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Impact of human activity on the thermal behaviour of an unheated church

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ABSTRACT

A fifteenth-century church in Spain has been studied to determine the temperature changes that occur inside due to the activity and use of the building. Daily thermal amplitude has been employed as a detection system to measure occupation and use. Eleven sensors have been sited around the building, recording temperature data every 10 min over 655 days – including the lockdown period.

An exhaustive analysis of temperature data revealed that the high inertia of the church's thermal envelope allows for an almost constant temperature during daily cycles (with variations of less than 2.2 °C), independent of weather conditions. In addition, the stratifications occurring are not high and depend on the operation of the building. A change of staff during the period analysed has been detected using this method. The sensors closest to the openings were more affected by the temperature variation, according to the external parameters. It has been possible to see the correlation of daily mean indoor and outdoor temperatures, but we have found that daily outdoor and indoor thermal amplitude were not correlated. Analysis of the temperatures measured suggests that it is possible to detect changes in the normal use of the building.

1. Introduction

Churches are unique buildings, with a special heritage value due to decorations such as frescoes. Many of them continue to function as places of worship, and they often have the presence of tourists as well, which implies a significant increase in the number of people who come to visit them. The modernisation of church buildings to achieve thermal comfort conditions in the cold season increases the presence of tourists and the disturbance of the indoor climate [1]. According to Turcanu et al. [1], churches have two characteristics: first, they are used intermittently; and, second, the churchgoers keep their street clothes on, which highly influences the thermal comfort requirements [2].

Another aspect to consider is the age of the church. For example, baroque churches present a high thermal mass overall, resulting in a more stable interior microclimate [3], while temperature fluctuations are greater in more recent architectural styles [4]. Beck and

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Nomenclature

Subscripts

T	temperature (°C)
ΔT	thermal amplitude (°C)
av	average
d	daily
in	indoor
m	mean
out	outdoor
f	floor
c	ceiling
s	sensor

Koller [3] found that buildings of worship with a high thermal mass did not show rapid variations of the indoor microclimate. Moreover, setting the floor temperature is usually a compromise between three factors: the outdoor climate, the comfort of churchgoers and the conservation of heritage with heating system [2] or without heating or cooling system [5].

On the other hand, one of the problems in naturally ventilated churches in a cold climate was the very high relative humidity throughout the year, which created a greater risk of mould and algae growth [6,7]. A study of several small historic churches in Spain concluded that natural ventilation in spring, the presence of people and the use of an ageing heating system in the winter resulted in fluctuations in the indoor environments that mainly affect the stability of temperature and relative humidity (RH) [8,9]. Several works have studied the optimal heating system for churches, ensuring both heritage conservation and high thermal comfort to churchgoers [1–3,6–8,10–12]. In this type of historic building, thermal comfort is not compatible with the conservation of the building or with current energy efficiency policies [13,14].

Following growing interest in the detection of changes in thermal performance and their use in a wide range of buildings [15–17] also considering warm climates [18,19], this study aims to describe how to analyse temperature changes that occur inside a historic building considering architectural characteristics and relate them to the building's use, activity or external climate changes. This work could help professionals and researchers to assess fluctuations due to building use or occupancy in order to improve the thermal behaviour.

2. Materials and methods

2.1. Case study and data collection

Temperature sensors have been placed in different areas of the church to analyse its thermal behaviour. The analysis of the data collected during a period from September 28, 2018 to July 23, 2020 (a total of 655 days) has been used in the present work. The temperature data was collected from the Real Parroquia de los Santos Juanes de Valencia, one of the most important historic buildings in the city. It has a built area of approximately 832 m^2 and a volume of 14,500 m^3, with internal heights from 11 to 20 m for the side aisles and the central one. The glazing area is approximately 2.5% of the total vertical envelope. The space is limited externally by thick masonry walls and wooden windows with single panes of glass located at the top. Therefore, the original external walls are composed of load-bearing walls built with a double layer of ashlar on both external sides and a layer of mortar between them, with a total thickness of 62 cm. Indoors, the church does not have a fixed heating or air conditioning system. Instead, it has several temporary gas heaters turned on in winter and a set of simple low-power fans for the summer. In addition, the total volume is not completely sealed off, because the doors remain open due to the historical interest of the building, with many visits from tourists and churchgoers every day, and a maximum capacity of 200 people.

Low-cost monitoring equipment has been used to measure the internal parameters. This equipment is made up of a mini-PC control and storage community, 12 Si7021A20 wireless digital sensors from Silicon Labs™, which can be used to measure temperatures ranging from −40 to 125 °C, with a resolution of 0.02 °C and an accuracy of ±0.4 °C, recording average values every 10 min. The sensors have been individually calibrated for temperature; the calibration data is stored in the non-volatile memory of the device. This ensures the sensors are completely interchangeable, without the need for recalibration or changes to the software system [20]. During the period where the study took place, weather data was obtained from a weather station in Valencia, near the building analysed. Since the church has a large volume, the sensors were placed inside the building at two different levels and also in the main nave. Eleven temperature sensors have been placed inside the church: six of them at the level closest to the floor (F), which is at 3.2 m above ground level, and five at the height of the cornice before the baroque vault, which is 13.15 m above ground level, close to the ceiling (C). Sensors have been named by location and orientation. The orientation was used as the second letter, the nomenclature being N for north, S for south, W for west and NE for northeast. In addition, they have also been grouped according to the floorplan location and named with a number, covering the main access door (Zone 1), the central part (Zone 2) and the area near the altar (Zone 3), as can be seen in Fig. 1. Therefore, each sensor code assigned in Table 1 include: situation, orientation and zone inside the church.

