ENERGY CONSUMPTION BEHAVIOUR IN HISTORICAL CHURCHES

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ABSTRACT

The historical buildings are being categorized under low thermal comfort because of their primary construction materials and their architecture, requiring a large volume of air to heat/cool to achieve the human comfort levels required today. The existing problems within the historical churches are increasing, destroying not just the cultural heritage, but also affecting the health of people using them. This raises environmental concerns and questions as to how to preserve historic buildings, and artefacts, while providing acceptable indoor environments and thermal comfort for the users of these buildings. A case study church building was selected to be monitored. Data loggers were installed to measure/record temperature and relative humidity ranges. The results were analysed to assess thermal comfort according to CIBSE TM52 and CIBSE Guide A standards/guidelines. The results demonstrate that the indoor environments are, in majority of the times, cooler than the minimum acceptable standards, not achieving thermal comfort requirements for the occupants of the building.

INTRODUCTION

It is known that many of the historical churches survived hundreds of years with minimum maintenance and without any improvements in terms of comfort, due to the construction materials and technologies used in their period. The UK climate, that is cold/wet in winters and warm/wet in summers, may not provide suitable indoor environments in church buildings affecting users' health [21]. The structure and objects located in those churches may be at high risk of being damaged and even collapsing, resulting in reduced lifetime and value of buildings [1,13]. A general problem with historical churches is that due to the porous envelope proper ventilation is required to avoid the moisture being trapped in the materials resulting in further damages [31]. Detailed investigation on the building materials and construction methods is therefore a priority.

Historical churches

Of all the constructions, churches are one of the most globally important historical buildings, due to their cultural heritage which are defined as ‘culture named and projected into the past, and simultaneously, the past congealed into culture’ [20]. The UK climate conditions are found to be rather challenging being dominated by moisture with an external average relative humidity of 80% (Lawson-Smith, 1988). Due to the different performances of the wall materials, various micro-climates can be found on the historical buildings, [17]. Historical churches lean towards a range of common physical problems, that are mainly related to construction materials and insulation strategies, heating, ventilation as well as to weathering, chemicals and other environmental issues. Amongst all these problems, damp and condensation in the materials could be highlighted as most challenging issues. This problem arises as a result of the low temperatures on the surfaces, walls, glazing, floor or ceiling. The general combination of low temperatures with high air humidity is creating excessive moisture [18]. However, extreme changes in temperature can also expose timber furniture and structures to drying, expansion, shrinkage or deflection. A permanent water infiltration, which accumulates moisture, would create salt damage to walls and ceilings [18].

Constructed, in general over a floor level, without damp-proof membranes or vapour barriers, historical churches can retain a significant amount of water in the walls even with regular maintenance services in place. Additionally, defective ventilation and HVAC systems/strategies would affect both the building fabrics and people's health [3]. These are identified as the main cause of dampness and decay in most churches, as well as damage to vulnerable materials and contents [29].

One of the dominant factors of those problems in naturally ventilated churches is the high relative humidity which encourages the growth of mould and algae. The low temperatures in a cold climate and poor ventilation in warm/wet seasons are also contributing to the destruction of historic monumental and cultural heritage [15]. Those historical churches have been functioning for centuries in cold conditions without a central heating method in place; however, heating and thermal comfort become major issues when building occupants are brought into consideration [23,30].

Modern heating systems can be installed to improve thermal comfort in churches; however, without proper research, such systems may present risks in terms of preserving cultural heritage and result in irrevocable damage to building fabric, artefacts, organs, etc. [5,22].

Moreover, achieving and maintaining thermal comfort in churches is a major challenge due to the high energy due to large areas and heights. Space heating presents around 60% of the total energy consumption in the UK [14], while 80% of the energy used in the churches is for heating [6]. In many cases, inappropriate heating systems are damaging the building materials due to their installation processes. [24]. Yet, creating a balance between energy efficiency, thermal comfort and conservation is considered as a major challenge in historical churches. To this end, this research aims to evaluate the existing internal conditions in historical churches with the aim to improve the indoor environments, energy performance and thermal comfort.

