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A study of thermal comfort in naturally ventilated churches in a Mediterranean climate

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ABSTRACT

This paper investigates the status quo of the indoor comfort temperatures of a number of reference churches in Malta, ranging from large and small Baroque buildings to more contemporary buildings, throughout the twelve-month monitoring period of 2018. This is carried out as a first step towards understanding and evaluating the extent of comfort issues in these buildings. It was found that the thermal mass of buildings plays a very important role in controlling indoor temperature in these free running structures. The Baroque churches proved to have an overall high thermal mass when compared to the mid-20th century neoRomanesque style architecture, and late 20th century (post Vatican Council II style) contemporary architecture, with the result of a steadier indoor temperature in Baroque churches and higher fluctuations in temperature for the more recent architectural styles. This behaviour is mainly attributed to the lack of overall thermal mass of the building and higher solar gains through glazed elements, providing minimal "inertia" against external temperature fluctuations. This is evidenced by the results obtained in this study, which give a sound indication of the thermal comfort in naturally ventilated churches in a Mediterranean climate

1. Introduction

To date, peer reviewed literature has given little attention to the thermal comfort and energy performance of places of worship, such as churches in temperate climates of the Mediterranean region. This, probably due to the fact that the European Energy Performance for Buildings Directive (EPBD) [1], excludes religious buildings from the requirement that all new and renovated buildings are to be nearly-zero energy by 1st January 2021, which also applies to the Republic of Malta, a Southern European country in the central Mediterranean. Malta is an archipelago of islands, some 80 km south of Sicily (Italy), 284 km east of Tunisia and 333 km north of Libya, as shown in Fig. 1 below. [2], with a population of about 475,000 over an area of 316 km^2.

As a result, no attention has been given to the thermal and energy performance of such buildings, despite the fact that buildings occupy a significant floor area of public building space in the Maltese archipelago. It is pertinent to point out that in Malta there exists a ‘church density’ of one church per square kilometre. While, most of the existing churches are historic and have always been naturally ventilated, there is an ongoing trend to retrofit these places of worship with mechanical space heating and cooling equipment without due consideration to whether thermal comfort can be achieved through other natural means and passive energy efficiency measures. Natural ventilation is a traditional, and well-accepted passive cooling technique used in hot–humid regions [3] like Malta. In addition, little concern is given to the increased energy consumption via the installation of such equipment, and how the mechanically cooled and heated macro-climate impacts the conservation of artefacts and the building structure itself. In terms of the conservation of the building heritage and works of art, the ideal solution would be to maintain suitable environmental conditions over a constant period to maintain a constant macro-climate. However, the churches that opted to install mechanical space heating and cooling equipment, have climatization systems that are mainly used on cooling for very limited periods of time, coinciding with occupation during occasional events, to the detriment of artefacts and the building structure itself. In European countries where heating is of a major concern, localised systems to address the micro-climate without drastically altering the macro-climate have been introduced [4,5]. These include radiant floors, infrared radiation heating and low-temperature radiant emitters mounted in the pew. However, localised cooling sys-

Abbreviations: RB, Reference Buildings; T, Temperature.

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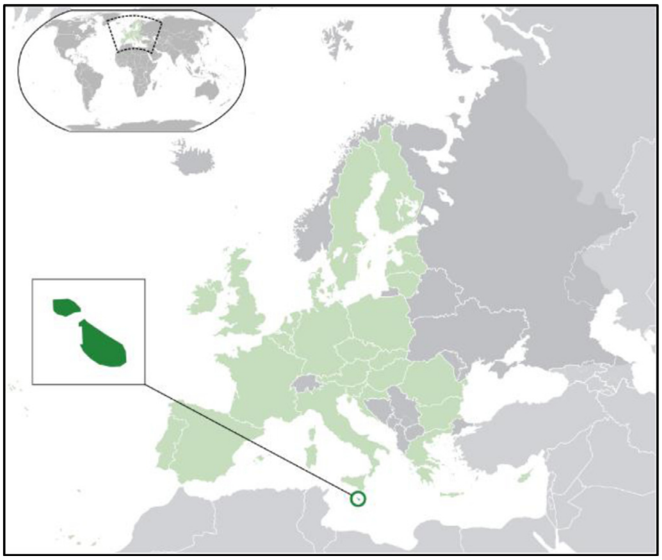

Fig. 1. The Location of Malta.

tems in warm climate regions to provide a desirable distribution of ambient temperature to the people occupying that space without drastically altering the macro-climate is so far sparsely addressed.

Up to now, publications to analyse thermal comfort in religious and historical buildings have mainly focused on air conditioned versus buildings in their natural thermal environment. Such studies have primarily assessed comfort using or adapting the ISO 7730 [6] Predicted Mean Vote (PMV) / Predicted Percentage Dissatisfied (PPD) model.

M.S. Al-Homoud, et al. evaluated five representative mosques in Saudi Arabia [7,8]. In this study, evaluation was based on utility bills and power meters to measure total energy usage and energy end use. It was established that for these mosques, which were located in a hot, humid climate, the largest share of electricity use (71–79%) was attributed to the HVAC system in space conditioning [9].

Several other papers were later published on the energy and comfort performance for three of the five mosques referred to above [7,8]. Using representative days from the data samples, they found that indoor conditions were often outside the comfort zone, as defined by Fanger's Predicted Mean Vote (PMV) model, despite active space conditioning [10]. Another paper evaluated potential energy efficiency measures through simulations of a typical mosque [11], reinforcing the energy and comfort benefits of insulation, whilst investigating the impact of operational zoning and HVAC system intermittent operation strategies on the energy performance of mosques, while thermal comfort is maintained.

In other studies, Budaiwi explored in simulation, using building energy modelling software, how different envelope parameters affect the energy performance of mosques [12]. Ah-Homoud, also in simulation, optimized envelope parameters for mosques in achieving minimal energy consumption [13]. A study on thermal comfort in mosques in Kuwait found that the perceived comfort for the occupants was 2.6 °C above that predicted by Fanger's PMV model [14].

In Northern Europe there was a growing concern in the 1960s among antiquarians and architects that medieval stone churches were suffering seriously from overheating [15]. Heating was said to contribute significantly to particle deposition on walls and vaults and to a dry climate, which was damaging wooden interiors and objects [16]. Since 1887, a directive for managing churches in Sweden required that heating should be kept to a minimum and be provided only during services [17]. In this regard there were conflicting views in Northern Europe on the need for heating in the 1960s and 1970s. In 1967, the Swedish National Institute of Building Research concluded that stone churches that had not been intended to be heated should remain unheated [18]. However, this advice does not seem to have had a noticeable influence on the management of churches. To the contrary, the 1960s seems to have been a time when many churches were permanently heated for the first time. A transition to intermittent heating rather than a complete shutdown of heating was seen as a solution [19–22].

Studies in Europe and the United States have also considered thermal comfort and have monitored the indoor temperatures and relative humidity (RH) levels. Loupa et al. [23] presented the results from two medieval churches in Cyprus and showed that the fluctuations in indoor temperatures, humidity levels, and levels of pollutants exceeded the recommended values. Niccolo‘ Aste et al. [24] analysed the hygrothermal behaviour of the Duomo (Milano Cathedral) and reported that fluctuations in relative humidity constitute a danger for the conservation of artefacts. Martinez-Garrido et al. [25] analysed San Juan Bautista Church at Talamanca de Jarama, Madrid, Spain, and established that the walls exhibit differences in water absorption, whose explanation is to be found in the various types of construction involved in its over seven centuries of building history, the weather conditions and the walls orientation. Marika Vellei et al. [26] accentuated the importance of relative humidity in determining the sensitivity of occupants within the adaptive comfort paradigm. Other papers analysed HVAC typologies [27], HVAC energy usage and occupant comfort and different heating systems in churches and religious facilities [28,29]. Niccolo‘ Aste et al. [30] analysed the Basilica di S. Maria di Collemaggio in L'Aquila, Italy. This work allows to confirm that pew-based friendly heating is an effective solution, combining comfort at microclimate level with significant energy savings and low or no impact on the artworks and on the building structures. This argument was further corroborated by Dario Camuffo et al. [31] following a detailed environmental monitoring conducted in the church of Santa Maria Maddalena in Rocca Pietore, Italy. The proposed heating approach in this study is to provide a small amount of heat directly to people in the pew area while leaving the macroclimatic conditions in the church undisturbed.

These papers, amongst other, aimed not only to design an improved heating system but also to verify its potential impact on artworks, especially in comparison with other systems. Possible impacts, on the microclimate and on artworks within the macroclimate, have been studied in terms of cause-effect relationships [32–34].

In Spain, churches first began to be heated in the nineteen sixties and seventies. In the absence of any regulation for this practice in such buildings until December 2012 (Spanish and European standard UNE-EN 15,759–1:2012 [35]), heating systems have been chosen in pursuit of occupants' thermal comfort, with no regard for the sustainable conservation of indoor church environments or the artistic heritage. High temperature and low RH values concentrated in the upper part of the church, while the environment conditions at the lower parts occupied by the congregation remained unsatisfactory [36].

In contrast, a study on Spanish rural churches resulted in a series of recommendations for the preventive conservation of such historic buildings, without compromising human comfort [36,37]. As these buildings were not originally designed or built for any manner of HVAC technology, installing systems to temporarily satisfy occupants' thermal comfort was to the detriment of the indoor conservation of the natural environmental conditions and churches' artistic and architectural heritage. The analogy between preservation and conservation of historical heritage and thermal comfort, particularly in heritage buildings and museums, is further evidenced in various works [38–40].

The European project "Friendly-Heating: Comfortable to People and Compatible with Conservation of Artworks Preserved in Churches" [38], addressed the problems caused by the continuous or intermittent heating of historic churches, which disturbs the macroclimatic conditions to which the building and the artworks preserved inside have acclimatised. The necessity to conserve the unique features of these spaces of worship and their heritage has prompted European regulations such as EN-15,757 [41] and EN-15,759–1 [35].

More recent studies in Spain by Munoz-Gonzalez et al. [42], focus on air conditioning and passive environmental techniques in historic churches in Mediterranean climate, assessing damage risk environmental conditioning techniques and their energy performance. This research analysed several possibilities for heating and cooling systems through simulation modelling of the unheated church of San Francisco de Asisi in Seville and the church of Nuestra Señora de la Merced in Moron (Seville), using the Predicted Mean Vote (PMV) / Predicted Percentage Dissatisfied (PPD) models.

The above review shows that there are very few studies/publications regarding religious facilities for the Mediterranean region. Many of the studies referred to above were mainly conducted for mosques in the hot-humid climates of the Eastern Region or for churches in the cool-summer humid climate of Western Europe using or adapting the ISO 7730 [6] Predicted Mean Vote (PMV) / Predicted Percentage Dissatisfied (PPD) model. However, comfort analysis in Köppen climate classification Csa (hot summer Mediterranean climate) using the EN 16,798–1 (previously EN 15,251) [43] adaptive comfort model, applicable for naturally ventilated buildings (without a mechanical cooling system) was not researched in detail. To this effect, the relative effectiveness of the findings is generally not applicable to the local scenario, whereby the method of construction differs and due to the predominantly hot climate, keeping the buildings cool as opposed to warm is of a major concern [44].

This study provides a first-hand experience of the status quo in a number of reference churches, which serve as the reference scenario of the indoor temperature in churches within a Mediterranean climate, using the EN 16,798–1 adaptive comfort model. Actual measured indoor/outdoor temperatures are used for the purpose of this study. The first part of this study will only focus on the thermal comfort aspect of these buildings. The specific aim of this research is to conduct a comparative analysis of five selected churches with varying characteristics, quantify and access the thermal behaviour of each of the selected five churches and determine their level of thermal comfort throughout the year (2018).

2. Method

This section explains the methodology that was adopted to perform a comfort analysis of church buildings in Malta. The church buildings chosen for analysis, the onsite measurements taken, and the comfort models used are all detailed below.

2.1. The church buildings under study

There are 359 churches in the Maltese Islands, with a church density of slightly more than one church per square kilometre. Hence, it is not practical to perform a comfort analysis on all of them. Analysis was therefore carried out on a smaller number of buildings, termed "reference buildings" (RBs), representing all categories of typical churches in Malta. RBs were chosen based on "*real example*" buildings having average physical and occupational characteristics for each of the church categories under study. The building stock categories were derived according to the location, construction period, building size and shape RB classification approach, as proposed by Ballarini et al. [45]. With respect to location, and given the small size of the islands (316 km²), only one climatic zone is usually studied and defined [46]. The building style is also heavily influenced by the period of construction. Thus, the main resulting criteria for classification were the following: 17th to mid-18th century Baroque period, mid-20th century neoRomanesque style architecture, and late 20th century (post Vatican Council II style) contemporary architecture.

