and their original construction features typically result in high energy consumption, posing considerable challenges in terms of sustainability and resource conservation. It is now essential to undertake interventions aimed at optimizing their energy performance, not only to ensure their preservation as historical heritage but also to adapt them to the energy efficiency standards required in the 21st century Fig. 1.

As shown in Fig. 2, the façades were built with a single layer of exposed pressed brick on the exterior. Although the main façade was later rendered, the rear façade has retained its original appearance. Consultation with the property owners and existing documentation confirms that no internal linings have been added since the building's original construction.

According to [63], the lack of construction-related knowledge significantly hinders the rehabilitation process, and they assert that in

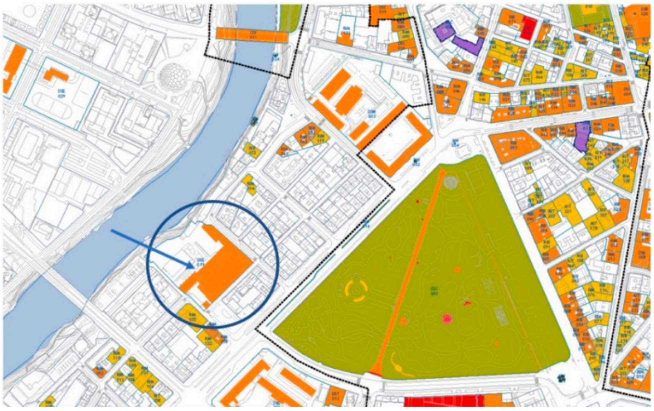

Fig. 1. Location map from the Valladolid General Urban Development Plan (PGOU). Indication of the northwest façade where the test is conducted.

situ testing is extremely valuable for obtaining realistic conclusions regarding the thermal behaviour of building elements. Considering the scarcity of published technical information on this topic, the present research also contributes to expanding knowledge of the thermal performance of building envelopes of this kind, which are commonly found in administrative buildings of the era.

In order to address the existing gap concerning the thermal behaviour of such envelopes, previous experimental studies have been conducted, primarily under laboratory conditions with controlled environments, also calibrating all measurement equipment [64–67]. In situ experimental measurements can also be found in the literature, generally guided by ISO 9869–1:2014 [68]. In this study, the measurement period exceeded five days, preserving the building's real conditions (as is standard in the application of the traditional Heat Flux Meter method). It is important to note that the present study stands out from existing research by performing in situ measurements using a recent method that enhances precision, shortens the measurement period, and avoids the use of heating/cooling equipment to maintain constant indoor temperature.

2.2. In situ thermal flow test

The building selected for the study meets the following criteria:

(1) it is located in a climatic zone with harsh winters, where temperatures drop below 0 °C, ensuring that the interior temperature is significantly different from the exterior temperature, in order to test its performance in adverse winter conditions in a typical Mediterranean climate (Csa), according to the Köppen climate classification, continentalised with cold winters due to its location in the interior of the peninsula (altitude close to 700 m);
(2) the façade is constructed entirely of brick masonry, with no coatings or added materials that could alter its composition;
(3) the structure has remained in its original state, with no interventions or restorations that might affect the wall's properties;
(4) it is currently in use, ensuring a stable indoor temperature throughout the analysis period; and
(5) it only has an active climate control system in winter, with time radiant heating.

The orientation of the façade chosen for the in-situ test was determined through preliminary visual inspection. To prevent direct solar radiation from distorting the data, a fully shaded area was selected and as specified in the standard ISO 9869–1:2014[68], protected by shadows cast from a nearby building and surrounding vegetation. The chosen location was the northwest rear façade, which had not previously undergone any intervention. This façade consists of a single exposed pressed brick wall. According to the technical and historical documentation consulted, as well as on-site verification, the wall thickness was determined to be 63 cm.

The building is equipped solely with a radiant heating system for winter conditions. Its operation is limited to the winter season (October–May) and coincides with the building's occupancy schedule, from Monday to Friday between 8:00 a.m. and 4:30 p.m. These operational conditions, together with the actual occupancy profiles, were taken into account during the monitoring campaign to ensure that the measured heat fluxes and thermal performance indicators accurately represent the building's real use.

Prior to the installation of the measurement equipment, a thermographic analysis of the selected wall (both exterior and interior) was conducted. The objective of this procedure was to identify and eliminate any singular points or heat sources that might introduce anomalies in the thermal energy flow, ensuring the most appropriate application of the methodology in those zones [69,70]. As shown in Fig. 3, the area under evaluation presented no interferences or potential sources of error that could compromise the results.

Fig. 3 shows the layout of the measurement points on either side of the wall Fig. 4.

2.3. Measurement equipment and procedure

Two heat flux sensors and two high-precision thermocouples were used to monitor the thermal behaviour of the wall. The sensors were

Fig. 2. Ground floor plan showing the location of the test (25/05/2025, https://valladolidcityoffilm.com/sol-portfolio/colegio-nuestra-senora-de-lourdes/).

