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MONITORING INDOOR TEMPERATURES OF PLACES OF WORSHIP: A FIRST STEP TOWARDS ENERGY SUSTAINABILITY

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ABSTRACT:

This paper attempts to investigate the status quo of the indoor climate of some churches in Malta, ranging from large and small Baroque buildings to more contemporary buildings, during the winter season. This is carried out through an investigation of measured temperature and humidity, 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 such free running structures. A contemporary church that was built of concrete showed extreme diurnal variations in indoor temperature during the winter season, which temperature was outside the comfort zone. On the other hand, Baroque churches had a relatively stable indoor temperature and they had fewer days where the temperature dropped below 18 °C.

Keywords: indoor comfort, churches, thermal mass, Malta

1 INTRODUCTION

Throughout the ages, places of worship have always occupied prominent areas in society, both as a focal point for the community and as a safe place for shelter. Over the years, places of worship were also considered as important monuments where religious art flourished. In more recent times, such centres occupied locally dominant areas within villages and town centres; and a number of bioclimatic design features were evident and effective, until society started demanding higher levels of comfort. Heating as well as cooling systems were installed in particular churches to satisfy the demands of the community. Little attention was given to the precious artefacts these churches held and still hold, due to the change in indoor climate.

This paper aims to provide a first glance on the winter season indoor climate of five churches, including a large Baroque church constructed of masonry globigerina limestone (St. Joseph Parish Church – Msida), two similar but smaller Baroque churches (Stella Maris Parish Church – Sliema and the air-conditioned St. Mary Parish Church – Balzan), a contemporary church built of concrete filled cavity between two leaf limestone walls and pre-fabricated concrete roof planks (St. Venera Parish Church – St. Venera) and a reinforced concrete church (Our Lady of Mount Carmel – Fgura).

2 LITERATURE REVIEW

As buildings consume a large portion of total energy consumption [1], energy efficiency and thermal comfort in historic and other buildings have become high-interest topics among scholars [2]. Research has demonstrated that retrofitting buildings to current energy efficiency and thermal comfort standards is essential for improving sustainability and energy performance and for maintaining built heritage of historic structures. However, among all of these building studies, it is only recently that in depth investigations centred on religious buildings, with their unique occupancy and energy usage.

Some of the few publications on religious facilities consist of experimental and simulation-based energy studies on mosques in the Middle East. M.S. Al-Homoud, et. al., evaluated five representative mosques in Saudi Arabia [3], [4]. 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 majority of electricity (71-79%) was consumed by the HVAC system in space conditioning [5].

Several other papers were later published on the energy and comfort performance for three of the five mosques referred to above. 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 [6]. Another paper evaluated potential energy efficiency measures through simulations of a typical mosque [7], 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 how different envelope parameters affect the energy performance of mosques [8]. Ah-Homoud, also in simulation, optimized envelope parameters for mosques in achieving minimal energy consumption [9]. 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 [10].

In Northern Europe there was a growing concern in the 1960s among antiquarians and architects that medieval stone churches were suffering seriously from overheating [11]. 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 [12]. Since 1887, a directive for managing churches in Sweden required that heating should be kept to a minimum and be provided only during services [13]. 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 [14]. 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 [15 – 18].

More recent 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. [19] 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. Martinez-Garrido et. al. [20] 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. Other papers analysed HVAC typologies [21], HVAC energy usage and occupant comfort and different heating systems in churches and religious facilities [22 – 24].

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 15759-1:2012), 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 [25].

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 [26], [27]. 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 heritage comfort and thermal comfort, particularly in heritage buildings and museums is further evidenced in various works [28], [29], [30].

On the other hand, in a cold climate, if dampness and mould growth are not controlled by conservation heating, dehumidification and adaptive ventilation, the architectural heritage and artistic wealth of mediaeval churches may be lost [31]. If dampness and mould growth can be avoided, artistic wealth may survive for centuries in unheated churches [32]. Unfortunately, as mediaeval churches were originally built and used unheated for centuries, damage mainly caused by a damp environment is generally evident [33], [34]. To this effect recent studies have been conducted in connection with the growing concern over the possible adverse consequences of the use of traditional heating. In countries with harsh climates (very cold, humid winters), expert opinion advised against their installation in churches, because they induce wide fluctuations in the indoor environment and affect the conservation of church heritage [35], [36], [37]. The indoor climate in churches without any climate control is mainly determined by the outdoor climate and hydrothermal performance of the building envelope.

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 microclimatic conditions to which the building and the artworks preserved inside have acclimatised.

As thermal comfort and the preservation of artworks often conflict with each other, a balance between the two needs is necessary. The proposed heating strategy is to provide a small amount of heat directly to people in the pew area, while leaving the conditions in the church, as a whole, undisturbed. This novel heating system is based on some low-temperature radiant emitters mounted in a pew to provide a desirable distribution of heat to the feet, legs and hands of people occupying that space.