Fig. 2. The Annunciation Parish Church, Balzan.

Fig. 3. Stella Maris Parish Church, Sliema.

Fig. 4. St. Joseph Parish Church, Msida.

In total five RB churches were chosen as follows. The Annunciation Parish Church of Balzan and the Stella Maris Parish Church of Sliema represent typical urban inland size churches for the 17th to mid-18th century Baroque period. The St. Joseph Parish Church of Msida has the same building category but has a much larger floor area and volume and is located by the sea. Santa Venera Parish Church of Santa Venera represents the typical mid-20th century neoRomanesque style architecture church, while Our Lady of Mount Carmel Parish Church of Fgura represents the contemporary building. Further history and architecture information on these churches can be found in [47]. Photographs depicting each church building is shown in Figs. 2 to 6 below.

Table 1 in Section 2.2 characterises each of these buildings in terms of form, envelope, system and operation as per data collection requirement for RBs identified in [48]. All the churches were mainly analysed for thermal comfort in their natural ventilated environment with no space heating and cooling. The baroque

Table 1
Physical characteristics of the church buildings under study.

Church	Location	Opening hours	Envelope	U-value (W/m^2K) [49,50]	Internal heat capacity (Kj/m^2K) [51]	Thermal diffusivity (m^2/s) [49–51]	Window to wall ratio	Floor area	Surface area (m^2) and air volume (m^3)	System	Glazing area open (%)
The Annunciation Parish Church, Balzan	Inland	Mon- Fri: 6:00–9:00am, 18:00–20:00pm, Sat 6:00–9:00am, 17:00–20:00pm, Sun 6:00–13:00pm, 17:00–20:00 pm	External wall	0.54	180	11.44×10^{-7}	$N = 3.6\%$	$718m^2$	1:2.25 (Sur. Area $3308m^2$ & Vol. $8337m^3$)	Naturally & Mechanically Ventilated	0%
			Glazing	6		3.4×10^{-7}	$S = 3.6\%$				
			Floor	1.92	154	2.42×10^{-6}	$E = 3.6\%$				
			Roof	2	180	9.69×10^{-7}	$W = 3.6\%$				
Stella Maris Parish Church, Sliema	Inland	Mon- Fri: 6:00–9:00am, 18:00–20:00pm, Sat 6:00–9:00am, 17:00–20:00pm, Sun 6:00–13:00 pm, 17:00–20:00 pm	External wall	0.49	180	11.44×10^{-7}	$N = 2.6\%$	$375m^2$	1:2.5 (Sur. Area $2490m^2$ & Vol. $5415m^3$)	Naturally & Mechanically Ventilated (ACs installed on 19/05/2018)	20%
			Glazing	6		3.4×10^{-7}	$S = 2.6\%$				
			Floor	2.55	200	2.42×10^{-6}	$E = 2.4\%$				
			Roof	2.33	180	9.69×10^{-7}	$W = 2.4\%$				
St. Joseph Parish Church, Msida	Seaside	Mon- Fri: 6:00–9:00am, 18:00–20:00pm, Sat 6:00–9:00am, 17:00–20:00pm, Sun 6:00–13:00pm, 17:00–20:00pm	External wall	0.49	180	11.44×10^{-7}	SW = 7%	$1261.5m^2$	1:3 (Sur. Area $4525.2m^2$ & Vol. $15,239m^3$)	Naturally Ventilated	3%
			Glazing	6		3.4×10^{-7}	SE = 2%				
			Floor	2.54	200	2.42×10^{-6}	NW = 6%				
			Roof	2.2	180	9.69×10^{-7}	NE = 7%				
Santa Venera Parish Church, Santa Venera	Inland	Mon- Fri: 6:00–9:00am, 18:00–20:00pm, Sat 6:00–9:00am, 17:00–20:00pm, Sun 6:00–13:00pm, 17:00–20:00pm	External wall	1.8	180	13.71×10^{-7}	SW = 0%	$1137m^2$	1:5 (Sur. Area $4136m^2$ & Vol. $19,682m^3$)	Naturally Ventilated	2%
			Glazing	6		3.4×10^{-7}	SE = 11%				
			Floor	2.07	200	2.42×10^{-6}	NW = 0%				
			Roof	1.03	120	9.69×10^{-7}	NE = 11%				
Our Lady of Mount Carmel Parish Church, Fgura	Inland	Mon- Fri: 6:00–9:00am, 18:00–20:00pm, Sat 6:00–9:00am, 17:00–20:00pm, Sun 6:00–13:00pm, 17:00–20:00pm	External wall	2.52	227	7.6×10^{-7}	$N = 18\%$	$661.4m^2$	1:3 (Sur. Area $2185m^2$ & Vol. $7446m^3$)	Naturally Ventilated	23.5%
			Glazing	6		3.4×10^{-7}	$S = 18\%$				
			Floor	2.24	200	2.42×10^{-6}	$E = 18\%$				
			Roof	2.52	227	7.6×10^{-7}	$W = 18\%$				

Fig. 5. Santa Venera Parish Church, Santa Venera.

Fig. 6. Our Lady of Mount Carmel Parish Church, Fgura.

churches are mainly composed of thick masonry globigerina limestone load bearing walls (varying in thickness between 1.5 m and 2.0 m) supporting a vaulted roof and dome structure. In contrast, the neo Romanesque style church is composed of two leaf (0.23 m each) load-bearing globigerina masonry walls with concrete infill supporting reinforced precast planks forming the roof. The more contemporary and modern church is built in concrete (with thickness reduced to only 0.15 m), whereby the strength of the structure is derived from its form rather than its sheer mass. A depiction of the different methodologies of constructions is shown below.

2.2. On site measurements

The five churches were monitored for one year during the period between January and December 2018, both months included. The two parameters measured for all churches at 5-minute intervals were the air temperature (°C) and the percentage relative humidity (RH) for both the interior and exterior environment. However, for the purpose of this study comfort analysis according to EN 16,798–1 has considered the internal and external temperatures. The physical characteristics of the church buildings under study are tabulated in Table 1 below.

Onset's HOBO MX1101 data loggers were used to measure and transmit dry bulb temperature and relative humidity (RH) data wireless to mobile devices via Bluetooth Low Energy (BLE) technology. The MX1101 data logger measures RH and Temperature. Technical specifications of the adopted instruments are shown in Table 2 below [52] and the location of the sensors is depicted in Figs. 7 to 11 below.

2.3. Thermal comfort analysis

Current thermal comfort standards are based on either heat balance or adaptive models. The EN 16,798–1 standard includes both the heat balance model (PMV/PPD Model) and the Adaptive Comfort Model. According to EN 16,798–1 [43], the PMV/PPD Model is applicable for mechanically heated and /or cooled buildings, while the adaptive comfort model should be applied to buildings without mechanical cooling (naturally ventilated).

The PMV/PPD Model is a heat balance model that examines thermal physiology by presuming controlled uniform conditions and precise analysed variables such as activity level, thermal resistance of clothing, air temperature, mean radiant temperature, relative air velocity, and water vapour pressure in ambient air [53]. In this model, comfort conditions are fixed (i.e. independent of external factors such as outdoor temperature) and occupants are assumed not able to adapt to the external environment.

In contrast, the adaptive model investigates the dynamic relationship between occupants and their general environments based on the principle that people tend to react to changes that produce discomfort by seeking methods of restoring their comfort levels [54]. Such adaptation includes physiological, psychological, and behavioural adjustments simultaneously [54–56]. Therefore, the adaptive model provides greater flexibility in matching optimal indoor temperatures with outdoor climate, particularly in naturally ventilated buildings [57–60]. Adaptive standards can therefore be considered more appropriate for supporting comfort in low energy buildings [56,57,61–63].

The EN 16,798–1 Adaptive Comfort Model provides acceptable indoor temperature limits as a function of the exponential weighted running mean of the outdoor temperature. Given that this study assesses thermal comfort mainly in naturally ventilated churches, with Balzan and Sliema Parish Churches being mechanically cooled for interim periods during the summer and autumn, the EN 16,798–1 Adaptive Comfort Model is the model of interest for this study. It must be noted that for the scope of this study the deviation between the operative temperature, which is employed in standard EN 16,798–1 Adaptive Comfort Model and the dry-bulb air temperature, which was directly measured from the sensors is negligible, as already demonstrated in previous published literature [64].

The churches under study also meet the criteria that allows application of the adaptive model, namely that buildings are used mainly for human occupancy having sedentary activities and where occupancy may have flexibility to adapt their clothing to the indoor and/or outdoor thermal conditions. The relationship adopted by EN 16,798–1 between the operative comfort temperature and the outdoor running mean temperature are depicted in Fig. 12 below.

2.4. Key

Θ_{rm} = Running mean outdoor temperature °C.
Θ_o = Indoor operative temperature °C.
The equations representing the lines in the figure are:

Category I upper limit: $\Theta_o = 0.33\Theta_{rm} + 18.8 + 2$ lower limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 - 3$

Category II upper limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 + 3$ lower limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 - 4$

Category III upper limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 + 4$ lower limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 - 5$ where Θ_o = indoor operative temperature, °C

Θ_{rm} = running mean outdoor temperature, °C

These limits apply when $10 < \Theta_{rm} < 30$ °C for upper limit and $15 < \Theta_{rm} < 30$ °C for lower limit.

As can be identified from the Fig. 12, the model provides comfort limits according to three different categories depending on the level of expectations of the occupants. For churches, category III level has been selected, which reflects an acceptable, moderate level of expectation for existing buildings. Description of the applicability of the categories I to IV as per EN 16,798–1 is explained in Table 3 below.

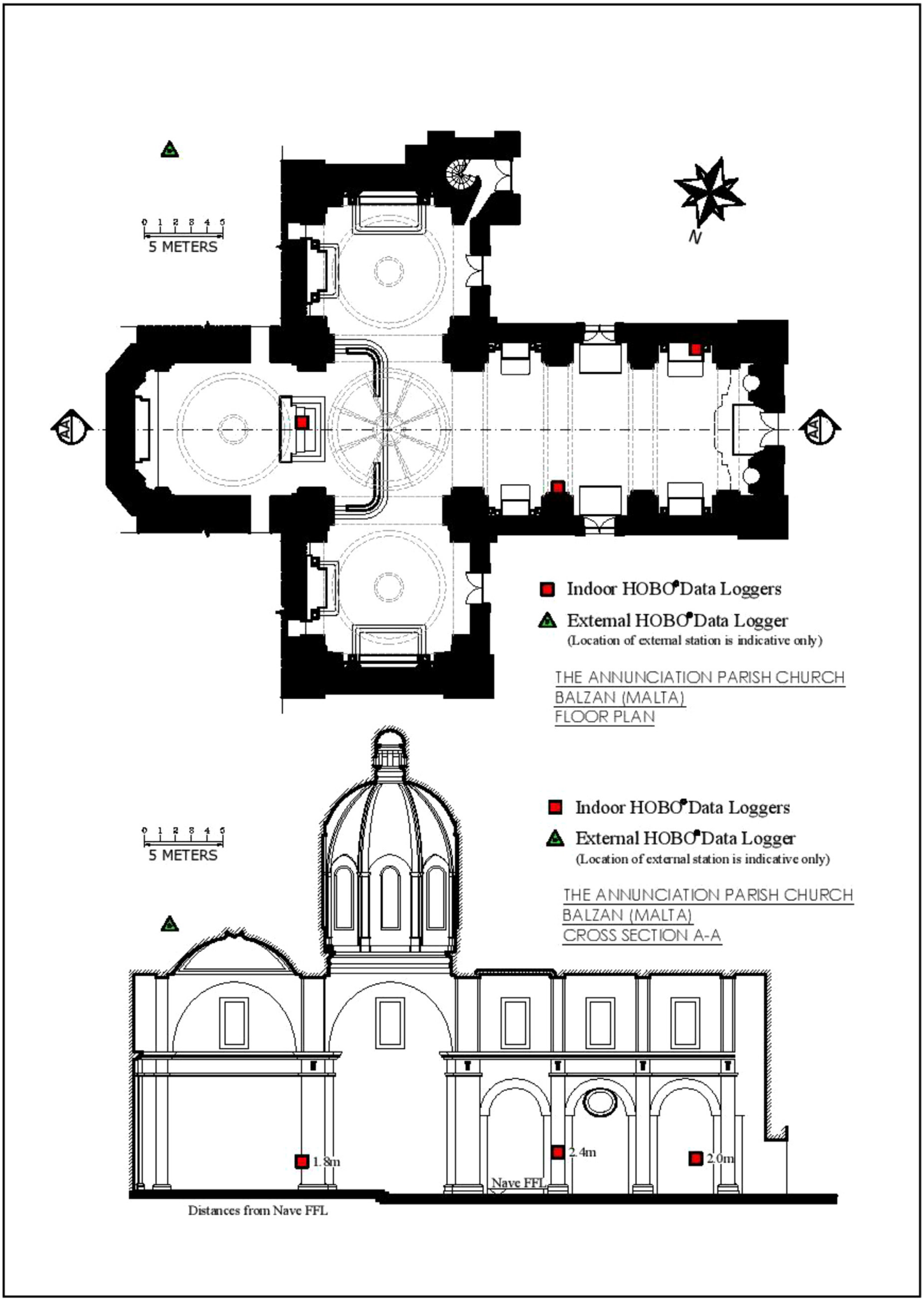

Fig. 7. The Annunciation Parish Church, Balzan.