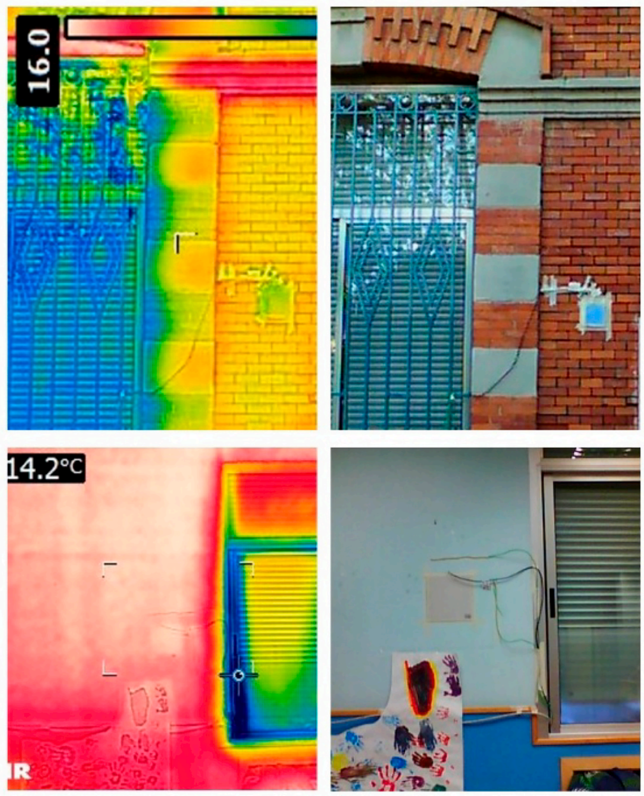

Fig. 3. Thermographic image and positioning of the plates used for the test.

previously calibrated and verified in the laboratory, ensuring consistent results within the required accuracy margins. The associated measurement uncertainty was ± 0.02 % for the thermal flux and ± 0.05 °C for the temperature probes, values that are within the accepted range for in situ thermal characterisation.

Due to the difference in surface roughness, two types of heat flux sensors were used: a rigid one, suitable for the smooth interior surface, and a flexible one, suitable for the rough exterior surface. Both devices provide measurements in W/m^2 regardless of their dimensions, so it was not necessary to apply subsequent corrections to the recorded data. Each thermocouple was installed next to the corresponding heat flux sensor on both sides of the wall, following the installation guidelines established by ISO 9869–1:2014 [68].

The equipment used for the test consisted of:

A heat flux sensor, model FQAD19T by Ahlborn (250 mm × 250 mm × 1.5 mm), made of epoxy resin, with an accuracy of 0.02 % of the measured value, suitable for smooth surfaces, which was installed on the interior surface of the wall.

A heat flux sensor, model FQAD18TSI by Ahlborn (120 mm × 120 mm × 3 mm), with an accuracy of 0.02 % of the measured value, adapted to the irregular surface of the brick façade.

Four thermocouples for surface temperature measurement, installed both indoors and outdoors, with an accuracy of ± 0.05 °C and ± 0.05 % of the measured value.

A data logger, model Almemo 2590 by Ahlborn, with an accuracy of 0.03 %, used to store heat flux and surface temperature data. The unit, labelled 3-Soria 2020, was configured to record data every 15 min.

A thermal imaging camera, Flir Thermacam B29, with a thermal sensitivity of 0.1 °C, a temperature measurement ranges from − 20 °C to + 100 °C, spectral range from 7.5 to 13 μm, and a brick emissivity value of 0.9.

The total test duration was 45 days in winter conditions, following the methodology established in the international standard ISO 9869–1 [International Standard ISO 9869–1. Thermal insulation—Building elements—In-situ measurement of thermal resistance and thermal transmittance. Part 1: Heat flow meter method. 2014] [68], specifically from 4 March to 18 April 2024, with the usual winter heating period. In the present study, the in situ measurements are performed under transient conditions to analyse the evolution of the heat flux across the wall at each instant due to temperature differences, without focusing on phenomena such as delay or thermal inertia, aiming primarily to quantify the potential energy savings during winter conditions rather than the mechanisms causing them.

In line with previous experiences using the HFM method, heat flux sensors are typically. installed on only one side of the building component under evaluation [26,71,72]. However, the application of dual-sided heat flux sensors (i.e., sensors on both interior and exterior surfaces; see Fig. 3) can significantly reduce measurement errors [73]. Even in the presence of field-testing failures, human errors, or unfavourable on-site conditions, dual sensors not only provide cross-verification but also improve the overall accuracy of the results.

The sensors recorded data at different times of the day, which was important given the outdoor temperature fluctuations. In addition to the heat flux sensors, four probes—two indoor and two outdoor—were installed to measure both air and surface temperatures.

The positioning of the heat flux plates on the wall was determined based on three factors. Firstly, it was essential that the cables could connect all plates and probes to the data logger, which collected all the recorded information. Secondly, thermal bridges were to be avoided, which were identified through infrared thermography. Thirdly, the plate must be suitable for the type of surface to avoid distortions in the measurement. The measured heat flow is obtained in W/m^2, so the different dimensions of the plates are not representative (see Fig. 3b).

Fig. 5 shows the variation in heat flux recorded by both plates over the study period. According to the established convention, positive values indicate that energy is being transferred outwards from the heated surface, whereas negative values indicate energy being transferred inwards, into the surface of the wall (i.e., in the opposite direction).

3. Results

The following observations can be derived from the analysis:

The heat flux measured by the plate located on the interior face of the wall is consistently negative, indicating that the indoor environment continuously acts as a heat source towards the wall:

From Monday to Friday, the flux remains steady, with abrupt increases corresponding to the periods when the building is in use and the heating system is operating on working days (8:00 to 16:30).

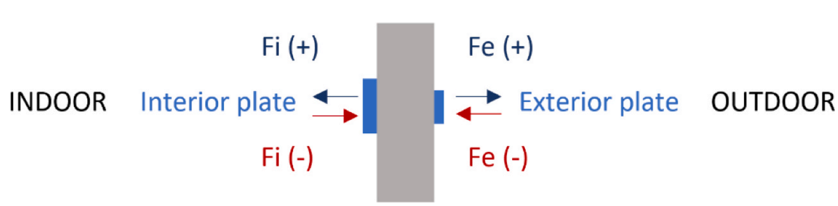

Fig. 4. Diagram of the test set-up. Sign convention.