Due to little heat dispersion, this novel system not only significantly reduces the risk of mechanical stress in wooden artworks and panel or canvas paintings, fresco soiling and cyclic dissolution-recrystallization of soluble salts in the masonry, but is also energy-efficient. The detailed environmental monitoring was conducted in the church of Santa Maria Maddalena in Rocca Pietore, Italy over a 3-year period to verify the performance of the novel heating system in comparison to the warm-air system that was active earlier in the church. The methodology and results of this comprehensive and multidisciplinary study were included in three draft standards of the European Committee for Standardisation intended for use in the study and control of environments of cultural heritage objects.

In parallel, scholars from Texas A&M University presented the results of a long-term, in-depth energy study of architecturally similar church buildings in the US, including building lighting consumption and occupancy patterns, in an effort to identify energy efficiency opportunities in religious buildings [39], [40]. These studies revealed that religious facilities are understudied, especially considering the extent of total floor area and energy usage they represent. The Energy Conservation Reference and Management Guide for churches [41] and the Historic Boston's Energy Conservation Program for Churches resulted in lowering the energy costs of participating churches, whilst achieving the desired internal comfort [42].

Strikingly, there are notably very few studies/publications regarding religious facilities in the Mediterranean region. 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. 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, cooling as opposed to heating is of major concern.

This study provides a first-hand experience of the status quo in some churches with the aim of developing a strategy for controlling the indoor climate for better thermal comfort, in a Mediterranean climate.

3 EUROPEAN ENERGY DIRECTIVES AND PLACES OF WORSHIP

Linking places of worship with thermal comfort is of paramount importance, because it can be considered as a physical reflection of an inner peace status that human beings have always sought when visiting these temples. Though the churches under review vary in their structure, all follow similar occupancy patterns. All these religious buildings have a large gathering area, which is only occupied during specific periods of time ranging between low and nearly full capacity. The remaining time exhibits minimal or no occupancy. This infrequent occupancy results in a lower overall energy intensity (measured in annual kWh/m²) [43] and this prolongs the payback period of any traditional energy efficiency measures (EEMs), to times that are often beyond cost effectiveness [44].

Nevertheless, the world's global dependence on energy has been increasing at an alarming rate. According to the International Energy Agency (IEA), from 1971 to 2014, world-wide energy consumption increased by 92% [45]. The building sector has contributed to a large portion of this increase. In fact, in 2009, the United Nations Environment Program (UNEP) attributed more than 30% of global greenhouse gas emissions and 40% of total energy consumption to the building sector [46].

Within the EU, Malta is working to reduce the effects of climate change and establish a common energy policy. As part of this policy, European Heads of States or Governments agreed in March 2007 on binding targets to increase the share of renewable energy. The Renewable Energy Action Plan (NREAP) for Malta highlights the need to step up efforts on all fronts to achieve the 2020 target for a renewable energy share through the use of renewable technology. Malta together with all other European Union Member States have agreed on legally binding national targets for increasing the share of renewable energy, so as to achieve a 20% share for the entire Union by 2020. The urge imposed by national and EU laws, with Malta's accession into the EU, was further accelerated as a result of the 2008 oil price hike, the global credit crunch and the volatility of the tourism industry, which is the major source of income for Malta.

To meet this common target, each Member State needs to increase its production and use of renewable energy in electricity, heating, cooling and transport. Although renewable energies are an integral part of our fight against climate change, they also contribute to national growth and increased energy security. Throughout the recent past years, several efforts were made by Government and Maltese professional bodies, to raise awareness with regards to renewable energy applications and to a lesser extent on energy conservation and efficiency.

A number of fiscal incentives were also introduced to invest in renewable energy systems. This, coupled with the increase in energy and services charges, a number of medium and large entities have opted to revise their energy profile; however, there are so far no standard procedures adopted to ensure maximum benefit to the customer and the environment. Furthermore, to date, this sector has been largely dependent on EU funded subsidy schemes. The downside to this is that of course whilst these funds are not unlimited, the market tends to be dependent on the availability of funding, and this therefore creates a largely fluctuating take-up of the available technology.

One step towards standardisation has been made by the publication and implementation of Technical Guidance F (2006) on the Minimum Requirements on the Energy Performance in Buildings Regulations, effective as of January 2009, which was further upgraded in 2016, to include building services. Furthermore, the Services Division, within the Building Regulation Office launched the Malta Energy Certification Software for both domestic and non-residential buildings, exempting amongst other places of worship (L.N. 376 of 2012) [47]. As the years passed by, the National Energy Policy was published in December 2012 [48] and the National Renewable Energy Action Plan updated reports have been published for 2014 [49], showing that Malta has reached 5% renewable energy share. However, energy efficiency in buildings remains quite weak and dispersed. This is even more pronounced in places of worship, given that no legal requirements for energy efficiency apply.

