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Prioritising Passive Measures over Air Conditioning to Achieve Thermal Comfort in Mediterranean Baroque Churches

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Abstract: Malta, as a member of the European Union (EU), has pledged to become carbon neutral by the year 2050. Concurrently, the need for thermal comfort for people within places of worship has expanded tremendously in recent years. As a result, prioritizing passive methods over mechanical air-conditioning systems in such buildings is an essential step toward protecting the macroclimate while achieving a sustainable and comfortable indoor environment. Using DesignBuilder-EnergyPlus software, this paper examines the effectiveness of selective passive measures in two free-running church buildings. Results show that certain passive measures alleviate severe high and low indoor temperatures, resulting in a more comfortable environment. Environmental control, on the other hand, present difficult conservation challenges. Historic church buildings were initially built to make use of passive design features for internal comfort, and this study shows that they outperform expectations and, in general, outperform more contemporary church structures.

Keywords: thermal comfort; passive measures; Mediterranean climate; natural ventilation; DesignBuilder; modelling



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1. Introduction

In a world where climate-related temperature fluctuations are increasing building cooling and heating demand, reducing the usage of heating, ventilation, and air conditioning (HVAC) systems in a culture that now demands higher levels of comfort is becoming increasingly difficult. According to the NASA Global Land-Ocean Temperature Index, the year 2020 tied with 2016 for the warmest year on record since record keeping began in 1880, illustrating an exponential growth in global surface temperatures to date [1]. In addition, the June 2021 global surface temperature in Europe was the second warmest June on record with a temperature departure of +2.36 °C (4.25 °F) [2]. Moreover, as the COVID-19 restrictions were lifted, and economies recover, the International Energy Agency (IEA) 2021 report highlights that the global energy demand is set to increase by 4.6% in 2021.

At the European level, there is a clear push towards carbon neutrality by 2050; nevertheless, more ambitious contributions from all sectors are necessary to accomplish this aim. While the world's attention was focused on the rollout of the Coronavirus vaccine and global markets at the end of 2020, the EU agreed on the greatest ever economic stimulus plan for all member states. Malta's National Energy and Climate Plan (NECP) [3–5] currently follows that of the European Union and, given that this is a time when energy and climate issues are at the forefront of political and public debate, any implications of climate change are very much more noticeable. Concerns regarding the energy performance of

heritage buildings have developed in the recent decade, mostly because current energy-efficiency measures in such structures remain relatively low and dispersed. Prioritizing passive measures (PM) over active air-conditioning systems to increase indoor thermal comfort in such buildings is, therefore, an essential step towards a more sustainable living.

Malta, the southernmost European country located in the Mediterranean Sea, occupies a church density of slightly more than one church per square kilometre. As a result, considering Malta's relatively large number of churches, prioritizing PM within such structures will alleviate the high demand for energy needed should active systems be considered as opposed to passive measures. Thus, this study aims to assess the potential of applying passive measures to enhance indoor thermal comfort levels measured according to the EN 16798-1 standard in two church buildings: one representing the typical Baroque churches in Malta, and the other representing a distinct contemporary style of architecture. Moreover, this study also aims to identify why a trend to install ACs in Baroque churches is emerging. (Refer to Figure 1.)



Figure 1. Emerging trend to install air conditioners in Baroque churches. Photograph by author RCV (2018).

Accordingly, the following research questions were asked:

- Why revert to air conditioning for cooling during short-duration religious service functions, rather than optimising the use of passive measures?
- How can these emerging cooling challenges especially due to climate change be effectively addressed?

To address these questions, the following was carried out.

- I. Modelling in DesignBuilder-EnergyPlus to determine the sources of overheating, as well as evaluate the impact of applying several passive energy-efficiency measures.
- II. Validation of software simulation results with actual data monitoring of temperature and humidity within a Baroque church and a modern church building.
- III. Evaluation of the best energy-efficiency measures that can be applied to achieve an improved level of indoor comfort in renovated/retrofitted places of worship.

Nowadays, most of the population living in such warm climates has grown accustomed to conditioned spaces, from their homes to their modes of transportation, to their workplaces, and to other areas of leisure and entertainment, thus spending a significant

portion of the day within controlled environments. Attending a 30–45-min religious service function, many times on a weekly basis, is not necessarily acceptable in this circumstance. Improving ambient conditions in free-running places of worship with passive measures (PM) may provide an effective remedy. The added value of this work is not only to contribute to upgrading heritage retrofitting policies, guidelines, and building codes in the local context, which lacks such initiatives, but also to extend the results to other regions of a similarly warm Mediterranean climate and provide guidance for policymakers to upgrade standards of these historical church buildings.

2. Passive Techniques

There are numerous PM that can be used in buildings today to increase their energy efficiency. These are divided into two categories: those related with heating performance and those associated with cooling performance. In Malta, although throughout the year there exist four seasonal changes, the most dominating changes are particularly the cold and warm temperatures during winter and summer, respectively. However, given that Malta lies within a Mediterranean climate and is particularly dominated by hot summers and mild winters, cooling performance PM are more appropriate. The main criteria of passive cooling measures are to prevent buildings from overheating by blocking solar gains and removing internal heat gains from within the building. These include reflective and radiative paint, thermal mass, low window-to-wall area ratio (S/W), passive ventilation (operable windows), and nocturnal cooling [6]. Natural ventilation and passive cooling techniques have been two important features in typical architectures, with domed and vaulted roofs extensively used in hot dry regions [7]. Therefore, huge potential exists to exploit the benefits of energy-efficient retrofitting. The Energy Efficiency Directive [8] obliges Malta to adopt national building-renovation strategies, including the eco-refurbishment of public buildings, many of which have heritage value. Although the regeneration of heritage buildings is gaining popularity in Malta, the role of energy-efficient refurbishment remains generally unexplored.

2.1. Reflective and Radiative Paint

Al-Obaidi et al. (2014) established that implementing reflective and radiative approaches in roofing systems as a passive measure would help decrease the effect of heat penetration. However, this strategy is not without limitations. It is worth emphasizing that, in accordance with such constraints, the physical properties of the building should be properly understood in order to reflect solar radiation from structures by natural means [7]. For instance, the application of high-reflective (cool) exteriors, particularly for roofs, could provide low-cost and efficient solutions to decrease heat flux through the building envelope during warm periods [9]. This provides a high coefficient of solar reflectance with a Solar Reflective Index (SRI) of over 82 [10]. Zhang Yin et al. (2017) studied the application of a retro-reflective coating material on the external building envelope and concluded an average indoor temperature decrease by 2.4 °C, when compared to the reference building without the retro-reflective material [11]. The finding established in [12] further explains the fluctuations in indoor temperatures due to the installation of reflective materials which, in turn, resulted in a temperature change by as much as 7 °C. This could be carried out by utilising a process simply known as ‘cool roofing,’ designated to reduce the absorbed radiation, hence having less heat transferred inside the building [13]. Other studies reported an average decrease in the indoor air temperature by 2 °C through the application of a cool roof-coating membrane [14]. Ibrahim, H.S.S. et al. (2021) also assessed the effectiveness of cool roofing techniques on a heritage building located in Cairo. The application was in the form of a white acrylic roof paint (solar reflective material) with a thickness of 0.002 m, which gave a result of up to 15.8% in comfort improvement [15]. Becherini F. et al. (2018) also recommended the use of an infrared reflective (IR) coating to reduce indoor temperatures [16].

This coating has been demonstrated to be more appropriate for cities with hot summer temperatures, making it a viable alternative for structures in Malta. As churches in Malta are designated Grade 1 structures and are registered on the National Inventory of Cultural Property of the Maltese Islands (NICPMI), such intervention is not applicable to the building façades, and out-of-sight roof treatments would be more suitable and less damaging to the historical value of these churches. (Refer to Figure 2.)



Figure 2. Initiatives and examples of cool roofs. **(Left):** The Collegiate Archmatrix Parish Church of Saint George, Qormi (Malta). **(Mid):** The Basilica of Christ the King, Paola Parish Church (Malta). **(Right):** The Saint Publius Parish Church, Floriana (Malta). Photographs by author RCV (2018–2020).