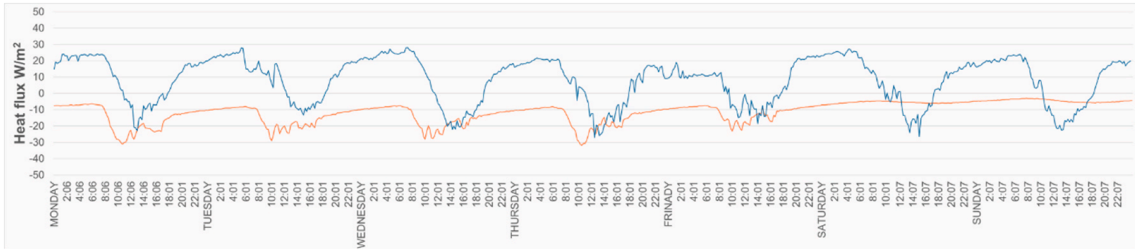

Fig. 5. Heat flux measured by the exterior and interior plates during a winter week (11–17/03/2024). FeP= Heat flux measured by plate placed on the exterior face of the wall (W/m^2) FiP= Heat flux measured by plate placed on the interior face of the wall (W/m^2).

During Saturday and Sunday, when the building is unoccupied and the heating system is not operating, the flux remains stable without significant variation.

In contrast, the flux recorded by the plate on the exterior face of the wall shows variations in sign throughout the day. It is important to note that the test area was specifically selected to avoid direct solar radiation on the plate from distorting result.

A downward trend in the heat flux is observed, coinciding with a rise in temperature in the intermediate zone of the wall, even reaching negative values. This indicates heat flow directed into the wall from the exterior environment.

Under these conditions, it can be concluded that there is a daily period during which the exterior environment contributes to heating the wall, at times more significantly than the interior side.

On Saturday and Sunday, when the building is not in use and the heating system is not operating, the heat flow from the exterior into the wall is sustained, contributing more to heating than the interior environment.

Fig. 6 shows the difference in ambient temperatures inside and outside during the monitoring period. As observed, the air temperature values recorded in Table 1 show significant fluctuation over the study period, allowing for a more accurate assessment of thermal behaviour. This fluctuation is similar to that observed in the surface temperature measurements recorded by the plates (Fig. 7). The following can be noted from the analysis of ambient temperatures:

Indoor air temperature begins to rise from 08:00 and starts to drop again after 16:45, coinciding with the operating periods of the heating system on working days. The interior wall surface temperature shows similar behaviour, though with fewer fluctuations.

On non-working days, the temperature continuously drops (quasi-linear pattern) with a slope similar to that of working days. Outdoor temperature variation does not significantly influence this.

The temperature at 08:00 increases progressively throughout the week, as do the daily maximum temperatures, before beginning to fall again over the weekend when the building is unoccupied and the heating system is not operating.

Temperatures at 16:45 appear to be consistent across working days, dropping over the weekend.

Outdoor ambient and surface temperatures are always positive.

On working days, temperature increases occur around 08:00, similar to the indoor temperature trend.

On non-working days, no correlation is observed between variations in indoor and outdoor temperatures, and the values even tend to converge.

From the environmental temperature graph—particularly the weekend data (see Fig. 6)—it can be confirmed that increases in outdoor temperature do not influence the indoor temperature.

From the obtained information and as shown in the graphs (Figs. 8 and 9), the temperature measurements clearly indicate that, at all times, the interior space temperature is higher than that of the exterior. Consequently, the theoretical heat flow according to Fourier's Law must always be unidirectional, from the interior environment to the exterior, being directly proportional to the temperature difference between both surfaces and depending on the thermal transmittance coefficient of the wall (0.8 W/mK for solid brick, according to similar in situ studies previously conducted under controlled laboratory conditions [64–67]) and the thickness of the wall. This implies that, throughout the analysed week, the wall acts as a dissipative element, continuously losing heat to the outside. The comparison with Fourier only reflects the discrepancy in his statement regarding permanent unidirectional flow, which is precisely what the results obtained in this research contradict.

Subsequently, based on the "in situ" values recorded during the selected period and according to Fourier's Law, the theoretical heat flow was determined using the temperature difference between the inner and outer surfaces of the wall and the thickness of the wall, along with the thermal conductivity coefficient of the brick, knowing that the theoretical heat flow through a wall is directly proportional to the temperature difference between its two faces, and can only be directed in one way: from the warmer face to the cooler one.

However, based on the established sign convention, Fig. 8 confirms the existence of a variable negative heat flow measured by the exterior plate during certain time periods. The collected data, graphically represented, allow for a precise analysis of the heat flow magnitude and specific daily periods over a standard week in which the wall absorbs heat from both environments — interior and exterior — contrary to what would be expected during the winter period.

Specifically, a deviation from the classical Fourier's Law was observed, with a daily period during which the heat flow is negative.

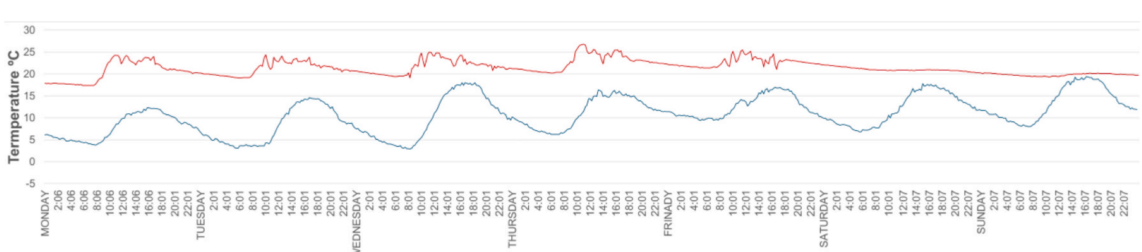

Fig. 6. Representation of ambient temperatures measured by the outdoor and indoor sensors during a winter week (11–17/03/24) TeS= Outside ambient temperature measured by the outdoor probe (°C) TaiS = Inside ambient temperature measured by the indoor probe (°C).