In view of the heritage and traditional buildings as civilization attestation, the EPBD [50], [51] article 4, paragraph 3 states: “Member States may decide not to set or apply the requirements referred for the following categories of buildings: buildings and monuments officially protected as part of a designated environment or because of their special architectural or historic merit, where compliance with the requirements would unacceptably alter their character or appearance”. Historic buildings, including churches, have thus not been considered.

Nevertheless, such uncontrolled and sometimes harsh indoor environments are impacted by local factors, which may put at risk the conservation of a church’s cultural assets [52]. This in itself is a misfortune, because places of worship still serve as the focal point for many congregations and communities of all religions. It is there that pro-environment measures leading to better comfort can encourage citizens to duplicate in their own homes and thus lead to a ripple effect in reducing energy consumption across Europe.

The preliminary results of this paper demonstrate the gravity of the situation. The data gathered for the first quarter of 2018 (winter season) from within the five churches under review, show substantial fluctuations in indoor environments primarily affecting temperature (T) and relative humidity (RH); which parameter induce efflorescence, plaster blistering, detachment, as well as drying and cracking of artwork.

4 DESCRIPTION OF THE CHURCHES UNDER STUDY

In order to arrive to a meaningful analysis of the architecture, structural detailing, paintings and other works of art vis-a-vis the environmental conditions, artistic and architectural heritage, a detailed review of Melitensia publications and dissertations were carried out at the University of Malta. These were mainly dissertations and Masters Theses of the Faculty of Arts dealing with artworks and historic architecture of old churches, but not on energy use or indoor comfort. Reference was also made to various publications including books [53], [54], [55], [56], [57], feast programmes, exhibition reviews, newspapers as well as church archives, Archiepiscopal and National Archives. Unfortunately, these archives contained very little information. No studies were found in Malta that deal with energy performance in churches or other places of worship. Nonetheless, tangible first-hand information was obtained from persons who were involved in one way or another either with history of Maltese churches or the specific construction or maintenance of the churches under study.

As mentioned earlier, the five churches selected have varying methodologies of construction, ranging from masonry construction to reinforced concrete. Table 1 shows the footprint area of the five churches and the air volume inside them.

The Malta Planning Authority has scheduled these buildings as Grade 1 monuments and are listed on the National Inventory of the Cultural Property of the Maltese Islands (NICPMI).

Table 1: Areas and Volumes Analysis.

Parish Church	**Footprint Internal Area (m^2)**	**Air Internal Volume (m^3)**
Balzan	563	8,800
Stella Maris	526	7,850
Msida	1,155	17,350
Fgura	881	7,890
Santa Venera	1,231	21,770

Note: Results are indicative and for comparative analysis only.

4.1 Our Lady of the Annunciation Balzan Parish Church

Balzan became a parish on the 14th August 1655 and in December 1669 work started on the building of the existing Parish Church. Though it is reported that part of the building was in use after four years from commencement, works were completed by 1695, under the direction of architects Lorenzo Gafa and Giovanni Barbara. The church was built in the form of a Latin cross. A belfry was also added in 1708, which today includes 6 bells made in Annecy, France by Fonderie Paccard. The methodology of construction is mainly of load bearing masonry walls supporting a vaulted roof and dome structure, built with globigerina limestone blocks and roofed over by a composition of 'deffun' layer.

It is pertinent to mention that in 2006, the Balzan Heritage Commission was set up to establish the cause of the fallen Emvin Cremona Painting in the dome of the Rosary Laterial Chapel, within the Balzan Parish Church earlier on that year. The Commission was given the responsibility to undertake observation, recommend/undertake various studies and draft up a report on this case. The board remarked that a combination of causes may have affected the painting, one of which was the possible introduction of the air-conditioning system installed in the last decade, which may have caused climatic fluctuations that resulted in detachment.

Figure 1: Photographs of the façade and nave with installed AC units of Balzan Parish Church.

4.2 Our Lady Star of the Sea, Stella Maris Parish Church, Sliema

In April 1853, the construction of Stella Maris Parish Church, dedicated to Our Lady Star of the Sea, 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 methodology of construction is mainly of loadbearing masonry walls supporting a vaulted roof and dome structure, built with globigerina limestone blocks. The original roofing material, still present, include a 'deffun' layer with the adequate falls to eliminate ponding. 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.

Figure 2: Photographs of the façade and nave of Stella Maris Parish Church, Sliema.