2.2. Data analysis

To obtain a representative value for the indoor temperature, a selection of measurements have been made using daily thermal amplitude for each sensor placed inside the church. After this screening of data, the indoor average temperature was obtained on a 10-min basis, along with the daily indoor thermal amplitude. Once indoor data was obtained, a comparison between indoor and outdoor data was done. Indoor thermal amplitude has also been calculated to analyse changes in the use of the building. These changes have been confirmed using thermal variations on floor sensors in the morning (from 8 to 11 a.m.) and by measuring indoor average temperature at night (from 20 to 23 h).

The first step was to obtain a representative value for the indoor environment, the indoor average temperature every 10 min (T_{avin}) has been used, depending on the number of sensors validated (n) and the temperature for each sensor (T_s). Second step was to detect changes, to do it, daily values for the sensors have been used to calculate the daily thermal amplitude for indoors using the average readings for the sensors (T_{avin}) and the outdoor weather data (T_{out}). And last step explored has been daily mean temperature (T_{md}) from 0:00 to 24:00 h, for indoor average sensors (T_{avin}) and for outdoors (T_{out}) as well.

Boxplots display batches of data obtained. Five values from a set of data are conventionally used: the extremes, the upper and lower hinges (quartiles), and the median [21].

3. Results and discussion

The following procedure has been used [22] in an attempt to systematically capture different levels. The levels requiring

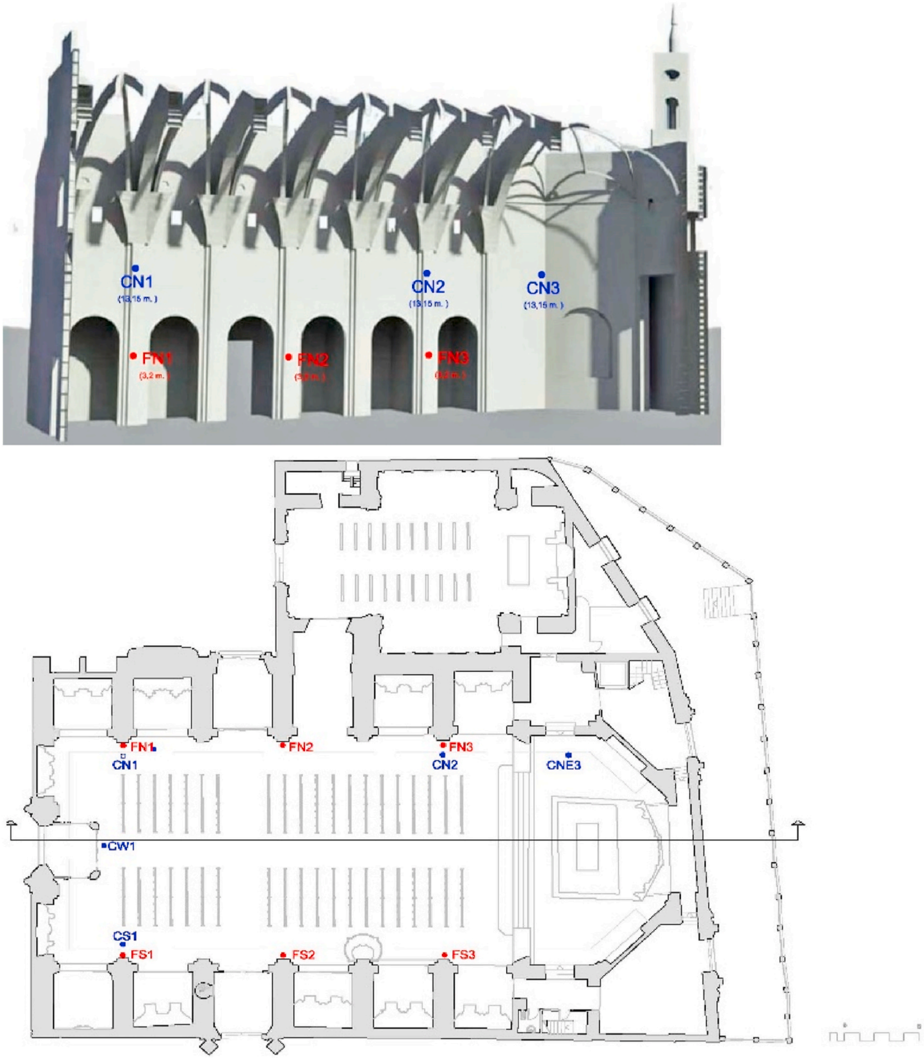

Fig. 1. Plan view and cross-section showing the location of the sensors. Sensors in red at 3.2 m and sensors in blue at 13.15 m from the floor level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Summary of missing and outlier data for the whole period.

Sensor	Orientation	Days with missing data	Days with outliers' range
CN1	North	21	0
CS1	South	15	0
CW1	West	14	175
CN3	North	23	1
CNE3	North	181	0
FN1	North	50	0
FS1	South	15	0
FN2	North	19	34
FS2	South	21	0
FN3	North	4	43
FS3	South	60	0

consideration were the collection of raw data, the measurements required and the control volumes, as well as the object with which the measurements are associated, and understanding the signal at an appropriate level of detail, i.e. how the measurement has been adapted and what features will be looked for in the data.

In this case, the raw data came from the eleven sensors in different positions, taken every 10 min, and the control volume employed was the whole building. The granularity of the signal used was the daily thermal variation and the statistical test was a boxplot test.