RESEARCH METHODOLOGY

Case study – Church of Saint Mary de Haura, Shoreham-by-Sea, UK

The history of the church dates to the Norman period and was built at the end of 11th century by Phillip de Braose, son of William Braose which was fighting with William the Conqueror in 1066 at Hastings Battle. Throughout the medieval periods, Saint Mary de Haura was one of the largest and most important parish churches in Sussex [16]. The church is a listed Grade I building in rather poor conditions due to a slow decay [16].

The existing structure is half of the church (Figure 8), which was divided by large round columns. The space could hold hundreds of people, and it measured around 30 metres by 20 metres, with two wide side aisles, and later, a large south porch. Constructed over only one floor, the main structure of the church is made of Caen stone imported from Normandy and local flint, while for the interior structures used a less durable stone, the roof being covered in tiles manufactured in old Horsham (Figures 1,2,3). The actual stage of the church requires repairs to stone parts, roof and gutters [16]. Regarding the actual heating system used in St Mary's, this is provided through a central heating system with 21 radiators at floor level. Being only a part of the initial building, by curiosity, it was researched for the cause of collapsing the nave in the late 1600s, but the true reason is still a mystery [26].



Figure 1: St Mary de Haura Church (left); Internal space of the church (middle); Column with old paint (right)

METHODOLOGY

Understanding the individual energy consumption behaviour, while having in mind that the energy performance targets were an exemption to the churches due to the missing of benchmarks on the energy efficiency of construction methods and materials used, will help on finding the best solution on improving the overall energy consumption [13]. The first part of the methodology is to analyse the energy performance of the building materials such as stone, limestone, brick and wood, picking up three thickness to consider for the walls of 800mm, 1000mm and 1200mm. The U-values shown in Table 1 have been achieved using the formula applied in the examples below:

Assuming that the walls are made of 0.8m limestone with thermal conductivity of limestone of 1.5 W/mK, the U-Value of 800mm is 1.5 x 1000/800 = 1.9 W/m^2K approximative. The same assumption with the walls of 0.8m stone with thermal conductivity of hard stone of 2.33 W/mK, the U-Value of 800mm is 2.33 x 1000/800 = 2.9 W/m^2K approximative.

The results show a high U-value for stone historical churches due to their high thermal conductivity, which means they have a low thermal resistance, following a high loss of heat through those walls. Resulting in a rise of the relative humidity due to the large thermal mass which keeps the church in a cool condition until summer.

Table 1: U-values calculated for diverse construction materials of the church

Material	Thermal Conductivity (W/mK)	U-Value of 800mm wall thickness (W/m^2K)	U-Value of 1000mm wall thickness (W/m^2K)	U-Value of 1200mm wall thickness (W/m^2K)
Limestone	1.50	1.9	1.5	1.25
Stone (basalt, granite)	2.33	2.9	2.33	1.94
Building brick	0.73	0.91	0.73	0.60
Wood (softwood/hardwood)	0.12/0.17	0.15/0.21	0.12/0.17	0.10/0.14

When it comes to thermal comfort, a 'reasonable comfort' can be considered only when at least 80% of occupants within that building are feeling comfortable from a temperature point of view and this comfortable level is varying due to the changes of outdoor temperatures and the adaptability of humans during the time to the new temperatures [23]. The control of thermal comfort within historical buildings, in particular, within a church is very challenging because it needs to be considered through many simultaneously aspects, such as the occupants' thermal comfort and optimal interior environment suitable for preservation of the artwork and the fragile building components [28]. While humans can adapt their behaviour to deal with the thermal environment by adding or removing clothes or changing their position up to a certain temperature and a relative humidity level, this is not working the same way while about the materials. For example, to keep the wooden furniture safe and mould fungi away, an equilibrate moisture level should be considered between 30% and 80% with an environment relatively dry, this means a relative humidity (RH) below 76% [25].