2.2. Thermal Mass

Thermal mass can be used as a means for passive cooling. Thermal mass is linked to the material within the building envelope that can help minimise temperature fluctuations throughout the day. This is brought about by the effect of heat absorption during periods of high solar radiation and the dissipation of heat as the surrounding atmosphere begins to cool. This phenomenon is most efficient in climates where there are significant fluctuations between the day and night-time ambient temperatures, but this is not the case for the Central Mediterranean Region. Thus, within the local climate, high night-time temperatures result in limited fluctuations between day and night (5.9 °C difference), thus limiting the dissipation of heat gained throughout the day through the building envelope. Hence, although thermal mass is beneficial during the day, the building must be ventilated during the night to enhance dissipation of the stored heat energy [17]. F. Sharaf (2020) evaluated the thermal mass efficiency of construction materials in improving the thermal performance of buildings so that human thermal comfort is achieved through less energy consumption. This case study was carried out on a building with two parts—an old part made of clay brick walls (40 cm thick) and an added part made of concrete brick walls (10 cm thick)—within the same climatic condition in the city of Al Mafrq, in Northern Jordan. Internal and external temperature measurements were recorded in both parts of the building and were then compared to evaluate the effect of different thermal mass performances. Results indicated that, for the old part of building with a higher thermal mass, reductions in energy use would be more efficient [18]. This concurs with another study carried out by T. Kuczynski et al. (2020), where two buildings, located in the Science and Technology Park in the University of Zielona Gora in central–western Poland, built with different building materials with different thermal masses, were compared to determine which one would be more feasible in terms of energy performance. Results indicated that the building with the higher thermal mass was more efficient with regards to reduction in energy use [19].

2.3. Natural Ventilation

In order to be more effective, thermal mass must be paired with proper night ventilation to disperse the heat emitted from within the thermal mass and, therefore, achieve lower mechanical cooling loads for the following day. [20,21]. Throughout the day, the indoor temperature is kept relatively low compared to the external temperature, because

the thermal mass introduces a delay in heat transfer to the indoor space. Conversely, throughout the night, when the outdoor temperature is relatively cooler, the thermal mass of the building will release its stored heat to both the external and internal parts of the building, hence raising its indoor temperature. Thus, to counteract this released heat and decrease the overall indoor temperature, ventilation must be introduced to allow the infiltration of cooler external temperature. Ventilation can be classified into two categories: “natural” or “mechanical”, with passive actions encouraged over active systems.

Natural ventilation, in other words passive ventilation, is generally categorised into: cross ventilation—which occurs due to a pressure difference between one side of the building and the other by drawing air in on the high pressure side and drawing it out on the low pressure side—and stack ventilation—where the cooler air enters the building at low levels, is heated by the occupants/radiant surfaces and as it becomes less dense and more buoyant, rises through the building to be ventilated to the outside through high level windows/vents [20].

M. Palme et al. (2017) investigated the potential use of natural ventilation as a mitigation strategy to reduce overheating in buildings under an urban heat-island effect (UHI—generated by intensive urbanization) in South America. Results showed that natural ventilation is a very beneficial approach to extract heat, accounting for a percentage of a circa 80% reduction [22]. T. Kuczynski et al. (2020) also established that, when night ventilation is introduced in a quick and effective manner within a building with a high thermal mass, temperatures during the night hours no longer reached the absolute maximum temperatures, thus improving the indoor ambient environment [23]. M. Darmanis et al. (2020) also highlighted the use of night ventilation as a beneficial cooling strategy in regions where the diurnal temperatures are very high (30–35 °C). The efficiency of the night-ventilation strategy was investigated by incorporating the use of an extractor fan in conjunction with a mechanical cooling system (AC). Results showed that night ventilation via the extractor fan decreased the average daily energy consumption of the mechanical cooling system by an average of 15–27%. Moreover, M. Darmanis et al. (2020) stressed that integrating both passive and mechanical cooling systems within buildings, referred to as “mixing mode” cooling systems, can decrease the overall carbon footprint of such buildings [24].

2.4. Nocturnal Cooling

Nocturnal cooling, also referred to as nocturnal radiative cooling, is a natural process that has to do with the cooling of a body through radiation to the night sky. Radiative cooling helps to cool down a building mass to create a heat sink for the following days’ thermal gains. Throughout the day, this cooling ability is lost due to the presence of solar radiation—however, at night, the heat loss from the radiative cooling system can cool the indoor air, as the material experiences a temperature drop by 2–12 °C below ambient.

B. Bokor et al. (2017) assessed this concept through two plates consisting of a backplate (bottom) and a corrugated, perforated metal plate on top (used as a radiator). The perforated plate cooled down below the night ambient temperature via long-wave radiation, forming a cold boundary on the external side of the plate. A fan creates a negative pressure in the air gap; thus, the cold boundary layer is dragged through the perforations and subsequently into the building. The assessment was carried out on buildings in European cities (Stockholm, Helsinki, Vienna, Lisbon) with results showing that the most optimal potential of nocturnal radiant air cooling can be obtained especially in dry climates with high diurnal temperature variations. The annual mechanical cooling energy saved through this system was in the range of 17–35% [25]. Similarly, P. Mulik et al. (2019) also documented successful outcomes through this concept, with results showing that the cooling energy demand of the building can be reduced by 28%. However, the design varied slightly from that of B. Bokor et al. (2017). In this case, the system was repeatedly circulating the same air within the room via the exhaust fan rather than dragging fresh air from the outside. As the air passes between the two metal plates, the heat is transferred to the surrounding metal plates; hence, their temperature increases whilst the temperature of the air decreases.

This cooled air is then fed back into the room [26]. H.S.S et al. (2021) also reported a total of 10.7% comfort improvement using nocturnal cooling on a heritage building located in Cairo [15].

2.5. Low Window-to-Wall Ratio

The optimal window-to-wall ratio is a window area that can reduce the entire yearly energy consumption for heating, cooling, and lighting [27]. A study conducted in the humid climate of Libya by S. Alghoul et al. (2017) revealed that an increase in the window-to-wall ratio on a south facade resulted in an increase in energy consumption during summer and approximately zero demand for heating during the winter [28]. When the worst possible window-to-wall ratio configuration is adopted, energy consumption can increase by up to 5–25% compared to when it is adopted in a more optimal manner [27].

T. Kaasalainen et al. (2020) investigated the influence of window-to-wall ratio and window orientation on cooling, heating and total energy consumption in a case study located in the city of Tripoli, Libya. According to the results, increasing the window-to-wall ratio increases cooling energy consumption in a hot environment, particularly on the southern façade, due to an increase in passive solar heating [29]. In conjunction with this, M. Alwetaishi (2019) investigated the influence of glazing-to-wall ratio in different microclimate regions in Saudi Arabia with hot/dry, hot/humid, and moderate climates. The results revealed that the East and South directions are the worst for gaining the most solar heat; hence, glazing systems in these directions should be minimized. According to this study, the best percentage of glazing-to-wall ratio in hot/humid and hot/dry climates is 10%, whereas it is 20% in mild climates [30].

3. Case Studies

Analysis of the physical and environmental factors of churches in Malta is based on studies of a number of churches, termed “reference buildings” (RBs). These RBs characterise the different types of churches in Malta and portray “real examples” with typical, physical, and statistical characteristics [31,32]. Out of the 359 churches on the Maltese islands, one of the churches chosen for this work represents the 17th to mid-18th century Baroque period, which accounts for the vast majority of churches in Malta in terms of building stock categories such as location, construction period, building size, and shape classification, as proposed by Ballarini et al. [33]. The other is a late-twentieth century (post-Vatican Council II) modern style. The Stella Maris Parish Church in Sliema (Baroque) and Our Lady of Mount Carmel Parish Church in Fgura (Contemporary) are both Grade 1 monuments on the Maltese Islands’ National Inventory of Cultural Property (NICPMI) [34].

3.1. Stella Maris (Our Lady Star of the Sea) Parish Church, Sliema (Malta)

The Parish of Stella Maris (Refer to Figure 3) is the oldest amongst the four parishes of Sliema town. In April 1853, the construction of the church, dedicated to Stella Maris, was undertaken and it was completed in 1855. Between 1876 and 1878, extensions were made, and the church was enlarged to its present size. The church suffered severe damage during World War II whereby, besides structural damages, various works of art were lost [35–37].