4.3 St. Joseph Msida Parish Church

Msida became a parish in 1867 and for several years the old church of the Immaculate Conception served as the Parish Church, which still exists today. The present Parish Church was built in the late 19th century with a design typical of the traditional baroque churches prevalent a century before. Works were brought to completion by 1889.

Figure 3: Photographs of the façade and nave (facing western end) of Msida Parish Church.

The plan is conventional and takes the form of a three-aisled Latin Cross, which was the most frequently adopted plan in the design of local Parish Churches. The façade comprises of a series of bays with the two outer bays surmounted by well-proportioned bell-towers. Lorenzo Gafa's design for St Catherine Parish Church of Żejtun appears to have been the source upon which the architect Andrea Grima based his design.

4.4 Our Lady of Mount Carmel Fgura Parish Church

The Parish Church of Fgura was built in the late 20th century (1988) and was dedicated to Our Lady of Mount Carmel on 1 February 1990, on a project by Perit Victor Muscat Inglott and structural engineer Perit Godfrey Azzopardi. This church is built in modern, post-Vatican II Council style and is one of the most original and boldest structures to be built in reinforced concrete on the Island. Its design is based on a square plan roofed over by a concrete shell structure that is symmetric about both axis. The main material supporting the building is concrete and the strength of the structure is derived from its form rather than its sheer mass. 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: Photograph of the façade of Fgura Parish Church.

4.5 Santa Venera Parish Church

Santa Venera Parish Church was constructed at various stages between 1954 and 2005, although the building is still incomplete, lacking bell towers and external finishing. Construction of the church began on 19 April 1956, to Romanesque Revival (Neo-Romanesque style) designs of Joseph D'Amato. After excavation works, the crypt was completed by June 1967 and was used as a provisional church. Due to this fact and the construction of other three churches in Malta by the Order of the Brothers of the Blessed Virgin Mary of Mount Carmel (Carmelites), construction works at Santa Venera were brought to a halt. On the twentieth anniversary since the opening of the crypt, Perit Louis A. Naudi, assisted by Godwin Aquilina and Lino Bartolo, were commissioned to continue works. The original plan was redesigned by Ġużeppi Galea from Rabat and works were executed by Attard Bros. Co. Ltd. The methodology of construction is mainly of loadbearing masonry walls supporting reinforced precast planks. The foundation stone was laid down on 6 October 1990 and works were brought to completion after fifteen years, with the last interventions seen by Perit Innocent Centorrino. The building was blessed and opened for veneration on 17 July 2005 [58]. This Church has yet to be consecrated.

Figure 5: Photographs of the façade and nave of Santa Venera Parish Church.

5 METHODOLOGY AND TECHNICAL DESCRIPTION OF EQUIPMENT USED

5.1 Onsite Measurements

Simultaneous measurements of air temperature (T) and relative humidity (RH) with data loggers were carried out in three different locations (with the exception of Fgura Parish Church), ranging from the western end, the nave and the altar. The loggers were placed at a height ranging from circa 1.7m to 3.5m from the finished floor level (FFL).
(Refer to Table 2).

Table 2: Location of Sensors – Vertical Height

Parish Church	Western End (m)	Nave (m)	Altar (m)
Balzan	2.0	2.4	1.8
Stella Maris	2.3	3.5	1.7
Msida	3.0	3.2	2.0
Fgura	-*	3.0	2.5
Santa Venera	2.0	2.0	2.4

*Due to the church layout, one sensor is covering both the Western End and Nave.

In order to obtain representative climatic data, dual channel digital air humidity and temperature sensors (data loggers) were placed at the best possible locations avoiding the influence of radiating sources and air flow. The loggers measured air humidity and temperature at five-minute intervals, with data collected on monthly basis.

In addition, outdoor air temperature and RH were measured at an ad hoc station near the respective churches or within their perimeters.

5.2 Research Methodologies and Logging Systems

The first step of the research consists in the continuous monitoring of the selected five Churches indoor environment. The monitoring operation regards measurement of the two most important parameters; temperature, T (°C) and RH (%).

With the exception of Stella Maris Parish Church, where HOBO UX100-003 data loggers were installed, Onset's HOBO MX1101 data loggers were used to measures and transmits temperature and RH data wirelessly to mobile devices via Bluetooth Low Energy (BLE) technology.

The MX1101 data logger supports the following measurements: RH and Temperature [59] and the specifications are shown in Table 3, below.

Table 3: Specifications of Data Logger

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.

6 ANALYSIS OF RESULTS

Figure 6 shows the indoor temperature profile of the nave of the five churches from December 2017 to March 2018.

It is evident that the worst performing church is the Fgura concrete church, where the indoor temperature follows the outdoor temperature especially for the peaks.

All the remaining churches are much better in terms of indoor climate conditions. Unlike the Fgura Church, there is also evidently a marked time lag for the outdoor temperature to affect the indoor temperatures, especially during consecutive days when the outdoor temperature plummets.

