Assessing Energy Performance and Indoor Comfort in Places of Worship

Robert C. Vella

Director: Prof. Ing. Charles Yousif

Co-Director: Prof. Francisco Javier Rey Martinez

Doctor of Philosophy (PhD) Degree in Industrial Engineering

Escuela de Ingenierías Industriales

Departamento de Ingeniería Energética y Fluidomecánica

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PREFACE

This doctoral dissertation is presented as a compendium of publications published in three scientific articles and one complimentary conference paper, in conformity to the ANECA criteria and in joint contribution, describing the overall objectives pursued, the methodology employed, and the results achieved within each respective research component.

LIST OF PAPERS

Complementary Paper

Complementary Paper entitled '*Monitoring Indoor Temperatures of Places of Worship: A First Step Towards Energy Sustainability Engineering Sustainability and Sustainable Energy'; (ESSE'*18) Conference organised by the Chamber of Engineers in collaboration with the Institute for Sustainable Energy of the University of Malta, ISBN: 978-99957-853-2-1 [1]

Statistics (August 2022)

Open Access Repository University of Malta

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Citations:	1
No. of Views:	104 views
File Downloads:	145 downloads

Paper 1

Scientific Article No.1 entitled *'A study of thermal comfort in naturally ventilated churches in a Mediterranean climate';* published by Energy & Buildings Journal, Volume 213, 2020, 109843, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2020.109843 [2].

Citations (August 2022)	
Google Scholar	17
Scopus	15
Clarivate Web of Science	12
Abstract views:	80
Full text downloads:	39
ResearchGate Reads:	105

Rank by Journal Impact Factor: 7.201 (2021)	
Energy & Buildings JCR Category	Q1
Rank in Category: Engineering Buildings and Construction	09/211
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Paper 2

Scientific Article No.2 entitled '*Thermal Comfort in Places of Worship within a Mediterranean Climate*'; published by Sustainability Journal 2021, 13, 7233, https://doi.org/10.3390/su13137233 [3].

Citations (August 2022)

Google Scholar	1
Scopus	1
Clarivate Web of Science	1
Abstract views:	797
Full text downloads:	737
ResearchGate Reads:	62

Rank by Journal Impact Factor: 4.17 (2021)

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Paper 3

Scientific Article No.3 entitled '*Prioritising Passive Measures over Air Conditioning to Achieve Thermal Comfort in Mediterranean Baroque Churches*'; published by Sustainability Journal 2022, 14, 8261, https://doi.org/10.3390/su14148261 [4].

Citations (August 2022)	
Google Scholar	0
Scopus	0
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Abstract views:	293
Full text downloads:	206
ResearchGate reads:	24

Rank by Journal Impact Factor: 4.17 (2021)	
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ABSTRACT

Buildings are responsible for more than 40% of the total energy consumption and greenhouse gas emissions in Europe. As a result, the EU has enacted several rules aimed at increasing energy efficiency and limiting the growth of energy demand. However, it is pertinent to point out that places of worship are exempt from getting an energy rating certificate under the European Union Energy Performance in Buildings Directive 2010/31/EU.

Malta is completely reliant on imported energy supplies due to a lack of fossil fuel resources. This, to the cost of national security, price volatility, political and environmental concerns, amongst other things. Controlling and managing energy use in buildings is one efficient strategy to reduce this reliance. Excessive energy flow through the building envelope and, unregulated use of air-conditioning are some common drivers of energy waste in buildings.

This thesis aims to assess the energy performance of places of worship and combine it with indoor comfort analysis. Passive measures to improve internal comfort levels are identified and prioritised to address heat transfer through the building envelope and mitigate the emerging trend of installing air-conditioning systems. This study takes into consideration the status quo of various places of worship of different building eras using a monitoring programme for temperature and humidity within these buildings. It further delves into the social aspect of how worshipers perceive the indoor comfort through questionnaires addressed to the occupants. Subsequently, it analyses how passive measures can improve the indoor ambient conditions through software design modelling using DesignBuilder-Energy Plus software.

This analysis show that historic church structures outperform expectations. The heritage building typology provides promising possibilities for lowering energy consumption, maintaining balanced environmental conditions for artifacts, and meeting occupant comfort standards. The findings pertaining to the monitoring program demonstrate that the church buildings under study, representing the 17th to mid-18th century Baroque period, are termed as thermally comfortable in accordance with the EN16798-1 standard category 3 comfort limits. Moreover, results exhibit the capacity of their heritage construction typology, to maintain balanced environmental conditions when compared to the fluctuated indoor

temperatures in the contemporary churches. The latter, pertaining to the more contemporary construction methodologies of the churches, jeopardises their thermal comfort, having recorded temperatures exceeding the broadest comfort range limits. Findings through statistical analysis of both quantitative research based on indoor measurable data and qualitative research based on replies to questionnaires from churchgoers, also show that there is a significant correlation between the actual thermal comfort levels measured in accordance with the EN 16798-1 standard and the expected thermal comfort experienced by congregants in most of the parish churches under review.

The implementation of passive measures within selected churches, particularly the implementation of solar control strategies that improves the building envelope's thermal performance, significantly decreased heat discomfort. The outcome highlights differences between diverse types of church buildings, depending on their era, site constraints and methodology of construction, together with a list of passive and non-intrusive recommendations for enhancing the comfort of worshipers and improving the energy efficiency aspects of these buildings, whilst respecting their architectural heritage and artefacts with which they are adorned.

RESUMEN

Los edificios en la EU representan más del 40 % del consumo total de energía y el 36% de las emisiones de gases de efecto invernadero, GEI. Como consecuencia de esto, la EU establece un marco político en materia tanto de energía como de cambio climático promulgado varias directivas y programas de acción como el Green Deal, destinadas a aumentar la eficiencia energética, y reducción de los gases GEI. Es pertinente señalar que los lugares de culto están exentos de obtener un certificado de calificación energética en virtud de la Directiva de Eficiencia Energética en Edificios de la Unión Europea 2010/31/UE.

Malta depende completamente de los suministros de energía importados debido a la falta de recursos propios de combustibles fósiles, al costo de la seguridad nacional, la volatilidad de los precios, las preocupaciones políticas y ambientales, entre otras cosas. Una forma eficaz de reducir esta dependencia es gestionar y controlar el consumo energético de los edificios. El flujo excesivo de energía a través de la envolvente del edificio, el uso no regulado del aire acondicionado y la falta de ventilación son causas comunes de la ineficiencia de energía en los edificios. Estos factores no pueden resolverse fácilmente y, a su vez, es necesario realizar una cantidad considerable de investigación para identificar las principales debilidades de cada uno de ellos.

Esta tesis tiene como objetivo el análisis e identificación de las medidas tecnológicas pasivas que se pueden adoptar en los lugares de culto, para abordar la transferencia de calor a través de la envolvente del edificio y la tendencia emergente de instalar sistemas de aire acondicionado. Este estudio tiene en cuenta el status quo de varios lugares de culto de diferentes épocas de construcción, profundiza en el aspecto social de cómo los fieles perciben el confort interior y analiza cómo las medidas tecnológicas pasivas pueden mejorar las condiciones ambientales. Para llevar a cabo la metodología de este estudio se establece un programa de monitorización de temperatura seca y humedad relativa dentro de los edificios, de culto, así como cuestionarios de elaboración propia, dirigidos a los miembros de la comunidad y su análisis estadístico. Otra herramienta teórica empleada, es una simulación dinámica de energía, mediante el software reconocido internacionalmente DesignBuilder que *utilza el motor de cálculo Energy plus y se aplica a un número seleccionado de lugares de culto representativos.*

El análisis muestra que las estructuras históricas de la iglesia superan las expectativas. La tipología de edificio patrimonial brinda posibilidades prometedoras para reducir el consumo de energía, mantener condiciones ambientales equilibradas para el patrimonio artístico y cumplir con los estándares de confort térmico de los ocupantes. Los hallazgos relacionados con el programa de monitorización demuestran que los edificios de la iglesia en estudio, que representan el período barroco del siglo XVII a mediados del siglo XVIII, se denominan térmicamente confortables de acuerdo con los límites de confort de categoría 3 de la norma europea EN16798-1. Además, los resultados muestran la capacidad de su tipología de construcción patrimonial para mantener condiciones ambientales equilibradas en comparación con las temperaturas interiores fluctuantes en las iglesias contemporáneas. Este último, perteneciente a las metodologías constructivas más contemporáneas de las iglesias, pone en peligro su confort térmico, habiéndose registrado temperaturas que superan los límites más amplios del rango de confort. Los resultados del análisis estadístico de la investigación cuantitativa basada en datos medibles en interiores y la investigación cualitativa basada en las respuestas a los cuestionarios de los feligreses también muestran que existe una correlación significativa entre los niveles reales de confort térmico medidos de acuerdo con la norma EN 16798-1 y el confort térmico esperado por los feligreses en la mayoría de las iglesias parroquiales bajo revisión.

La implementación de las medidas tecnológicas pasivas dentro de las iglesias seleccionadas, particularmente la implementación de estrategias de control solar que mejoran el desempeño térmico de la envolvente del edificio disminuyó significativamente la incomodidad por calor. El resultado destaca las diferencias entre los diversos tipos de edificios de iglesias, según su época, las limitaciones de la ubicación y la metodología de construcción, junto con una lista de recomendaciones pasivas y no intrusivas para mejorar el confort térmico de los fieles y los aspectos de eficiencia energética de estos edificios, respetando su patrimonio arquitectónico y artístico que lo componen.

ACKNOWLEDGMENTS

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DECLARATION OF INTEREST

None.

TUTORS DECLARATION

Universidad de Valladolid, Escuela de Doctorado

Prof. Ing. Charles Yousif and Prof. Francisco Javier Rey Martinez hereby declare that this work entitled: “Assessing Energy Performance and Indoor Comfort in Places of Worship”, presented by Robert C. Vella (Malta) for obtaining the title of Doctor of Philosophy, has been carried out under our supervision through the Doctoral Program in Industrial Engineering within Escuela de Ingenierías Industriales, Departamento Ingeniería Energética y Fluidomecánica, Universidad de Valladolid, in collaboration with the Institute for Sustainable Energy, University of Malta.