The building approach is characteristic of Maltese baroque churches, with loadbearing masonry walls supporting a vaulted ceiling and dome structure made of globigerina limestone blocks, which is a Global Heritage Stone Resource (GHSR) [38]. The main cupola, which has arched windows and an upper cornice supported by corbels, stands on an octagonal drum that serves as a foundation. The dome is supported by circular masonry rings. The dome, the main nave, and the rest of the church’s roofs are all covered in “deffun.” The “deffun” technique consists of various graded gravels (from rough and big grains to smaller thin grains), followed by a lime layer with beaten crushed pottery (clay) powder over it, laid to falls, which results in a relatively low thermal transmissivity (U-value) for the roof.



Figure 3. External and internal photographs of Stella Maris Parish Church, Sliema (Malta)—Baroque church; photographs by author RCV (2020).

3.2. *Our Lady of Mount Carmel Parish Church, Fgura (Malta)*

The Parish Church of Fgura (Refer to Figure 4) was constructed in the late twentieth century (1988) and consecrated to Our Lady of Mount Carmel on 1 February 1990. This church is designed in a modern, post-Vatican Council II style and is one of the most unique and daring reinforced concrete constructions on the island. It is built on a square layout with a reinforced concrete shell construction that is symmetric around both axes. The primary structural material is concrete, and the structure's strength is derived from its shape rather than its sheer bulk. The layout from the exterior is pyramidal, with a triangular opening on each four sides, which gives the impression of a floating building.



Figure 4. Internal and external photographs of Our Lady of Mount Carmel Parish Church, Fgura (Malta)—contemporary church; photographs by author RCV (2020).

4. Methodology

In this paper, the impact of PM was analysed using software modelling for two church buildings, one representing the typical characteristics found in most churches in Malta, and the other representing a distinct contemporary style of architecture through its use of construction materials and form. The results obtained through the interpretation of experimental data and software simulations are intended to identify the effect of PM on indoor thermal comfort, establish the most effective PM, and determine whether or not these measures have the same hierarchy of importance for historical and contemporary

churches alike. This was accomplished by creating DesignBuilder-Energy Plus models with specified PM for both church structures to optimize their performance.

4.1. On-Site Measurements

The churches were monitored using HOBO MX1101 data recorders for three consecutive years, in 2018, 2019, and 2020. Data loggers were used to continually measure the two parameters of air temperature (°C) and percentage relative humidity (percent) for both the indoor and outdoor settings [39]. These simultaneous measurements were taken at several areas, including the narthex (also known as the western end), the nave, and the altar. To collect representative climatic data, the data loggers were installed between 1.7 m and 3.5 m above the finished floor level (FFL), eliminating the impact of radiating sources and air movement. Data recorded at the congregation's seating area was used due to stratification in large, indoor areas and variations in temperature and humidity levels at different levels. The outdoor data was collected using external stations installed within the churches' grounds. Bluetooth low energy (BLE) technology was used to wirelessly retrieve data to mobile devices.

4.2. Adaptive Comfort Model

The EN 16798-1 Adaptive Comfort Model, which offers acceptable indoor temperature limitations as a function of the exponential weighted running mean of the outdoor temperature, is the model of interest in this work [40]. It should be noted that, for the purposes of this study, the difference between the operative temperature used in the EN 16798-1 Adaptive Comfort Model standard and the air temperature measured directly from the data loggers and that simulated using the DesignBuilder software, was determined to be negligible [41].

The approximate Formula (1) representing the outdoor running mean temperature follows [40].

$$\Theta_m = (\Theta_{ed-1} + 0.8 \Theta_{ed-2} + 0.6 \Theta_{ed-3} + 0.5 \Theta_{ed-4} + 0.4 \Theta_{ed-5} + 0.3 \Theta_{ed-6} + 0.2 \Theta_{ed-7})/3.8 \quad (1)$$

Θ_m = outdoor running mean temperature for the considered day (°C).

Θ_{ed-1} = daily mean outdoor air temperature for previous day (°C).

Θ_{ed-i} = daily mean outdoor air temperature for the i -th previous day (°C).

Category III comfort level was selected for the church buildings (free running) under study, as this reflects an acceptable, moderate level of expectation for short-term occupancy. The equations representing the upper (2) and lower (3) limits for the indoor operative temperature as a function of the exponentially weighted running mean of the outdoor temperature follow here below [40]. These limits apply when $15 < \Theta_{rm} < 30$ °C for upper limit and $10 < \Theta_{rm} < 30$ °C for lower limit [40].

$$\text{Upper limit: } \Theta_o = 0.33 \Theta_{rm} + 18.8 + 4 \quad (2)$$

$$\text{Lower limit: } \Theta_o = 0.33 \Theta_{rm} + 18.8 - 5 \quad (3)$$

Θ_o = indoor operative temperature, °C.

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

The thermal comfort within the churches was derived from the simulated indoor air temperature and the established comfort limits in accordance with EN16798-1 standard. Although thermal comfort does not depend solely on temperature, from the data collected in this study it can be deduced that, in spaces with low air velocity and where air temperature and mean radiant temperature are similar, air temperature alone can be a reasonable indicator of thermal comfort [41].

It is pertinent to point out that, throughout the period under review (2018, 2019 and 2020) in mid-2018, AC units were installed in Stella Maris Parish Church (without due consideration to artefacts and any damage to the structure AC units may portray). However, their use was limited to a short-term period, and Coronavirus disease (COVID-19)

caused a disruption in church attendance in 2020 and, therefore, the data collected mostly reflected that of a free-running building. Moreover, concerns have been raised about the likelihood of the spread of the disease through the operation of air-conditioning, and with respect to internal air-circulation, clean and natural ventilation as opposed to recirculated air-conditioning was advocated for [42].

4.3. DesignBuilder Model

For the purpose of this study, DesignBuilder Software version 7.0.0.088 [43] was used for computer simulations. This software, an advanced user interface to Energy Plus, is a standard building simulation tool, providing access to all of the most commonly required simulation capabilities covering building fabric, thermal mass, glazing, shading, and renewables amongst others.

The full geometry of the two churches under review were created in AutoCAD (refer to Figure 5) and later transposed to DesignBuilder version 7.0.0.088 software to generate an accurate and precise 3D model (refer to Figure 6). The respective building envelope characterisation, occupancy schedules, and lighting fixtures were modelled to resemble the true building and the respective indoor environments. (Refer to Table 1.)