The best performing church is the Msida Parish Church, where indoor temperatures remain stable for much longer and only drop below 17 °C towards the beginning of February. However, within one month the temperature climbed again to a more comfortable value.

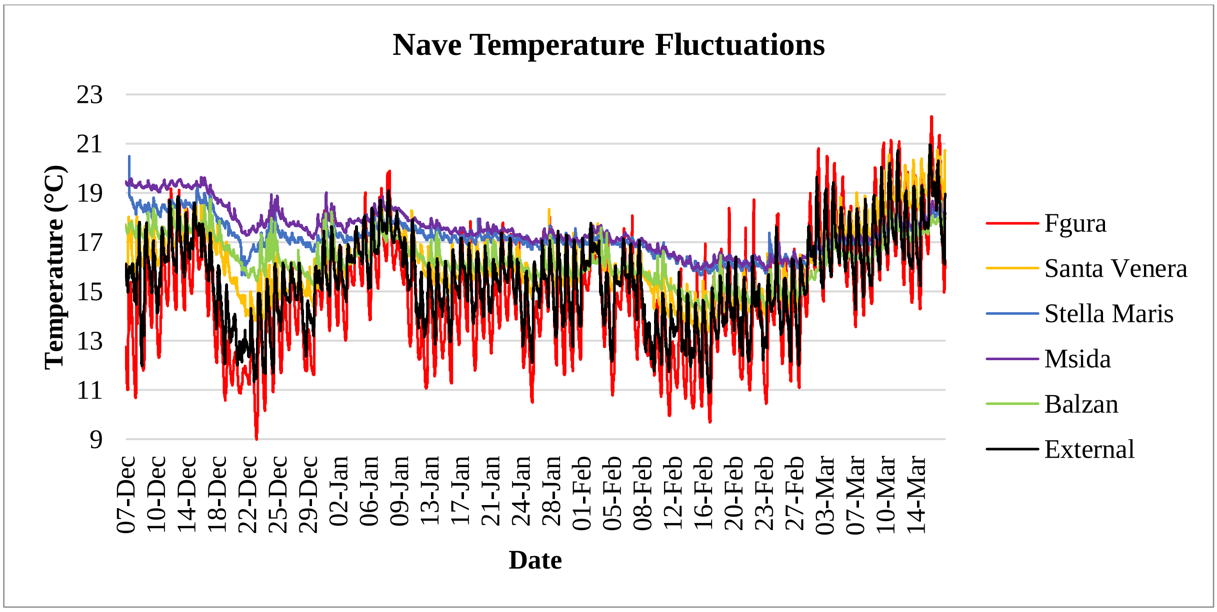

Figure 6: Comparative Analysis of Nave Temperature (T °C) Fluctuations of the five churches under study.

Balzan is the furthest away from the sea and is assumed to be least affected by outdoor RH. However, this is not the case. It is to be noted that this Church has a huge subterranean water reservoir and this could be a reason for creating a colder atmosphere due to evaporative cooling from the floor, thus affecting RH. This will be verified at a later stage of this on-going Ph.D. study.

It is to be noted that although the Balzan church has an air-conditioning system, it is not used for heating at all, despite the fact that its air temperature is about 2 °C lower when compared to the Msida and Stella Maris churches. This gives an indication that the congregation is more resilient to sustain colder rather than hotter temperatures outside the comfort zone.