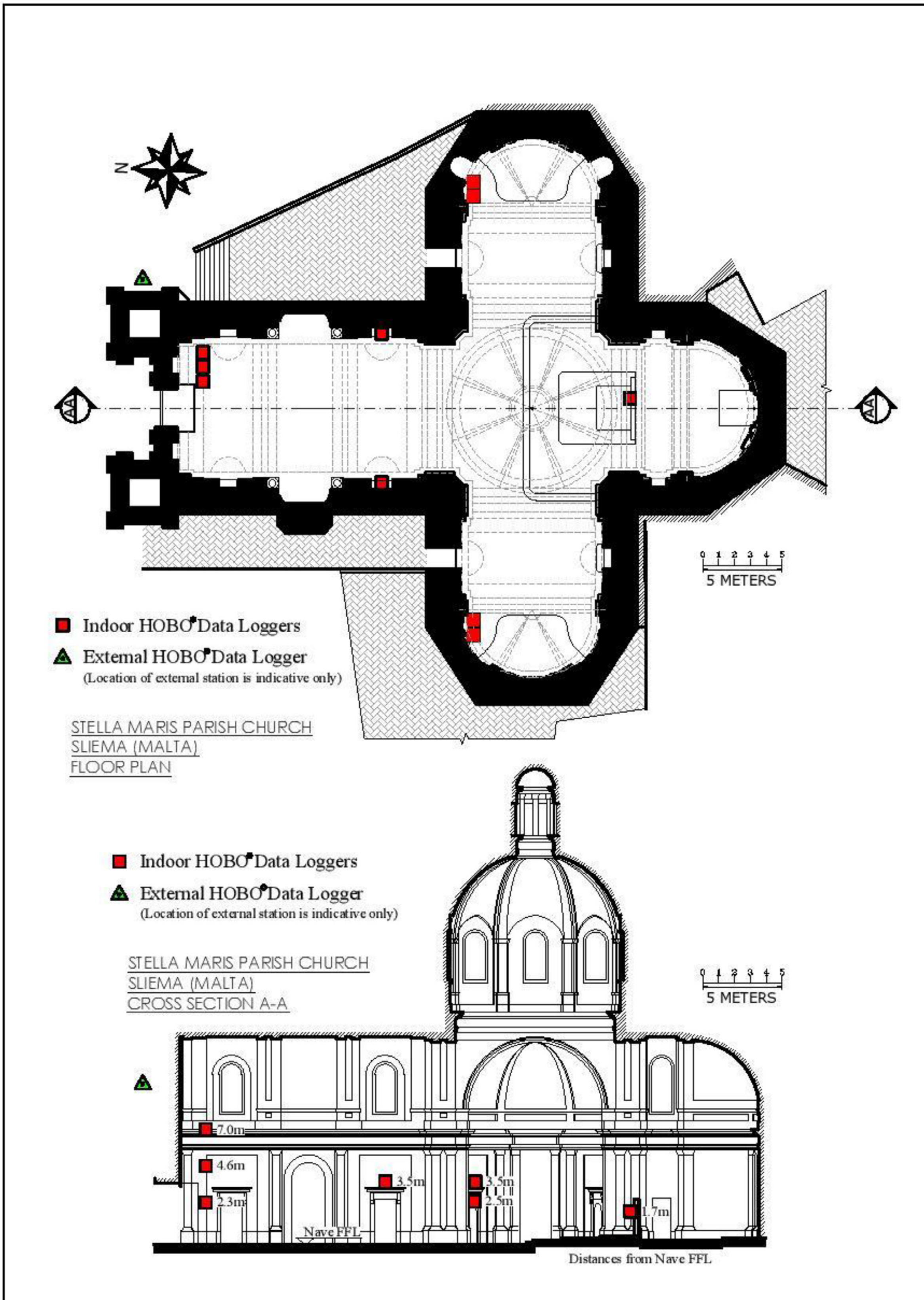

Fig. 8. Stella Maris Parish Church, Sliema.

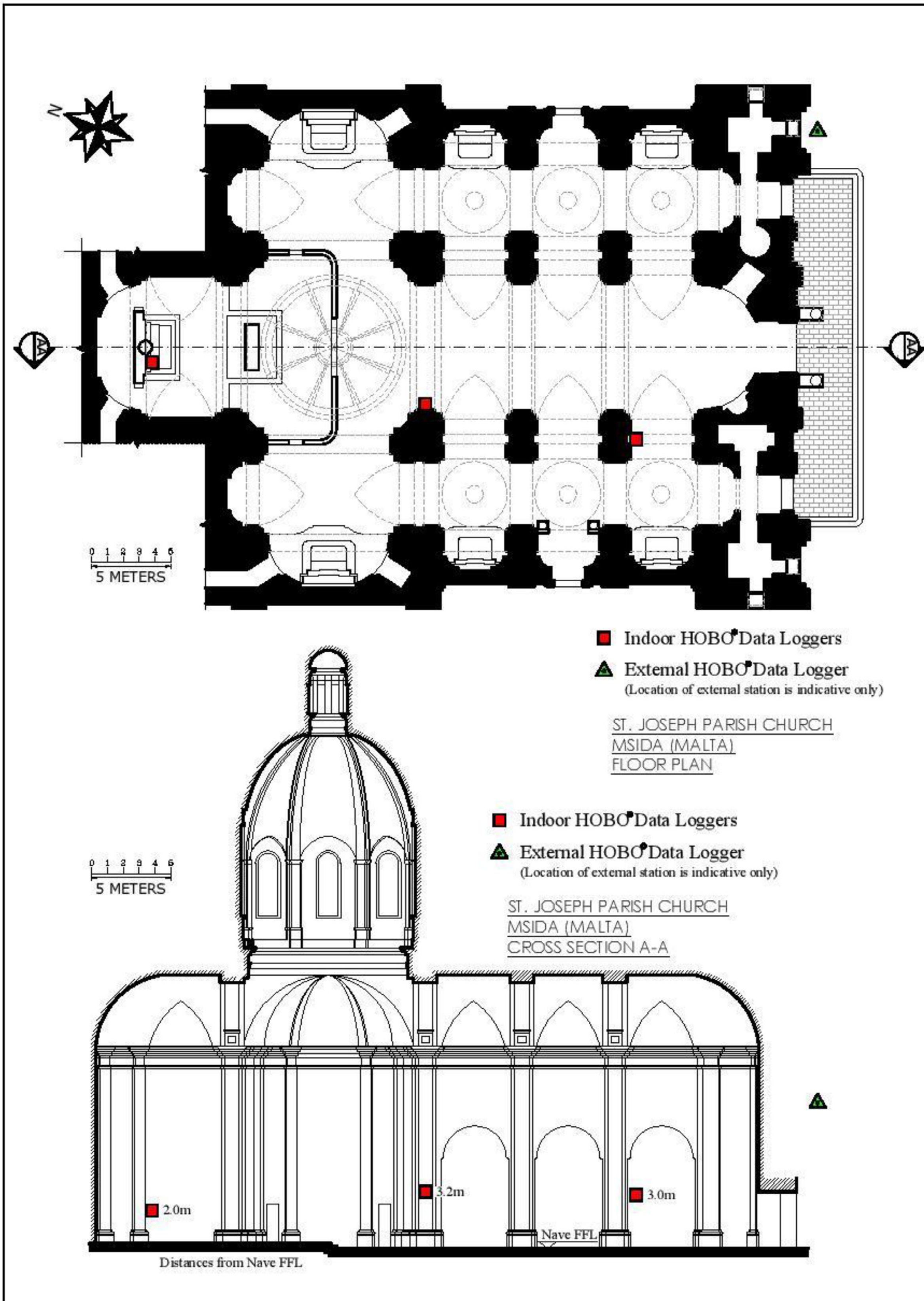

Fig. 9. St. Joseph Parish Church, Msida.

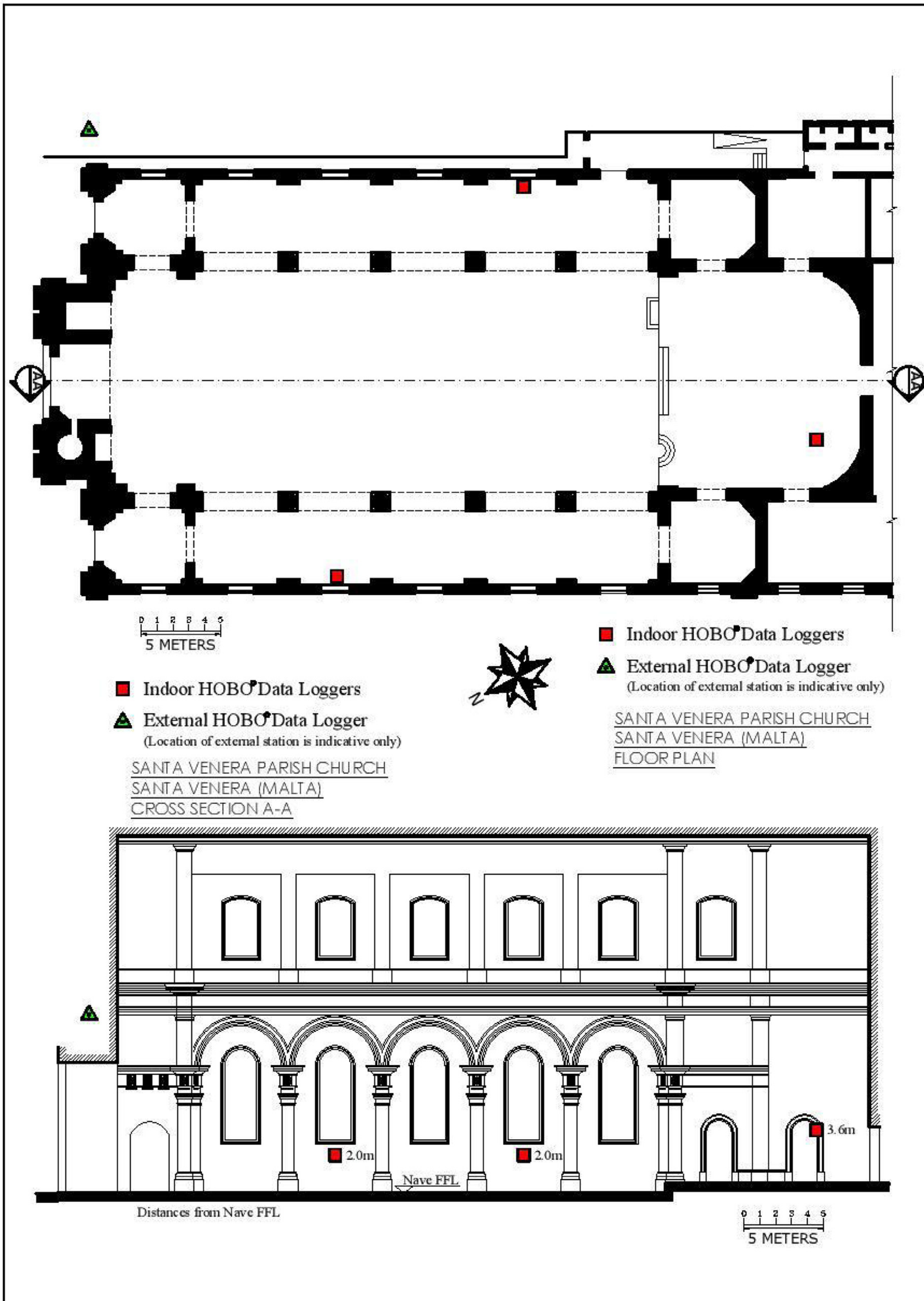

Fig. 10. Santa Venera Parish Church, Santa Venera.