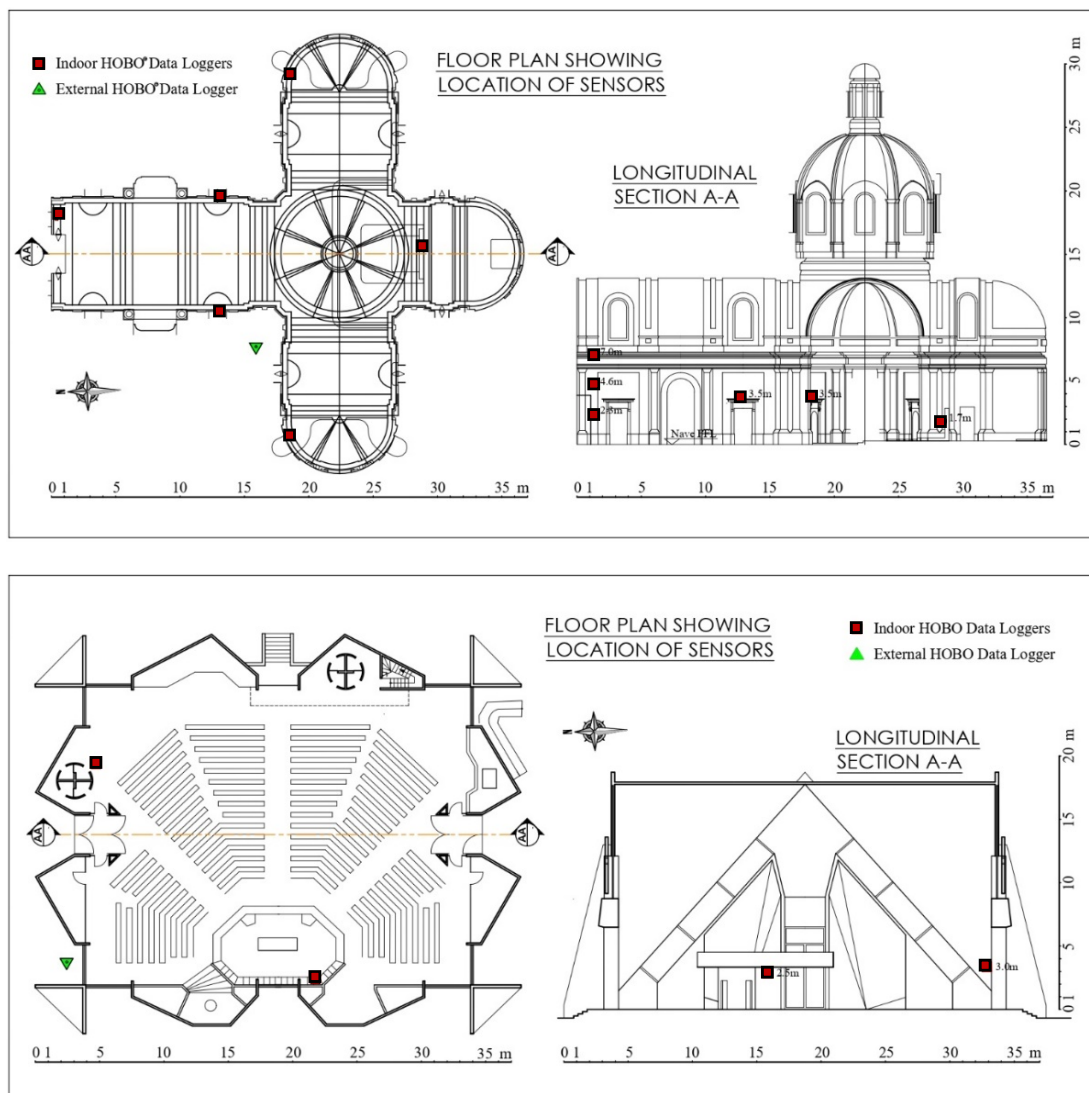


Figure 5. Church building models—plans and sections. (Above): Our Lady Star of the Sea, Stella Maris Parish Church, Sliema (Malta). (Below): Our Lady of Mount Carmel Fgura Parish Church, Fgura (Malta).

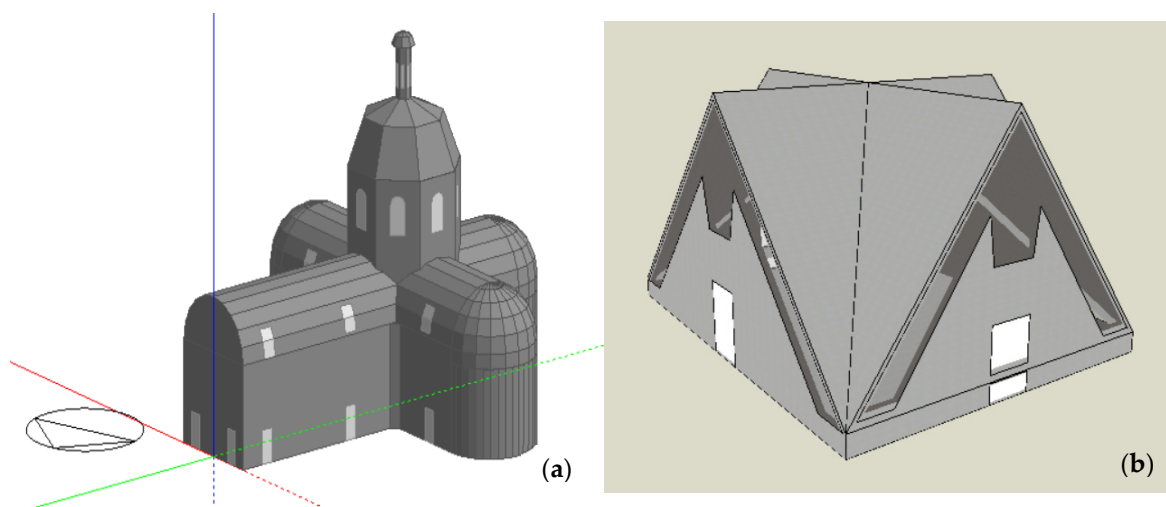


Figure 6. Church buildings modelled on the DesignBuilder V6 platform. (a) Our Lady Star of the Sea, Stella Maris Parish Church, Sliema (Malta) and (b) Our Lady of Mount Carmel Fgura Parish Church, Fgura (Malta).

4.4. DesignBuilder Software Validation

A comparison of the simulated temperature containing PM with the simulated temperature excluding PM was performed to assess the efficiency of the applied passive measures within the church structures. Prior to this stage, the program was evaluated to ensure that the margin of error between the simulated indoor temperature output, excluding PM, and the monitored data is acceptable. This was accomplished by installing the “2018 Weather File” acquired from the Malta International Airport (MIA) within the DesignBuilder program and running a simulation for a full year. The indoor hourly average measured temperature for 2018 was compared to the simulated hourly data of the indoor mean air temperature. Subsequently, the hourly simulated data and the measured hourly values were compared. This process was repeated for all years (2018, 2019 and 2020) using the respective Weather File for each year and for both churches under study (refer to Figures 7 and 8). From the graphs portrayed in Figures 7 and 8, it was established that the lowest margin of discrepancy deemed acceptable was that for the year of 2019 with an average percentage difference of 2.57% for the Sliema parish church and 6.73% for the Fgura parish church. Thus, the PM were integrated within the respective DesignBuilder models utilizing the 2019 Weather File.

Table 1. Physical characteristics of the church buildings under study.

Church	Location	Opening Hours	Envelope	U-Value (W/m ² K) [44,45]	Internal Heat Capacity (KJ/m ² K) [46]	Thermal Diffusivity (m ² /s) [44–46]	Window-to-Wall Ratio	Floor Area	Surface Area (m ²) and Air Volume (m ³)	System	Glazing Area Open (%)
Stella Maris Parish Church, Sliema	Inland	Mon–Fri: 6:00–9:00 a.m., 18:00–20:00 p.m.; Sat 6:00–9:00 a.m., 17:00–20:00 p.m.; Sun 6:00–13:00 p.m., 17:00–20:00 p.m.	External wall	0.49	180	11.44×10^{-7}	N = 2.6%	375 m ²	1:2.5 (Sur. area 2490 m ² and vol. 5415 m ³)	Naturally and 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%				
			Roof	1.03	120	9.69×10^{-7}	NE = 11%				
Our Lady of Mount Carmel Parish Church, Fgura	Inland	Mon–Fri: 6:00–9:00 a.m., 18:00–20:00 p.m.; Sat 6:00–9:00 a.m., 17:00–20:00 p.m.; Sun 6:00–13:00 p.m., 17:00–20:00 p.m.	External wall	2.52	227	7.6×10^{-7}	N = 18%	661.4 m ²	1:3 (Sur. area 2185 m ² and vol. 7446 m 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%				