3.1. Selection of the most representative sensors

The daily thermal amplitude (ΔT_{ds}) for each sensor has been used to determine which sensors have been disturbed in the data collection. It is noticeable that almost all the results have the same shape and variation within a band of 2 °C, which allows us to decide which sensors are giving the correct data. In Table 1 the numbers of days with missing data or outliers for the daily thermal amplitude (ΔT_{ds}) are summarised. This allows us to decide which sensors can be removed in the period when solar radiation causes disturbances or when there is missing data. There are 376 days without missing data and, for the rest of the days, at least one sensor is missing.

3.2. Average temperature (T_{avin})

After the selection of data considered in section 3.1, the average temperature (T_{avin}) was calculated on a 10-min basis using the average of eleven sensors (five for the floor and six for the ceiling). Three different mean lines were generated to analyse the data selected: the mean for the upper area (ceiling), the mean for the lower area (floor) and the mean of all of them.

3.3. Daily thermal amplitude (ΔT_{din})

Once we have obtained the average with all the available data (T_{avin}), the daily thermal amplitude (ΔT_{din}) was calculated and the variations were obtained with a boxplot (section 2.2). The extreme of the lower whisker is 0.0636 °C, the lower hinge is 0.30 °C, the median is 0.40 °C, the upper hinge is 0.62 °C, the extreme of the upper whisker is 1.10 °C and the maximum value is 2.2 °C.Indoor daily thermal amplitude and boxplot data are shown in Fig. 2. Therefore, it is possible to say that the daily thermal amplitude inside the

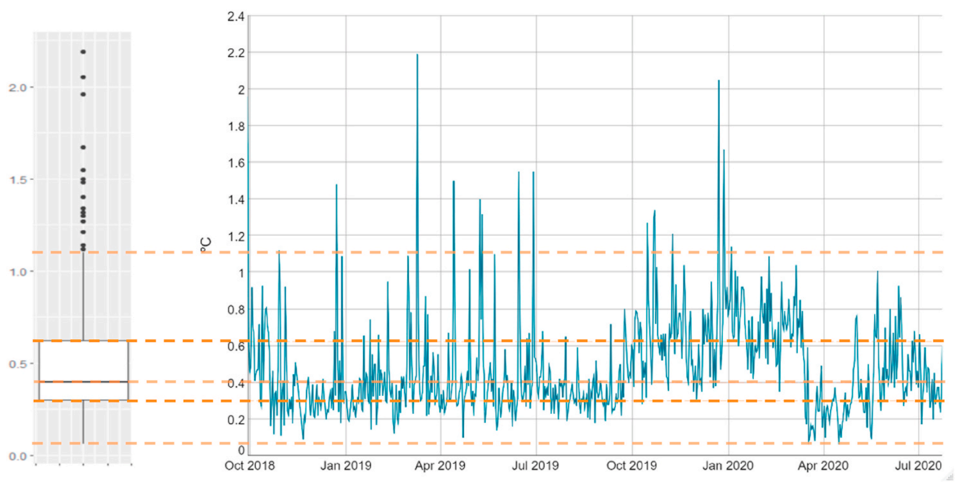

Fig. 2. Indoor daily thermal amplitude (ΔT_{din}) for the whole period, from September 18, 2018 to July 23, 2020.

church (ΔT_{din}) is small throughout this period.

Fig. 3 shows daily thermal amplitude outdoors (ΔT_{dout}). A boxplot test was also applied: the extreme of the lower whisker is 1.5 °C, the lower hinge is 5.4 °C, the median is 6.9 °C, the upper hinge is 9.0 °C, the extreme of the upper whisker is 14.4 °C and the maximum value is 19.8 °C. From this range it can be appreciated how daily thermal variations are significantly higher outside than inside, so we can say that the indoor temperatures are stable thanks to the construction typology.

3.4. Comparison between indoor and outdoor variations

In order to compare internal and external variations of temperature, Fig. 4 was developed for the whole period. To develop this graph, a weekly average value (6 data/hour x 24 hour/day x 7 days = 1008 data entries) was employed in order to reduce noise in the representation and to see any differences more easily. Outdoor temperature (T_{out}) is normally (97%) below the average temperature inside the church (T_{avin}), but this is not caused by insulation. Rather, the effect is caused by the solar gains the walls receive all through the year because there are no high buildings around that overshadow the church. Solar gains produce a heating effect in a warm Mediterranean climate. Thus, in buildings with high inertia and without a heating or cooling system, it is important to take into account the contribution of solar gains. We can see that stratification has been produced between temperature average for ceiling (T_{avc}) and floor (T_{avf}). From February to August, the temperature average for ceiling (T_{avc}) is above the floor temperature (T_{avf}). Therefore, when the outdoor temperature increases, it has a higher effect on the ceiling mean temperature. The reverse effect can be seen from September to January throughout this period.

Relation and dependence between the outdoor and indoor air temperature are shown in Fig. 5. It should be noted that there is a raised interdependence between daily mean indoor temperature (T_{dmin}) and daily mean outdoor temperature (T_{dmout}), using the daily average temperature, where the R^2 index is near 0.93. This is because there is no heating or cooling support, meaning the outdoor temperature (T_{out}) has a marked effect on the indoor temperature (T_{avin}).