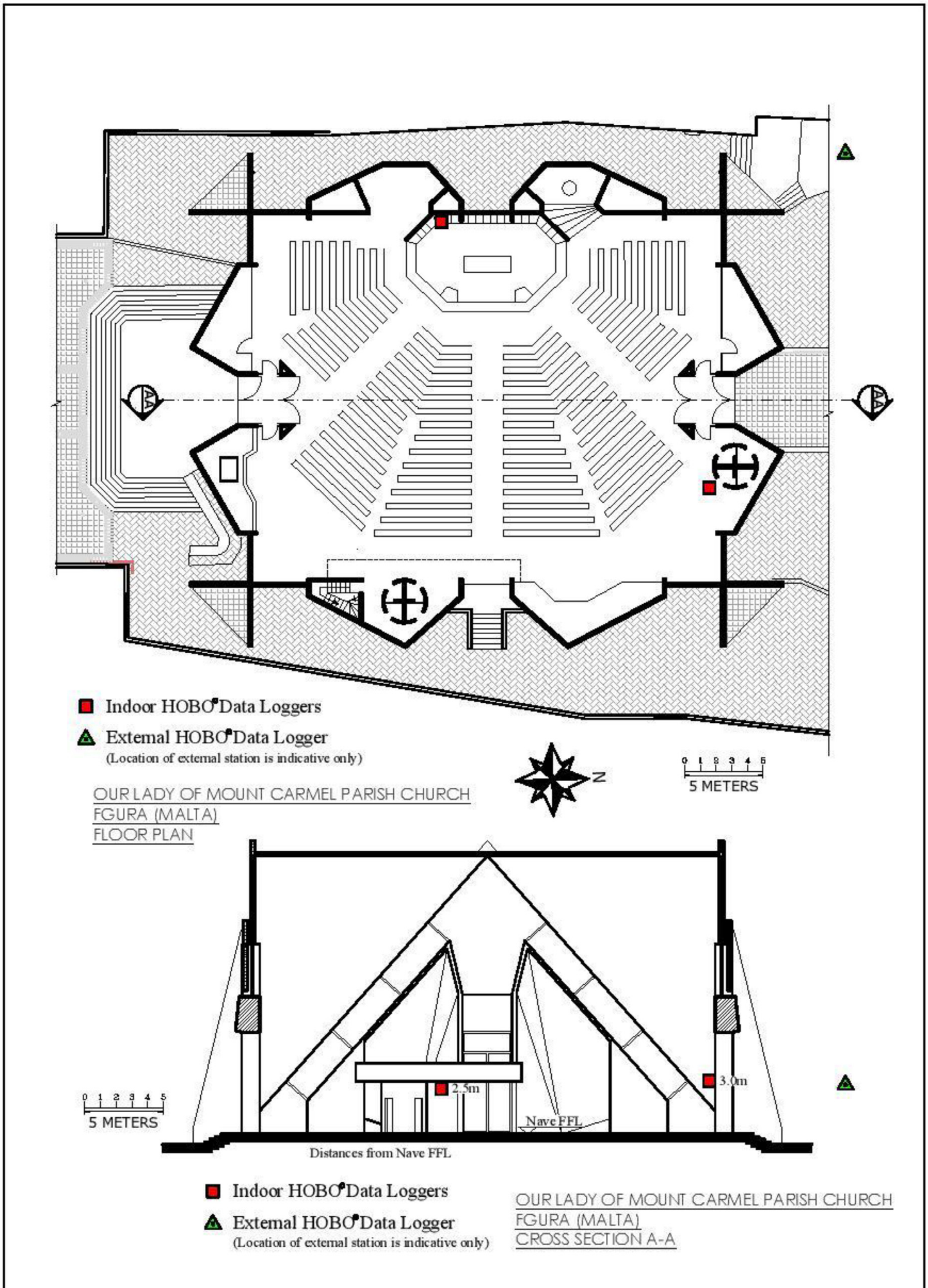

Fig. 11. Our Lady of Mount Carmel Parish Church, Fgura.

Table 2
Accuracy and resolution of the adopted measure instrument.

Temperature Sensor	
Range	−20° to 70 °C (−4° to 158°F)
Accuracy	±0.21 °C from 0° to 50 °C (±0.38°F from 32° to 122°F)
Resolution	0.024 °C at 25 °C (0.04°F at 77°F)
Drift	<0.1 °C (0.18°F) per year
RH Sensor*	
Range	1% to 90%, non-condensing
Accuracy	±2.0% from 20% RH to 80% RH typical to a maximum of ±4.5% including hysteresis at 25°C (77°F); below 20% RH and above 80% RH ±6% typical
Resolution	0.01%
Drift	<1% per year typical

* As per RH sensor manufacturer data sheet.

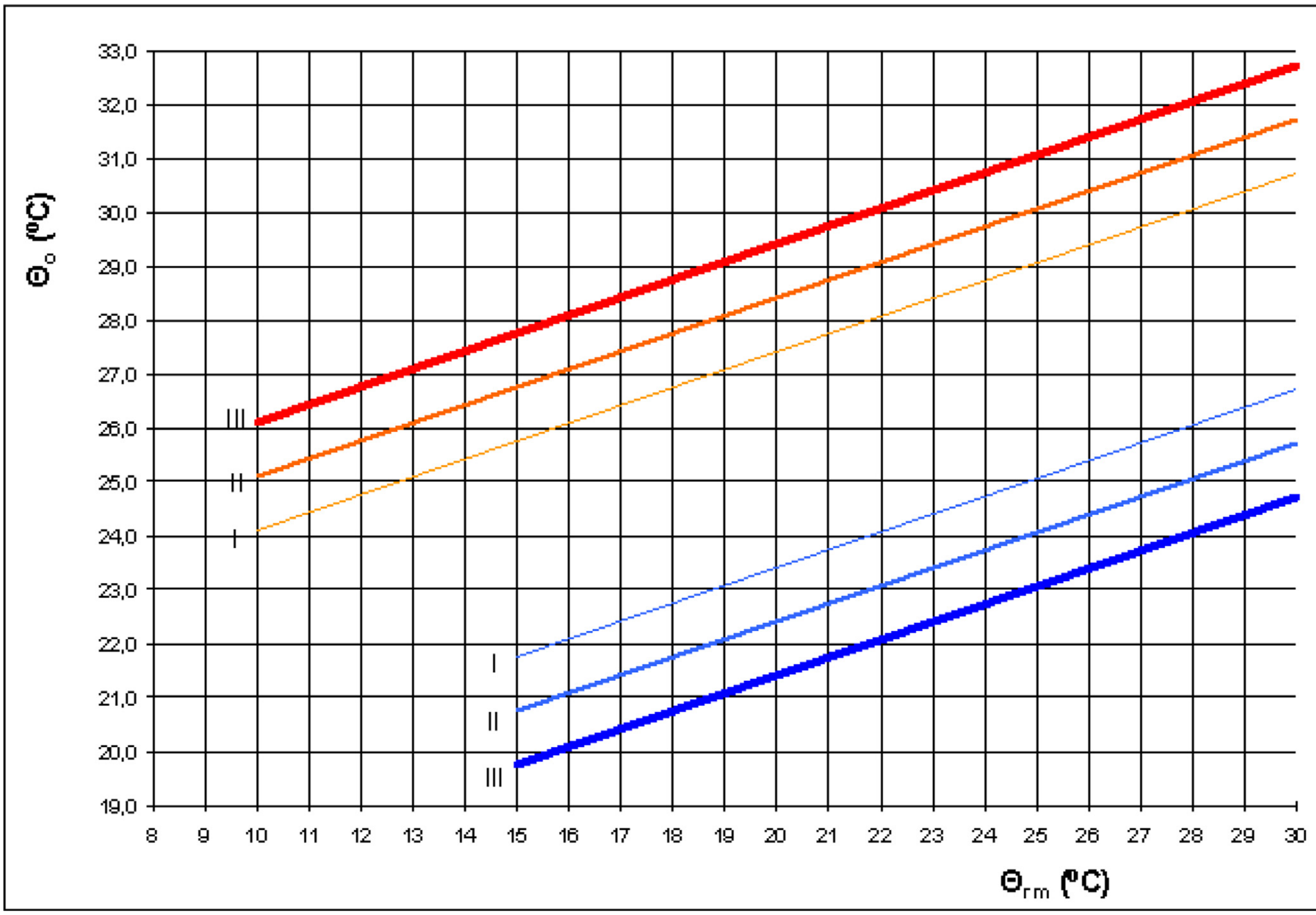

Fig. 12. Design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially weighted running mean of the outdoor temperature [43].

Table 3
Description of the applicability of the categories used (EN 16,798–1).

Category	Description
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements
II	Normal level of expectation and should be used for new building and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Sample dry-bulb air temperatures was recorded at five-minute interval for the year 2018 and retrieved from three HOBO calibrated sensors located along the main nave. These were situated at a height that reflects the actual environment experienced by the church occupants and avoiding the influence of direct solar radiation. As mentioned above, comparative studies between the three sensors were carried out. As an example, the comparative analysis for Stella Maris Parish Church (Sliema) is graphically depicted in Fig. 13 below. The results of the other churches under review also proved to be giving similar results.

The temperature readings obtained for the internal and external environments of the five churches were tabulated in excel format. These measurements were then transposed from 5-minute intervals to hourly values by taking the respective mean per hour from

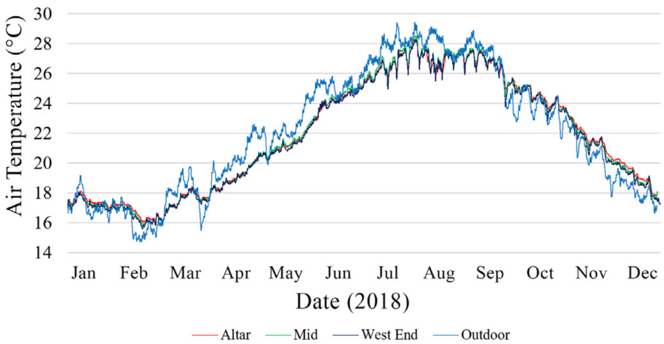

Fig. 13. Comparative analysis of hourly data retrieved from centrally located sensors on the main nave and outdoor station at Stella Maris Parish Church, Sliema.

the readings once any data outliers were omitted. Each dot on the represented graphs below mark the hourly mean values and the resulting sinusoidal wave between the vertical axes mark the diurnal cycle.

The annual readings throughout Spring, Summer, Autumn and Winter, were further analysed to establish which period of the year for each selected church is within the comfort limit of category III level. The following formula was used to generate the outdoor mean temperature in conformity with EN 16,798–1 standard and the resulting values were interpolated into the category III formulae referred to above:

$\Theta_{rm} = (\Theta_{ed\text{-}1} + 0{,}8\ \Theta_{ed\text{-}2} + 0{,}6\ \Theta_{ed\text{-}3} + 0{,}5\ \Theta_{ed\text{-}4} + 0{,}4\ \Theta_{ed\text{-}5} + 0{,}3\ \Theta_{ed\text{-}6} + 0{,}2\ \Theta_{ed\text{-}7})/3.8$ where:

$\Theta_{rm=}$Outdoor Running mean temperature for the considered day (°C)

$\Theta_{ed\text{-}1}$ = daily mean outdoor air temperature for previous day

α = constant between 0 and 1 (recommended value is 0.8)

$\Theta_{ed\text{-}i}$ = daily mean outdoor air temperature for the *i th* previous day

The upper limits for the summer design and typical weeks were increased by 1.2 °C due to the presence of fans with 0.6 m/s wind speed as shown in the formula below:

Category III Summer design and typical upper limits: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 + 4 + 1.2$

The typical weeks for all four seasons and the design weeks for both summer and winter seasons were determined through the use of the statistical function tool of EnergyPlus engine through Design Builder using the 2018 Malta weather file. An hourly EPW file containing the actual data collected for the measured outdoor conditions of each church was created to comply with EnergyPlus requirements. This enabled the (EPW) weather file designed for 2018 to be processed in Design Builder and to automatically identify the design and typical weeks based on statistical data [65].

The typical week was considered in addition to the design week to compare the resulting difference in comfort during a typical week (the week that is composed with the most frequently occurring/repetitive temperatures out of a whole season) versus the worst case (hottest or coldest) design week. For the typical and design weeks, a time series plot was then carried out by plotting the measured hourly outdoor air temperatures and indoor air temperatures on the same graph as the comfort temperature limits to identify the extent to which the buildings can meet EN 16,798–1 adaptive comfort limits. It must be noted, that the comfort analysis has concentrated on Winter, Spring, Summer and Autumn typical and design weeks, as it can be reasonably assumed that if comfort is met in these reference weeks, it can be met for all the other weeks throughout the year. The results to the above are graphically shown in Section 3 below for each respective church, reflecting the level of comfort for existing buildings within selected category in conformity to EN 16,798–1.

3. Results & discussions

Results graphically represented in Figs. 14–18 below clearly illustrate significant variations in the mean hourly temperatures (T) between the different churches. These variations were also evidenced between the mean indoor and outdoor T recorded throughout 2018 depicted in Figs. 19–23 below. In all churches, it is apparent from the results obtained that the presence of a large congregation induced limited sporadic fluctuations in the church interior ambient conditions.