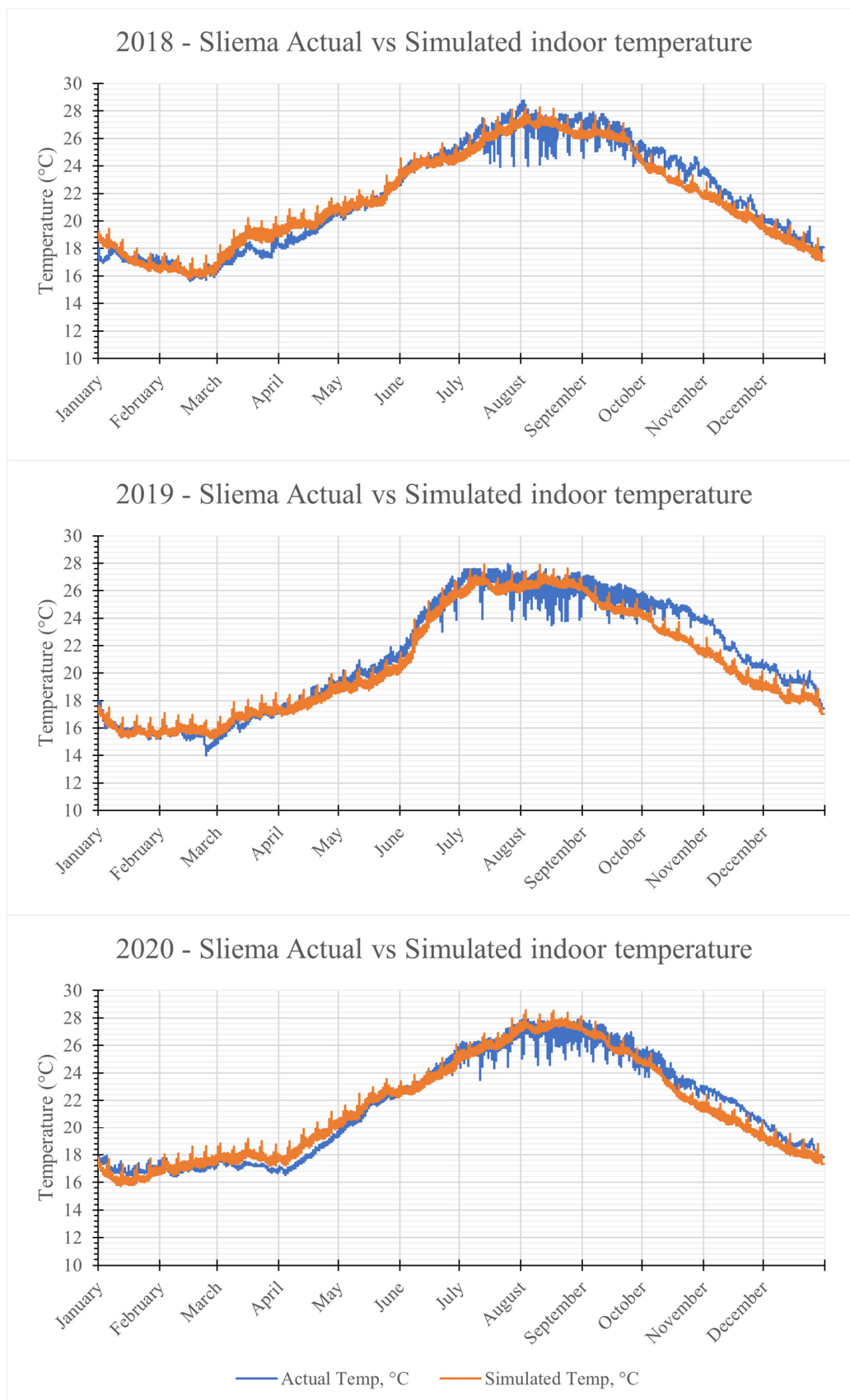


Figure 7. Stella Maris Parish Church actual vs. simulated indoor temperature.

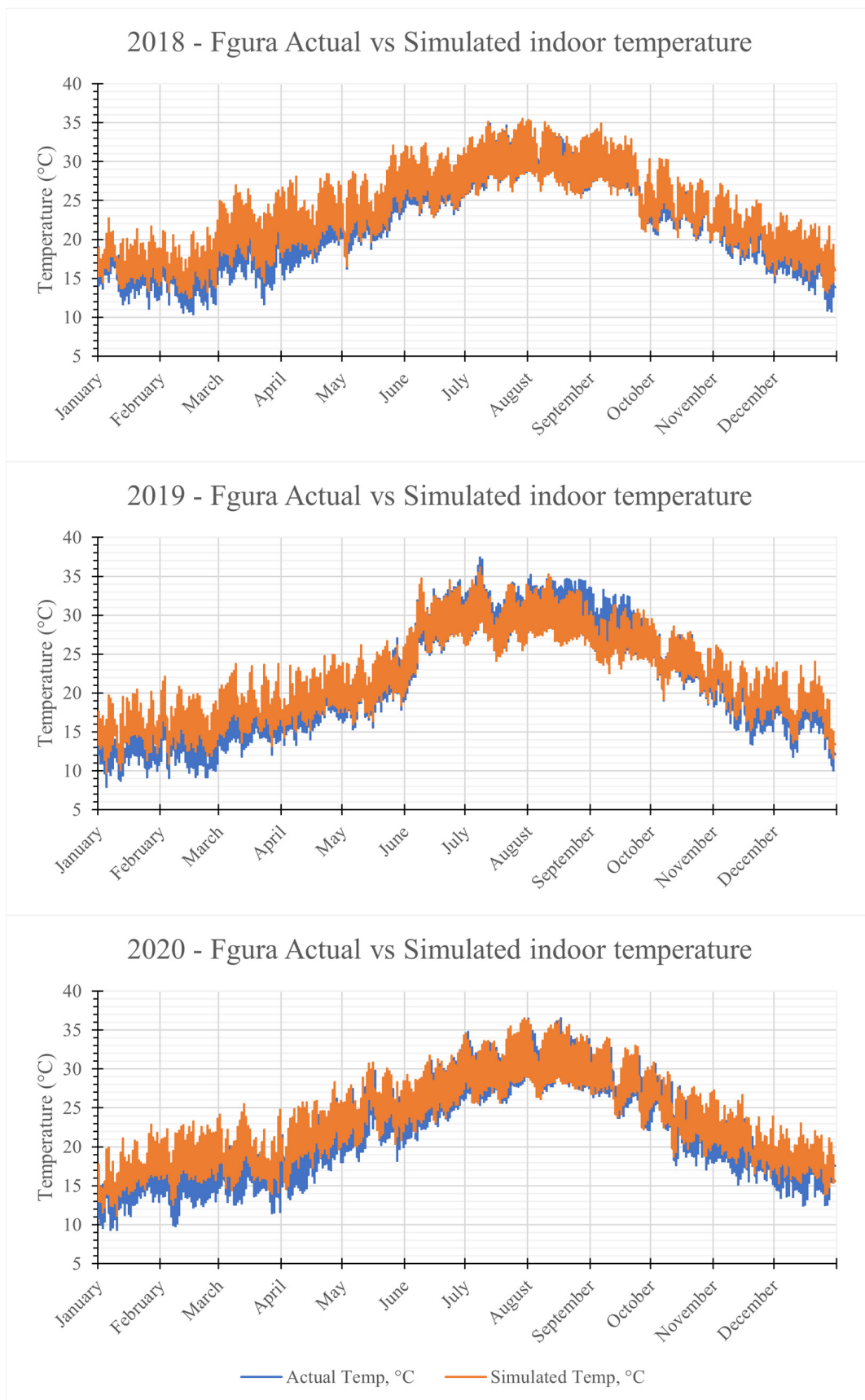


Figure 8. Fgura actual vs. simulated indoor temperature.

4.5. Passive Measures (PM)

A diagnostic investigation of the building fabric through DesignBuilder software simulations established that the main source of heat gain (kW) affecting both Sliema and Fgura parish churches is through the roof, reaching a value of 8 and 28 kW during the summer typical week, respectively. Section 2 “Passive Techniques”, addressed the most common passive measures particularly oriented towards passive cooling. Though not all passive measures discussed are feasible given the architectural importance of these churches and their aesthetic significance, the following measures gave favourable results.

The first passive measure of interest is a layer of white acrylic polymer paint in the form of a liquid membrane on the roof. The idea behind this type of passive measure is attributed to the findings described in Section 2.1. In addition, all roofs require a type of water-tight material laid over the surface, either in the form of a torch weld sheet membrane or liquid membrane. In this case, a liquid membrane was the preferred choice given that it aids in preventing water penetration through the building fabric as its basic function, it can be easily applied over the existing surface conditions and, more importantly, it comes in light shade colours such as white which supports the notion of ‘cool roofs,’ as described in Section 2.1. The applied thickness considered was that of 3 mm. This thickness varies between 2 mm to 4 mm [47].

The second passive measure to yield positive results was the application of “EPS—extruded polystyrene (standard)’ with a thickness of 5 cm and 10 cm. The aim behind this passive measure is to introduce an insulating material to reduce the U-value and, hence, decrease the rate of heat transfer through the building envelope. The material was implemented on building surfaces that are more exposed towards direct solar radiation, excluding areas that defer architectural importance, such as facades. The adopted thicknesses of 5 cm and 10 cm are standard thicknesses readily available on the open market, although custom orders can also be considered [48].