Table 1
Ambient temperatures (°C) and time schedule.

	8:00 h (°C)		Maximum Tª/hour (°C)		16:45 h (°C)		Minimum Tª /hour (°C)	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Monday	18.1	3.9	24.3 / 10:50 h	12.03 / 15:51 h	24	12.2	19.1 / 5:46 h	3.1 / 5:31 h
Tuesday	19.9	3.6	24.4 / 10:01 h	14.6 / 16:45 h	23.8	14.6	19.4 / 5:46 h	2.9 / 8:16 h
Wednesday	20.3	3.0	25.0 / 11:16 h	18.0 / 16.16 h	23.4	18.0	20.2 / 6:00 h	6.2 6:01 h
Thursday	21.1	6.6	26.8 / 11.01 h	16.16 / 15:07 h	25.3	15.6	21.4 / 5:00 h	9.4 / 5:00 h
Friday	22.1	9.9	25.5 7 11:31 h	16.9 / 17:16 h	23.2	16.9		6.8 / 5:31 h
Saturday	21.00	7.7		17.6 / 15:52 h	21.0	17.2		8.0 / 7:22 h
Sunday	19.4	9.2		19.4 / 16:22 h	20.1		18.9 / 6:22 h	8.1 / 6:52 h

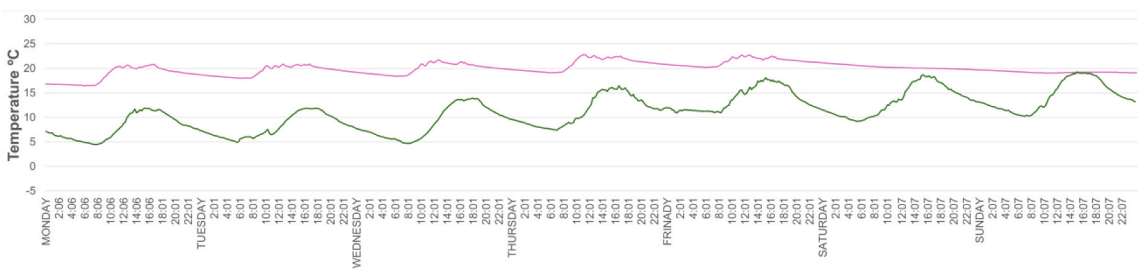

Fig. 7. Representation of surface temperatures measured by the exterior and interior plates during a winter week (11–17/03/24) TseP= Outside surface temperature of the wall measured by the outside plate (°C) TsiP = Inside surface temperature of the wall measured by the inside plate (°C).

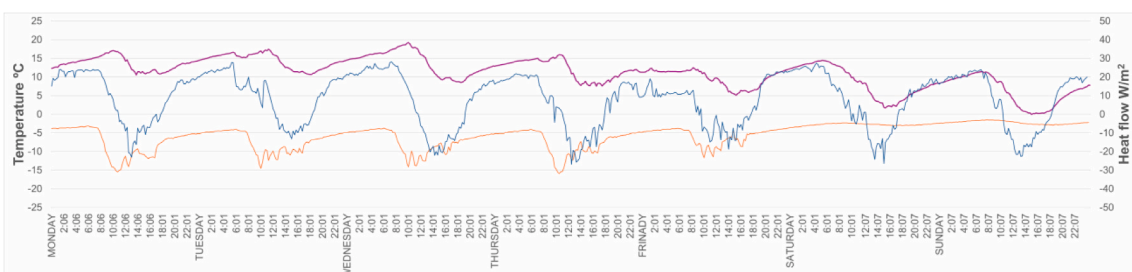

Fig. 8. Representation of the heat flows measured by the plates and according to Fourier's Law during a winter week (11–17/03/24) Theoretical heat flow according to Fourier's Law (W/m^2) FiP= Heat flux measured by the plate placed on the interior face of the wall (W/m^2) FeP= Heat flux measured by the plate placed on the exterior face of the wall (W/m^2).

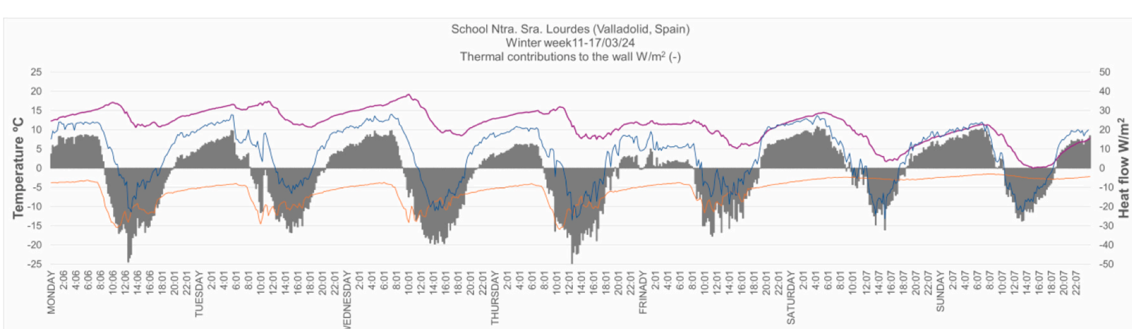

Fig. 9. Representation of the heat flows measured by the plates and according to Fourier's Law during a winter week (11–17/03/24) Theoretical heat flow according to Fourier's Law (W/m^2) FiP= Heat flux measured by the plate placed on the interior face of the wall (W/m^2) FeP= Heat flux measured by the plate placed on the exterior face of the wall (W/m^2) FiP + FeP= Sum of the heat flows measured by both plates (W/m^2).