This analysis has allowed us to count the monthly days according to the daily thermal amplitude for the whole period, so that using a boxplot we have been able to sort them by quartiles. Comparing the thermal amplitude data for each quartile, we can say that the outdoor daily thermal amplitude (ΔT_{dout}) is considerably higher than the indoor daily thermal amplitude (ΔT_{din}). In Table 2 we have summarised the percentage of days for each month presented with the daily thermal amplitude for the indoor (ΔT_{din}) and outdoor (ΔT_{dout}) for each quartile. We observe that, from November 2018 to September 2019, there is similar monthly thermal behaviour, with a higher number of days where the thermal amplitude belongs to the first and second quartile. Meanwhile, from October 2019 to February 2020 there is an increase in the number of days in the third and fourth quartile, which indicates that there is a change of habits in the use of the building. This is due to a change in the staff who control the opening and closing of the church. During the month of March 2020 there is also a drastic decrease in the amplitude of the first quartile, which is due to the fact that the lockdown period begins on March 14, 2020, forcing the closure of all worship spaces. During the month of April, there are only seven days (23% of the 30 days of the month) in which a greater thermal amplitude is detected in the second quartile, with 0% in the second and third quartiles, and the percentage with thermal amplitude in the first quartile is 77% (23 days of the 30 days of the month). From May 18, 2020, the activity recovers, to coincide with the ending of the lockdown, when churches were allowed to be one third occupied. Thus, in the months of May and June 2020, activity gradually recovered, although with a new response to the current situation in an effort to prevent COVID-19 contagion, in which the number of days with greater thermal amplitude increased.

Having analysed the days whose thermal amplitude average sensors (ΔT_{avin}) is higher than 1.1, which is above the extreme of the upper whisker, a total of ten days was obtained. In Fig. 6a and Fig. 6b we can see how the temperatures increased in the afternoon for days with thermal amplitude average sensors (ΔT_{avin}) is higher than 1.1. For this reason, we analysed thermal amplitude (ΔT_{avin})

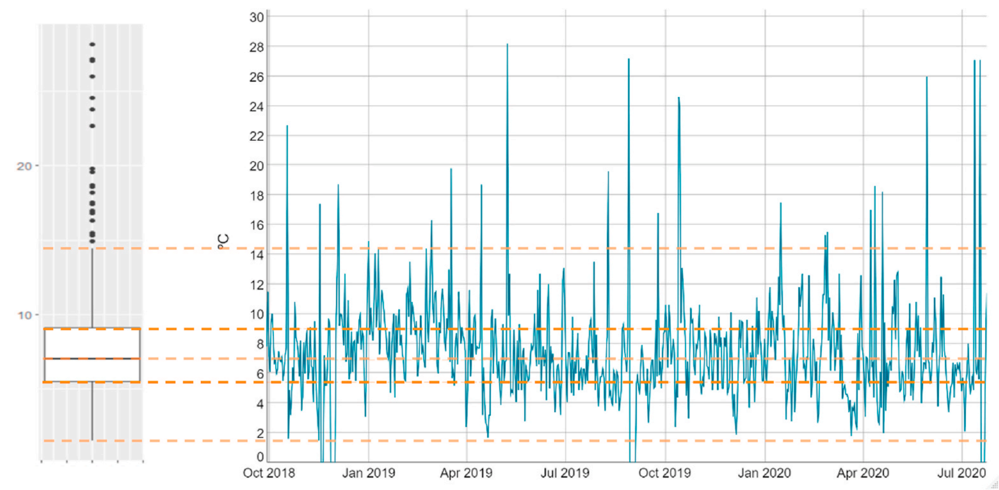

Fig. 3. Outdoor daily thermal amplitude (ΔT_{dout}) for the whole period, from September 18, 2018 to July 23, 2020.

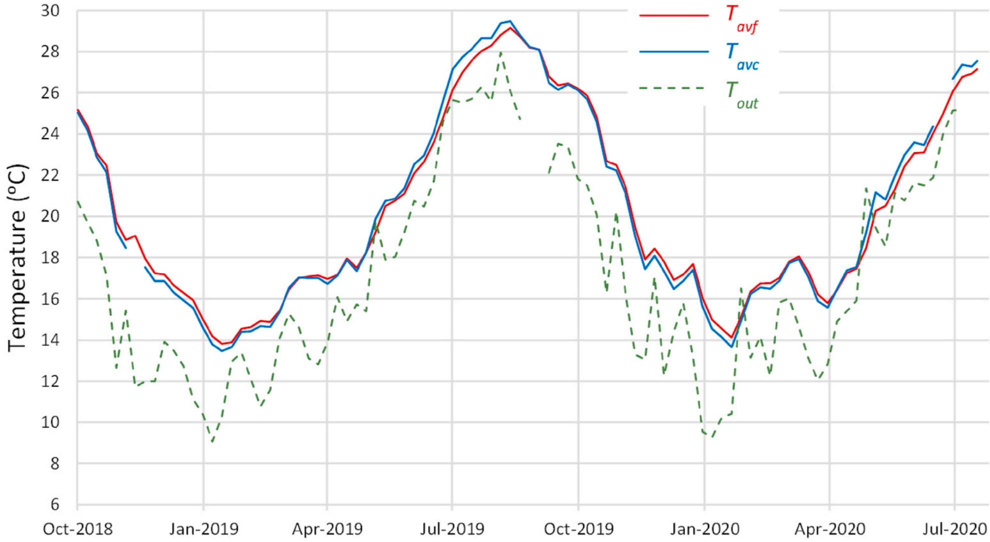

Fig. 4. Temperature average floor (T_{avf}), for ceiling (T_{avc}), and outdoor temperature (T_{out}) for the whole period, from September 18, 2018 to July 23, 2020.