In terms to delivering this research and proposing a solution, it is necessary to investigate the standards required for the indoor environment to compare further with the data collected. Having said that, the British Standards BS EN 15759-1:2011- Conservation of cultural property. Indoor climate Guidelines for heating churches, chapels and other places of worship [4], as well as CIBSE standards [10] will be used as guidelines for this study. According to BS EN 15759-1:2011, the relative humidity is representing a critical parameter from the preservation point of view [4]. The studies show that the historical churches achieve a relative humidity of 60%-80%, being already over the conservation tolerances [2]. Maintaining the relative humidity at 58% RH within churches requires a temperature of 30°C; this is while the indoor temperature should be limited to 22°C for preservation purposes [2]. On the other hand, the relative humidity is not a critical factor for the occupants, if ranging between 30% and 80%. The main issue seems to be the temperature that should range between 18°C and 22°C [12]. Despite all the above, Curteis [11] argues that many standards are not appropriate for the environment of historical churches because those are set mostly for stable conditions, while on historical churches does exist a multitude of different microclimates at the same time. However, the current sustainability requirements impose some efforts to be made, where possible, to diminish the need for energy and the resulting environmental impact [27].

Data collection & Adaptive Approach of TM52

The main methodology used to assess the thermal comfort in historical church buildings within this research is monitoring the environmental conditions of temperature and relative humidity in the case study building. Eltek data loggers and EmonTH and EmonPi sensors were installed in various locations in the church (see Figure 4) to collect the temperature and humidity data for the period between 27 November 2019 and 11 December 2020 inclusive. During this period, the dashboard data could be accessed online through a portal for visualization of the current environment in the church. Still, there are some missing data due to the overwriting of data, while some of the data was restricted by the limitation of batteries (due to Covid travel restriction to maintain data loggers), for a total of 41 full days in the periods between 09 May 2020 and 19 May 2020, 20 May 2020 and 6 June 2020, 17 June 2020 and 25 June 2020, 11 November 2020 and 15 November 2020. Apart from missing full days of data, there was also missing some data on other days for a few hours only. Luckily, this was not a major issue and all the information gathered was enough to support this investigation accordingly.

The method to be used is the adaptive approach of CIBSE TM52 [15] and the criterions 1,2 and 3 of the assessment [9]. The comfortable temperature (Tcomf) will be calculated based on the Running Mean of the daily mean outdoor temperature (Trm) for each hour of each day on which internal data has been collected by using the formula:

$$Tcomf = 0.33\ Trm + 18.8$$

Where Trm can be obtained using the external hourly temperatures calculated under the formula below using 30 days before of each day of analysis, which would be in this case the 28 October 2019 to 26 November 2019 inclusive, to obtain the Trm for our first day of investigation, 27 November 2019:

$Trm = (1- \alpha)(Tod\text{-}1 + \alpha Tod\text{-}2 + \alpha 2\ Tod\text{-}3 + \alpha 3\ Tod\text{-}4 + \alpha 4\ Tod\text{-}5 \ldots\ldots\ldots. + \alpha 29 Tod\text{-}30)$
Where α is equal to 0.8.

But, if Running Mean *(Trm) is lower than 10, then T(comf) = 0.09Trm+22.6*, *if Trm greater than 10 then T(comf) = (0.33 Trm) + 18.8*.

Applying the formulas from above to achieve Tcomf, in an excel spreadsheet, a minimum acceptable temperature (Tmin), a maximum acceptable temperature (Tmax) and an upper limit temperature (Tupp) would be achieved applying the formulas below:

$Tmin = 0.33\ Trm + 15.8$
$Tmax = 0.33\ Trm + 21.8$
$Tupp = 0.33\ Trm + 25.8$

Where Tmin will be 3° lower than Tcomf , Tmax will be 3° higher than Tcomf and Tupp will be 4° higher than Tmax. Following those, DeltaT (ΔT) will be obtained to can carry on the assessment via Criterion 1,2 and 3. DeltaT (ΔT) would be the result of:

$Top – Tmax = \Delta T$

Due to the missing radiant temperatures (Tr) in the collected data, to calculate the operating temperatures (Top), ΔT will use the internal hourly temperatures (Tin) instead of Top. The data temperatures will then be assessed via the Criterions 1, 2 and 3 to achieve a true result for this research regarding the risk of overheating or overcooling of the church. Criterion 1 will assess the number of hours when the indoor temperatures are higher than the maximum temperature with 0.5°C or more, using the DeltaT formula above. Criterion 2 assess the number of times this type of incident happens during every 24 hours. While under Criterion 3 will be assessed the number of hourly incidents when indoor temperatures reach or exceed the upper limit temperatures allowed [9].