During this interval, an increase in the wall temperature is recorded, caused by heat flow coming both from the interior space, due to the thermal input from the heating system, and from the exterior environment.

By summing the negative heat flows originating from both the interior and exterior environments, the total heat flow affecting the wall is determined. This combined flow demonstrates the simultaneous influence of thermal contributions generated inside the building by the heating system and outside. In Fig. 9, this information is shaded in grey, providing a clear visualization of the total contribution of both heat flows to the thermal behaviour of the wall.

We studied the correlation between the heat flows measured by the plates and the interior ambient temperature. Following the sign convention established in Fig. 4, the observations from Figs. 10 and 11 are as follows:

– When the exterior temperature begins to rise, the wall warms up and the heat flow measured by the exterior plate starts to decrease, reaching negative values.

Heat flow periodically moves into the wall from the exterior environment, even though the interior temperature remains higher than the exterior temperature.

– As expected, the heat flow measured by the interior plate always shows negative values.

Heat flow is always directed into the wall from the interior environment.
The heat flow into the interior of the wall increases as the indoor temperature rises due to the heating system being on from Monday to Friday. During the weekends, this flow decreases proportionally with the drop in indoor temperature.

– As shown in Fig. 10, when the temperature difference is greater, the flow difference begins to be positive, and consequently, the wall ceases to receive heat flow contributions.

Table 2 shows the total daily time during which the summation heat flux is negative for the analysed period.

The analysis of the total daily duration of NEGATIVE HEAT FLOW recorded over a full week reveals a general trend towards longer periods on weekdays compared to weekends. The average total daily time was estimated at more than 10 and a half hours (10 h and 39 min), suggesting a time window of significant interest during the evaluated period, representing over 40 % of the entire daily cycle (24 h).

On weekdays (Monday to Friday), the observed values were as follows: Monday (10 h 55 m), Tuesday (12 h), Wednesday (12 h), Thursday (12 h) and Friday (10 h 45 m). These data reflect consistency in prolonged periods, with a peak from Tuesday to Thursday (12 h), and a relative minimum on Friday (10 h 45 m). In contrast, weekends show a marked reduction in total time, registering 8 h 36 m on Saturday and 8 h 15 m on Sunday.

This difference between weekdays and weekends aligns with typical time organization patterns in academic and work contexts, where weekdays concentrate the majority of scheduled activities, and consequently, heating use is necessary during the winter day. The weekly distribution of time clearly demonstrates this structure, with the highest values from Monday to Thursday, followed by a gradual decrease towards the weekend, during which work pace slows (Friday) and halts (Saturday and Sunday). Minor fluctuations within the day are also evident, which is consistent with a flexible or adaptable work regime, potentially influenced by external factors or specific requirements of the study and work environment.

These findings allow consideration of the potential implications for time management strategies to optimize occupant performance and well-being, as well as the need for planning that allows recovery during weekends, where an average reduction of 2 h 30 m compared to weekdays is observed.

Since the wall does not behave identically throughout the week, the time period (specified in the table) during which the sum of the heat flows measured by both plates is negative has been analysed for each day, relating this to the difference in surface temperatures of the wall. As seen in the graphs, very high regressions were obtained onwards every day of the week, which remain the following day, when the heat flow turns positive. With a view to the possible installation of devices that enable the effective use of energy, the longest possible daily periods have been sought, with sufficiently representative data and the highest possible determination coefficients.

The obtained graphs and equations allow us to determine when the wall is capable of supplying heat based on the difference in its surface temperatures, indicating the potential for its utilization.

The high value of the regression coefficient confirms the existence of a direct relationship between the exterior-interior temperature difference and the negative heat flow, indicating significant heat transfer from the interior to the exterior of the system.

Fig. 12 shows the regression graphs for a full week (Monday to Sunday).

The detailed analysis of the daily regressions provides key insights into the thermal behaviour of the wall, reflecting a strong correlation with determination coefficients (R) that vary throughout the week, indicating differentiated patterns and specific dynamics in heat transfer between the interior and exterior environments. P-values ≤ 0.05 indicate that the data are sufficiently significant. The results obtained for each day are as follows:

Monday: R = 0.968. This high value reflects a very strong correlation, suggesting notable stability in heat flow on this day. The relationship between the variables is practically linear, highlighting consistent thermal behaviour.
Tuesday: R = 0.9199. Although the correlation remains significant, the decrease in the coefficient suggests greater variability in thermal behaviour, possibly influenced by climatic fluctuations or changes in internal heat input.
Wednesday: R = 0,9011 and p-value = 0,044. Although these values are high and sufficiently representatives, they are the lowest fit of the week, indicating greater dispersion in the data compared to other days. This behaviour could be linked to specific disturbances in