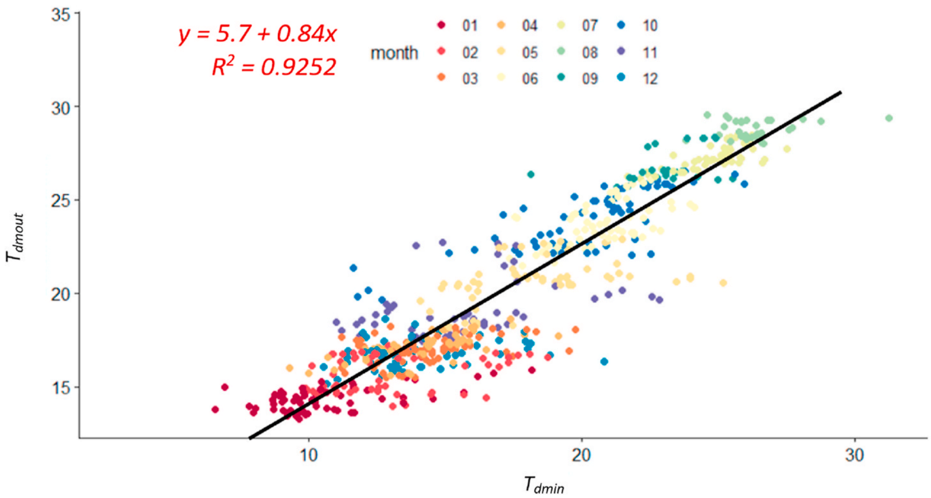

Fig. 5. Graphical comparison between daily mean indoor temperature (T_{dmin}) and daily mean outdoor temperature (T_{dmout}) for Valencia, from September 18, 2018 to July 23, 2020.

obtained from 21:00 to 23:00. With this data, we have analysed 26 days whose thermal amplitude between 21:00 and 23:00 was over the upper whisker of 0.3181.

A detailed analysis of the indoor temperature also shows that there is a repeated drop in the early morning throughout the whole period analysed. In the case of the morning drop, it does not make sense to distinguish them as they are very repetitive, although it is possible to see different schedules in which the drop in temperature appears in the morning. The downward peaks are very sloped, last between 90 and 120 min, and then rise and return to the normal trend. This drop is related to the opening of the doors in the morning, occurring when the outside temperature is lower than the inside temperature, as shown in Fig. 6c and d.

In view of this effect, produced repeatedly in the mornings throughout the period analysed, it was considered appropriate to analyse which sensors were more affected: on the floor (T_{avf}) or on the ceiling (T_{avc}) sensors. In Fig. 7 we can see that average temperature on the floor sensors (T_{avf}) are most affected by the downward movement. These morning dips tell us when activity starts inside the church. Thus, we can see that the floor temperatures (T_{avf}) are more affected by this change, so we relate these peaks to the renewal of air from outside when the church opens at 8 a.m. Thus, both the upward and downward peaks indicate activity inside at different times, although we know that there are no heating or cooling system.

As it is a space without a heating or cooling system, when there is a thermal variation in a reduced period of time – less than 1 h (the analysis interval when looking for drops) – it will be due to the difference in temperatures between the indoor and outdoor air, and

Table 2
Percentage of days for each month presented with the daily thermal amplitude for the indoor (ΔT_{din}) and outdoor (ΔT_{dout}) for each quartile.

Year	Month	Indoor				Outdoor			
		1st Q	2nd Q	3rd Q	4th Q	1st Q	2nd Q	3rd Q	4th Q
2018	October	23%	32%	13%	32%	19%	48%	19%	13%
2018	November	53%	40%	3%	3%	47%	27%	10%	17%
2018	December	35%	48%	6%	10%	6%	19%	32%	42%
2019	January	39%	45%	13%	3%	6%	19%	26%	48%
2019	February	25%	61%	7%	7%	0%	29%	18%	54%
2019	March	29%	39%	13%	19%	6%	19%	32%	42%
2019	April	27%	60%	0%	13%	27%	30%	20%	23%
2019	Mayo	42%	35%	10%	13%	29%	35%	19%	16%
2019	June	27%	47%	13%	13%	23%	37%	13%	27%
2019	July	19%	65%	13%	3%	26%	45%	16%	13%
2019	August	45%	48%	6%	0%	42%	35%	13%	10%
2019	September	33%	50%	10%	7%	47%	37%	10%	7%
2019	October	3%	19%	32%	45%	16%	26%	19%	39%
2019	November	0%	17%	27%	57%	30%	20%	40%	10%
2019	December	0%	23%	29%	48%	26%	39%	13%	23%
2020	January	0%	3%	23%	74%	23%	23%	19%	35%
2020	February	0%	3%	17%	79%	17%	28%	14%	41%
2020	March	42%	10%	13%	35%	48%	13%	23%	16%
2020	April	77%	23%	0%	0%	33%	40%	3%	23%
2020	Mayo	26%	42%	10%	23%	23%	42%	13%	23%
2020	June	3%	47%	20%	30%	30%	50%	7%	13%
2020	July	22%	61%	13%	4%	40%	47%	7%	7%