DATA ANALYSIS AND DISCUSSIONS

For the purpose of collecting temperature and relative humidity, Eltek data loggers and EmonPi nodes sensors were installed within the church in various locations like choir room, by the entrance, altar area, by the organ, north wall, on pews area and boiler room, collecting quantitative data for each individual area to the online dashboard portal and from where it has been downloaded.

As stated above, the collected data was not complete for all the areas for the entire period between November 2019 and December 2020, and there is missing data on the north wall for April, May, June, October, November and December, while the other areas, apart from Pew 2 which is complete, has missing data in October, November and December. The data captured from the loggers and sensors installed in the church has been analysed and transformed in the table below (Table 2) of minimum and maximum temperatures and relative humidity for an initial understanding of the existing thermal situation each month. Those different zones are more or less heated and so, variations in temperatures from zone to zone were found.

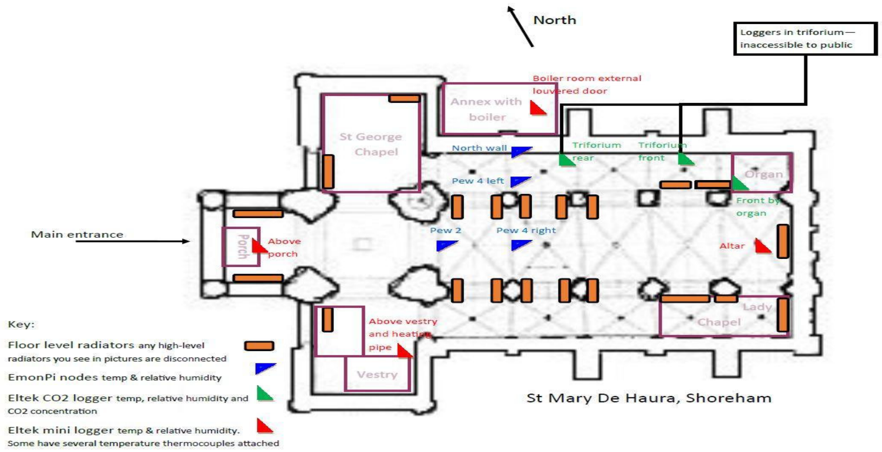

Figure 4 - The floor plan of the church showing the position of radiators, loggers and sensors installed

Table 2 : Minimum and maximum internal temperatures and relative humidity in the church

Area	Nov 19	Dec 19	Jan 20	Feb 20	Mar 20	Apr 20	May 20	Jun 20	Jul 20	Aug 20	Sept 20	Oct 20	Nov 20	Dec 20
Choir Room	13.5°C-15.7°C	12.5°C - 17.5°C	11.6°C-15.8°C	11.6°C-15.2°C	11.4°C-15.1°C	11.4°C-14°C	13.3°C-15.6°C	15.8°C-18.1°C	17.5°C-24.6°C	18.5°C-25°C	18°C-23.7°C	-	-	-
North Wall RH	64%RH-75.4% RH	59.1% RH - 71.6 %RH	62.3% RH -79.4 %RH	68.3% RH -85.6% RH	64.5% RH -75.1% RH	-	-	-	69.2% RH - 86.5% RH	73.3% RH - 87.1% RH	71% RH - 89.4% RH	-	-	-
North Wall Temp	13.1°C-16.1°C	13°C-18.6°C	10.8°C-15.9°C	11.2°C-14.6°C	11.8°C-15°C	-	-	-	17.6°C-19.7°C	18°C-22.5°C	17.8°C-18.8°C	-	-	-
Pew 2 RH	63.2% RH - 74.9% RH	47.2% RH - 72.1% RH	53.5% RH -80.5% RH	64.9% RH -86.6% RH	59.2% RH -79.2% RH	64.9% RH - 75.8% RH	68.4% RH - 74.5% RH	65.1% RH - 80.6% RH	65% RH - 83.7% RH	59.3% RH - 84% RH	65% RH - 80.6% RH	70.7% RH -87.7% RH	67.8% RH -87.9% RH	73.6% RH - 83.6% RH
Pew 2 Temp	12°C-18.2°C	11.7°C - 22.2°C	10.2°C-17°C	10.1°C-17°C	10.2°C-19.9°C	10.4°C-14.9°C	13.2°C-16.5°C	16.2°C-19.8°C	17.3°C-20.3°C	17.2°C-23.4°C	16.8°C-19.9°C	12.9°C-17.9°C	11.4°C-18.4°C	8.5°C-12.5°C
Pew 4 left RH	61.4% RH - 71.1% RH	48.1% RH - 81.2% RH	56.5% RH -71.1% RH	63.2% RH -71.1% RH	55.9% RH -71.1% RH	61% RH - 71.1% RH	64.1% RH - 74% RH	64.5% RH - 81.5% RH	69.8% RH - 82.1% RH	69.9% RH - 85.4% RH	67.8% RH - 82.1% RH	-	-	-
Pew 4 left Temp	12.4°C-17.3°C	12.1°C - 20.6°C	11.2°C-17.6°C	10.7°C-16.6°C	10.4°C-17.9°C	10.5°C-17.6°C	13.1°C-15.9°C	13.5°C-18.1°C	17°C-19.6°C	18.4°C-22°C	17.5°C-19.5°C	-	-	-
Pew 4 RH	58.1% RH - 71.1% RH	50.7% RH - 64.7% RH	60.7% RH -75.9% RH	65.3% RH -81.6% RH	55.9% RH -69.4% RH	61.2% RH - 75.2% RH	68.2% RH - 74% RH	68.8% RH - 81.5% RH	72.5% RH - 82.2% RH	68.9% RH - 84.8% RH	67.8% RH - 82.1% RH	-	--	-
Pew 4 Temp	12°C-18.6°C	11.7°C - 20.2°C	10.5°C-15.9°C	11°C-15.2°C	10.9°C-18.2°C	-	13.1°C-16°C	15.9°C-18.4°C	16.9°C-19.3°C	18.1°C-22.3°C	16.9°C-19.1°C	-	-	-