Date: 26 August 2022

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Prof. Ing. Charles Yousif
Director

Prof. Francisco Javier Rey Martinez
Co-director

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LIST OF ABBREVIATIONS

ACs	Air Conditioners
BLE	Bluetooth Low Energy
BMJ	British Medical Journal
CO2	Carbon Dioxide
COVID	Coronavirus Disease
CTS	Current Thermal State
EEMs	Energy Efficiency Measures
EPBD	European Union Energy Performance in Buildings Directive 2010/31/EU
EPS	Extruded Polystyrene Standard
ESSE	Engineering Sustainability and Sustainable Energy
EU	European Union
EUCA	Energy Union and Climate Action
FFL	Finished Floor Level
GHSR	Global Heritage Stone Resource
H	Humidity
HSS	Heritage Stones Sub-commission
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IMQ	Indoor Microclimatic Quality
IUGS	International Union of Geological Sciences
MIA	Malta International Airport
MOD	Meteorological Office Data
NECP	National Energy and Climate Plan
NICPMI	National Inventory of the Cultural Property of the Maltese Islands
NOAA	The National Oceanic and Atmospheric Administration
NREAP	National Renewable Energy Action Plan
PM	Passive Measures
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RBs	Reference Buildings
RH	Relative Humidity
SCH	Superintendence of Cultural Heritage
SPSS	Statistical Package for the Social Sciences
T	Temperature
TSS	Thermal Sensation Survey
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organisation
ZEBs	Zero Energy Buildings

SETTING THE SCENE

According to the National Oceanic and Atmospheric Administration's (NOAA) annual report for 2022, the nine years from 2013 to 2021 were all among the ten warmest on record [5], with a European record of maximum temperature in 2021 of nearly 49˚C in Sicily. The average temperature over worldwide surfaces in 2021 was 0.84 degrees Celsius higher than that of the 20th-century, with a global land and ocean temperature 1.04˚C above the average. Scientists envisage that at the current rate of heating, the planet might reach the 1.5˚C increase in the 2030s, underscoring the global climate crisis. Rises in the amount of greenhouse gases in the atmosphere during the industrial revolution are mostly the product of human activity and are largely responsible for observed temperature increases; accountable amongst other for mass die-offs in coral reefs, and the decimation of coastal communities.

As the globe struggles with climate-related heat waves, sustainable energy behaviours, or aspects of lifestyle, avenues need to be sought to reducing air conditioner demand, which accounts for a substantial portion of energy consumption in buildings. Ecological communities are commonly touted as a model for sustainable living because they have a strong environmental self-identity and values and are more likely to engage in environmentally friendly and energy-saving activities. However, it is questionable if members of these communities would behave as intended, particularly when faced with acute environmental conditions such as heat waves.

Global energy consumption from air conditioners is anticipated to triple by 2050, as temperatures rise, and climate-induced extreme heat events become more frequent and intense. According to projections, AC installations will increase from 1.6 billion units in 2018 to 5.6 billion by 2050 [6]. This expansion will be driven mostly by fast growing economies experiencing higher temperatures and warmer years. According to energy demand scholars, reorienting behaviours toward pro-environmental cooling measures might generate massive energy and environmental advantages [7]. However, such increases are backed by people's own perceptions of the environment and driven by people's ever-demanding lifestyles [8,9]. Although promising, research utilising social science models to explain pro-environmental behaviours has mainly focused on behaviours in the Global North, with only a few studies in the Global South. Despite this, cooling behaviours in the Global South are expected to contribute to increased future global cooling demand [10,11]. To this effect, there is a need to focus more explicitly on the motivations and behaviours underlying peoples' ownership and use of ACs considering the rise in climate-induced heat events and changing weather patterns. Thus, through assessing energy performance and indoor comfort in places of worship, utilising free-running reference buildings, this study explores why a trend to install ACs in Baroque churches is emerging to deal with lifestyle and weather patterns. Therefore, the research questions can be summarised as follows:

- *To what extent are places of worship both traditionally and newly built conforming to indoor comfort levels in accordance with the EN16798-1 standard?*
- *How do communities frequenting places of worship relate to the indoor comfort conditions for different seasons?*
- *To what extent do passive building envelope measures and their prioritisation contribute towards improving the indoor building environment in places of worship and therefore avoiding the installation of mechanical air-conditioning systems?*

To answer the above questions, this thesis investigates the energy performance rating of five different representative churches and determine the relationship between the actual thermal comfort levels measured according to EN 16798-1 standard, the expected thermal comfort of attendees, and the effectiveness of selected passive measures.

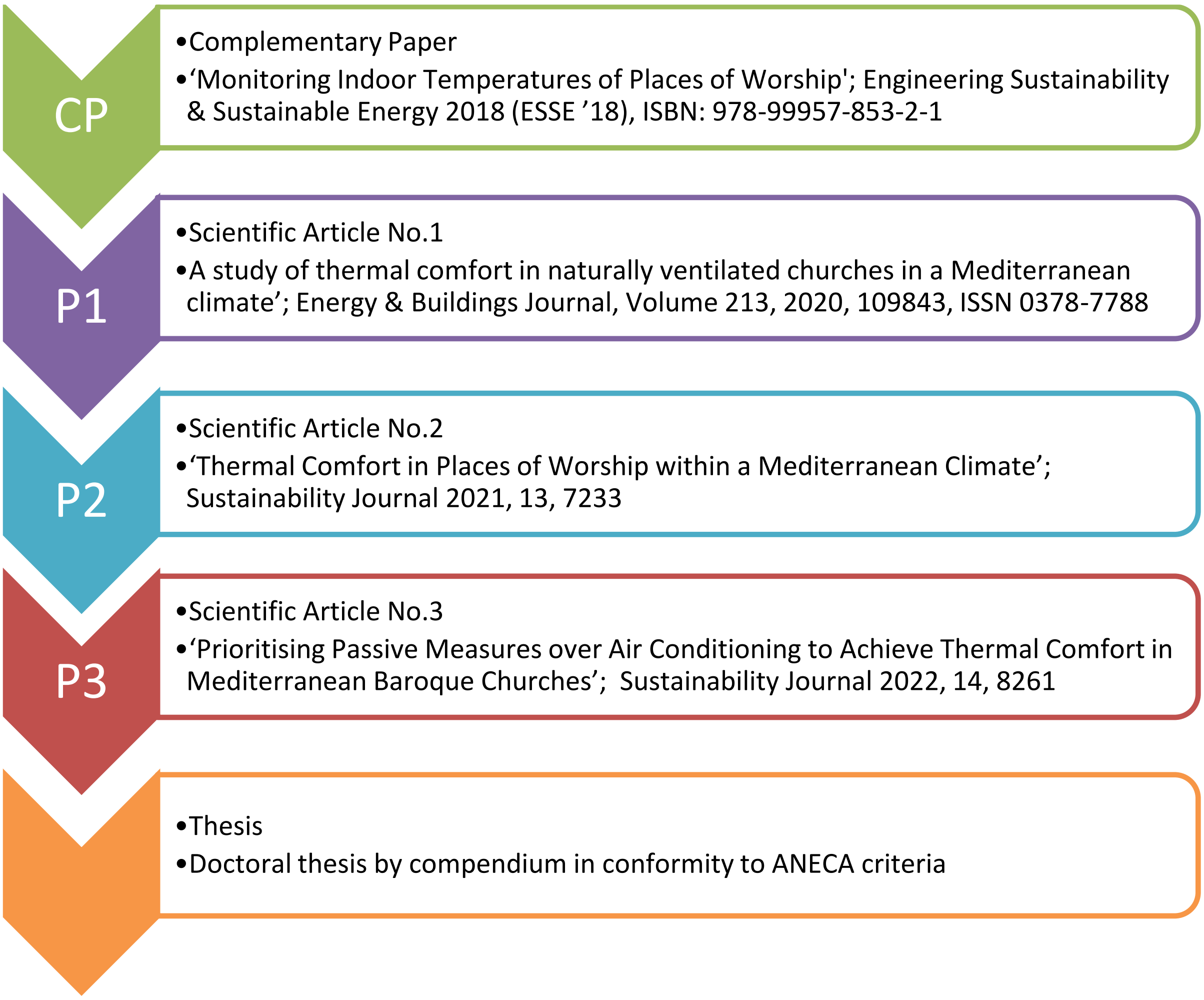
The key research contributions are cohesively published through Scientific Articles, to focus on:

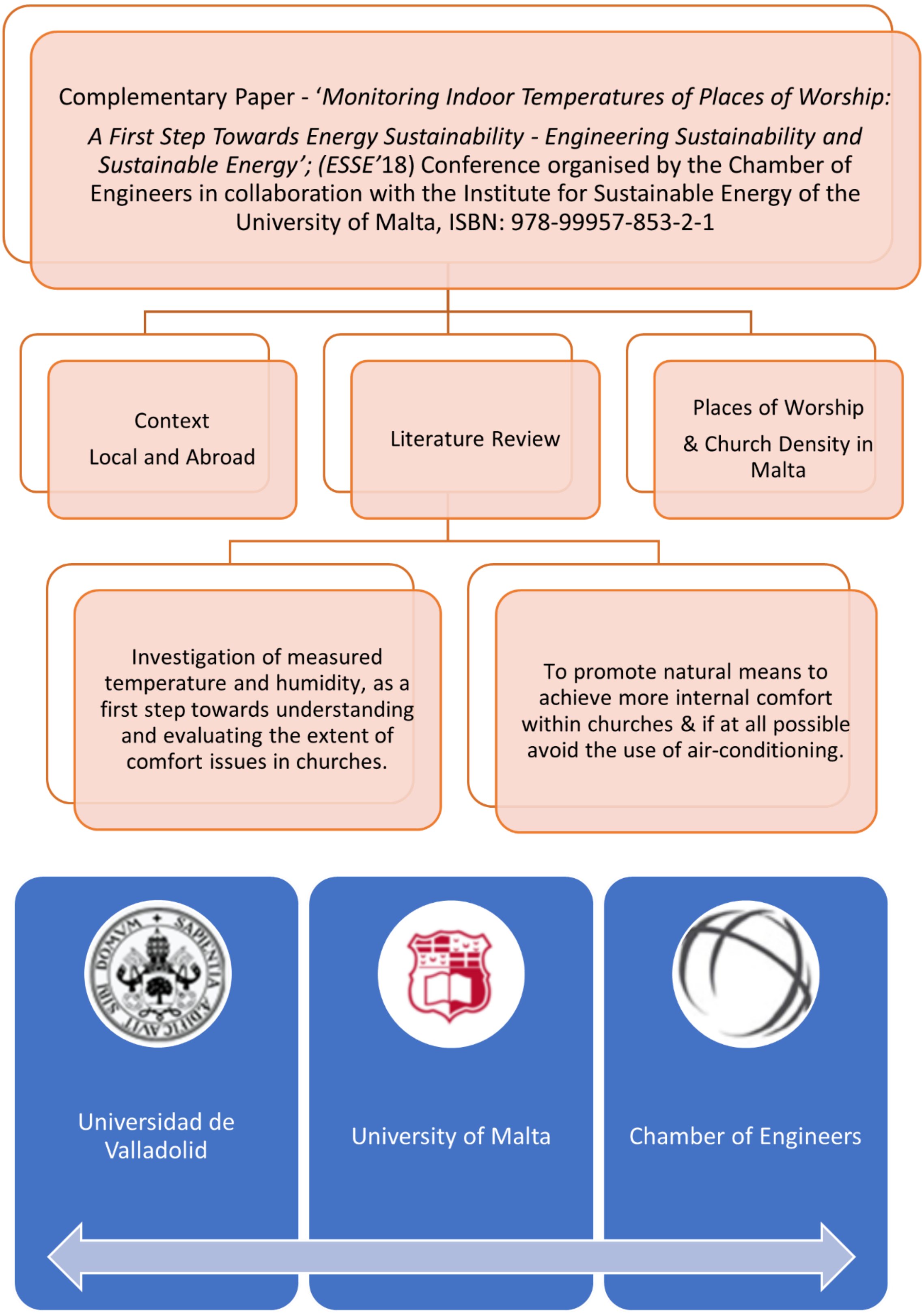
- Research on building and construction methodologies for different eras such as vernacular architecture and modern sacred buildings.
- Software simulation (DesignBuilder-EnergyPlus) to determine the energy performance.
- Validation of software simulation results with actual data monitoring of temperature and humidity within a select number of representative places of worship.
- Qualitative Analysis of worshipers' perception of indoor comfort, by means of questionnaires.