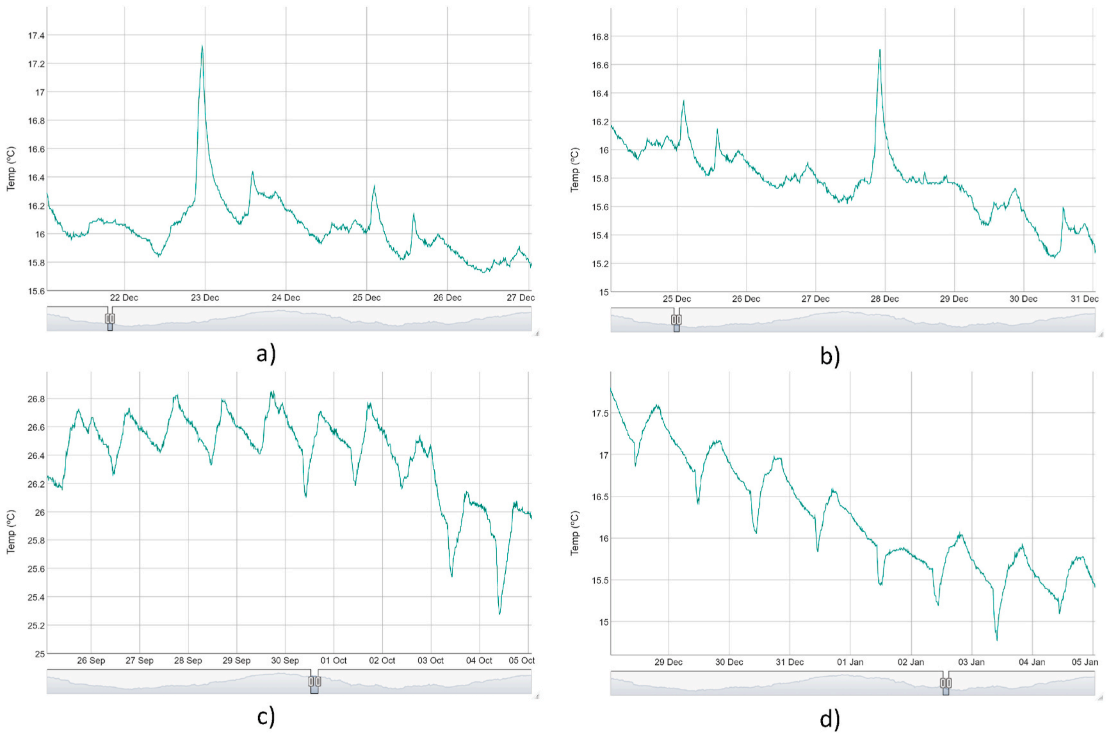

Fig. 6. Indoor average temperature (T_{avin}): a) from December 21, 2018 to December 27, 2018, b) from December 24, 2018 to December 31, 2018, c) from September 25, 2019 to October 6, 2019 and d) from December 29, 2019 to January 5, 2020.

therefore this difference is given by ventilation. Since the volume is very large and the church opening takes place when the outside temperature is lower than the inside temperature, both in summer and winter, the high temperature drop in the morning is related to ventilation. The total closure of the church during the lockdown has allowed us to analyse the differences in thermal amplitude with previous situations. To do this, we first analysed the conditions from March 14, 2020 to May 18, 2020. As we have already mentioned, the indoor average temperature on the floor (T_{avf}) are the ones that allow us to visualise the temperature drops when the church is

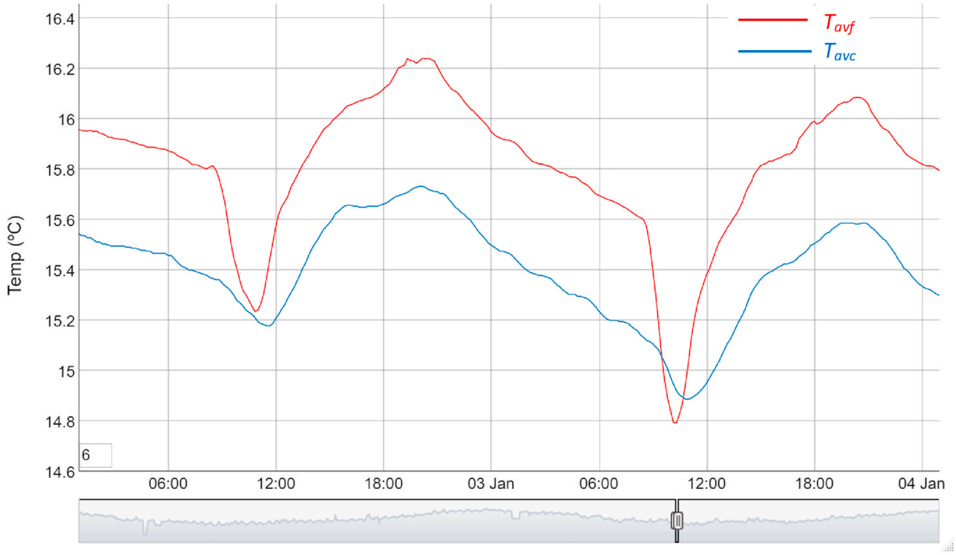

Fig. 7. Indoor average temperature on the floor (T_{avf}) and on the ceiling (T_{avc}) during January 3, 2019 and January 4, 2019.

opened, so the first thing we will see is the average value of the floor temperature sensors as shown in Fig. 8, which corresponds to the lockdown period. Here we can clearly see the difference between the average values collected before and after the lockdown, where the downward movement can be seen.

Having previously seen that the door opening in the morning is detected by the average floor temperature (T_{avf}), we have analysed the temperatures in the morning from 8 to 11 a.m. since this is the time interval when there is the greatest drop in opening, as the outdoor temperature (T_{out}) is lower than the indoor temperature (T_{avin}). Fig. 9 shows the values of the indoor temperature obtained with the indoor daily thermal amplitude (ΔT_{din}) and the minimum value of thermal amplitude on the floor sensors ($\min(\Delta T_{avf})$) from 8 to 11 a.m. during the whole period analysed. In this graph, we can easily see that, during the whole period, there are regular temperature drops in the mornings. These drops are smaller in the hottest months.