Figure 4 shows the position of data loggers and sensors: two of the EmonPi nodes were positioned in the middle of the church with a distance of about 2-3 meters between them and another one been installed on the north wall as considered to be the coldest part within the church due to the sun position on the south and to detect the differences in temperatures between the sitting area with radiators nearby and the coldest wall surface. The Eltek base station is positioned on the bookshelf of the choir room while the EmonPi base station on the floor of the choir room. The sensors nodes were placed on the walls and under the pew fourth at the rear and front, and an Eltek logger placed under the front altar. Two other loggers placed in triforium (north side) are allowing an analysis of any vertical differences in humidity, while other four loggers placed at the entrance, boiler room, altar/organ area and vestry room are allowing for monitoring the relative humidity on all ends of the church.

Temperatures within the church

The principal factor for the thermal stress in buildings is related to inappropriate internal temperatures. Such internal temperatures are being influenced by the external weather that also affect other internal environments.

Other factors influencing the comfort levels include the clothing and types/levels, air movement and quality, radiant heat and the number of occupants [8]. According to CIBSE Guide A, the indoor temperature, at a comfort level within churches, should be between 19°C and 21°C in the winter months [7]. For the temperatures below 19°C, the occupants are feeling cold and are forced to wear more clothes which may makes them uncomfortable. Above 21°C, occupants may start feeling too warm, and if even higher, they will start sweating and creates discomfort [7]. For the historical artefacts and artwork, temperatures between 16°C and 20°C would be optimal. It is considered that even going down to 10°C, is not harmful to objects, but anything below 10°C will increase the risk of condensation, which should be avoided in historical buildings/churches [19].

Table 2 above, shows that the observed temperatures are not within the ranges recommended by CIBSE. The church registers even lower temperatures in the winter period and, as well in the summer, which result is the thermal discomfort. High temperatures are also observed in some winter months in Pew areas 2 and 4, comparing to the other areas in the church that may be due to the radiant heat coming from the radiators in the close vicinity. Generally, the internal temperatures in the church during winter is not exceeding 18.5°C and temperature ranges vary from an area to another and also influenced by the external temperatures. The average temperatures during winter, when the heating system is off, is between 8.5°C and 14.5°C maximum. The registered higher temperatures in winter months around some afternoon hours, is assumed to be due to the people occupying the church while heating system was on.