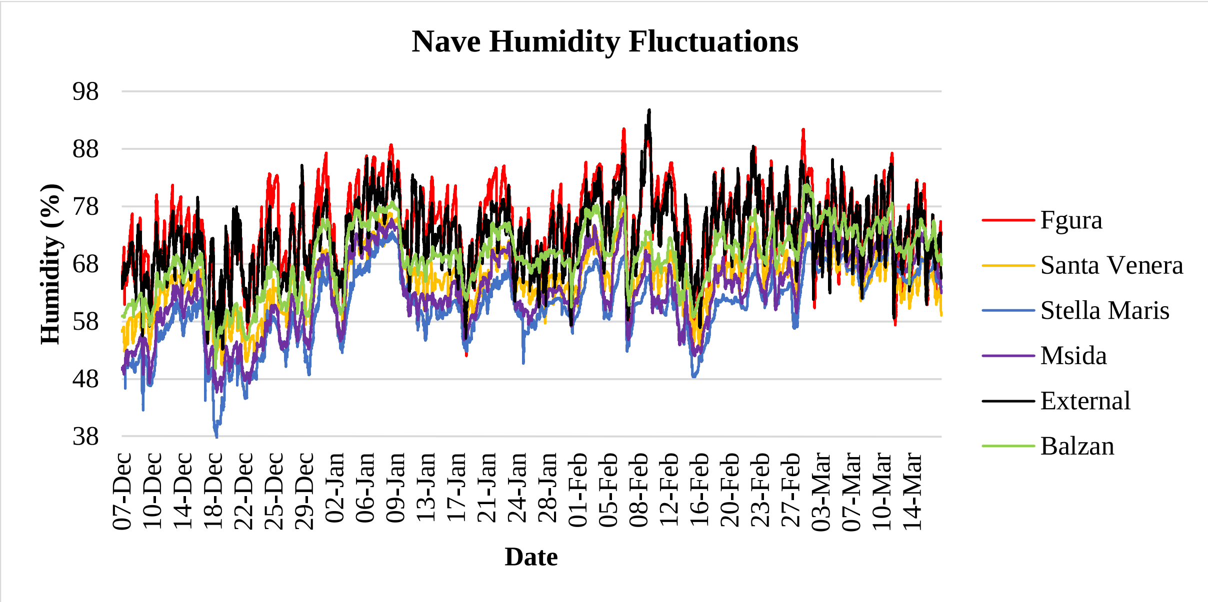

Figure 7: Comparative Analysis of Nave Humidity (RH %) Fluctuations of the five churches under study.

The effect of presence of congregation in a church could also affect the indoor temperature and humidity. For this purpose, two days were chosen for each church, namely on Christmas day of 25th December 2017 when the church is considered to be full and on a Monday, when the church would have much lower attendance of people.

For the Balzan Church, there is a marked drop in temperature on Christmas day when the doors are opened in the morning. This was compensated by the presence of people during the religious functions both in the morning, noon time and at 6:00 p.m.

On the contrary, there was no drop in temperature, when the church was opened on 12th February. This is because the indoor temperature of the Church has by now dropped and the stored energy in the thermal mass of the church had been depleted after two and a half months of winter season. Also, given that attendance during the week is low, there was no change in the church's indoor temperature during the day.

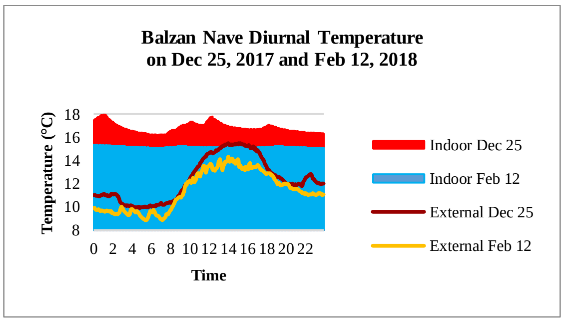

Figure 8: Comparative Analysis of Nave Diurnal Temperature (T °C) Fluctuations of Balzan Parish Church.

With regards to humidity, it is noted that it is stable for both days, despite changes in the outdoor RH. One explanation could be that the indoor RH is dominated by the effect of the underground water reservoir. The presence of people on Christmas day had very little effect.

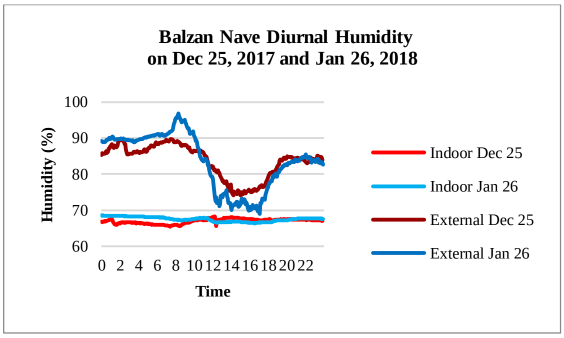

Figure 9: Comparative Analysis of Nave Diurnal Humidity (RH %) Fluctuations of Balzan Parish Church.

Note: Humidity for days post-Jan 26 up to Feb 12 was recorded at 100% and thus could not be used for interpretation.

At Stella Maris Church, Figure 10 shows that the presence of people on Christmas day may have added slightly lower than 1 °C to the indoor temperature. On the other hand, the RH has marginally increased towards noon time. On a regular Monday, the humidity is hardly affected by the presence of people. One interesting feature is that the RH inside the church is much lower than outside. This could be attributed to the hygroscopic characteristics of the limestone walls.

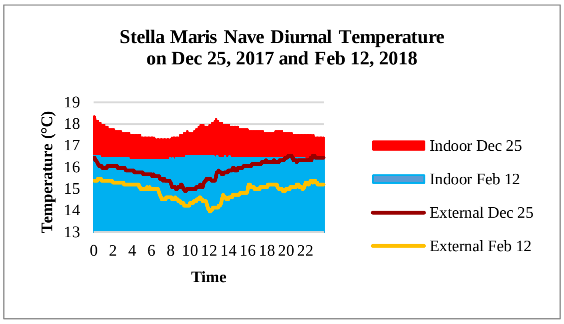

Figure 10: Comparative Analysis of Nave Diurnal Temperature (T °C) Fluctuations of Stella Maris, Sliema Parish Church.