In addition to the above observations, the plots for both Balzan and Sliema Parish Churches (Figs. 14 and 15), also highlight the use of mechanical cooling due to abrupt decrease in the internal T, when the external T is increasing. This is mainly depicted in both summer design and typical weekends (4–5th August and 15–16th September), when the air-conditioners were switched on for intermittent cooling periods. The use of mechanical cooling was used only in weekends and feast days, as the expected number of people attending Holy Mass is higher in weekends when compared to weekdays. More importantly, this graphical representation of free running structures with intermittent mechanical cooling, highlights the fact that notwithstanding indoor temperature was recorded within comfort limits, the requirement for mechanical cooling is still sought after.

For the winter design week, where the outdoor T is at its minimum, all churches had the internal T below the lower limit of comfort. However, as the Baroque churches have an overall high thermal mass when compared to the mid-20th century neoRomanesque style architecture, and late 20th century (post Vatican Council II style) contemporary architecture, the internal T showed steady behaviour throughout the days, while it fluctuated between day and night for the more recent architectural style churches. This behaviour is also evident in those churches for respective seasonal typical weeks, as shown in Figs. 14-18 above. The lower overall thermal mass in contemporary churches is further aggravated by the higher percentage of glazing. Glazing causes solar overheating in summer, especially for East and West directions, as in the case of Santa Venera and Fgura Churches. Also, given that the U-value of glazing is high (around 6 W/m²K), it serves as a medium for heat losses from within the church to the outside atmosphere, during winter.

In contrast to the winter typical week, the spring typical week showed a significant improvement in comfort. The overall recorded indoor and outdoor T are higher due to recorded exterior warmer temperatures on approaching the summer season, thus resulting with an indoor air temperature within the comfort limit for all churches. However, indoor T readings show fluctuations with higher amplitude for more contemporary churches (Santa Venera and Fgura), when compared to Baroque churches (Sliema, Msida and Balzan). This behaviour is once again mainly attributed to lower overall thermal mass of the building, providing minimal "inertia" against temperature fluctuations. This is evidenced by the fact that the indoor T fluctuates in tandem with the outdoor T.

During the summer design and typical weeks, the Baroque churches satisfy the thermal comfort levels, given that all recorded indoor T fall within the EN 16,798–1 [43] category III comfort zone even when the outdoor T reached peak temperatures ranging from 30 °C to 37 °C. This highlights an important difference in the construction methodology from the Baroque churches in relation to the more contemporary structures, which prove to be thermally unconfortable. The difference is mainly in the building envelope which is made up of masonry blocks (high thermal mass) with thick walls ranging from 1.5 – 2 m, thus having low heat trans-

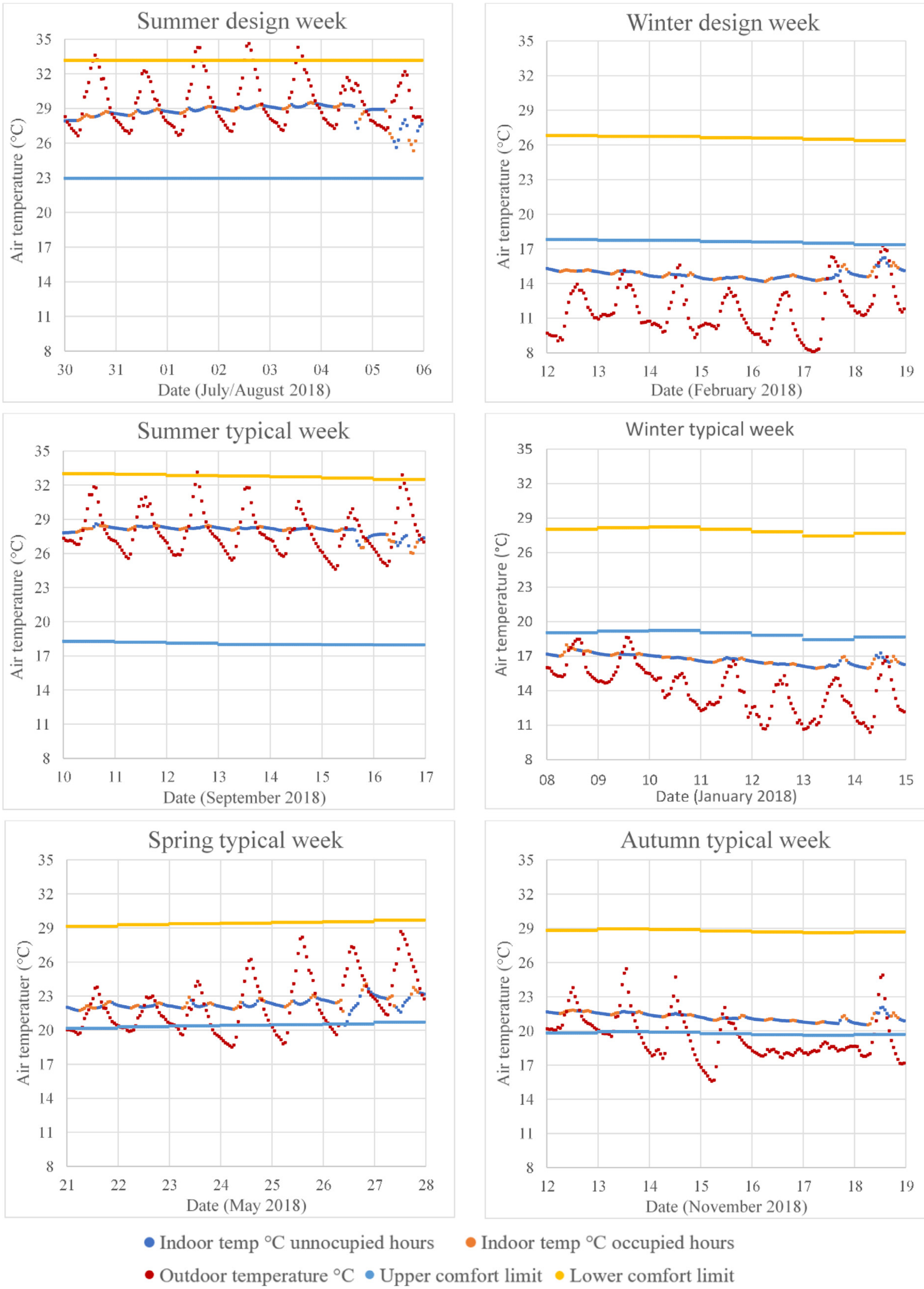

Fig. 14. Balzan – The Annunciation Parish Church – EN 16,798–1 Category 3 Comfort Analysis.

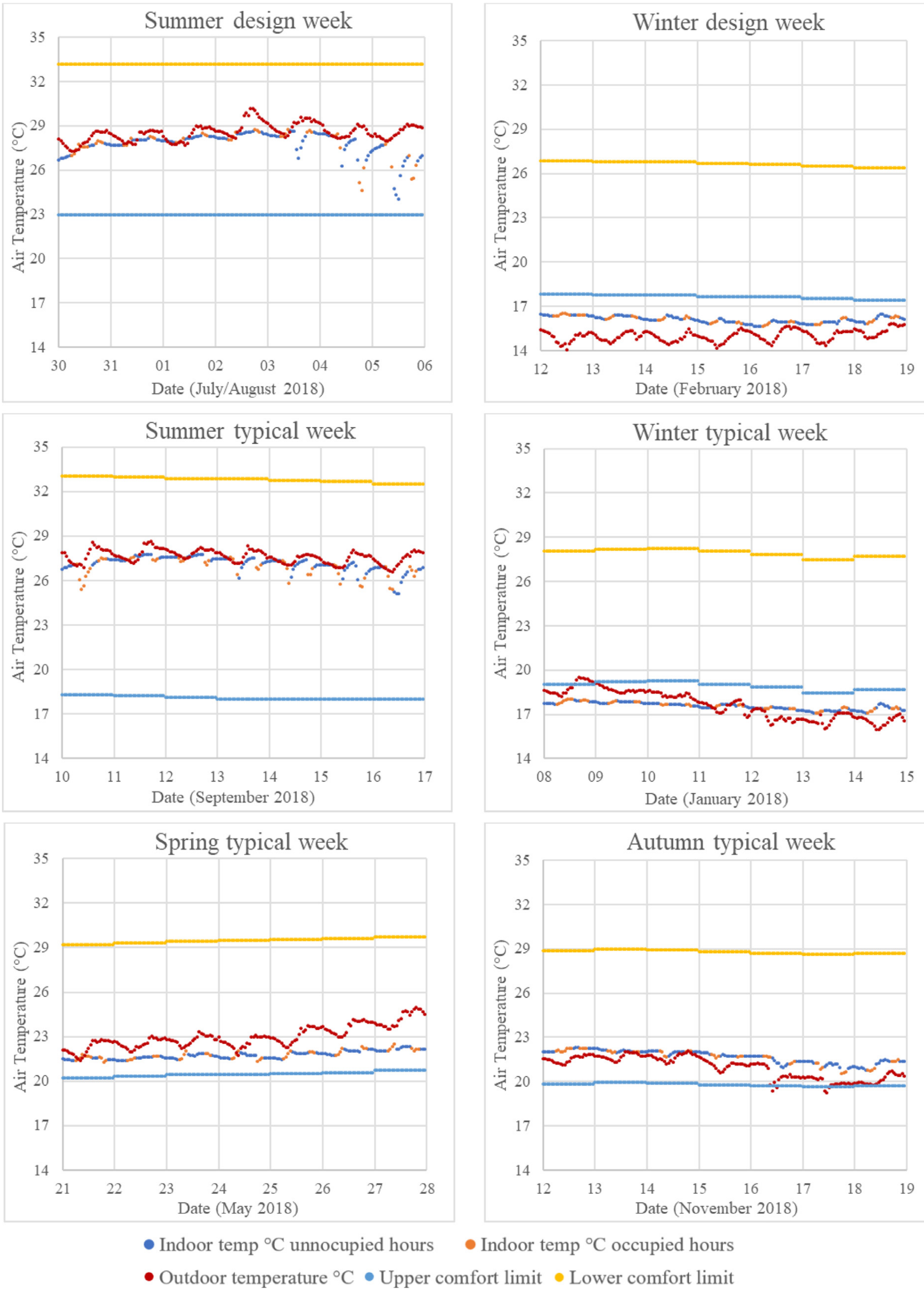

Fig. 15. Sliema – Stella Maris Parish Church – EN 16,798–1 Category 3 Comfort Analysis.

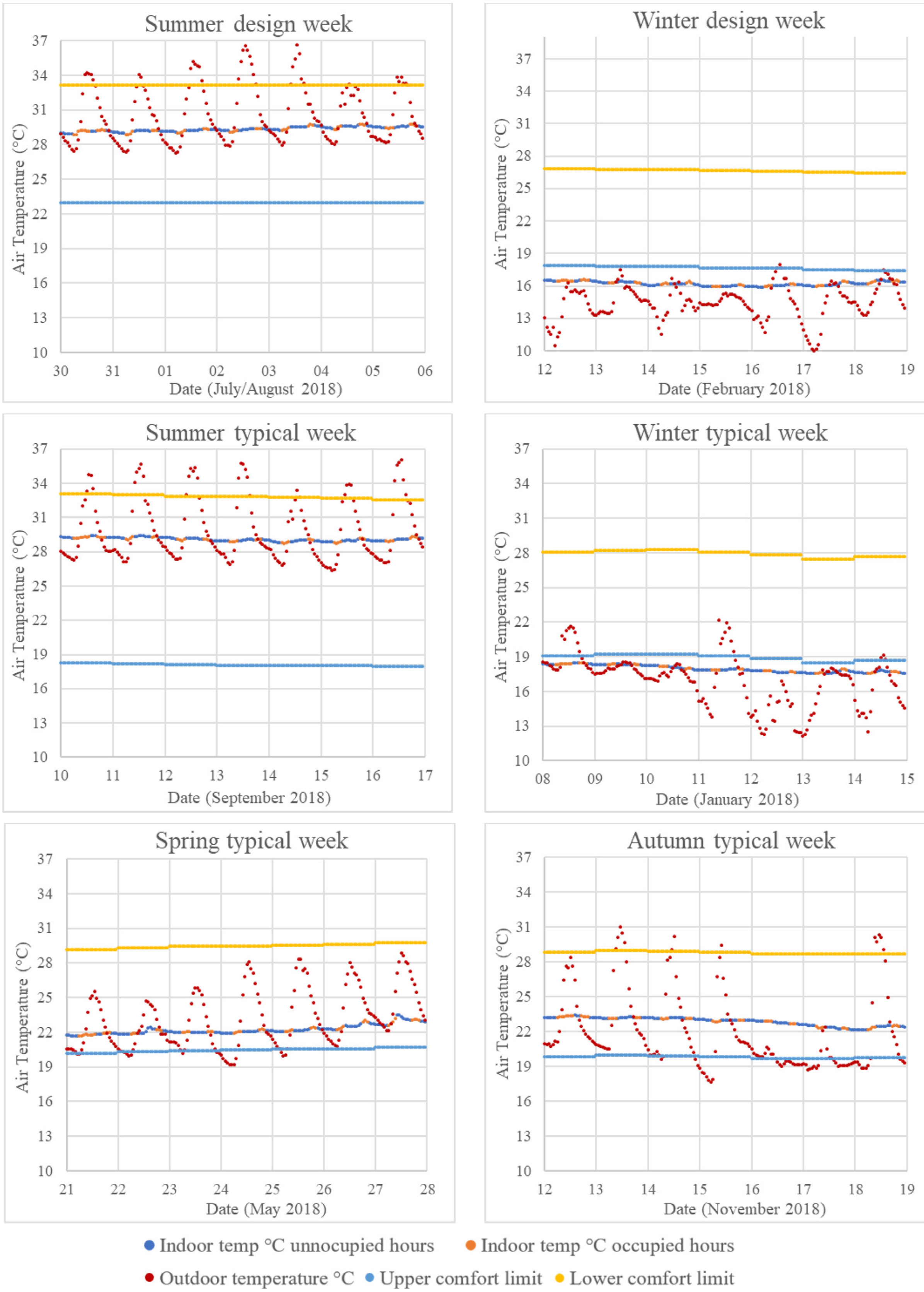

Fig. 16. Msida – St. Joseph Parish Church – EN 16,798–1 Category 3 Comfort Analysis.