The observations show that the choir room, in the coldest months, register the lowest temperatures than any other areas. The north wall also registered low temperatures during winter similar to the choir room. On the other hands, during summertime, according to CIBSE Guide A, the internal environment within churches should be able to achieve a range between 22°C and 25 °C [7]. Analysing the data obtained, the conclusion drawn is that only in August the temperatures in the church were in between parameters suggested by CIBSE Guide A during daytime. Due to the lack of insulation, and south facing orientation, the choir room shows higher temperatures than the rest of the church during July, August, and September. During summer, the choir room (a low ceiling wooden freestanding construction built within the church) can be easily overheated, while the other areas in the church can be still within the range if the external temperature increase. It should be noted that, due to its characteristics, the choir room performance may be significantly different in comparison with the other areas in the church.

Relative humidity within the church

In general terms, a relative humidity below 25% can cause skin dryness and shocks due to static electricity, while in opposite direction, a relative humidity over 80% can make feel skin sticky and uncomfortable, leading to condensation and mould growth on surfaces and creating difficulties in breathing. The optimal recommendations for relative humidity within churches in the UK is between 40% and 70%, according to CIBSE Guide A [7]. From the historical artwork and artefacts point of view, the humidity must be carefully monitored for displayed artwork, as well as the ones in the storage and not exceeding the range of 40% - 70%. If below 40%, the artefacts and materials will be at risk of drying out. If above 70%, the growth of mould, pest and fungal infestation would be major risks. Rapid fluctuation od relative humidity may also increase the risk of condensation [19].

Keeping the relative humidity at a recommended level will assure the conservation of the building and wellbeing of occupants. When observing the RH% at St Mary's church, in the majority of months, the relative humidity was exceeding 70%. The coldest months are showing a relative humidity slightly over the limit of 70% but not lower than 50.7%. On the positive side, the materials and artefacts are not at risk of drying out and people can feel just about comfortable from this point of view.

The summer data shows a really massive increase in the humidity within the church due to the higher temperatures registered in the interior. The inappropriate ventilation in warmer period is representing a factor for the higher humidity and an issue for the church. All the areas with loggers installed are significantly affected by high humidity rates, the worst of all being the north wall.

The consistency of relative humidity in those months is between 59.3% and 89.4% which is representing a propitious environment for the growth of mould and fungal. Furthermore, these are affecting the building materials by producing condensation at surfaces level and conduct to slow decay while people may feel uncomfortable with difficulties in breathing, sticky wet skin, and an increased risk of pulmonary disease, asthma or allergies.

Thermal comfort assessment – Adaptive approach of CIBSE TM52

The adaptive approach of the TM52 method used to assess thermal comfort conditions. Because it was no possible to collect the operating temperatures from the church, the internal temperatures collected from Pew 2 were used instead, because there were no missing data and due to its position in the middle of the church. The results show that the church is reaching very low temperatures during winter and temperatures raised only when the heating was on or when the external temperate raised.