- Modelling and evaluation of the best passive energy efficiency measures that can be applied to achieve an improved level of efficacy in new or renovated/retrofitted places of worship.

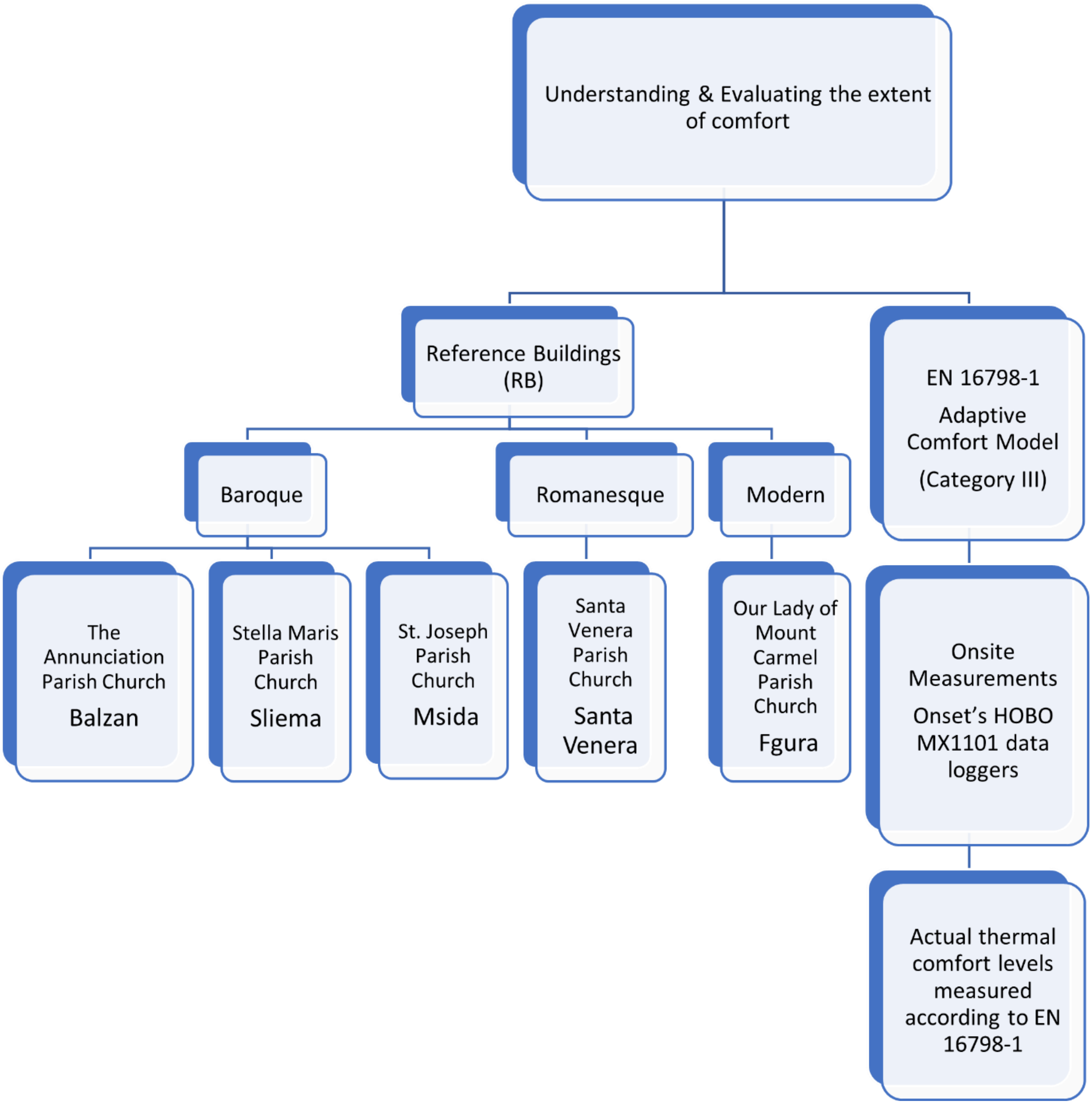
Innovations and improvements recommended are presented in this thesis by compendium with due consideration to comfort vis-à-vis the increase in outdoor temperature, whilst considering responsible actions to reduce greenhouse gas emissions and respecting the buildings architectural heritage and artefacts with which they are adorned.

The benefit of this study further benefits policy makers and experts to identify and assess harmonized strategies and policies to address Energy Performance and Indoor Comfort, enhancing both the environmental and economic effectiveness of these efforts. The research methodology is summarised through the following conceptual study framework.

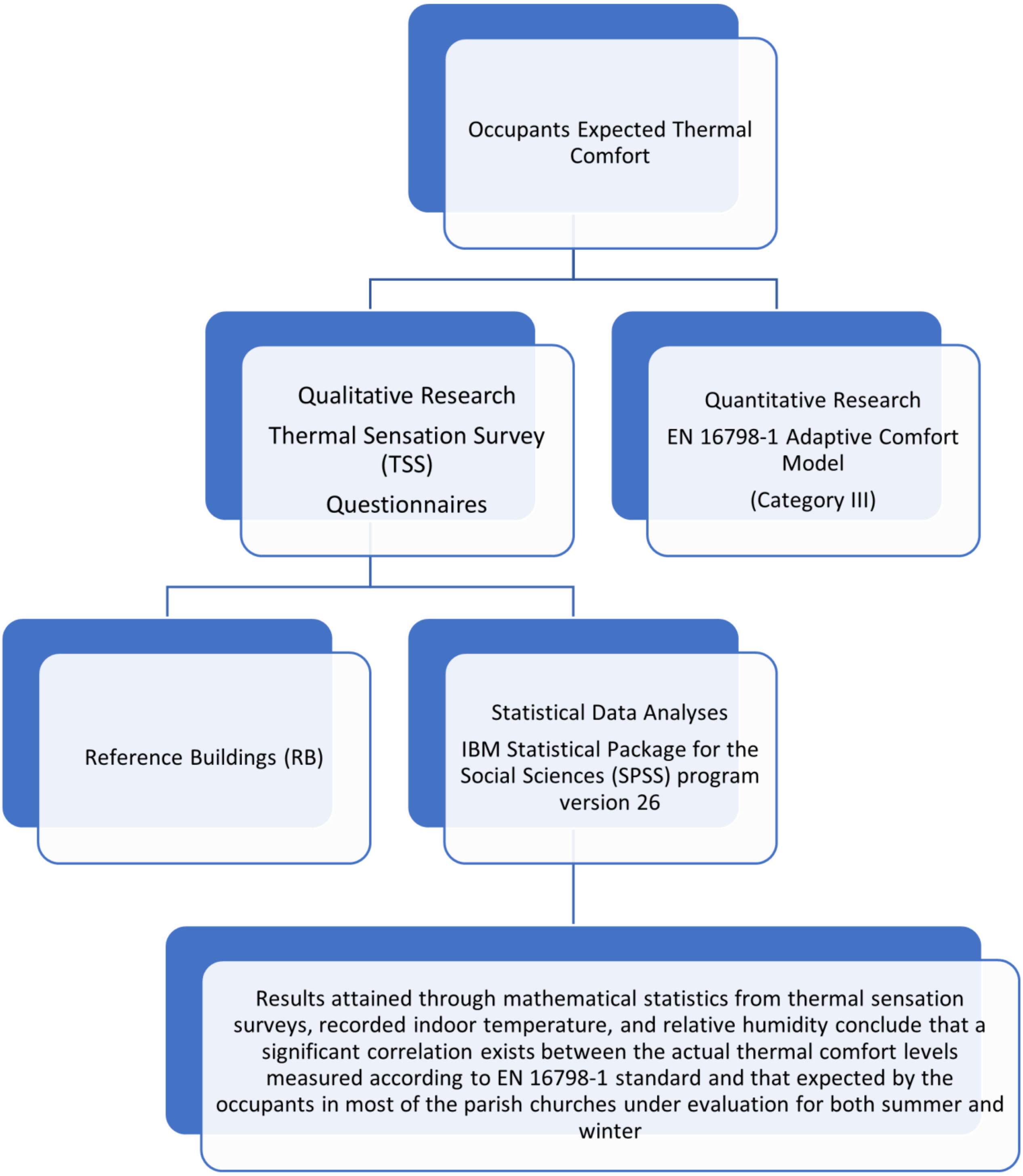



Complementary Paper - ‘*Monitoring Indoor Temperatures of Places of Worship:*
*A First Step Towards Energy Sustainability - Engineering Sustainability and Sustainable Energy’; (ESSE’*18) Conference organised by the Chamber of Engineers in collaboration with the Institute for Sustainable Energy of the University of Malta, ISBN: 978-99957-853-2-1
Context
Local and Abroad
Literature Review
Places of Worship
& Church Density in Malta
Investigation of measured temperature and humidity, as a first step towards understanding and evaluating the extent of comfort issues in churches.
To promote natural means to achieve more internal comfort within churches & if at all possible avoid the use of air-conditioning.
Universidad de Valladolid
University of Malta
Chamber of Engineers

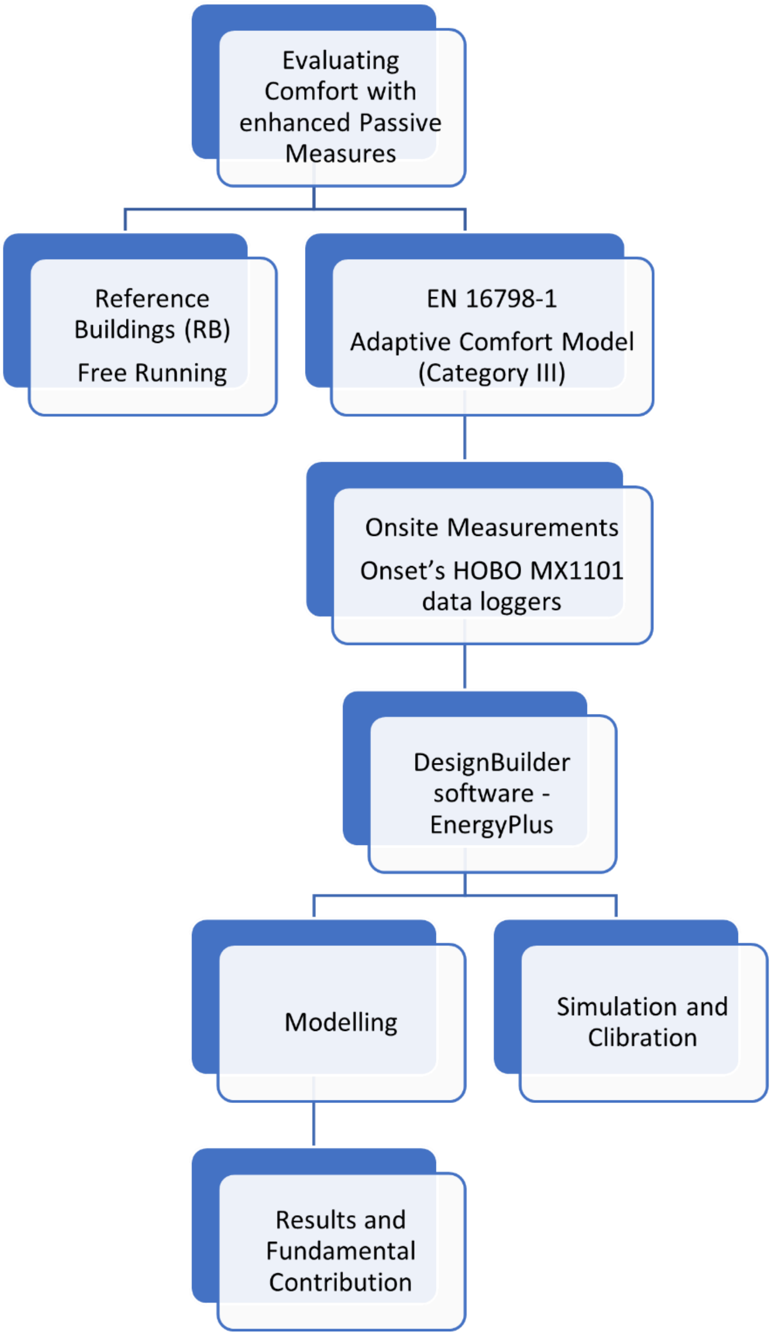
Scientific Article No.1 - *'A study of thermal comfort in naturally ventilated churches in a Mediterranean climate';* published by Energy & Buildings Journal, Volume 213, 2020, 109843, ISSN 0378-7788