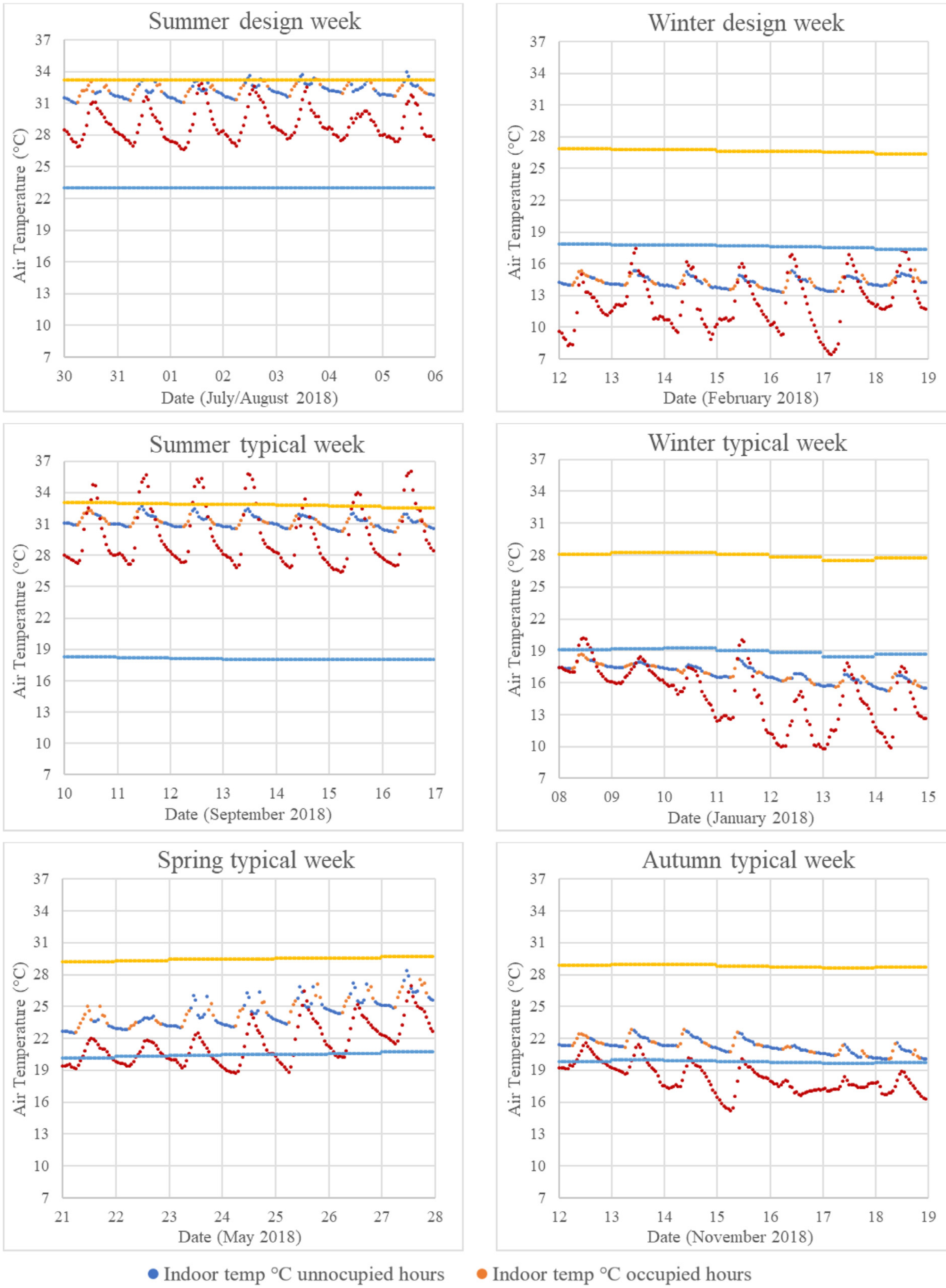

Fig. 17. Santa Venera – Santa Venera Parish Church – EN 16,798–1 Category 3 Comfort Analysis.

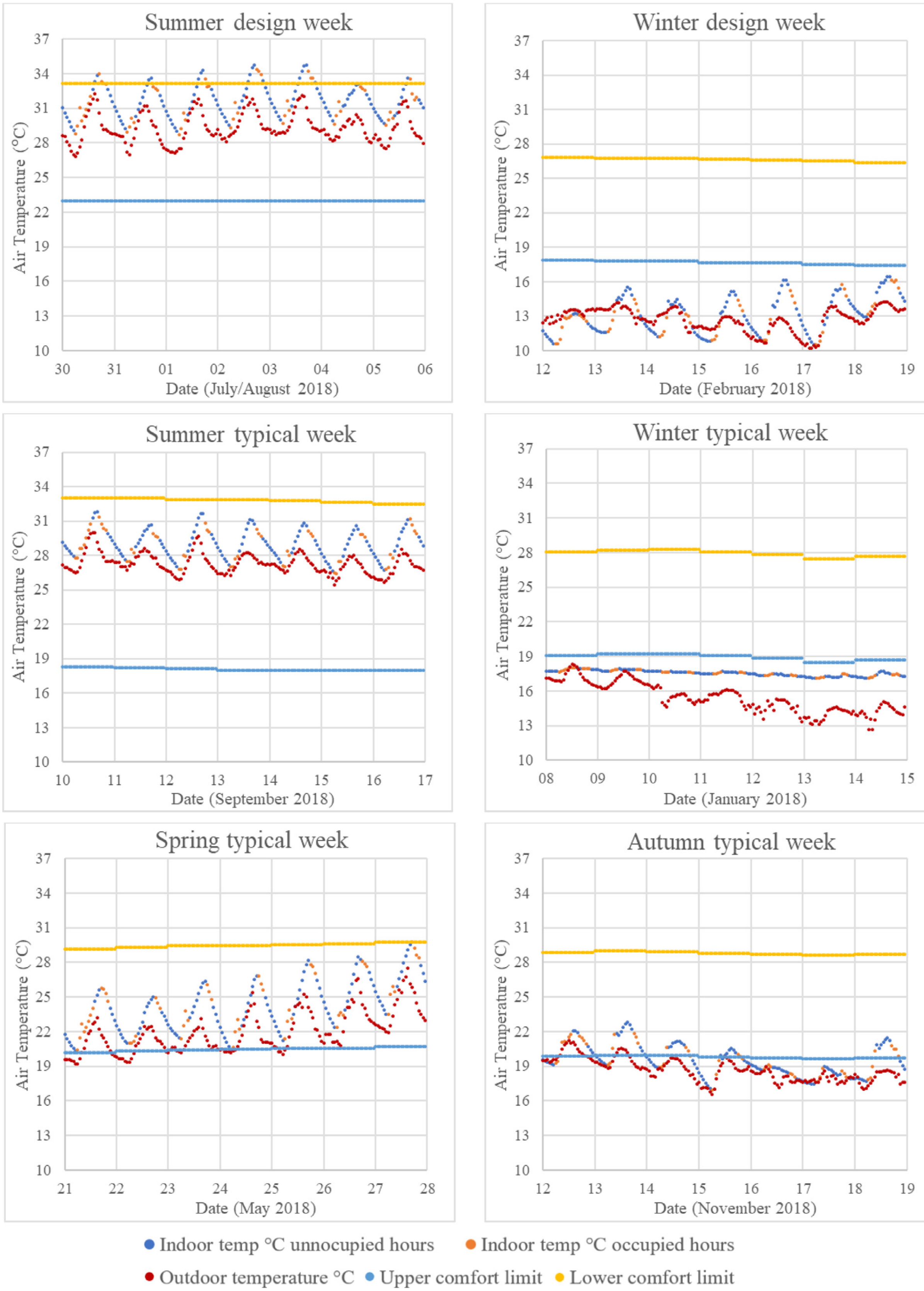

Fig. 18. Fgura – Our Lady of Mount Carmel Parish Church – EN 16,798–1 Category 3 Comfort Analysis.

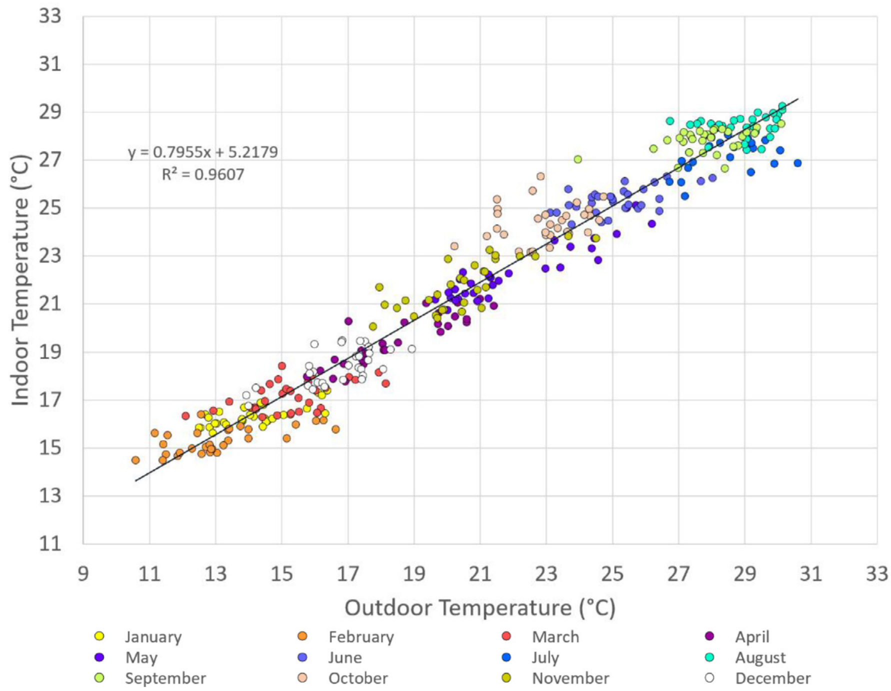

Fig. 19. Graphical comparison showing the daily average internal and the external temperature for The Annunciation Parish Church, Balzan.