4.6. DesignBuilder Simulations

The simulations were carried out for four periods throughout the year 2019, being summer design week, summer typical week, winter design week and winter typical week. These typical simulation periods were derived from the “Statistics data” generated by the EnergyPlus weather data translation utility, based on the selected “Hourly weather data” (Malta—weather file) that was uploaded to the DesignBuilder software. The simulations and their results are based on the integrated “2019 Weather File” obtained from the Malta International Airport (MIA) and particularly focus on the main seating area of each respective church where the highest number of occupancy/m² is situated. Moreover, the simulations were set to run during occupancy hours only.

5. Results and Discussion

The analysis of each passive measure was performed independently to enable the evaluation and comparison of their respective performance and efficacy. The 3 mm thick white acrylic polymer paint sprayed on the roofing surface of both parish churches was the first examined passive measure to yield satisfying results, followed by the installation of the EPS—expanded polystyrene (5 cm and 10 cm). The relationship between the simulated indoor air temperature, excluding PM and that including PM, with respect to the EN16798-1 category III comfort limits, was derived in all cases using the adaptive comfort model, establishing their level of comfort (comfortable or uncomfortable) while also assessing the degree of comfort.

In its existing state, the Sliema parish church is termed as thermally comfortable during its summer design/typical weeks and winter design week, as its simulated indoor temperature lies within the category III EN16798-1 comfort limits (refer to Figure 9). Conversely, during its winter typical week, most of the days are termed as thermally uncomfortable as its indoor temperature lies slightly below the lower comfort limit. More importantly, results portrayed in Figure 9 show that the integrated passive measure has an overall positive

effect on the indoor thermal performance, as temperatures decreased by an average of 0.76 °C during the summer design week and 0.42 °C during the summer typical week. As the optimum thermal comfort lies equidistant from the upper and lower limits and the decrease in the indoor temperature results in a further approach towards the lower limit, the result from such PM help further reduce the indoor temperature.

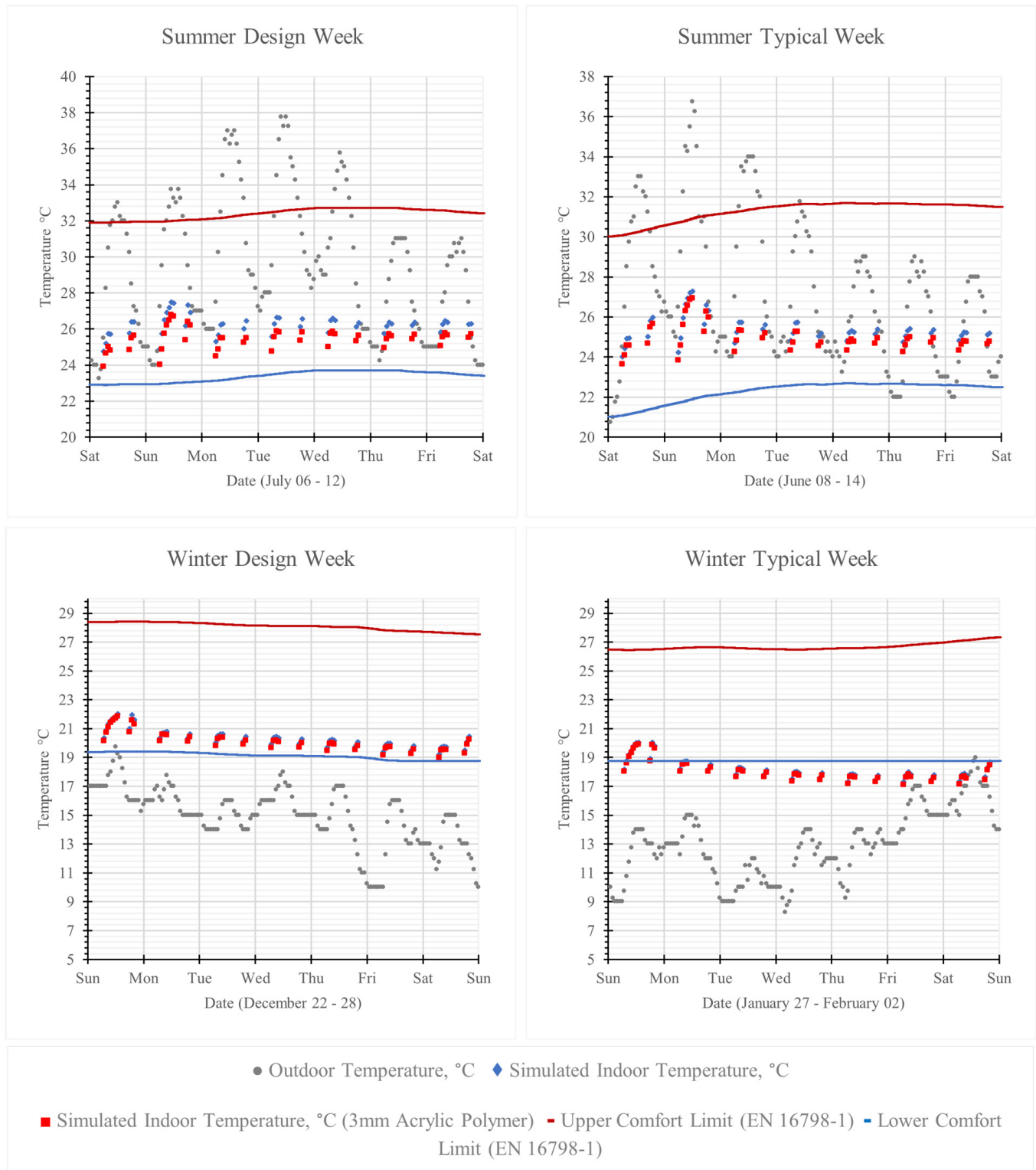


Figure 9. 2019—Stella Maris Church simulated indoor temperature when 3 mm white acrylic polymer paint is applied to the roof (occupied hours).

On the other hand, the decrease in temperature during the winter design/typical weeks averaging to a temperature decrease by 0.19 °C and 0.15 °C, respectively, is less positive. This is attributed to the decrease in the solar absorbance at the roof surface due to the “cool roof” phenomena explained in Section 2.1. However, given that such a climate is predominantly affected by high temperatures and that occupants can adapt to the colder temperatures with additional clothing, such a result is deemed to be less of a concern for the Maltese islands.

The same analysis and application were carried out on the Fgura parish church. In general, its overall existing indoor temperature performance with respect to the category III EN 16798-1 comfort limits is less comfortable when compared to that of the Sliema parish church. This result is shown in Figure 10, whereby a total of 15 and 14 occupied hours out of 47 are termed as thermally uncomfortable during the summer design/typical weeks, respectively. The same applies to its performance through the winter design/typical weeks, with most of the days termed as thermally uncomfortable, particularly during the winter typical week.

Through the application of the 3 mm white acrylic polymer paint, it can be identified that the Fgura parish church can be termed as more comfortable than in its existing state. This is evidenced through its decrease in indoor temperatures, hence decreasing the hours of discomfort. The indoor temperatures were decreased by 0.59 °C and 0.53 °C within the summer design/typical weeks, respectively. Thus, discomfort hours were decreased to 9 and 11 h out of a total of 47 occupied hours within the summer design/typical weeks, respectively.

The application of the 5 cm EPS—extruded polystyrene layer on the roof of the Sliema parish church proved to be more effective than the 3 mm White acrylic polymer paint application (Refer to Figure 10). This result is portrayed in Figure 10, with an average decrease in the indoor temperature of 1.00 °C and 0.59 °C within the summer design/typical weeks, respectively. Thus, with the indoor temperature further approaching the lower comfort limit and hence attaining a much cooler temperature during a hot summer, reaching maximum outdoor temperatures of 37.85 °C. In addition, the EPS layer also positively effects the indoor temperature during the winter design/typical weeks, attaining an increase in temperature. Indoor temperatures increased by an average of 0.22 and 0.51 during the winter design/typical weeks, respectively, resulting in a decrease in discomfort hours (39 to 33) during the typical week. In terms of effectiveness, the EPS gave superior results to those of the acrylic polymer paint, given its positive effect over both the summer and winter periods.

A 10 cm EPS—extruded polystyrene layer was also applied and analysed to test the inversely proportional relationship of thickness to indoor temperature performance. Results in Figure 11 show that the relationship is indeed correct as the increase in thickness resulted in a further decrease in temperature. However, the degree by which the thickness increases to the decrease in the indoor temperature is not directly proportional, as a 50% increase in its thickness did not result in a 50% further decrease in the indoor temperature. Indoor temperatures further decreased from 1.0 °C to 1.12 °C and from 0.59 °C to 0.68 °C during the summer design/typical weeks, respectively. This implies that the 5 cm EPS—extruded polystyrene layer is more cost-effective.