Scientific Article No.2 - *'Thermal Comfort in Places of Worship within a Mediterranean Climate'*; published by Sustainability Journal 2021, 13, 7233



Scientific Article No.3 - *'Prioritising Passive Measures over Air Conditioning to Achieve Thermal Comfort in Mediterranean Baroque Churches'*; published by Sustainability Journal 2022, 14, 8261



Results & Fundamental Contribution

Historic church structures outperform expectations and, in general, outperform newer church buildings.

Implementing solar control measures, especially coating roof surfaces with white solar-reflective paint, can greatly reduce heat discomfort.

The use of thermal insulation materials for roofs as part of a thermal management strategy increases the thermal performance of the building envelope.

The limits imposed by the architectural aesthetical characteristics of heritage buildings limit the implementation of some passive solutions.

The heritage building typology may preserve balanced environmental conditions for antiques while achieving indoor occupant comfort criteria through passive techniques.

Preventing temperature and humidity swings is not necessarily a solution to interior comfort because any changes to the church's inside environment may generate new concerns.

Only with a thorough grasp of local building construction techniques and building block characteristics can one analyse the influence of 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 where 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.

Air Condition units installed in Baroque churches are not justified.

CHAPTER 1: INTRODUCTION

The church or chapel is a frequent component of the landscape in Malta. There are 359 churches on the islands of Malta and Gozo, which are divided into two dioceses (313 in Malta and 46 in Gozo). There are 78 parishes (63 in Malta and 15 in Gozo) and 6 national parishes among them [12]. This translates to a "church density" of somewhat more than one church per square kilometre. Added to that, there are a number of other buildings that are used for worship such as the Mosque in Paola, the Anglican Cathedral in Valletta and other smaller Anglican churches and meeting places of different religions.

1.1 Historical Overview of Ecclesiastical Architecture in Malta

In early times, medieval religious buildings were crude constructions mainly in the shape of plain rectangular volumes. Their structural support system consisted of a series of masonry arches spaced at regular intervals supporting horizontal rows of flagstones (known as "*xorok*" in Maltese). The exterior of the chapel was usually devoid of any ornamentation and the bare appearance of the façade was only relieved by a simple arched entrance portal, surmounted by a small circular window and a bell-cot [13].

When the Order of St John arrived in Malta in 1530, numerous foreign military engineers and master masons collaborated with Maltese artisans to develop practical building construction techniques and structural systems that were adapted to the local conditions. The local building industry was influenced by the shortage of timber on the island and the rich availability of globigerina limestone. It is pertinent to point out that by the time the Order was granted the island in fiefdom, Mannerism had already superseded the Renaissance style on the Italian architectural scene [14]. It is only in this historical context, and with an understanding of the time difference, that one can understand why Renaissance architecture did not thrive in Malta. After the Great Siege of 1565, the Knights of Malta set about an ambitious project; the building of Valletta. Pope Pius IV sent his foremost engineer, Francesco Laparelli, to build the city both as a fortress to defend Christendom and as a cultural masterpiece. Following the victory of the Knights of Malta and the decisive Ottoman defeat at the Battle of Lepanto in 1571, under Grandmaster Jean Parisot de la Valette, the Knights went about erecting the so-called 'city built by gentlemen for gentlemen' [15], [16]. The capital itself was designed to include at its heart the conventual church of St. John the Baptist, by Maltese architect Girolamo Cassar who worked initially as an assistant to Francesco Laparelli, before taking over the project himself [17], [18].

Following the unsuccessful Ottoman effort to take Malta in 1565, worries of living outside a walled city faded, and farmers' villages evolved into towns. This process was formally qualified by the creation of new parishes, with their number exponentially growing from ten in 1436 to seventy-eight today (63 in Malta and 15 in Gozo). This is because parishes function as the place's *genius loci*, providing a symbolic and physical point of reference for the local's communal life.

The Order's long-established system of government ended with the Code de Rohan which in turn remained in vigour even during the first decades of British rule. The Code de Rohan was commissioned in 1776, by the then Grand Master Emanuel de Rohan Polduc, the last Grand Master of the ruling Order of St John [19]. Following the expulsion of the brief French occupation (1798-1800) by the British, the ostentations of the Baroque era were replaced by the clarity of the enlightened modern administrators. A stronger sense of adaptation and renewal had replaced the earlier forms of proclamation. Due to this, the local form of the Baroque tradition, which had aggressively developed during the period of the Knights of St. John (1530-1798), struggled to survive in the first half of the 1800s. The Baroque's expression of culture became increasingly influenced by the system of the British Administration of the Crown Colonies in the Seventeenth and Eighteenth Centuries [20], [21], [22].

The dominant presence of foreign rulers, whether the outgoing Knights or the relatively self-keeping British, compelled the Maltese architects and artists alike to articulate their own art, by assimilating the foreign influence through local syntheses. Indeed, the most beloved pattern of the Maltese Church can perhaps be considered to have been set by Maltese architect and sculptor Tommaso Dingli (1591-1661) whose work is on an almost classical balance, adorned with fine, almost filigree, stone carving, yet never allowed to run rampant [22]. The Parish Church of St. Mary in Birkirkara (refer to Figure 1) and the Matrix Parish Church of the Nativity of Mary in Naxxar (refer to Figure 2) are two of the ecclesiastical buildings attributed to Dingli.

Figure 1: The Parish Church of St. Mary in Birkirkara. The dome and roof were destroyed in an earthquake on 24 June 1856.

Figure 2: The Matrix Parish church of the Nativity of Mary in Naxxar. Photograph by author RCV (2022).

Between the late seventeenth and eighteenth centuries, various parish churches were remodelled to a larger form to accommodate the increasing number of parishioners and to project symbolically a greater degree of prestige and status, becoming more lavish and ornate. The parish church of Our Lady of Graces in Zabbar, designed by Maltese architect Giovanni Bonavia (1671-1730), is one of the most monumental and ornate Baroque churches on the Island (refer to Figure 3 and Figure 4). Likewise, is the Basilica of the National Shrine of the Blessed Virgin of Ta' Pinu in Għarb Gozo, which masterpiece is the work of Maltese architect Andrea Vassallo (1856-1928) (refer to Figure 5).

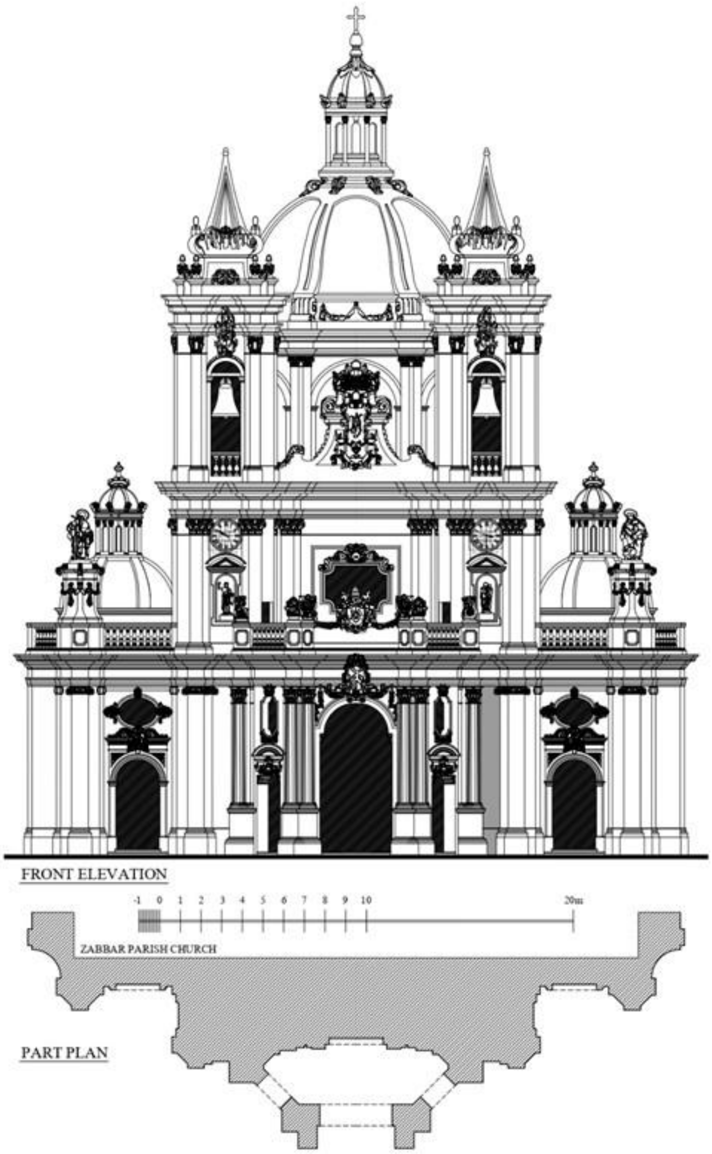


Figure 3: Part Plan and Elevation of The Parish Church and Sanctuary of Our Lady of Graces in Zabbar.

Figure 4: The Parish Church and Sanctuary of Our Lady of Graces in Zabbar. Left: The ceremony of the raising of the cross on top of the dome in 1928. Right: Photograph by author RCV (2022).

Figure 5: Basilica of the National Shrine of the Blessed Virgin of Ta' Pinu, Għarb, Gozo. An architectural masterpiece built between 1920 and 1931 with superb sculptures and craftsmanship in Maltese Limestone. Photograph by author RCV (2022).