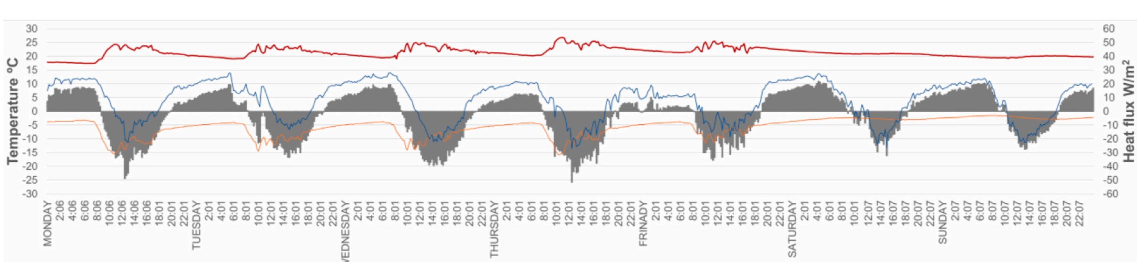

Fig. 10. Inside ambient temperature and heat flux during a winter week (11–17/03/24) TaiS = Indoor ambient temperature measured by the probe (°C) FiP= Heat flux measured by the plate placed on the interior face of the wall (W/m^2) FeP= Heat flux measured by the plate placed on the exterior face of the wall (W/m^2) FiP + FeP= Sum of the heat flows measured by both plates (W/m^2).

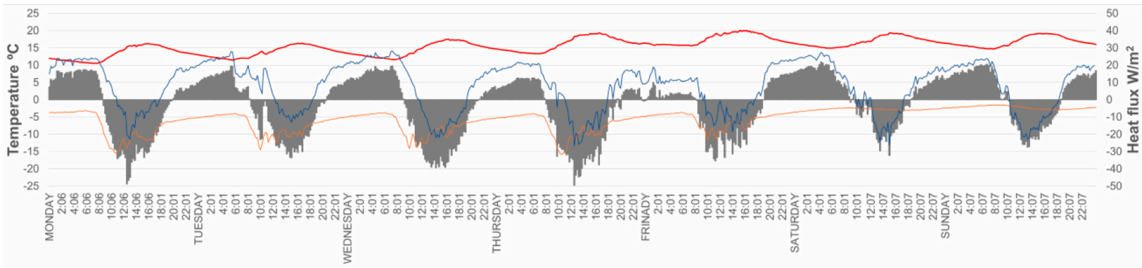

Fig. 11. Intermediate wall temperature and heat flux during a winter week (11–17/03/24) TªMm = Intermediate temperature of the wall (°C) FiP= Heat flux measured by plate placed on the interior face of the wall (W/m^2) FeP= Heat flux measured by plate placed on the exterior face of the wall (W/m^2) FiP + FeP= Sum of the heat flows measured by both plates (W/m^2).

Table 2
Time periods during which the summation heat flux is negative.

	Start	End	Total time
Monday	8:51 h	19:46 h	10 h 55 *m*
Tuesday	8:31 h	20:31 h	12 h
Wednesday	9:01 h	21:01 h	12 h
Thursday	8:01 h	20:01 h	12 h
Friday	8:16 h	19:01 h	10 h 45 *m*
Saturday	9:46 h	18:22 h	8:36 *m*
Sunday	10:22 h	18:37 h	8:15 *m*

internal or external conditions, warranting further analysis to understand these fluctuations.

Thursday: R = 0,9124. The solid fit on this day indicates a tendency towards stability in heat transfer, reaffirming the pattern observed on days with higher correlation.

Friday: R = 0.9649. This coefficient again reflects a strong correlation, similar to Monday, consolidating the consistency of heat flow and emphasizing the combined influence of internal and external factors.

Saturday: R = 0.9556. The strong correlation recorded confirms a trend of stable thermal behaviour, which could be exploited in energy management scenarios.

Sunday: R = 0.9827. This is the highest value of the week, representing an exceptionally strong relationship between the variables. The thermal stability on this day could be key for sustained energy utilization strategies.

A detailed analysis of the indoor environment has already shown the evident influence of temperature increase on the heat flow in the direction of the wall (Fig. 10), revealing that this relationship differs during the weekdays when the heating is switched on (Fig. 12). Indoor temperature data indicate that it begins to rise at 8:00 a.m. and starts to fall at 6:00p.m. every weekday, with an average temperature during this period of 23.1 °C, which is 2 °C above the comfort temperature of 21 °C, recommended temperature for heating calculations according to RITE (IT 1.1.4.1.2) [74], EN 16798–1:2019 (Category I, high quality) [75] and ASHRAE 55–2020 (20–24 °C, with 21 °C as a specific reference for homes, offices and schools) [76].

During the test, the exterior temperature ranged from a minimum of 2.9 °C to a maximum of 19.4 °C. According to the 30-year historical data provided by the State Meteorological Agency (AEMET) [77] in Valladolid, Spain, the average minimum and maximum temperatures in March are 1.9 °C and 14.8 °C, respectively. The measured daily mean temperature difference was 10.1 °C, lower than the 30-year historical average of 12.9 °C. The mean temperature during the test was 10.7 °C, compared to the historical mean of 8.3 °C reported by AEMET. This indicates, as expected, that progressive increases in exterior temperatures will also raise the wall temperature during winter months. The novelty of this study lies in demonstrating that, even during a midwinter month with moderate temperatures and thermal swings, it is possible to exploit the heat stored in the walls to reduce the energy required to heat interior spaces.

Furthermore, considering that March corresponds to the final period of the heating season (heating period in Valladolid: October–May, total 32 weeks), it is expected that this gain will persist at least during months with similar historical average temperatures (March average in Valladolid: 8.3 °C according to AEMET 1991–2022), i.e., March, April, May, and October. This suggests that similar behaviour can be expected over 16–17 weeks, and although variations may occur during the colder winter months, it is likely to occur similar behavior too throughout the heating season, at least to the same extent, since there will be enough a temperature difference indoor-outdoor.