The indoor temperature performance outcomes for the Fgura parish church (refer to Figure 12) after the application of the 5 cm/10 cm EPS—extruded polystyrene are less noticeable in the summer design/typical weeks as compared to those during the winter period. The drop in indoor temperature during the summer design week was 0.20 °C and 0.21 °C for the 5 cm/10 cm EPS, respectively, but it was just 0.05 °C for both the 5 cm/10 cm EPS for the typical week. During the winter design week, however, the drop in interior temperature was 0.69 °C and 0.64 °C for the 5 cm/10 cm, respectively, and 0.70 °C and 0.60 °C for the 5 cm/10 cm, respectively.

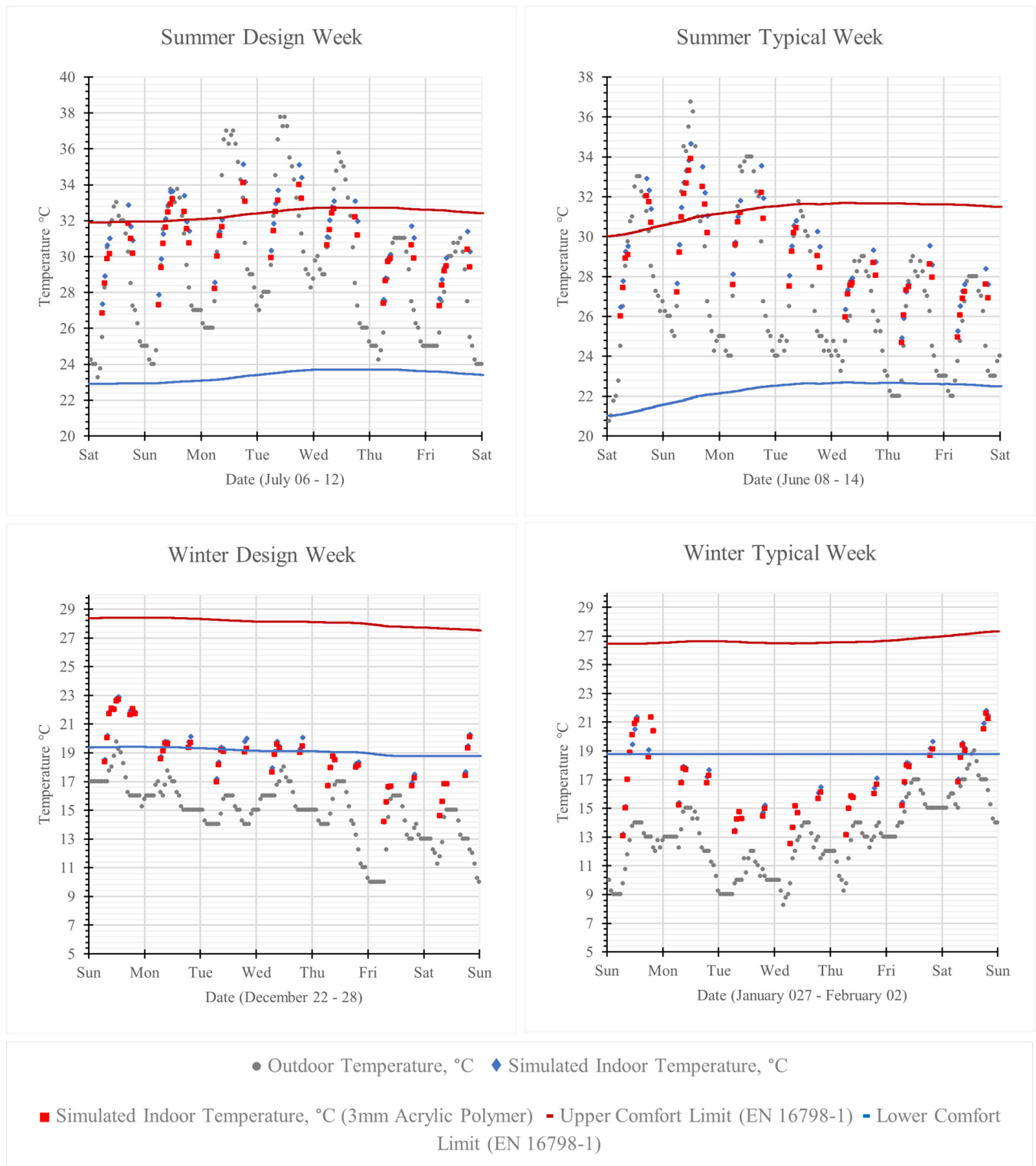


Figure 10. 2019—Our Lady of Mount Carmel simulated indoor temperature when 3mm white acrylic polymer paint is applied to the roof (occupied hours).

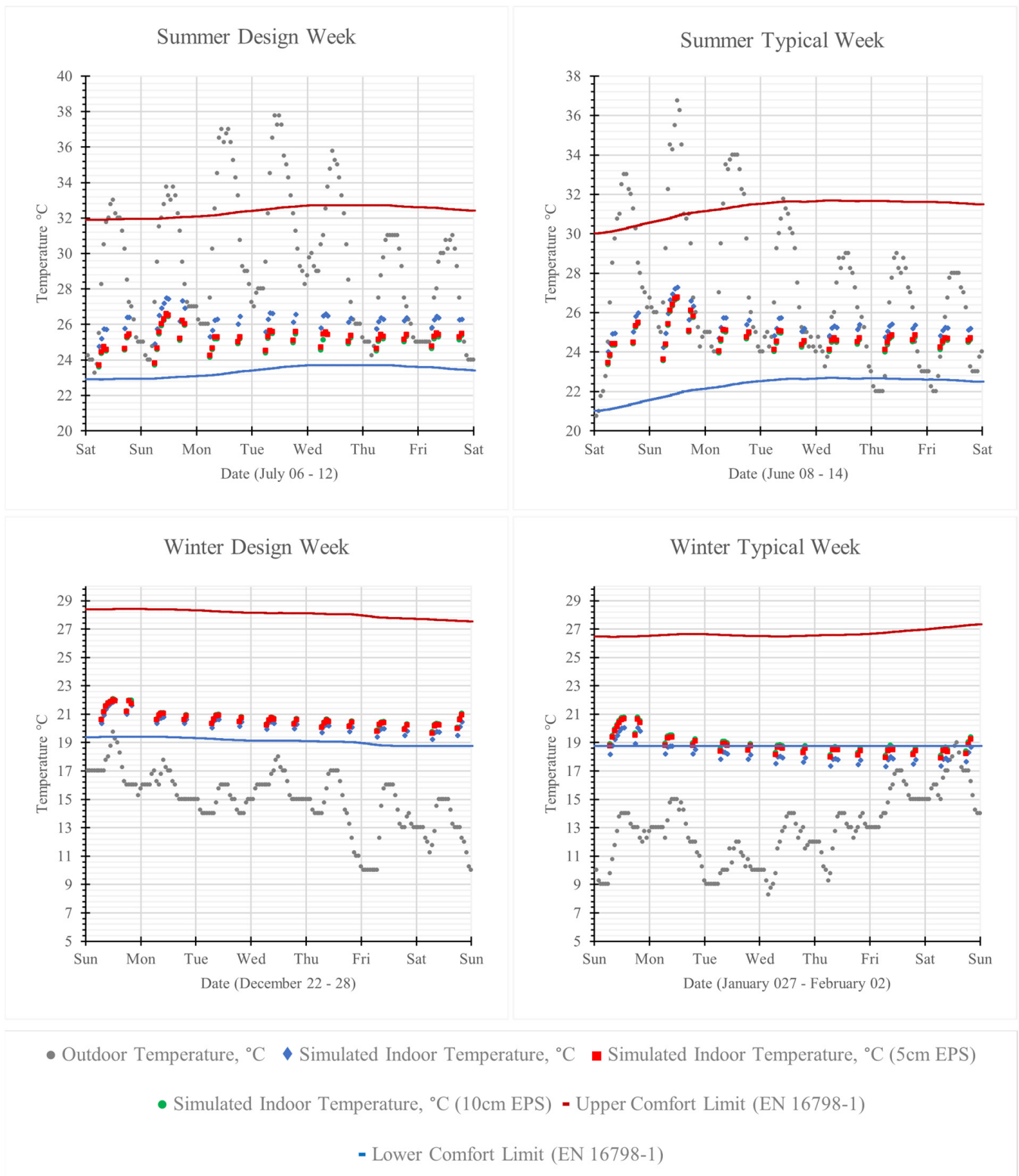


Figure 11. 2019—Stella Maris Church simulated indoor temperature including 5 cm/10 cm EPS—extruded polystyrene roof insulation (occupied hours).