This brief historical review of the growth of religious architecture in Malta highlights the church's leading role in Maltese life and demonstrates how the church has served as the fulcrum of activity in the Maltese community. In view of today's ecclesial and societal circumstances, this thesis emphasizes the relevance of the Church in supporting energy savings, CO_2 emissions reduction, and extra advantages coming from church building renovation. According to research, upgrading buildings to current energy efficiency and thermal comfort requirements is critical for enhancing sustainability and energy performance as well as preserving the architectural legacy of old structures [23,24]. However, amid all of these architectural studies, in-depth research into religious structures together with their distinctive occupancy and energy consumption, have only recently been conducted.

1.2 Developments Abroad

Though active heating and cooling of churches is new in Malta, there was a rising worry among antiquarians and architects in Northern Europe in the 1960s where medieval stone cathedrals were suffering from acute overheating [25]. Heating was attributed to be the main cause of particle deposition on walls and vaults which led to damage being caused especially to wooden interiors and objects. Since 1887, a Directive was implemented which required that heating within churches in Sweden should be kept to a minimum and be provided only during services [1]. In this respect there were several conflicting opinions in Northern Europe on the requirement for heating in the 1960s and 1970s. The Swedish National Institute of Building Research ruled in 1967 that stone churches which weren't initially designed to be heated should be left unheated [26]. Conversely, the management of the church does not appear to have been significantly impacted by this suggestion. On the contrary, it appeared that the 1960s was a time when several churches were permanently heated for the first time. A solution was a switch to intermittent heating rather than a total shutdown [27–29]

Recent European studies have also investigated thermal comfort, measuring indoor temperatures and relative humidity (RH) levels. Loupa et al. provided findings from two medieval churches in Cyprus, demonstrating that changes in internal temperatures, humidity levels, and pollution levels surpassed suggested limits [30]. Varas-Muriel et al. investigated the San Juan Bautista Church in Talamanca de Jarama, Madrid, Spain, and discovered that the walls have varying levels of water absorption, which they attribute to the diverse types of construction used over centuries, weather conditions, and wall orientation [31]. Other studies, such as that of Terill et al. established that through the application of insulation, ventilation and solar screen systems within church buildings, a reduction in the Solar Heat Gain Coefficient (SHGC) is evident [32]. Also, L. Bencs et al. conducted a study comparing the conventional, hot air heating systems in a mountain church within the village of Rocca Pietore in the Italian Alps. Results exhibited a considerable influx of external air through the hot air carried ducts [33]. Camuffo et al. investigated a novel heating system whereby a small amount of heat was supplied directly to the occupants within the pew area, such as to the feet, legs and hands, while leaving the overall conditions of the church undisturbed. This with the main aim to significantly reduce the risk of mechanical stresses in wooden artworks amongst other valuable artefacts whilst attaining occupant thermal comfort [34].

Research on Spanish rural churches resulted in a set of recommendations for the preventative maintenance of such ancient buildings while maintaining human comfort [35]. Because these structures, like those in Malta, were not initially intended or built for HVAC technology, temporarily installing systems to fulfil residents' thermal comfort was detrimental to the conservation of natural climatic conditions and churches' artistic and architectural legacy. Various works [36–38] demonstrate the connection between heritage comfort and thermal comfort, notably in heritage buildings and museums.

In contrast, if moisture and mould development are not managed by conservation heating, dehumidification, and adaptive ventilation in a cold environment, the architectural history and artistic value of mediaeval churches may be lost [39]. If humidity and mould development are prevented, artistic treasures can endure in unheated churches for millennia [40]. Unfortunately, because mediaeval churches were initially built and used unheated for centuries, moisture damage is visible [41,42]. In this regard, research have been done in response to the rising concern about the potential negative implications of conventional heating. Expert opinion advised against their installation in churches in countries with extreme climates (particularly cold, humid winters), because they generate huge changes in the internal atmosphere and harm the conservation of church history [43–45]. Without temperature control, the internal climate in churches is mostly dictated by the external environment and the hydrothermal performance of the building envelope.

The European project *“Friendly-Heating: comfortable for people and compatible with the conservation of artworks preserved in churches”*, addressed the issues caused by continuous or intermittent heating of historic churches, which disrupts the microclimatic conditions to which the building and the artworks preserved inside have acclimatized [46]. Because thermal comfort and artwork preservation frequently clash, a compromise between the two demands is required. The proposed heating approach is to supply a little quantity of heat directly to persons in the pew area while leaving the church's macro conditions unchanged. This unique heating system is based on several low-temperature radiant emitters set in a pew to offer a suitable distribution of heat to those occupying that space's feet, legs, and hands. This new approach not only considerably decreases 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 due to limited heat dispersion, but it is also energy-efficient. At the Santa Maria Maddalena church in Rocca Pietore, Italy, extensive environmental monitoring was done over a three-year period to compare the performance of the new heating system to that of the old warm-air system [34]. Three draft standards of the European Committee for Standardisation designed for use in the investigation and management of settings of cultural heritage items contain the methodology and findings of this extensive and diverse study.

Surprisingly, the Mediterranean area has extremely few research or publications that discuss religious facilities. Studies were mostly done for churches in the cool-summer humid environment of Western Europe or for mosques in the hot-humid climates of the Eastern Region (it should be noted that unlike churches, mosques do not feature works of art such as paintings). As a result, the findings' relative efficacy is typically not relevant to the local situation, where the building style is different and cooling rather than heating is of a primary concern because of the region's predominately hot environment.

1.3 European Energy Directives and Places of Worship

It is crucial to make the connection between thermal comfort and places of worship because it may be viewed as a physical depiction of the inner serenity that visitors to these temples have long sought. Despite having different architectural styles, churches all have comparable occupancy trends. There is a sizable gathering area in each of these places of worship, used intermittently with attendance ranging from minimal and almost full. The remainder of the time shows little to no occupancy. Due to the reduced total energy intensity (measured in yearly kWh/m^2) caused by the occasional occupancy, typical energy efficiency measures (EEMs) frequently have longer payback periods and are therefore not always cost-effective [47].

However, the world's reliance on energy has been growing at a concerning rate. The International Energy Agency (IEA) estimates that the global energy consumption rose by 92% between 1971 and 2014 [48]. A major amount of this growth has come from the building industry. In reality, the construction industry including operational emissions was responsible for 35% of all energy use and more than 38% of worldwide greenhouse gas emissions in 2020, according to the 2020 Global Status Report for Buildings and Construction [49]

Malta is attempting to lessen the consequences of climate change and create a uniform energy strategy within the EU. The European Heads of State or Government adopted binding objectives to enhance the percentage of renewable energy as part of this strategy in March 2007. In order to meet the 2020 objective of renewable energy, it is imperative to intensify efforts on all fronts, according to Malta's Renewable Energy Action Plan (NREAP). Malta and the other members of the European Union have come to an agreement on legally enforceable national goals for raising the proportion of renewable energy in order to reach a 20 percent Union-wide share by 2020. Due to the rise in oil prices in 2008, the global economic crunch, and the unpredictability of the tourist sector, the urge imposed by national and EU regulations was further accelerated, leading to 22.1% renewable energy out of the total energy used in the EU in 2020 [50].

The energy union strategy (COM/2015/080), published in March 2015 [51], outlines the EU's initial steps toward sustainable energy and aims to create a union that gives European consumers, households, and businesses access to safe, sustainable, competitive, and reasonably priced energy. In order to promote the shift away from fossil fuels and toward cleaner energy sources, and to fulfil the EU's Paris Agreement goals to reduce greenhouse gas emissions, the EU finished a thorough reform of its energy policy framework in 2019. This led to an agreement on a new set of energy regulations known as the "Clean Energy for All Europeans package," which proved an important step to put the 2015 energy plan into practice [52]. The EUCA Regulation, also known as EU Regulation 2018/1999 on the Governance of the Energy Union and Climate Action, was approved in 2018. This laid the groundwork for the legal framework, the governance framework, the strategies, and the policies necessary to fulfil the objectives of the energy union and the long-term EU greenhouse gas emission obligations (consistent with the Paris Agreement).

Malta, like every other EU Member State, established a 10-year integrated National Energy and Climate Plan (NECP) for the years 2021–30 in accordance with the EUCA Regulation and with the goal of meeting the EU's energy and climate target to reduce greenhouse gas emissions levels by 2030 [53]. Malta's contribution is set at 10% in the NECP's list of individual national overall objectives for the proportion of energy from renewable sources in gross final energy consumption in 2020. Additionally, EU leaders decided to establish an ambitious goal in December 2020 to reduce greenhouse gas emissions by 55% (compared to 1990 levels) by 2030.

The Clean Energy for All Europeans package, which was based on suggestions from the EU Commission issued in November 2016, consists of eight legal acts passed between May 2018 and May 2019. The new regulations are anticipated to have a significant positive impact on consumers, the environment, and the economy. They will also make a significant contribution to the EU's long-term plan to become carbon neutral by 2050 [54].

The European Green Deal [55], an ambitious set of policies that should allow European residents and companies to profit from a sustainable green transition, aims to make Europe the first climate-neutral continent by 2050. Each Member State must expand its production and usage of renewable energy for electricity, heating, cooling, and transportation if they are to reach this shared goal. Although Malta's annual energy usage is less than 2,500 GWh, demand for electricity is growing due to the country's expanding population, economy, and tourism. In recent years, Malta has attempted to upgrade and diversify its electrical system, moving away from inefficient coal and heavy oil-fuelled electrical generation to one based on natural gas, with oil serving as a backup, and an electricity interconnector to Sicily, Italy. The next phase is a €322 million Malta-Italy gas pipeline, which the government hopes to have operational by 2024 [56] and replace the permanently moored natural gas ship that now supplies the power plant.

Renewable energy sources play a crucial role in the battle against climate change, but they also boost economic growth and energy security at the national level. Government agencies and Maltese professional organisations have undertaken a number of attempts in recent years to increase public understanding of renewable energy uses and, to a lesser extent, of energy conservation and efficiency. Additionally, financial incentives for purchasing renewable energy systems were implemented. Numerous medium-sized and big organisations have chosen to update their energy profiles as a result of this and the rising cost of energy and services; however, no standard methods have yet been implemented to guarantee the greatest possible benefit to the client and the environment. Additionally, up until now, this industry has relied heavily on subsidy programs, supported by both the national government and the EU.

Studies pertaining to building energy efficiency, on the other hand, remain poor and sporadic. This is especially true for places of worship, where the legacy and historic architecture serve as proof of civilisation. EPBD exempt "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" [57]. Nevertheless, there is a recent trend in Malta whereby churches are being installed with invasive AC units to address the hot summer indoor environments, which may jeopardise the conservation of the respective church's cultural assets.

1.4 Sustainable Energy and the Church

The concept of net zero energy buildings is gaining hold in many parts of the world, including all EU Member States, since buildings provide great possibilities for energy savings at reasonable rates. Electricity consumption in both the domestic and commercial sectors has been registered on the increase year after year [54]. Concurrently, electricity consumption scenarios are changing with new pricing policies, stricter EU directives such as Directive

2010/13 and time bound incentives to encourage consumers and entrepreneurs to invest and own renewable energy systems [58].