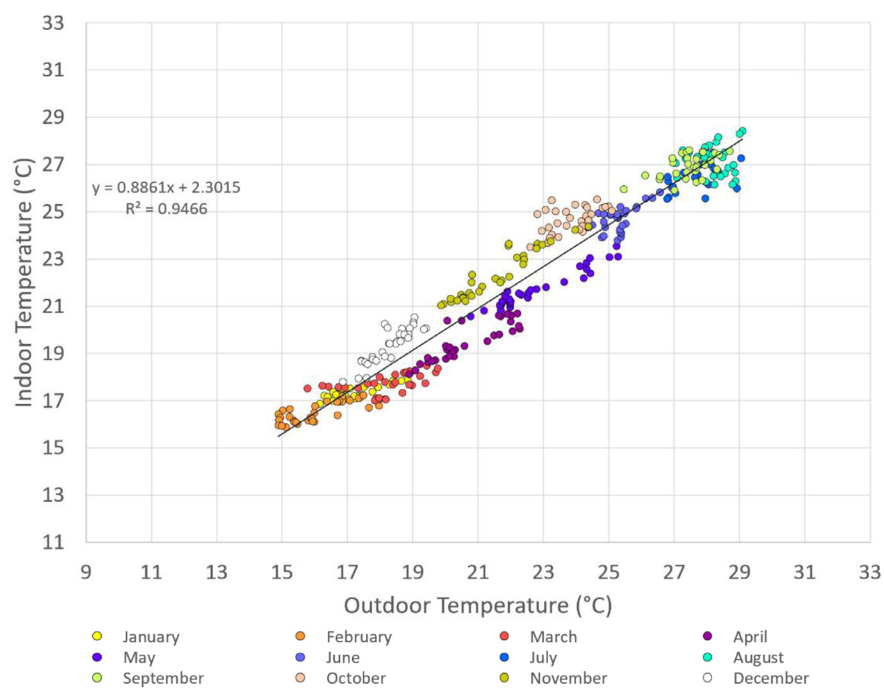

Fig. 20. Graphical comparison showing the daily average internal and the external temperature for The Stella Maris Parish Church, Sliema.

fer (U-value) through the structure, which prevents the indoor T from fluctuating.

Moreover, the glazing to wall area ratio is trivial in Baroque churches when compared to more contemporary styles, comprising only 3% of the total external surface area of the church (Table 1 refer). Conversely, the more contemporary churches depict a more fluctuating indoor T, which works in tandem with the outdoor T, resulting in uncomfortable conditions (Figs. 17 and 18 as compared to Figs. 14–16), for summer design weeks. During mornings for the design and typical weeks, the Fgura Parish Church conformed with EN 16,798–1 [43] Category III thermal comfort requirements, however the recorded afternoon temperatures tend to increase to the extent of exceeding the comfort limit making the church thermally uncomfortable. In this case, the role of glazing is more prominent in increasing indoor thermal discomfort, when compared to the Baroque churches. Moreover, the wall U-value of the Fgura Parish Church is the highest among all churches.

Although the Fgura Parish Church has a higher percentage of glazing when compared to the other RBs, the absolute total area of glazing is higher in Santa Venera Parish Church. This makes the internal temperatures of this church the highest on average among all churches. Glass by itself has a very low thermal mass value and

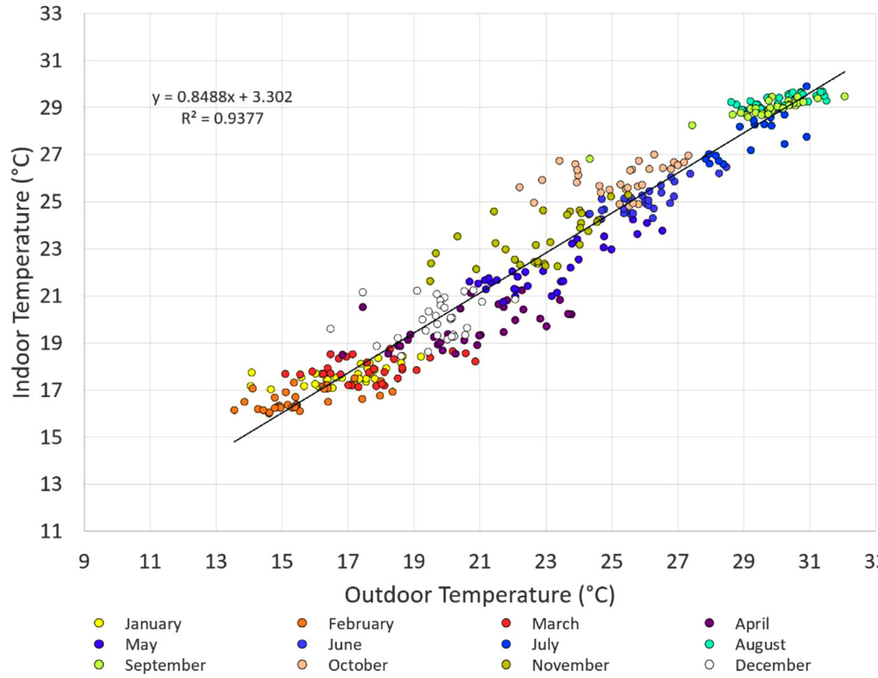

Fig. 21. Graphical comparison showing the daily average internal and the external temperature for The St. Joseph Parish Church, Msida.

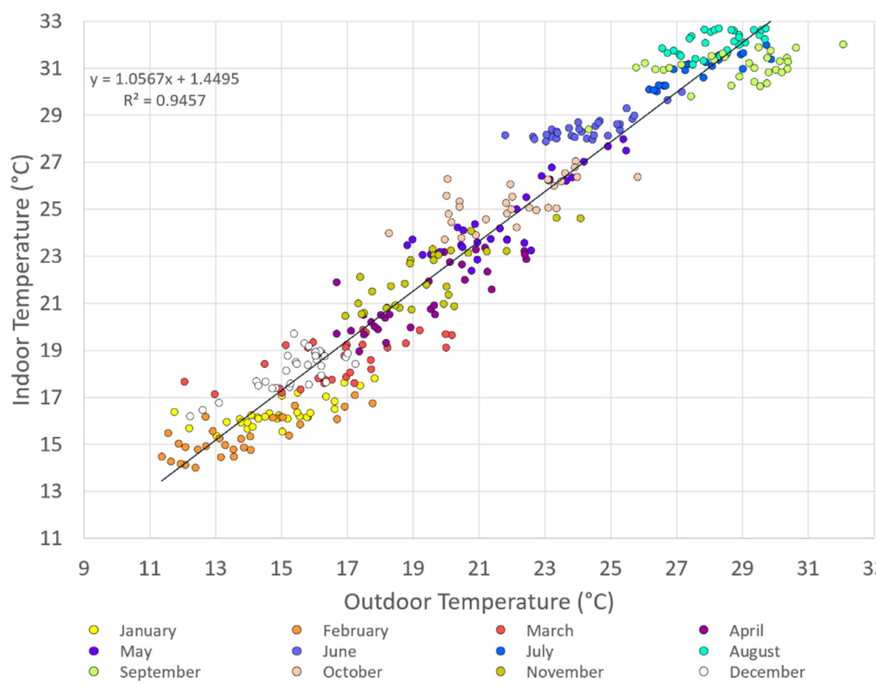

Fig. 22. Graphical comparison showing the daily average internal and the external temperature for The Santa Venera Parish Church, Santa Venera.

at the same time allows solar radiation to pass through and overheat internal space, especially in summer. This is augmented by the fact that the windows are facing south-east and south-west, which are the most critical directions that contribute to highest solar radiation infiltration in the late morning and early afternoon hours, when the solar radiation is relatively high and falling directly on the windows and walls. Furthermore, Santa Venera Parish Church is the only church out of the five under review whereby the *antiporta* (that is a door placed behind the main door to create a small porch) is missing, resulting in induced significant fluctuations in indoor environmental conditions by natural infiltration during service hours.

In Autumn, the Baroque churches prove to be thermally comfortable as all the internal T lie within the thermal comfort zone. The internal T is maintained constant even though the external T fluctuates beyond the comfort limits. On the other hand, the typical week of the Santa Venera Parish Church lies within the comfort limits, but the indoor T fluctuates with the outdoor T. The Fgura Parish Church has proven to be thermally uncomfortable for the typical week, as for most of the time the recorded internal T lies

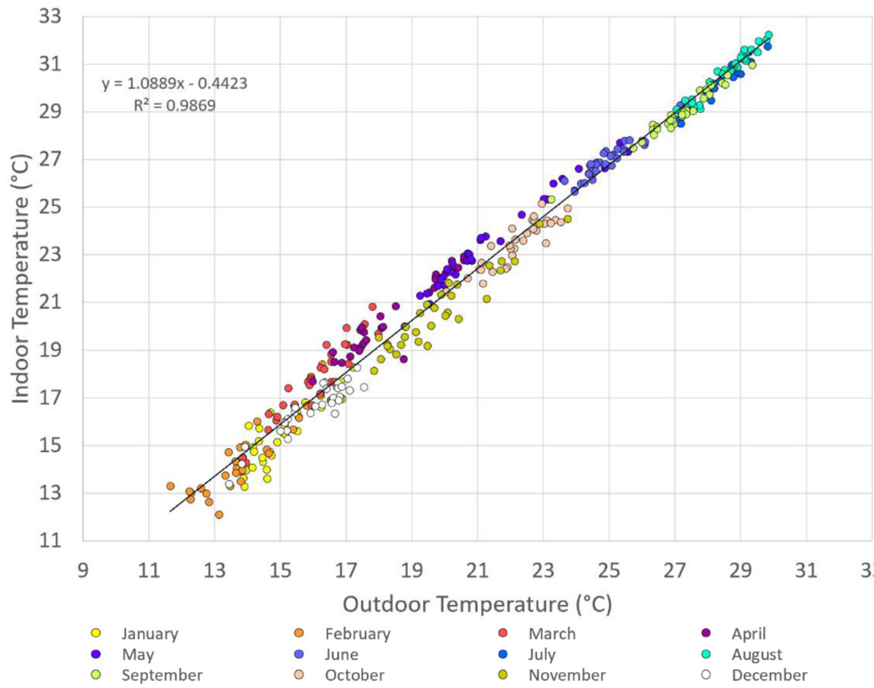

Fig. 23. Graphical comparison showing the daily average internal and the external temperature for Our Lady of Mount Carmel Parish Church, Fgura.

outside the comfort zone, making it non-compliant with the EN 16,798–1 [43] thermal comfort requirements.

Figs. 19–23 show the daily average internal dry-bulb temperature versus the external dry-bulb temperature for the five selected churches, for the period January to December 2018. A strong positive linear relation between the two variables is observed (Pearson correlation (R) > 0.94) This strong linear relation clearly indicates that these churches may be considered as free-running buildings, whereby the external temperature has a marked effect on the internal temperature.

One also notes that the derived linear regression equations for both contemporary churches of Fgura and Santa Venera showed that the indoor temperature was higher than the corresponding outdoor temperature, depicted by the gradient value being larger than 1. This shows that there seems to be at least another factor that is present in these churches that drives the temperatures higher than the ambient temperature. This could be the effect of solar gains, given that these two churches have larger window to wall ratios, when compared to the other three baroque churches.

4. Conclusion

This paper has studied the status-quo of five different churches with respect to thermal behaviour over one full year of analysis (2018). The results attained during this study were mainly derived from a comparison of outdoor T to indoor T by applying the EN 16,798–1 adaptive comfort model. The study has shown that baroque churches, having a higher thermal mass than contemporary churches, exhibit lower indoor temperature fluctuations and comply better with the EN adaptive comfort model especially during the summer period. In contrast for the winter typical and design weeks, the observed hourly temperatures during the occupancy period are below the EN 16,798–1 thermal comfort limits for all churches, implying thermal discomfort. Given that the buildings are free running, for all churches both in winter and summer, a strong positive correlation between the outdoor and indoor hourly dry bulb temperatures was observed.

The study anticipates that regions within the subtropical zone, such as the Mediterranean, require the integration of new criteria for improved applicability in terms of a better way to predict comfort and to better relate to the occupants' level of expectation and comfort levels. All churches in Malta, in particular Baroque churches, were not designed to be mechanically heated or cooled. Today's elevated comfort thresholds threaten the conservation of the fabric and artefacts in the historic churches. In order to address these problems a tailor-made solution for each church would be beneficial not to alter the general indoor macro-climate, whilst addressing the micro-climate where the worshipers congregate. One equation does not fit all, and any intervention should consider the adoption of energy-efficient and preservation-friendly measures. To this effect, an interdisciplinary study needs to be carried out for churches in Malta prior to considering a mechanical air-conditioning system as results from this study show that HVAC systems are not always necessary.

Declaration of Competing Interests

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.

CRediT authorship contribution statement

Robert C. Vella: Methodology, Software, Validation, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Francisco Javier Rey Martinez:** Validation, Writing - review & editing, Supervision. **Charles Yousif:** Conceptualization, Methodology, Software, Resources, Writing - review & editing, Supervision. **Damien Gatt:** Methodology, Software, Validation, Writing - review & editing.