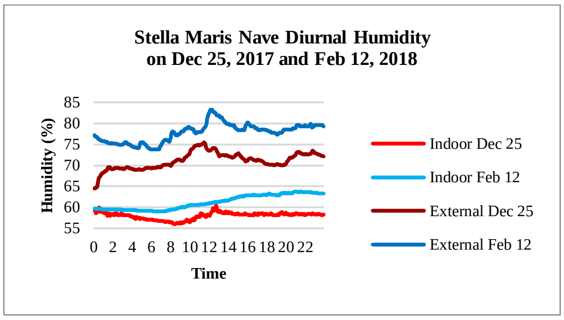

Figure 11: Comparative Analysis of Nave Diurnal Humidity (RH %) Fluctuations of Stella Maris, Sliema Parish Church.

The Msida Parish Church external temperature showed a marked increase after 09:00 a.m. This is due to the fact that the temperature sensor was subjected to direct solar radiation, given that it was placed in a small window on the façade, which is facing south-east. In December, the sun is at its lowest with an enhanced direct effect on the sensor. Opening the Church in the morning led to a small drop in temperature, which is much lower than that reported in other churches. This is because the air volume is large for this church. The presence of people on Christmas day did not significantly change the indoor temperature for the same reason.

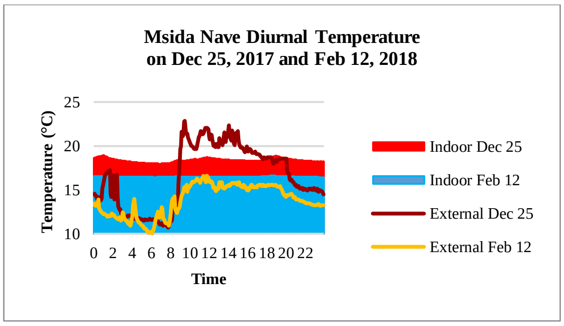

Figure 12: Comparative Analysis of Nave Diurnal Temperature (T °C) Fluctuations of Msida Parish Church.

Internal RH is well within the comfort limits (40-70 %), for both days. This is another church that is entirely built of limestone and this could help stabilise the internal RH.

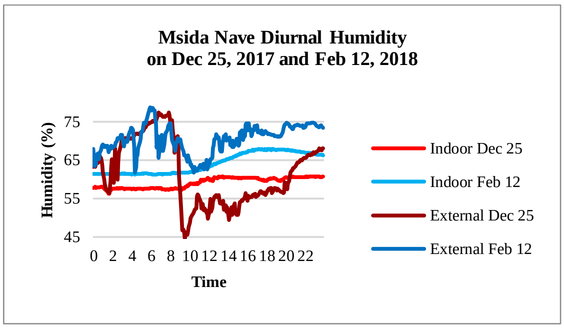

Figure 13: Comparative Analysis of Nave Diurnal Humidity (RH %) Fluctuations of Msida Parish Church.

The Fgura Parish Church shows a marked low indoor temperature for both days. Moreover, there is a strong swing of temperature between morning and night within the church. This is clearly an atypical case, where the effect of an entire concrete un-insulated construction, reflects in poor indoor comfort. Moreover, it is noted that the church gets colder than the external temperature at night due to evaporative cooling of the concrete, as well as the existence of large single glass structures that allow heat conduction to the outside air.

This church suffers both in terms of temperature and humidity. This is because concrete is not porous and therefore tends to separate the outside humidity from the inside, albeit the fact that it quickly conducts heat to and away from the building.

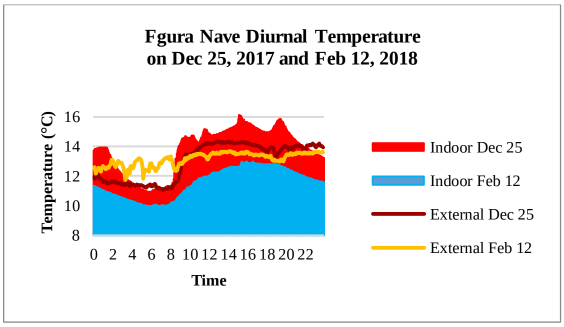

Figure 14: Comparative Analysis of Nave Diurnal Temperature (T °C) Fluctuations of Fgura Parish Church.

The indoor RH at Fgura Parish Church is high, due to the lower indoor temperature. It is the only church that has high RH beyond the comfort zone of 40-70%. This adds to the feeling of coldness.