With the Pope's encyclical letter Laudato Si' from April 2015 [59], the Roman Catholic Church, too, raises concerns about what is happening to our shared home. Pope Francis encourages everyone and not only Christians to recognise “the rich contribution which the religions can make towards an integral ecology and the full development of humanity.” 'Ecological Education and Spirituality,' the concluding chapter of Laudato Si', welcomes everyone to the heart of ecological conversion. The importance of environmental education cannot be underestimated. In line with the teachings of Laudato Si’, numerous States gathered in New York in April 2016 to sign the COP21 Paris Agreement on Climate Change. As a result, all stakeholders agreed that the era of fossil fuels is ending, and that it is time to focus more on energy efficiency and renewable energy, in all structures, and for all human activities [60].

1.5 Thermal Comfort vs Artworks Preservation

The adoption of temperature regulation stems from the need to balance various factors which promote inadequate climate control in places of worship. These factors may include amongst others, human comfort, energy costs, damage, and long-term viability. Temperature fluctuations are the underlying cause of damage to materials which expand as their temperature rises and shrink as it declines. Repetitive fluctuations can give rise to fatigue cracking. Though most artefacts are many times not sensitive to such fluctuations, particularly at micro-level, the analysis of the risks from temperature fluctuations is complex and many uncertainties remain [61]. Even where it is not visible, water is to be found almost everywhere. Damp in buildings can originate from roof, foundations, or exposed walls. Although rising damp is a typical problem in churches, if moisture is removed from wood, ivory, or bone, they shrink and are prone to break and warp. Similarly, laminar organic goods like paper, parchment, leather, and natural fabrics lose flexibility and become more brittle. In general, materials that contain moisture become brittle below 40% RH. On the other hand, in extremely wet environments, with above 65 to 70% RH, mould grow, and metals corrode.

Additionally, biodeterioration is more pronounced and colours fade more quickly at high RH [62].

Usually, churches are exposed to dampness which is easily absorbed by warm air. This phenomena is experienced when the congregation departs and the church is in turn closed, forcing the temperature to drop [63]. Water condenses on any surface below the dew point of the air, which itself may be near saturation. When this water from the wall evaporates, the water inevitably carries salts, which then crystallise as efflorescent. Efflorescence can appear on top of or underneath the paint surface. The latter is more of a concern since when the wall dries, the evaporation zone moves inwards. Condensation can dissolve contaminants in the air and redissolve efflorescence, and it may do so both above and below the surface. Each cycle produces more damage, hence cyclic heating and cooling circumstances should be avoided [64–68]. Paintings on the wall are safest when they are dry, or at least not absorbing moisture from the environment. As documented in the Parish Church of the Annunciation of Our Lady, Birgu (Vittoriosa) by the author during this period of report, fluctuations in indoor environments affected relative humidity stability, and as a result, efflorescence as well as plaster blistering and detachment in the inside walls, drying and cracking in the timber, and disaggregation in the stone were evident (refer to Figure 6).

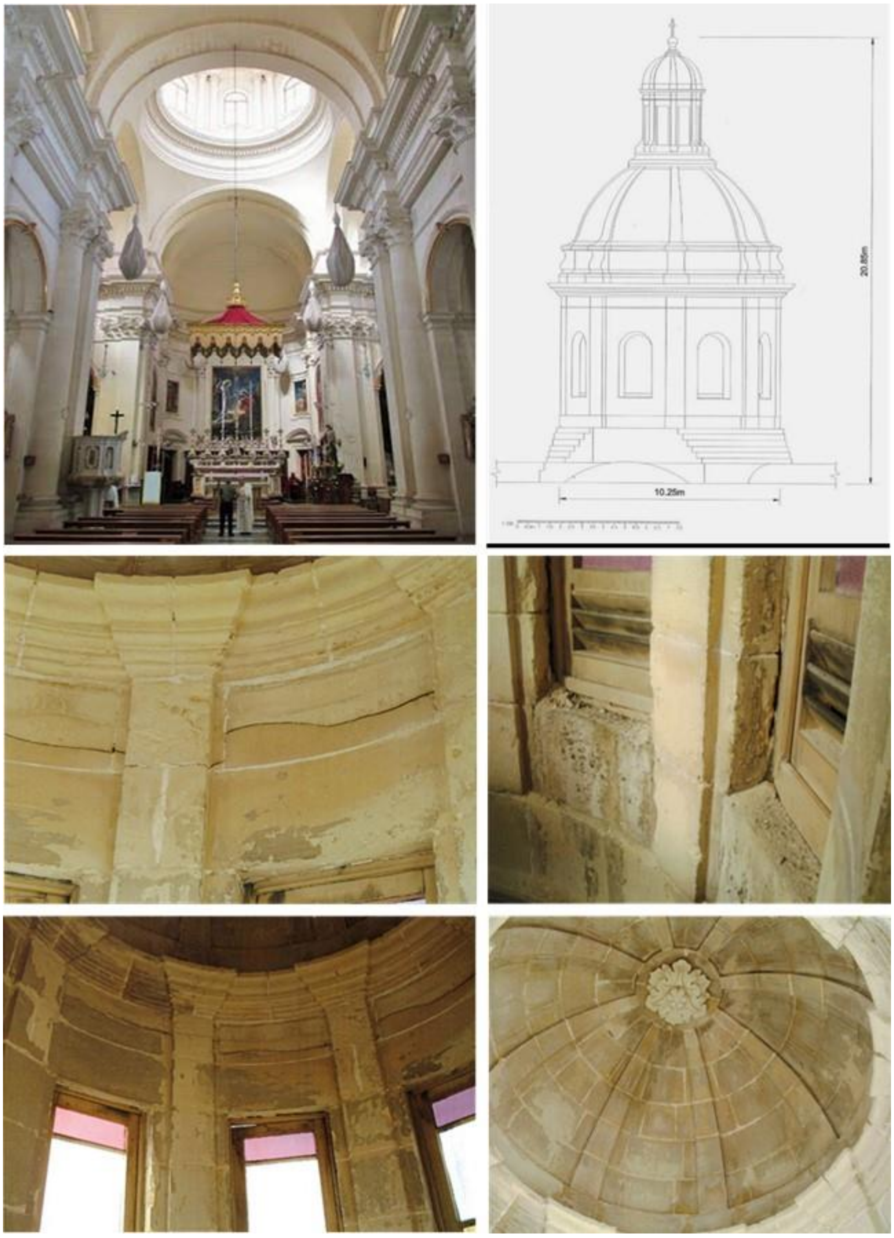


Figure 6: The Parish Church of the Annunciation of Our Lady, Birgu (Vittoriosa). Photographs by author RCV (2016).

The course of action advised is to manage the microclimate for human comfort within churches, in particular those decorated with art and artifacts, without changing the macroclimate. Churches frequently serve as more than simply a place of worship; they are decorated with distinctive architectural features and works of art (refer to Figure 7). When it comes to heating, Bordass utters, that the main objective of assessing the internal microclimate of churches is to gauge and enhance users' comfort [69]. But the strategy should be "Heritage First," with emphasis on creating the ideal microclimates for the preservation of structures and artifacts. This comparison between thermal comfort and heritage comfort is also made in La Gennusa et al. [37] and Corgnati et al. [38], where the contradiction between user comfort and artifact quintessential condition in churches and museum buildings has been shown.

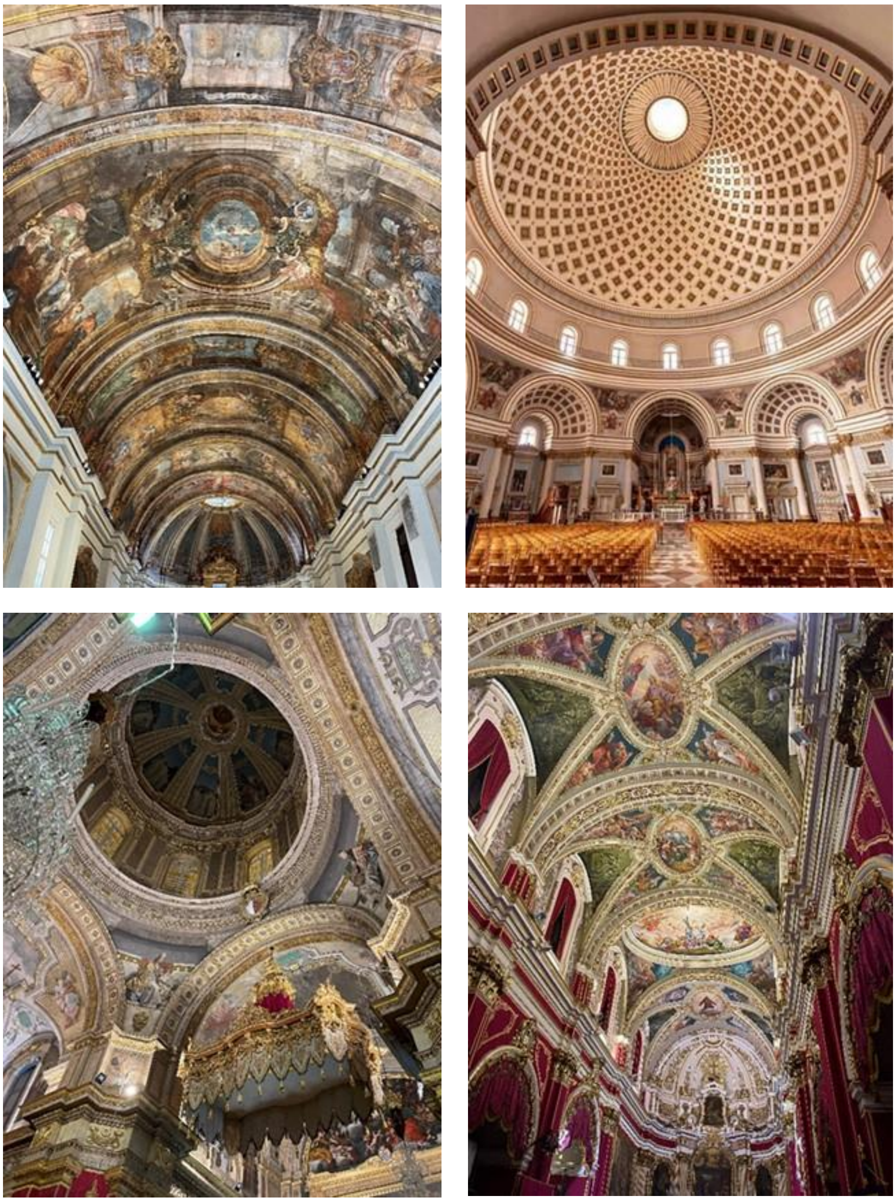


Figure 7: Remarkable works of art and artefacts in churches. Photographs by author RCV (2022).

Top left: Our Lady of Victory Church (Valletta, Malta) commemorating the Knights of St John's victory over the Ottoman invaders on 8 September 1565.

Top right: The Sanctuary Basilica of the Assumption of Our Lady (Mosta, Malta) the third largest unsupported dome in the World.

Bottom Left: The Basilica and Collegiate Proto-Parish Church of Saint Paul (Rabat, Malta).

Bottom Right: The ceiling of St Joseph Church (Rabat, Malta).