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References

[1] E. Parliament, Commission delegated regulation (EU) No 244/2012 of 16 January 2012 supplementing directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating, 2012.
[2] R. Palen, EU Population up to Nearly 513 Million on 1 January 2018, Eurostat Press Off. (2018). http://ec.europa.eu/eurostat/documents/2995521/9063738/3-10072018-BP-EN.pdf (accessed April 11, 2019).
[3] D.H.C. Toe, T. Kubota, Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates using ASHRAE RP-884 database, Front. Archit. Res. (2013), doi:10.1016/j.foar.2013.06.003.
[4] Ł. Bratasz, R. Kozłowski, D. Camuffo, E. Pagan, Impact of indoor heating on painted wood - Monitoring the altarpiece in the church of santa Maria Maddalena in Rocca Pietore, Stud. Conserv. 52 (2007) 199–210, doi:10.1179/sic.2007.52.3.199.
[5] D. Camuffo, A. Della Valle, Church Heating: A balance between conservation and thermal comfort, in: 2007.
[6] ISO, ISO 7730:2005 Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, 2005.
[7] M.S. Al-Homoud, A.A. Abdou, I.M. Budaiwi, Mosque energy performance. Part I : energy audit and use trends based on the analysis of utility billing data, J. King Abdulaziz Univ. Eng. Sci. (2005) 155–173.
[8] M.S. Al-Homoud, A.A. Abdou, I.M. Budaiwi, Mosque energy performance. Part II : monitoring of energy end use in a hot-humid climate, J. King Abdulaziz Univ. Eng. Sci. (2005).
[9] M.S. Al-Homoud, A.A. Abdou, I.M. Budaiwi, Assessment of monitored energy use and thermal comfort conditions in mosques in hot-humid climates, Energy Build 41 (2009) 607–661.
[10] P.O. Fanger, Thermal comfort analysis and applications in environment Engineering, (1970).
[11] I. Budaiwi, A.A. Abdou, HVAC system operational strategies for reduced energy consumption in buildings with intermittent occupancy: the case of mosques, Energy Convers. Manag 73 (2013) 37–50, doi:10.1016/j.enconman.2013.04.008.
[12] I. Budaiwi, Envelope thermal design for energy savings in mosques in hot-humid climate, J. Build. Perform. Simul. 4 (2011) 49–61, doi:10.1080/19401491003746639.
[13] M.S. Al-Homoud, Envelope thermal design optimization of buildings with intermittent occupancy, J. Build. Phys. 33 (2009) 65–82, doi:10.1080/19401491003746639.
[14] F.F. Al-ajmi, Thermal comfort in air-conditioned mosques in the dry desert climate, Build. Environ. 45 (2010) 2407–2413 10.1016.
[15] M. Legner, M. Geijer, On historical climate in swedish stone churches: postprints from the conference on energy efficiency in historic buildings, Visby Gotl., Univ. Press, 2012.
[16] Bjorn Linn, Öljeeldning orsakar svara skador I krykor (Oil heating causes severe damage to churches), Byggnads-Ingenjoren 1–2 (1969) 24–27.
[17] Helgo Zetterwall, Allmanna anvisningar rorande kyrkobyggnader (Guidelines regarding church buildings), (1887) 89.
[18] I. Holmstrom, I. Andersson, Restaurering av gamla byggnader ur framst teknisk och antikvarisk synvinkel (Restoration of old buildings from a technical and antiquarian point of view), (1967) 51.
[19] Knut Akesson et al., Vard av kyrkorum, Uppvarm. (Care churches heating). (1976) 6–7.
[20] RAA, Energibesparing I kyrkor (Energy conservation in churches), (1979) 1.
[21] RAA, Varme och ventilation I alder kyrkor (Heating and ventilation in older churches), (1982) 3.
[22] O. Antell, J. Karlstrom, Att sluta varma en kyrka (To cease heating a church), (1998) 7.
[23] L. G, C. E, K. I, R. S, Indoor microclimate, ozone and nitrogen oxides in two medieval churches in Cyprus, Atmos. Environ. 40 (2006) 7457–7466, doi:10.1016/j.atmosenv.2006.07.2015.
[24] N. Aste, R.S. Adhikari, M. Buzzetti, S. Della Torre, C. Del Pero, H.E. Huerto C, F. Leonforte, Microclimatic monitoring of the Duomo (Milan Cathedral): risks-based analysis for the conservation of its cultural heritage, Build. Environ. (2019), doi:10.1016/j.buildenv.2018.11.015.
[25] S. Martinez-Garrido, M.I. Aparicio, J.J. Fort R. Anaya, M.A.G. Izquierdo, Effect of solar radiation and humidity on the inner core of walls in historic buildings, Constr. Build. Mater. 51 (2014) 383–394, doi:10.1016/j.conbuildmat.2013.10.068.
[26] M. Vellei, M. Herrera, D. Fosas, S. Natarajan, The influence of relative humidity on adaptive thermal comfort, Build. Environ. (2017), doi:10.1016/j.buildenv.2017.08.005.
[27] A. Maahsen–Milan, K. Fabbri, Energy restoration and retrofitting. Rethinking restoration projects by means of a reversibility/sustainability assessment, J. Cult. Herit. 14 (2013) e41–e44, doi:10.1016/j.culher.2012.12.011.
[28] T.J. Terrill, B.P. Rasmussen, An evaluation of HVAC energy usage and occupant comfort in religious facilities, Energy Build 128 (2016) 224–235, doi:10.1016/j.enbuild.2016.06.078.
[29] L. Bencs, D. Limpens-Neilen, H.I. Schellen, B.A.H. Jutte, R. Van Grieken, Comparison of hot-air and low-radiant pew heating systems on the distribution and transport of gaseous air pollutants in the mountain church of Rocca Pietore from artwork conservation points of view, J. Cult. Herit. 8 (2007) 264–271 10/1016/j.culher.2007.05.001.
[30] N. Aste, S. Della Torre, R.S. Adhikari, M. Buzzetti, C. Del Pero, F. Leonforte, M. Manfren, Sustainable church heating: the Basilica di Collemaggio case-study, Energy Build. (2016), doi:10.1016/j.enbuild.2016.01.008.
[31] D. Camuffo, E. Pagan, S. Rissanen, Ł. Bratasz, R. Kozłowski, M. Camuffo, A. Valle, An advanced church heating system favourable to artworks: a contribution to European standardisation, J. Cult. Herit 11 (2010) 205–219, doi:10.1016/j.culher.2009.02.008.
[32] D. Camuffo, C. Bertolin, V. Fassina, Microclimate monitoring in a Church, in: 2010: pp. 43–47. doi:10.13140/2.1.3318.5926.
[33] H.E. Silva, F.M.A. Henriques, Microclimatic analysis of historic buildings: a new methodology for temperate climates, Build. Environ. (2014), doi:10.1016/j.buildenv.2014.09.005.
[34] H.E. Silva, F.M.A. Henriques, Preventive conservation of historic buildings in temperate climates. The importance of a risk-based analysis on the decision-making process, Energy Build. (2015), doi:10.1016/j.enbuild.2015.07.067.
[35] AENOR, UNE-EN-15759-1:2012- Conservation of cultural property, indoor climate in: Part 1: guidelines for Heating Churches, Chapels and Other Places of Worship, Madrid. (2012).
[36] M.J. Varas-Muriel, R. Fort, M.I. Martinez-Garrido, Monitoring the thermal-hygrometric conditions induced by traditional heating systems in a historic Spanish church (12th-16th C), Energy Build 75 (2014) 119–132.
[37] M.J. Varas-Muriel, R. Fort, M.I. Martinez-Garrido, A. Zornoza-Indart, P. Lopez-Arce, Fluctuations in the indoor environment in Spanish rural churches and their effects on heritage conservation: hygro-thermal and CO_2 conditions monitoring, Build. Environ. 82 (2014) 97–109, doi:10.1016/j.buildenv.2014.08.010.
[38] K. Fabbri, M. Pretelli, Heritage buildings and historic microclimate without HVAC technology: malatestiana library in Cesena, Italy, UNESCO memory of the world, Energy Build 76 (2014) 15–31.
[39] N. La Gennusa, G. Lascari, G. Rizzo, G. Scaccianoce, Conflicting needs of the thermal indoor environment of museums: in search of a practical compromise, J. Cult. Herit. 9 (2008) 125–134 http://www.sciencedirect.com/science/article/pii/S1296207408000186.
[40] S.P. Corgnati, V. Fabi., M. Filippi, A methodology for microclimatic evaluation in museum : application to a temporary exhibit, Build. Environ. 44 (2009) 1253–1260.
[41] AENOR, UNE-EN 15757, 2011- Conservation of Cultural Property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials, Madrid (2011).
[42] C.M. Munoz-Gonzalez, A.L. Leon-Rodriguez, M. Campano-Laborda, C. Teeling, R. Baglioni, The assessment of environmental conditioning techniques and their energy performance in historic churches located in Mediterranean climate, J. Cutural Herit. (2018) 74–82.
[43] EN 15251 European Standard. Indoor environmental input parameters for design and assessment of energy performance of buildings—addressing indoor air quality, thermal environment, lighting and acoustics, (2007).
[44] D. Gatt, C. Yousif, ZeroCO2 building - How low can we go: a case study of a small hotel in Gozo - Malta, Sustain. Energy 2016 Ise Annu. Conf. (2016) 30–37.
[45] I. Ballarini, S.P. Corgnati, V. Corrado, Use of reference buildings to assess the energy saving potentials of the residential building stock: the experience of Tabula project, Energy Policy 68 (2014) 273–284, doi:10.1016/j.enpol.2014.01.027.
[46] Charles Galdies, The Climate of Malta: statistics, trends and analysis 1951-2010, (2011).
[47] R. Vella, C. Yousif, F.J.R. Martinez, Monitoring indoor temperatures of places of worship: a first step towards energy sustainability, in: Eng. Sustain. Sustain. Energy 2018 (ESSE '18) Conf., University of Malta. Institute for Sustainable Energy & Chamber of Engineers (Malta), 2018: pp. 55–66.
[48] S.P. Corgnati, E. Fabrizio, M. Filippi, V. Monetti, Reference buildings for cost optimal analysis: method of definition and application, Appl. Energy 102 (2013) 983–993, doi:10.1016/j.apenergy.2012.06.001.
[49] ISO, ISO 6946:2007 Building components and building elements - Thermal resistance and thermal transmittance - Calculation method, (2007).
[50] ISO, ISO 10077-2:2017 Thermal performance of windows, doors and shutters — Calculation of thermal transmittance — Part 2: numerical method for frames, (2017).
[51] ISO, ISO 52016-1:2017Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: calculation procedures, (2017).
[52] HOBO Bluetooth Low Energy Temperature/Relative Humidity Data Logger. (n.d.), (n.d.). http://www.onsetcomp.com/products/data-loggers/mx1101 (accessed December 21, 2019).

[53] P.O. Fanger, Thermal comfort analysis and applications in environment engineering, (1972) 244.
[54] M. Humphreys, F. Nicol, Understanding the adaptive approach to thermal comfort, ASHRAE Trans 104 (1998) 991–1004.
[55] G. Brager, R. de Dear, Thermal adaptation in the built environment: a literature review, Energy Build 27 (1998) 83–96, doi:10.1016/S0378-7788(97)00053-4.
[56] S. Humphrey, J.D. N.ahrgang, F. Morgeson, Integrating motivational, social, and contextual work design features: a meta-analytic summary and theoretical extension of the work design literature, J. Appl. Psychol. 92 (2007) 1332–1356, doi:10.1037/0021-9010.92.5.1332.
[57] R. de Dear, G. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55, Energy Build 34 (2002) 549–561, doi:10.1016/S0378-7788(02)00005-1.
[58] M. Deuble, R. de Dear, Green occupants for green buildings: the missing link? Build. Environ. 56 (2012) 21–27, doi:10.1016/j.buildenv.2012.02.029.
[59] M. Humphreys, Chapter 15 the dependence of comfortable temperatures upon indoor and outdoor climates, in: Bioeng, Therm. Physiol. Comf., (1981) 229–250, doi:10.1016/S0166-1116(08)71092-6.
[60] F. Nicol, M. Humphreys, Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251, Build. Environ. - BLDG Env. 45 (2010) 11–17, doi:10.1016/j.buildenv.2008.12.013.
[61] A.G. Kwok, N. Rajkovich, Addressing climate change in comfort standards, Build. Environ. - BLDG Env. 45 (2010) 18–22, doi:10.1016/j.buildenv.2009.02.005.
[62] F. Nicol, M. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy Build 34 (2002) 563–572, doi:10.1016/S0378-7788(02)00006-3.
[63] F. Nicol, M. Humphreys, R. S, Adaptive thermal comfort: principles and practice, Adapt. Therm. Comf. Princ. Pract (2012) 1–175, doi:10.4324/9780203123010.
[64] N. Walikewitz, B. Jänicke, M. Langner, F. Meier, W. Endlicher, The difference between the mean radiant temperature and the air temperature within indoor environments: a case study during summer conditions, Build. Environ. (2015), doi:10.1016/j.buildenv.2014.11.004.
[65] U.S. Department of Energy, Simulation models – encyclopedic reference, in: EnergyPlusTM version 8.9.0 doc. Eng. Ref., (2018).