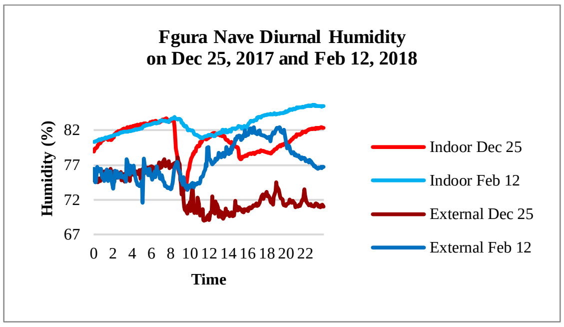

Figure 15: Comparative Analysis of Nave Diurnal Humidity (RH %) Fluctuations of Fgura Parish Church.

The Santa Venera Parish Church is the second least comfortable in terms of indoor temperature. It is shown in Figure 16 that the indoor temperature was already below 16 °C from the beginning of the winter seasons. However, unlike the Fgura church, the temperature did not drop much more in February. This is an indication that the construction materials and the methodology of construction have a detrimental effect on indoor temperature. In Santa Venera, the walls are much thicker than those of Fgura and although the core of the wall is filled with concrete, the external and internal leafs are of globigerina limestone blocks. This adds to the thermal mass and reduces temperature swings.

Indoor RH in Santa Venera Parish Church is within normal limits and there is no major comment on its behaviour.

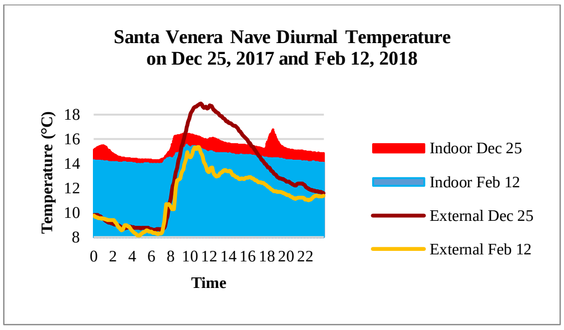

Figure 16: Comparative Analysis of Nave Diurnal Temperature (T °C) Fluctuations of Santa Venera Parish Church.

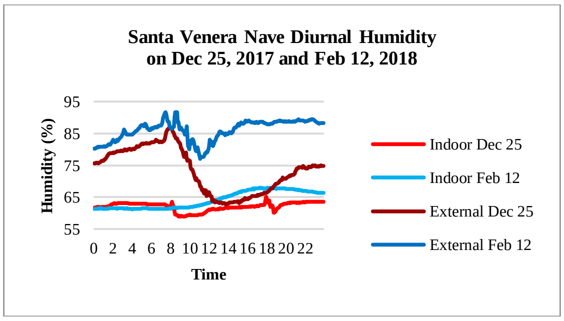

Figure 17: Comparative Analysis of Nave Diurnal Humidity (RH %) Fluctuations of Santa Venera Parish Church.

6 DISCUSSION AND CONCLUSIONS

The results achieved through the interpretation of the temperature and RH data gathered are intended to establish a standard approach rather than a standard methodology. This in view of the fact that every building presents unique challenges.

It is not correct to lump temperature and RH together under "climate control" or "the environment". It is best to discuss incorrect temperature and incorrect RH, as separate agents because both the damage to artifacts and the means of control are more dissimilar than similar, and because the entanglement of the two under "climate control standards" has led to many false generalisations and wasteful simplifications. Furthermore, the low-cost, low-energy, passive solutions for each are distinct and become sidelined in the quest for a single engineering solution to "climate" [60].

Generally, churches have thick walls made of globigerina limestone. The thickness of the wall offers good thermal inertia, delaying the internal temperature from being affected by the hourly/daily fluctuations outside the building. In addition, the hygroscopic building fabric could buffer the RH, as it absorbs and desorbs moisture from the air. This, as long as the air within the church is not exchanged with the air outside the building at a fast rate [61].

Another aspect that one needs to consider is the uneven temperature within the same building. These could pose bigger problems than fluctuations over time, especially for churches decorated with religious artifacts and fine arts. There are various ways in which uneven temperatures become a source of incorrect RH. In short, the most important form of incorrect RH, damp, is more often than not caused by humid air reaching localized cold spots. Whilst humans prefer to be heated in winter even if the result is a very low RH, it is imperative to understand that historic collections and artifacts are better off in cold temperatures accompanied by a moderate RH.

To this effect, prior to considering a hybrid system of active and passive systems, one must advocate for passive control systems and on a case by case basis ensure that any changes will not affect the artifacts inside the church.

The results presented in this paper serve as a preliminary study that will be expanded over a number of years, in order to understand the energy performance of such churches and provide the best solutions for comfort, also based on detailed modeling and simulation.

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