Several bioclimatic design aspects were visible and useful throughout the ages, until society began to expect a higher degree of comfort. Heating alongside cooling systems were installed in some churches to satisfy the demands of the community. However, little attention was given to the damage caused by the uneven temperature and humidity within the same buildings. These fluctuations could over time pose severe problems, especially for churches decorated with religious artifacts and fine arts [70]. The detachment and subsequent collapse of the dome painting in the Rosary lateral chapel of Balzan Parish Church (Malta) in 2006, is a case in point (refer to Figure 8). Although no exclusive cause for such collapse was determined, investigations concluded that the installed air-condition may have caused climatic fluctuations to the detriment of detachment.

Figure 8: Detail of part of the falling painting depicting the Plan of Salvation by Chevalier Emvin Cremona in 1977. Courtesy of the Balzan Heritage Commission 2006.

Right Bottom: Restored picture of the dome painting in the Rosary lateral chapel of Balzan Parish Church. Photographs by author RCV (2018).

Another collapse occurred on August 23, 2017, when a portion of the roof above the main altar of Rabat's medieval Church of Our Lady of Jesus (Ta' Giezu) collapsed (refer to Figure 9). Though this collapse was not attributed to internal temperature and humidity fluctuations, failure of the timber beams is attributed to weaknesses in strength due to environmental actions and subsequent deterioration. Variations in the local climate cause a timber beam's moisture content to vary, which causes the cross section to either shrink or expand. Internal strains and consequent failure are caused by uneven distributions of moisture content across the cross section and/or restraining deformations [71].

Figure 9: Church of Our Lady of Jesus (Ta' Giezu), Rabat, Malta. 16th Century Church Ceiling Collapse on 23 August 2017. Pictures courtesy of the Franciscan Fathers.

Churches' comfort cannot be viewed separately without taking into account the rich art and artifacts they contain. Whilst comfort in churches is of utmost importance, paintings and artefacts are an integral part of the historical patrimony of the national culture and worthy of universal appreciation. St John's Co-Cathedral (formerly known as Chiesa Conventuale di San Giovanni Battista) is a prime example, erected in Maltese limestone between 1572 and 1577 by the Knights of Malta on the design of Maltese architect Girolamo Cassar at the behest of Grand Master Jean de la Cassière (refer to Figure 10).

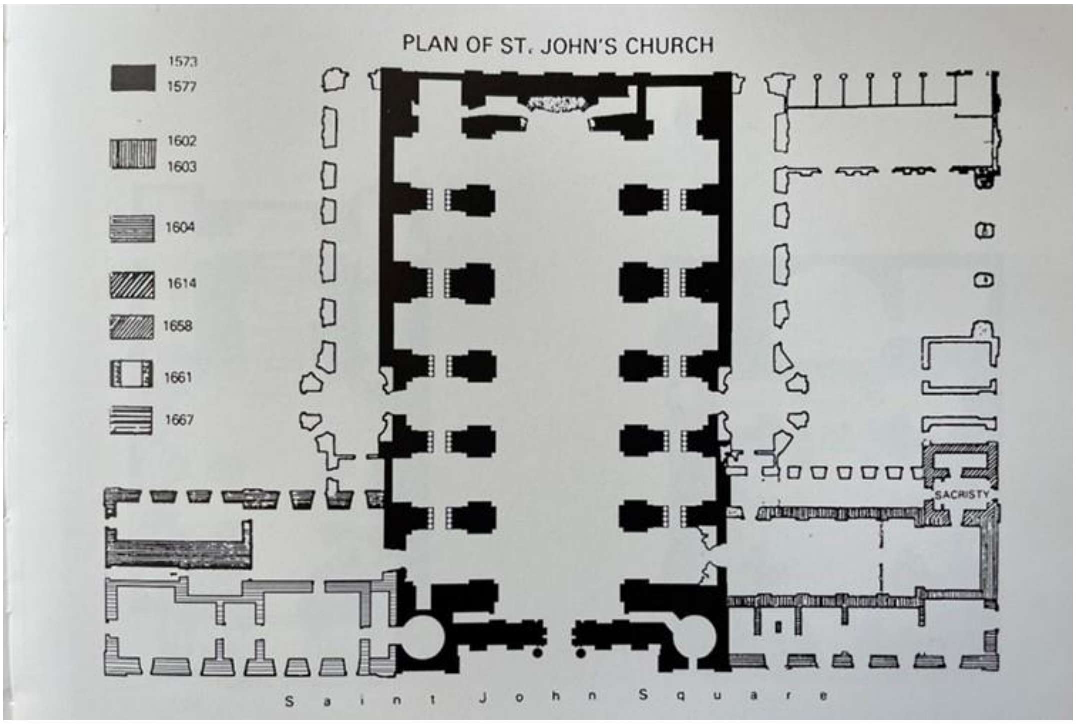


Figure 10: Plan of the 'Chiesa Conventuale di San Giovanni Battista', Valletta.

The facade of the cathedral, projects military prowess and is austere in appearance, unlike its interior, which is extremely ornate and decorated (refer to Figure 11). Mattia Preti created the complex carved stone walls, painted vaulted ceiling, and altars in situ. The cathedral contains eight rich chapels, each dedicated to a patron saint for each of the languages of the Order. Furthermore, the nave is covered with a remarkable unique collection of marble tombstones.

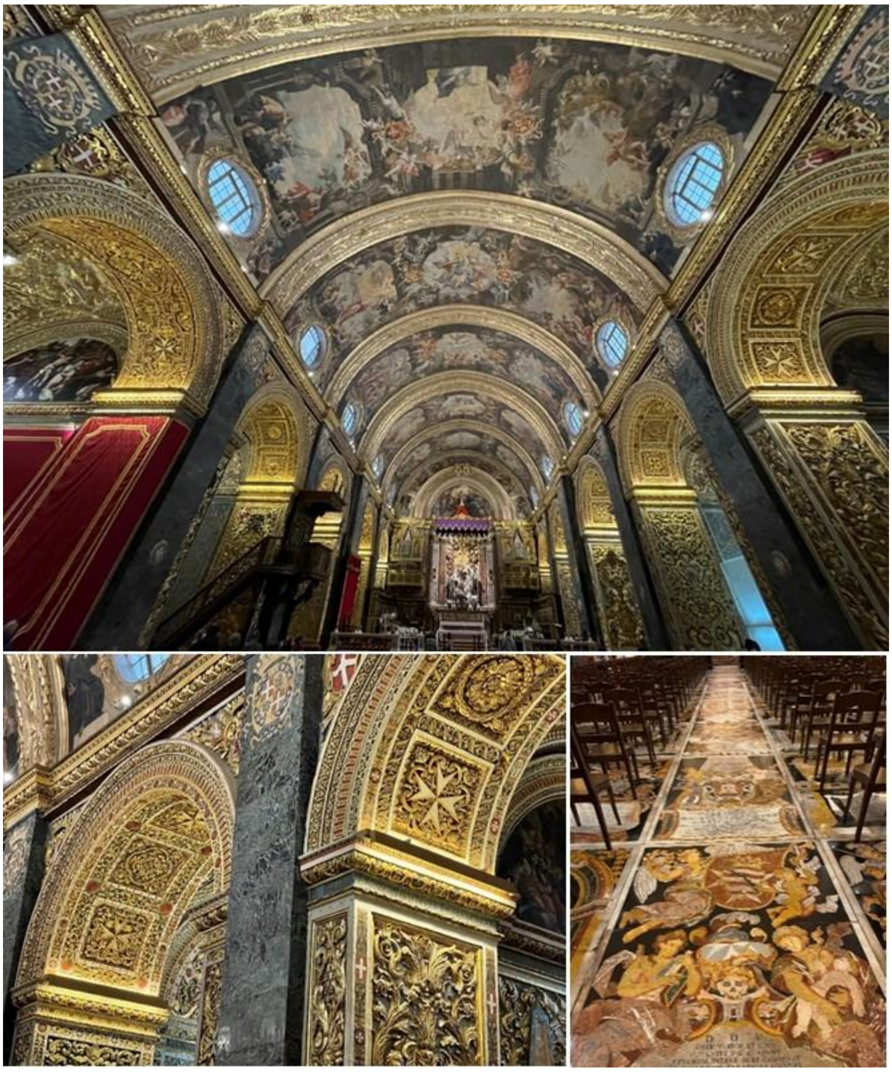


Figure 11: St John's Co-Cathedral, Valletta. Photographs by author RCV (2022).

The painting, representing The Beheading of Saint John the Baptist (1608), by Caravaggio (1571-1610), is the best-known work in the church (refer to Figure 12). Considered one of Caravaggio's masterpieces and being the only one signed by the artist, the canvas is displayed in the oratory for which it was painted. Restored in the 1990s in Florence, it presents the characteristic chiaroscuro of Caravaggio's work.

Figure 12: St John's Co-Cathedral, Valletta. Photographs by author RCV (2022).

Top: The painting representing the Beheading of Saint John the Baptist (1608), by Caravaggio.

Bottom: The Grand Masters' Crypt.

While enrolled in this PhD program, the author (RCV) was responsible of the St. John's Co-Cathedral Museum's ongoing development as Site Technical Officer. The new museum (refer to Figure 13) is intended to house the artifacts now held in storage. The restoration of the Bartolott Crypt, the creation of a new Tapestry Chamber, and the creation of the Caravaggio Wing, along Merchants Street, are all included in these expansion works. The project of restoring and constructing new areas entails interventions on one of Malta's most historically important monuments. Extensive research and investigations were conducted to ensure that no historical fabric is lost. All works are being conducted under the supervision of the Superintendence of Cultural Heritage (SCH) in liaison with various consultees, including the United Nations Educational, Scientific and Cultural Organisation (UNESCO).

Figure 13: The St John's Co-Cathedral Museum Project, Valletta. Courtesy of the St John's Co-Cathedral Foundation.

In Fabbri et al. [36] and Corgnati et al. [38], where Indoor Microclimatic Quality (IMQ) and Indoor Environmental Quality (IEQ) are compared, the parallel between heritage comfort and thermal comfort is described. The contradiction between visitor comfort and artifact conservation in museum structures like churches has also been demonstrated by La Gennusa et al. [37]. The key findings from the various research investigations conducted on the subjects of thermal comfort, indoor air quality, and energy consumption are summarized in more recent studies [69,72]. Results show how serious the problem is. According to the collected data, significant changes in interior settings largely impact temperature (T) and relative humidity (RH), which cause plaster to blister, crack, and detach.

The extensive oratory repair and conservation effort at St. John's Co-Cathedral in Valletta provides proof of this (refer to Figure 14). The apse's stone gilt carvings of the arch and ceiling as well as its mural paintings, which were done in both oil on canvas and oil on stone techniques, were restored. The project was challenging because of the wide range of creative methods and materials used in the creation of these numerous artifacts, as well as the intricate patterns and degrees of decay that were present. In order to ensure the preservation of this piece of art for the benefit of both present and future generations, it was necessary for specialists from several fields to work together transdisciplinary.