Analysing the variation in heat flow through the wall when the indoor temperature decreases by 2 °C, considering the wall's different behaviour throughout the weekdays (Fig. 13), an average energy saving of 3.94 W/m2 is obtained from Monday to Friday (see Table 3). To facilitate practical understanding, this value can be extrapolated to a value 3.31 kWh/m^2 per week which translates to an estimated annual saving of 105.9 kWh/m^2. For this building, with around 4,800 m^2 of façade surface, this equates to approximately 508,416 kWh per year heating savings at least. Compared, for example, with the average consumption of a home per year heating in mainland Spain (Csa climate), of 6,728.5 kWh according to the Ministry of Transport, Mobility, and Urban Agenda (2020) [78], this saving would be equivalent to the annual consumption of 75.6 homes, clearly demonstrating the practical relevance of the optimization of thermal flows identified through the HFM method.

4. Conclusions

The analysis of thermal performance in traditional brick masonry buildings presents a significant scientific challenge due to the high regional variability in materials, construction techniques, and wall typologies. This heterogeneity limits the applicability of generalized models, making localized approaches necessary. In this context, the present research provides empirical evidence through a representative case study in Spain, Csa according to the Köppen climate classification, whose applicability may extend to other world regions with similar clime and with similar constructions, given the international dissemination of vernacular solutions based on thick brick masonry walls.

Similar results could be expected in regions with comparable temperature conditions and thermal gradients. More generally, this scenario corresponds to Csa climate zones according to the Köppen climate classification, covering most of the Iberian, large areas of the Mediterranean coast of Europe (France, Italy, Croatia, Montenegro, Albania, Greece, Turkey, Syria, Lebanon, Israel, Morocco, Algeria, and Tunisia), as well as some regions in inland California and southwestern Australia.

The thermal characterization of these materials is complex due to their heterogeneous composition, variability in density, presence of cracks, and limited representation in current experimental databases. These conditions may lead to discrepancies in thermal flux

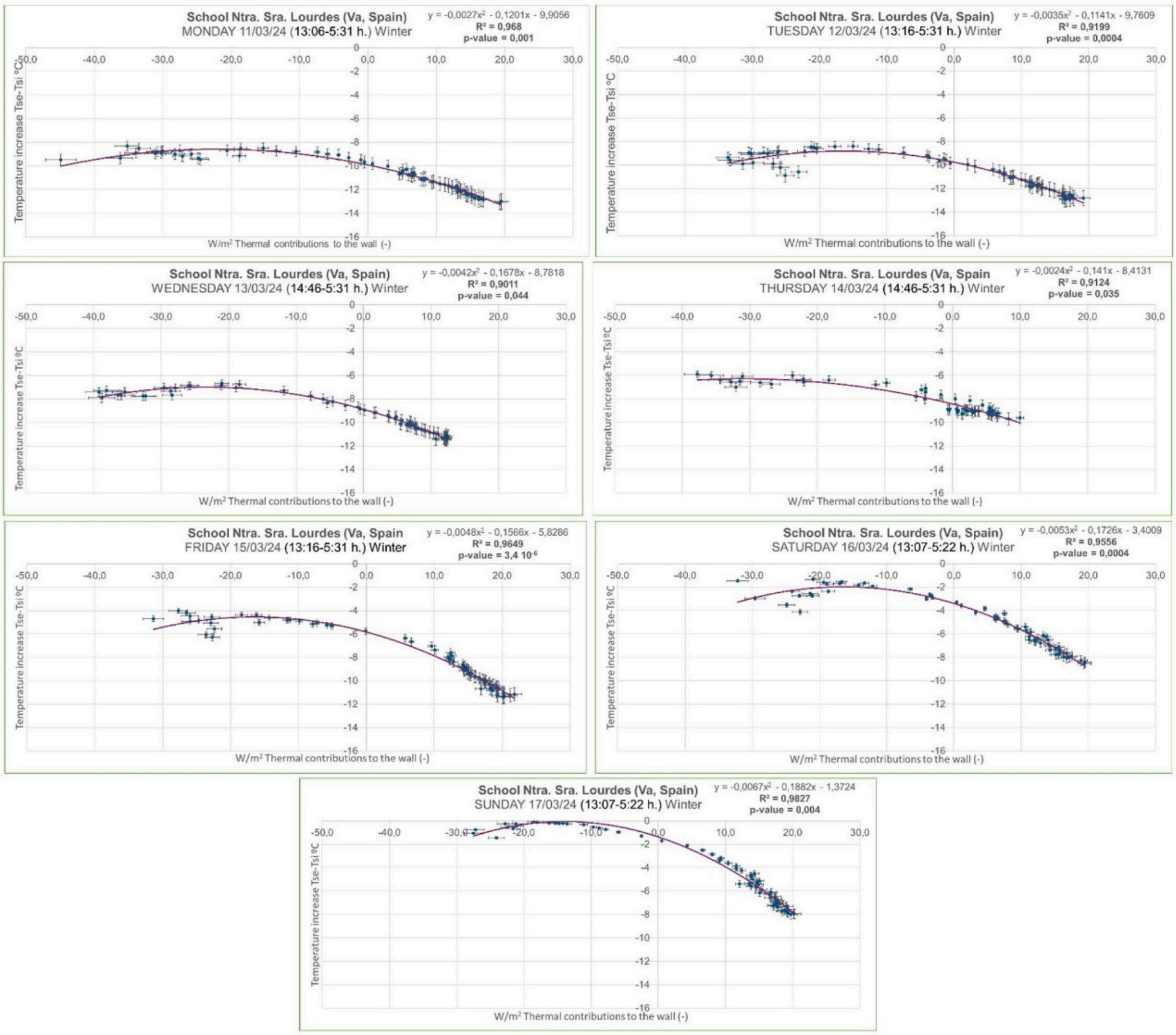

Fig. 12. Weekly regression plots (Monday to Sunday).