Analysing the values obtained during the three months of the lockdown has allowed us to see thermal behaviour between the indoor daily thermal amplitude (ΔT_{din}) and the minimum value of thermal amplitude on the floor sensors ($\min(\Delta T_{avf})$) from 8 to 11 a.m., as shown in Fig. 10. A boxplot has been made with the data obtained from both the Indoor daily thermal amplitude (ΔT_{din}) and minimum value of thermal amplitude on the floor ($\min(\Delta T_{avf})$) from 8:00 to 11:00, these values being the ones that have allowed us to compare with the values for the rest of the year. All the days of the year have been considered if the maximum value for the thermal amplitude calculated with the indoor amplitude (ΔT_{din} exceeds the value of the extreme of the upper whisker, which is 0.52 °C, and the minimum value of thermal amplitude on the floor ($\min(\Delta T_{avf})$) from 8:00 to 11:00, are less than −0.17 °C, which is the value of the first quartile. With this filter, we have obtained 344 days within these parameters (including the 90 days of the lockdown and the eight anomalous days), which means that 52% of the days that do not comply are within these parameters. This value is not representative, so we have looked for other relationships between temperatures.

Thus, we have added a new restriction: the periods in which the correlation between the daily thermal amplitude (ΔT_{din}) values and minimum value of thermal amplitude on the floor ($\min(\Delta T_{avf})$) must have more than seven consecutive days. From the results obtained, summarised in Table 3, it is possible to see that all the days are in the summer, except for the lockdown, which was in spring.

Visually it is easy to see the days in Fig. 10 with the thermal amplitude in the morning, from 8 to 11 a.m., and the temperatures for each period. In both periods we can observe that, when the outdoor temperature is over 30 °C, it impacts indoor thermal behaviour and a higher amplitude is obtained. This effect is directly related to the lockdown for 2020 May 2nd and 3rd, but it has a different effect in the summer of 2019, where it is not on the same day. We can say that the thermal amplitude is dampened when the temperatures rise in summer.

4. Discussion

This study was set up to collect data in a non-intrusive way inside an architecturally representative fifteenth-century church in the city of Valencia, to determine the temperature changes that occur inside the building due to its activity and use. This building has no air conditioning system, so indoor conditions depend solely on the climate and the use of the building.

This work proposes a detection system for changes according to the use of a public space for religious worship. This method was applied over 655 days, recording temperature data every 10 min from 11 different sensors. This period included the lockdown in Spain and therefore allowed us to observe the changes that occur in the thermal behaviour of the building. The lockdown measures implemented are reflected in the thermal behaviour of the building.

In detail, it was found that the high inertia of the church's thermal envelope allows for almost constant temperature values during

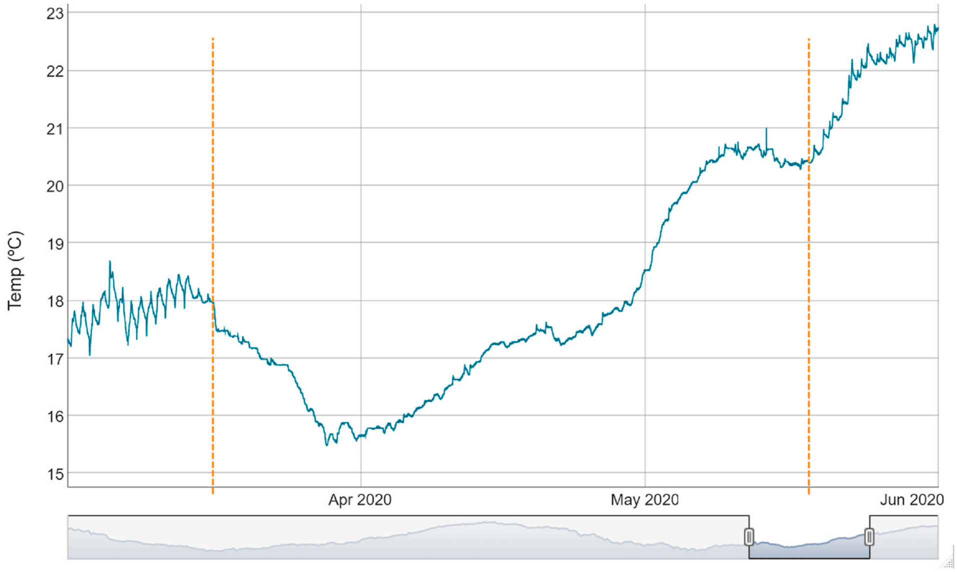

Fig. 8. Indoor average temperature on the floor (T_{avf}) from March 1, 2020 to April 30, 2020.