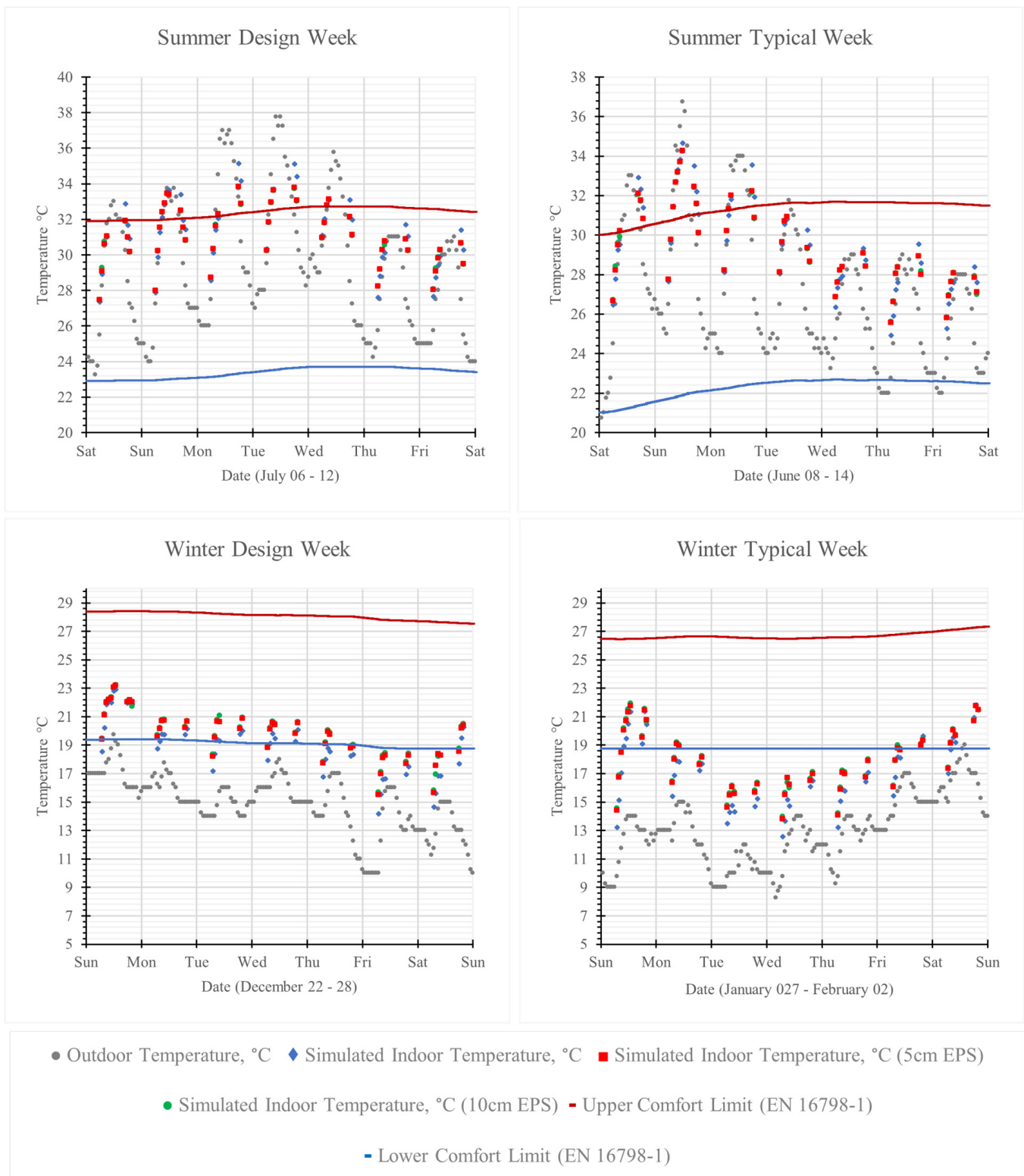


Figure 12. 2019—Our Lady of Mount Carmel Church simulated indoor temperature including 5 cm/10 cm EPS—extruded polystyrene roof insulation (occupied hours).

6. Conclusions

Historic church buildings were originally designed to exploit passive design measures for internal comfort, and this study indicates that historic church buildings outperform expectations and generally they also outperform more recent church buildings. The local

architectural typology was developed over centuries of experience with the purpose of providing a comfortable internal environment for building occupants. The heritage building typology, therefore, offers huge potential in reducing energy demand, retaining balanced environmental conditions for artefacts, and achieving comfort requirements for occupants. Notwithstanding this, a new trend is emerging whereby the criteria to improve thermal comfort has been limited to a paper exercise to calculate what air conditioner size is required to address cooling capacity. It is evident that, when faced with the choice of adopting energy-efficient passive measures, nature is considered of secondary importance while installation of ACs is perceived as crucial. This discernment led to unnecessary retrofit measures that may cause irreparable damage to the historic building fabric. To summarise the outcome of this study:

- Heat discomfort can be significantly decreased by implementing solar control strategies, more specifically by painting roof surfaces with white solar-reflective paint.
- The use of thermal insulation materials for roofs as part of a thermal control plan improves the building envelope's thermal performance.
- The limitations imposed by heritage buildings' architectural aesthetical values constrain the application of certain PM.
- Through PM, the heritage building typology has the ability to maintain balanced environmental conditions for artifacts and meeting indoor occupants comfort standards.
- Preventing temperature and humidity fluctuations is not always a solution to indoor comfort since any changes to the indoor environment within the church may introduce additional problems.
- Only with a thorough grasp of local building construction techniques and building block characteristics can one analyse the influence of the phased exclusion of external climates and the appropriate humidity and temperature values necessary to address human comfort.
- It is not appropriate to emphasize human thermal comfort within historic church buildings by employing unjustified mechanical systems at the cost of jeopardizing the integrity of the artifacts' historical value.
- Though it is becoming the norm that low-cost, low-energy, passive solutions for naturally ventilated historical buildings become side-lined in the quest for a single engineering solution, this is not sustainable.

When considering the limited duration parishioners utilise these buildings, within a brief timeframe of their choice, one must push for passive control systems and make the required modifications to increase indoor thermal comfort on a case-by-case basis. The findings of this study conclude that the air-conditioning units installed in Baroque churches are not justified. PM are more appropriate for use in churches, even though each church in Malta poses distinct and unique challenges. The presented results and recommendations give policymakers, architects, and engineers better knowledge of practical implementations of passive measures that may be effective for their preventative conservation without sacrificing human comfort. Without profound and imminent changes in our lifestyles, the objectives to becoming carbon neutral by the year 2050 will not be achieved.

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Abbreviations

PM	Passive measures
MOD	Meteorological office data
AC	Air conditioners
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
EU	European Union
NECP	National Energy and Climate Plan
SRI	Solar reflective index
IR	Infrared reflective
NICPMI	National Inventory of Cultural Property of the Maltese Islands
UHI	Urban heat-island effect
GHSR	Global Heritage Stone Resource
FFL	Finished floor level
BLE	Bluetooth low energy
COVID	Coronavirus disease
MIA	Malta International Airport
EPS	Extruded polystyrene (standard)
RBs	Reference buildings

Nomenclature

°C	degrees Celsius
°C	degrees Fahrenheit
Θ_o	indoor operative temperature, °C
Θ_{rm}	running mean outdoor temperature, °C
Θ_m	outdoor running mean temperature for the considered day (°C)
Θ_{ed-1}	daily mean outdoor air temperature for previous day (°C)
Θ_{ed-I}	daily mean outdoor air temperature for the i-th previous day (°C)
m	meters
cm	centimetres
mm	millimetres
kW	kilowatt

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