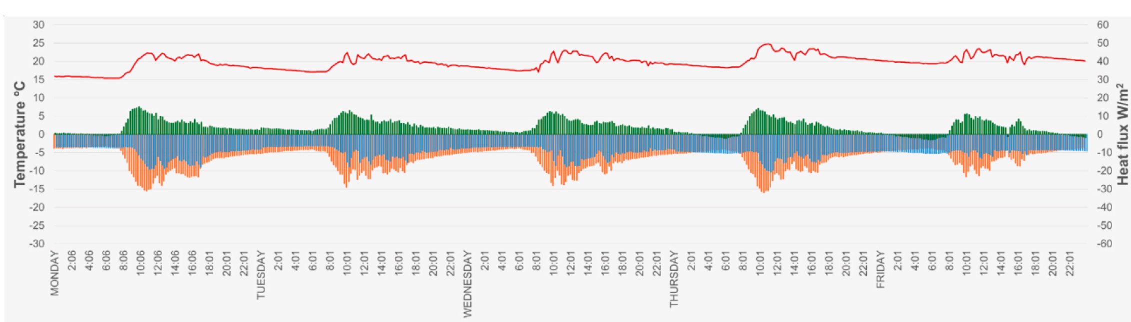

Fig. 13. Heat flux savings towards the exterior at the average comfort temperature (11–15/03/24) $TaiS_2$ = Temperature when the indoor ambient temperature measured by the probe decreases by 2 °C (°C) FiP= Heat flux measured by the plate placed on the interior face of the wall (W/m^2) Fi_2= Heat flux at the average comfort temperature 21 °C (W/m^2) FiP + Fi_2= Heat flux savings at the average comfort temperature (W/m^2).

measurements at different points within the wall. Through an in-situ measurement strategy, this research has expanded knowledge of the actual thermal behaviour of such construction systems, emphasizing the importance of accurately quantifying thermal transmittance in solid masonry walls to implement effective energy efficiency strategies, as highlighted by [26].

The comparative study with results derived from the theoretical Fourier model allowed a more comprehensive description of heat flows on both the interior and exterior surfaces of the wall, thereby helping to overcome a common limitation in measurement campaigns, which typically restrict analysis to the interior unidirectional flow [38,40].

The results also demonstrate that both incoming and outgoing heat flows can be characterized precisely, and that heat storage within the wall can be effectively estimated. This suggests that the applied methodology is valid across different seasons and under varying environmental conditions, even when the direction of heat flow changes during

Table 3
Average indoor temperature during heating hours (8:00 h-18:00 h).

	Plate Tª (°C)	Heat flux measured the plateFiP (W/m²)	Heat flux at the average temperature 21 °C Fi_2 (W/m²)	FiP + Fi_2 Heat flux saving (W/m²)
Monday	22.5	−14.8	−10.5	4.3
Tuesday	22.5	−14.4	−9.3	5.1
Wednesday	23	−14.3	−9.7	4.6
Thursday	24.3	−14.8	−11.2	3.6
Friday	23.4	−11.5	−9.4	2.1
AVERAGE	23.1	−13.96	−10.2	3.9

the monitoring period [79]. Moreover, the inclusion of the influence of direct solar radiation further strengthens the applicability of this approach in real-world settings [79].

Quantitatively, it is shown that reducing the interior temperature by 2 °C without compromising thermal comfort (maintaining it at 21 °C) yields an average energy saving of 3.94 W/m^2 from Monday to Friday. Extrapolating this value over the entire winter period, October to May in Valladolid (estimated at 32 weeks), results in an accumulated saving at least of 630.4 W/m^2, representing an estimated annual saving of 105.9 kWh/m^2, which in the study building means approximately 508,416 kWh per year, reinforcing the importance of efficient thermal control strategies in buildings.

From an operational standpoint, the high coefficients of determination observed on certain days (Monday, Friday, and Sunday) reflect greater thermal stability and consistency in heat transfer, suggesting these periods are optimal for harnessing the wall's thermal capacity. Conversely, the lower values recorded on Tuesday and Wednesday, although these values are high and sufficiently representatives, indicate greater sensitivity to external and internal variations, possibly associated with specific uses of the analysed administrative building, opening new lines of research into the influence of occupancy factors.

The detailed regression analysis allows not only the identification of thermal behaviour patterns of the wall but also their integration into predictive energy efficiency strategies. This anticipatory capability is particularly valuable in contexts of changing climatic conditions, enabling a tailored and dynamic thermal planning.

The findings reflect the wall's thermal behaviour under low outdoor temperatures and reduced solar gains, without capturing phenomena typical of summer conditions, such as higher solar radiation, increased outdoor temperatures, and the risk of indoor overheating. Therefore, while the winter results provide valuable insights into the wall's dynamic thermal behaviour and energy performance, their generalisation throughout the year should be made with caution, highlighting the need for complementary studies under summer conditions.

The studied wall—and, by extension, walls with similar characteristics—can act as a thermal moderator, releasing stored heat at strategic moments and actively contributing to the regulation of indoor temperature. This behaviour validates the initial objective of the study, highlighting the relevance of a more precise thermal management approach that reduces energy losses without compromising indoor comfort, and emphasizing the value of traditional construction solutions in the design of energy-efficient buildings. Furthermore, it underlines the usefulness of the methods employed to address the complex thermal behaviour of heritage elements, whose assessment remains an ongoing challenge in many intervention contexts involving the built heritage.

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CRediT authorship contribution statement

Gemma Ramón-Cueto: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.Paz Sáez-Pérez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.Soledad Camino-Olea:** Funding acquisition, Investigation, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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