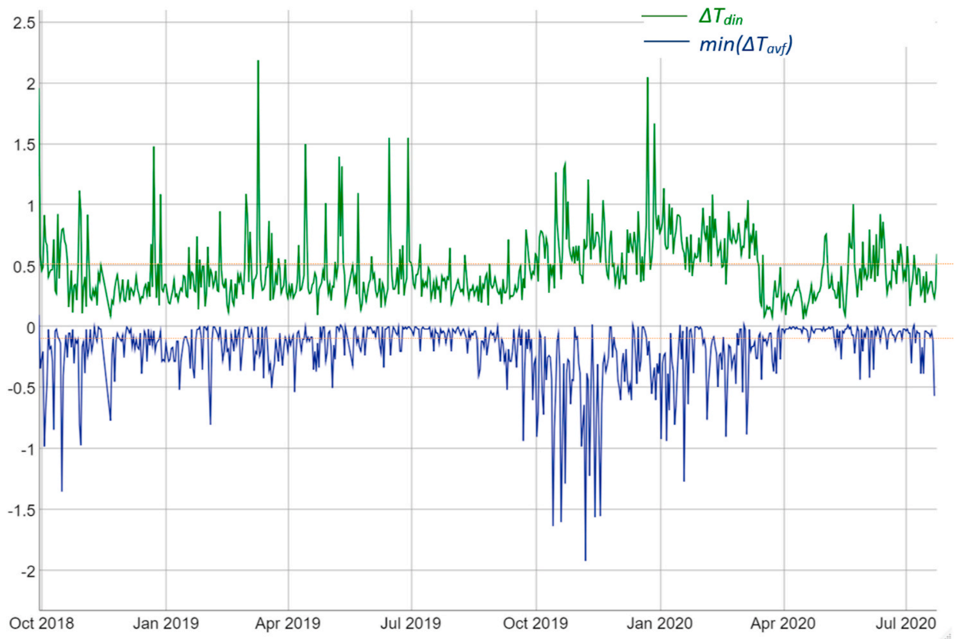

Fig. 9. Indoor daily thermal amplitude (ΔT_{din}) and minimum value of thermal amplitude on the floor ($min(\Delta T_{avf})$) from 8:00 to 11:00.

the daily cycles (with variations or daily thermal amplitude of less than 1.1 °C) and causes gradual and smooth changes with respect to the external conditions over the course of the seasons. In addition, the stratifications occurring at height are not very high and depend on the operation of the building. As there was a change of staff during the period analysed (in October 2019), this affects the thermal response and temperature stratification. It should be added that the sensors closest to the openings are more affected by the temperature variation according to the external parameters.

It has been possible to see the correlation of data between indoor and outdoor temperatures. Therefore, when the outdoor temperatures rise, the indoor temperatures also rise and vice versa. This shows that there is a constant exchange of air with the outside through the openings in the envelope. It has also been observed that the average outdoor temperature value was most of the time below the indoor temperature, so we can say that the solar gains throughout the year ensure the inside temperature is higher than the outside temperature. This effect is accentuated by the fact that the building is totally free from surrounding shade and receives direct radiation on all the external walls and roof throughout the year. However, when analysing the daily outdoor and indoor thermal amplitude, we

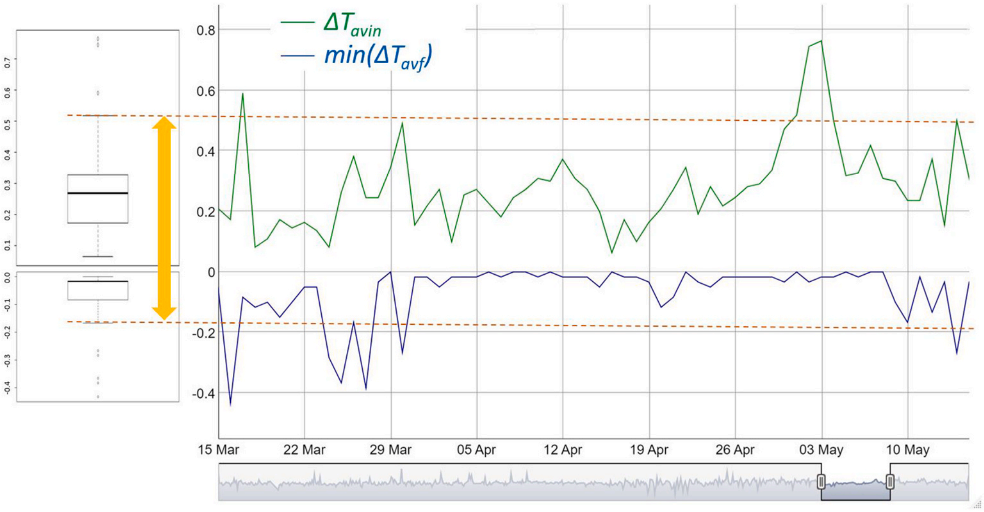

Fig. 10. Indoor daily thermal amplitude (ΔT_{din}) and minimum value of thermal amplitude on the floor ($\min(\Delta T_{avf})$) from 8:00 to 11:00.

Table 3
Periods with more than seven consecutive days with thermal variations similar to lockdown period.

Period	Nº days
2019, July 8th to 15th	8 days
2019, July 18th to 27th	10 days
2019, July 31st to August 7th	8 days
2019, August 26th to September 2nd	7 days
2020, March 30th to April 29th	31 days
2020, May 3rd to 11th	9 days

have not found any direct relationship between the two. Probably, as there is no infiltration control, there is an exchange with the outside air.

The analysis of the measured data suggests that it is possible to detect changes during the normal use of the building. Typically, in the morning due to the open door, or at night when there is a specific activity. All these changes disappeared during the three months of lockdown, where the extreme of the upper whisker of the indoor thermal amplitude varied from 1.1 during the normal period to 0.52 during the lockdown.

Using temperature data allowed us to explain the changes inside the building, but in summer it is not possible to detect these changes, because the temperature difference between outdoors and indoors is not enough. This is the higher limitation of the proposed method.

Author statement

Carolina Aparicio-Fernández: Conceptualization, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision. **José-Luis Vivancos:** Methodology, Formal analysis, Investigation; Resources, Writing - Review & Editing, Visualization, Project administration. **Víctor Pérez-Andreu:** Resources, Writing - Original Draft. **Jose M. Molines-Cano:** Resources,Writing - Original Draft.

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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