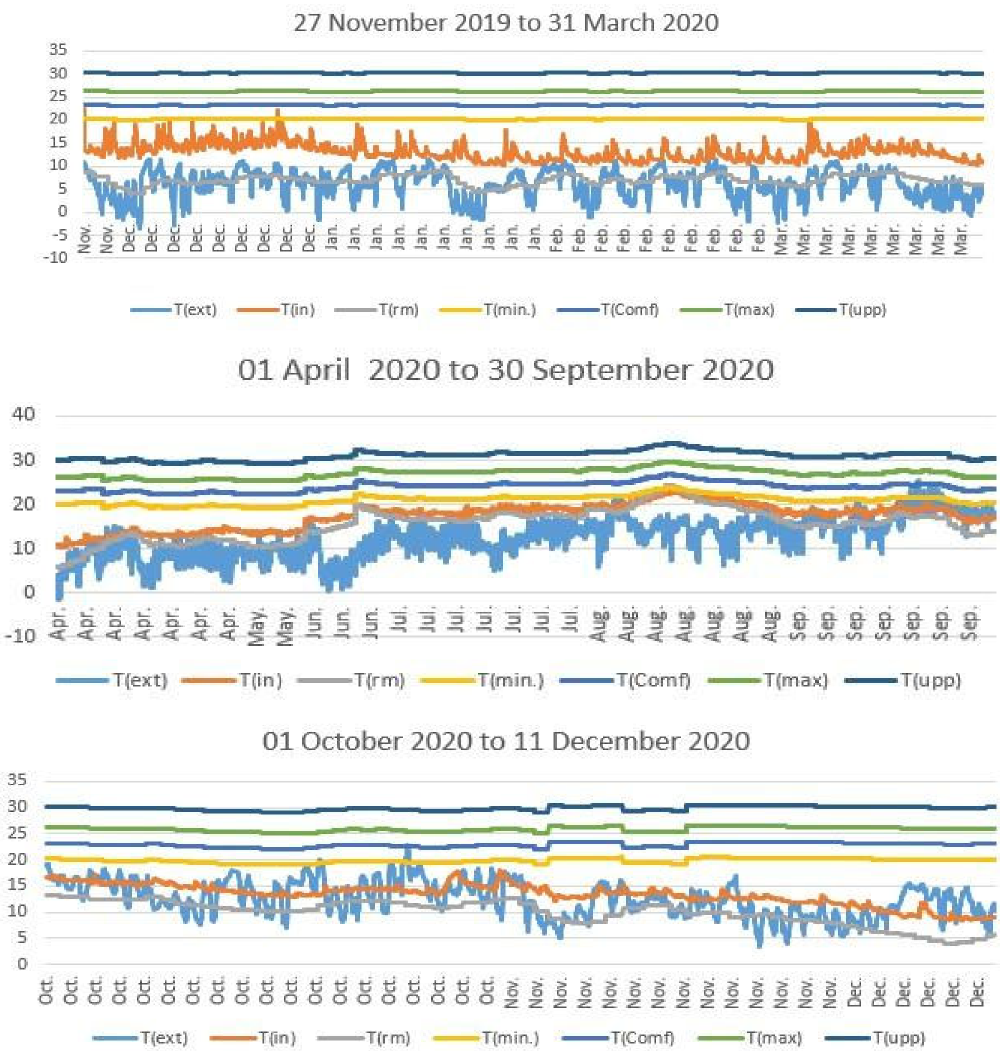

Figure 5:

The reason of assuming that heating was on is given by the radical fluctuations of temperatures when the external temperatures go in opposite directions to internal ones. For example, looking to January 2020 it can be observed the external temperature T(ext) showing temperatures dropping under 5°C up to -5°C, while the indoor temperatures T(in) in those periods shows a raise which occasionally, meets the minimum thermal requirements and close to meet the comfortable level. The same conclusion can be drawn for December 2019, February 2020, March 2020, when the external temperatures were rather low and heating was necessary. However, for the external temperature over 5°C, the indoor temperatures were influenced only by the external environment while the heating was not on keeping the internal temperatures between 10°C and 18°C. The results show that despite the warmer days in the winter months, heating is necessary to meet thermal comfort requirements.

Summer months registered a lower level of variations on indoor temperatures, keeping the indoor environment steadier between 14°C and 20°C during May, June, July, August, while the external temperatures fluctuated between 5°C and 20°C.

During April, September, October, November and December 2020, the external temperatures show a high rise, while the internal temperatures show more constant temperatures between 10°C and 15°C in December and up to 18.5°C in November 2020. In many cases the external temperatures during those months are warmer than the indoor ones, those variation being still high, between the lowest of -3°C in April up to the highest temperature registered of 27°C in September. This is assumed to be due to the high thermal mass of the church.

When assessing according to TM 52 assessment Criteria 1, 2 and 3, all temperatures are below the upper limit and maximum limit temperatures. As the assessment under the assessment criteria had the results equal to zero (pass) for each individual hour monitored in 381 days of monitoring, the conclusion was that the church is never at risk of overheating, but at high risk of overcooling.

CONCLUSION

The results of this research reveal that the indoor environments in historic churches may not be acceptable neither in terms of preserving artefacts nor in terms of thermal comfort for the occupants. Improvements are therefore required to make a balance between the requirements for the preservation of building materials and artefacts with thermal comfort and energy efficiency. Creating a balance between these factors can be a challenging task that required further research and investigation into the types and performances of various heating systems/strategies in historic churches. This may also depend on the priorities within each individual church depending on its use and historic values, artefacts, construction methods and materials. Although challenging, based on the results of this study, it could be argued that preserving valuable historic buildings while providing thermal comfort for the occupants is achievable.

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