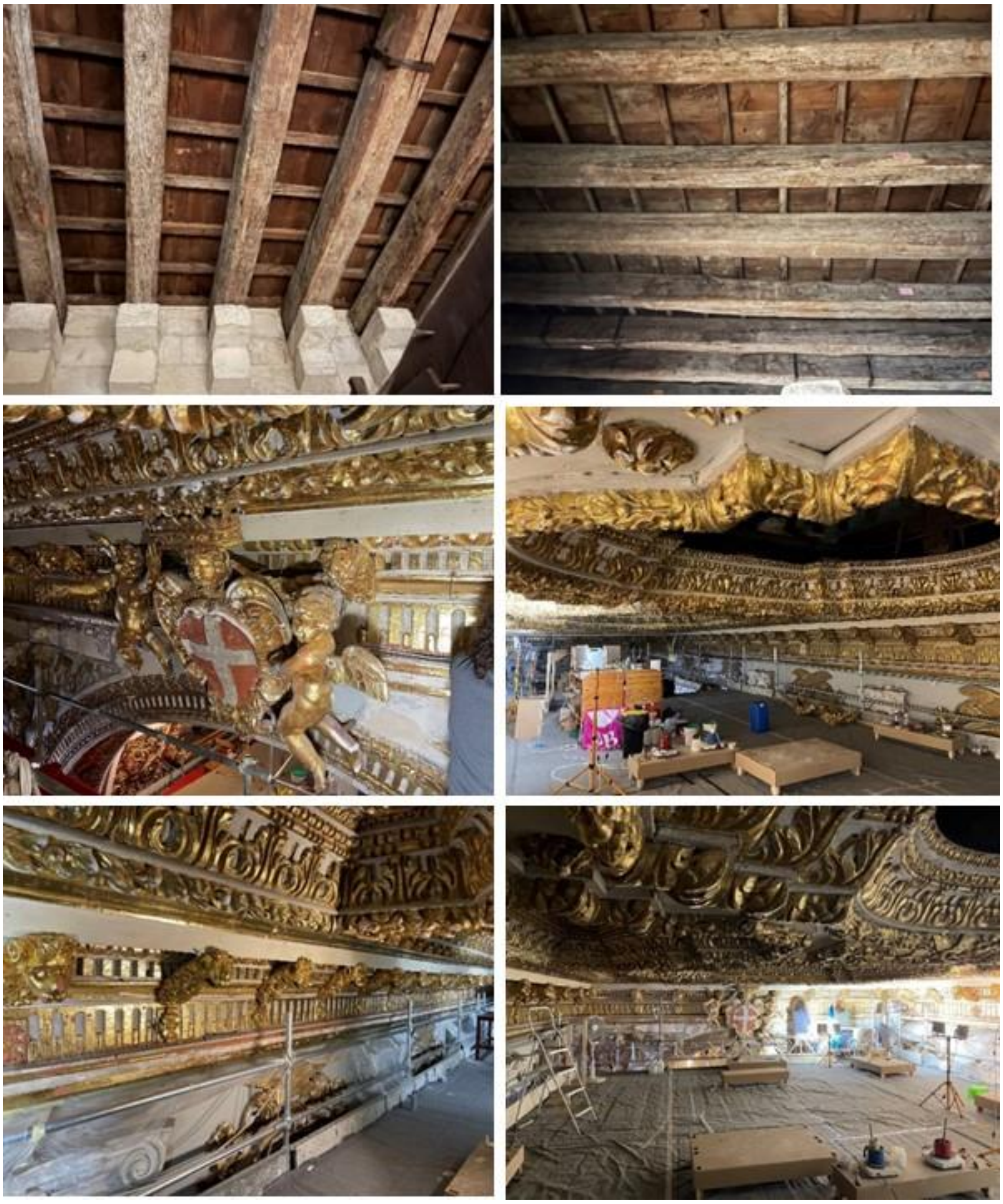


Figure 14: The Oratory Restoration Project. St John's Co-Cathedral, Valletta. Photographs by author RCV (2021).

Rising damp is also of a major concern in assessing Energy Performance and Indoor Comfort in Places of Worship. It is very important when considering rising damp to take into consideration the geology of the Maltese islands and the relation of the church building under review with the mean sea level, subterranean structures, orientation, distance from coastline and water features amongst other. Groundwater flow from these groundwater bodies might be caused by aquifers, faults/cracks, and rock matrix porosity [64]. It is also important to bear in mind that until around 150 years ago, only those who died of infectious illnesses or executed convicts were buried in cemeteries. To keep their dead close and on holy ground, people interred their family members in the cathedrals, chapels, and crypts of their cities and villages. It is only after the plague that struck Malta in May of 1813 through January of 1814, resulting in a death count of nearly 5,000 people, that burial practices were forced to change [73]. Only following the devastating plague, Burials Ordinance dated 10th May 1869, prohibited the burial of corpses within churches and to make other provisions in connection therewith [74].

Damp pertaining to fresh or sea water arising in historical buildings, including churches, is a well-known phenomenon that varies by region, many times leading to serious conservation issues. The phenomenon and the resulting decay have been extensively studied [75]. Nevertheless, it is pertinent to note that building masonry units and methodologies vary from one location to the other. These masonry materials, respond differently to the rising damp phenomenon, with varying mechanisms and contributing factors to water absorption, and this behaviour cannot be generalised. The varying characteristics of the building methodology, together with site conditions and ambient surroundings require specific evaluation that many times vary from one church to the other in Malta, let alone from one country to another. Rising damp is still one of the most frequent problems affecting historic masonry buildings worldwide because it compromises the performance of the building envelope, the health and comfort of the occupants, and the materials integrity. The problem of damp removal remains largely unsolved despite the significant effort made over the past century to understand the phenomenon of water capillary rise, as not only do the technologies used in the field frequently fail, but their operating principles in actual masonry have not yet been fully clarified. The Museum Project at St. John's Co-Cathedral in Valletta (refer to Figure 15) has successfully identified the complex relationship between indoor comfort, construction material specifications, the various characteristics of the building methodology, site conditions, ambient surroundings, and the historical rubble fills that were once a burial ground.

Figure 15: The St. John's Co-Cathedral Museum Project, Valletta. Photographs by author RCV (2022).

Another important aspect to bear in mind is the shortage of rainfall. According to data from the Meteorological Office of the International Airport of Malta based on the 1981-2010 period, a regular winter's yield of rainfall is 254.6mm. However, annual precipitation for the last two years (2020/2021) combined saw only 207.8mm of rain hit the island. With a yield between 250mm and 500mm of annual rainfall, Malta's climate is defined as semi-arid, while if precipitation persists below 250mm, the climate becomes that of a desert. This water shortage has affected Malta's history and even architecture. Thousands of reservoirs were excavated and built throughout Malta and Gozo over centuries to collect and store rainfall. In times of drought or siege, they supplied a lifeline to Malta's people and remain a source of pride for the Maltese. An example of a large potable freshwater reservoir is shown in Figure 16. Nevertheless, these too can become a source of upward movement of moisture through building materials by capillary action, if not properly maintained. The rise is also dependant on the masonry specifications; with horizontal "bridging", gravity or condensation being the main causes of dampness in walls.

Figure 16: Luqa Reservoir; known as the 'sunken cathedral', constructed at around 1907. Courtesy of the Malta Water Services Corporation.

CHAPTER 2: METHODOLOGY

2.1 Reference Buildings

As in the Maltese Islands, there are 359 churches, with a density of around one per square kilometre, it proved unfeasible to conduct an indoor comfort study for each church throughout this period of report. Therefore, a smaller representative number of churches, known as "reference buildings" (hereafter referred to as RBs), comprising most kinds of typical churches in Malta, were analysed in order to investigate the church building stock (refer to Table 1). RBs were chosen based on "actual example" structures with typical physical and occupational traits for each of the investigated church.

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. [76]. Given the limited size of the Maltese Archipelago (with an area of just 316km^2), distinct Mediterranean climate and the geographic position, one climatic classification zone address all RB climatic parameters.

Consequently, the key categorization criteria were as follows:

- 17th to mid-18th century Baroque period,
- mid-20th century neo-Romanesque style architecture, and
- late 20th century (post Vatican Council II style) modern architecture.

The Stella Maris Parish Church in Sliema and the Annunciation Parish Church in Balzan are examples of typical urban inland size churches from the 17th to the 18th centuries. The St. Joseph Parish Church of Msida is under the same construction type but is situated by the sea and has a significantly larger floor area and volume. The typical mid-20th century neo-Romanesque style church is Santa Venera Parish Church in Santa Venera, whereas the modern structure is Our Lady of Mount Carmel Parish Church in Fgura. These five churches are all recognized on the National Inventory of the Cultural Property of the Maltese Islands and scheduled by the Planning Authority as Grade 1 monuments (NICPMI). Photographs depicting each church building and tabled specifications follow.

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

Church	Location	Opening hours	Envelope	U-value (W/m^2K)	Internal heat capacity (KJ/m^2K)	Thermal diffusivity (m^2/s)	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	0%
			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	0%
			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%				

In order to arrive to a significant analysis of the architecture, structural detailing, paintings, and other works of art in relation to environmental conditions, artistic and architectural heritage, Melitensia publications and dissertations were thoroughly reviewed at the University of Malta. In contrast to studies on energy use or indoor comfort, the majority of them were Master's thesis and dissertations from the Faculty of Arts that focused on artworks and historic church architecture. Reference was also made to a number of other works, including books [77–80], feast programs, reviews of exhibitions, newspapers, church archives, Archiepiscopal, and National Archives. Unfortunately, not much information was available in these archives. Other than a recent undergraduate engineering dissertation to estimate the air-conditioning capacity needed for Stella Maris Church [81], no research dealing with energy performance in churches or other places of worship have been located in Malta. However, actual first-hand knowledge was gathered from people who were somehow connected to the history of Maltese churches or the specific building or upkeep of churches in Malta, in particular for the five selected reference churches.

2.2 Our Lady of the Annunciation Parish Church, Balzan

Balzan was established as a parish on August 14, 1655, and construction on the current Parish Church began in December 1669 (refer to Figure 17). The edifice was partially in use after four years of construction, according to a source, but Lorenzo Gafa and Giovanni Barbara, the architects, finished the work by 1695. A Latin cross design was used in the construction of the church. Also included in 1708 was a belfry, which now houses 6 bells produced by Fonderie Paccard in Annecy, France.

Construction was done primarily with load-bearing masonry walls that supported a vaulted roof and dome structure made of globigerina limestone blocks and covered with a layer of "deffun." The "deffun" technique involves laying out a variety of graded gravels (from large, rough grains to fine, thin grains), followed by a layer of lime, and overlying coating of beaten, crushed pottery (clay) powder.

Figure 17: Our Lady of the Annunciation Balzan Parish Church. Photographs by author RCV (2018).

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

The building of the Our Lady Star of the Sea-dedicated Stella Maris Parish Church began in April 1853 and was finished in 1855. Extensions were constructed between 1876 and 1878, giving the Church its current size (refer to Figure 18).

The principal building approach uses masonry load-bearing walls to support a dome structure and vaulted ceiling made of globigerina limestone blocks. The octagonal base of the main cupola, which is dominating, has arched openings and an upper cornice supported by corbels. The dome is supported by masonry rings that are round in shape. The dome, the main nave, and the remainder of the church's roofs are all covered in "deffun". The Parish of Stella Maris is the oldest amongst a total of four parishes in Sliema.

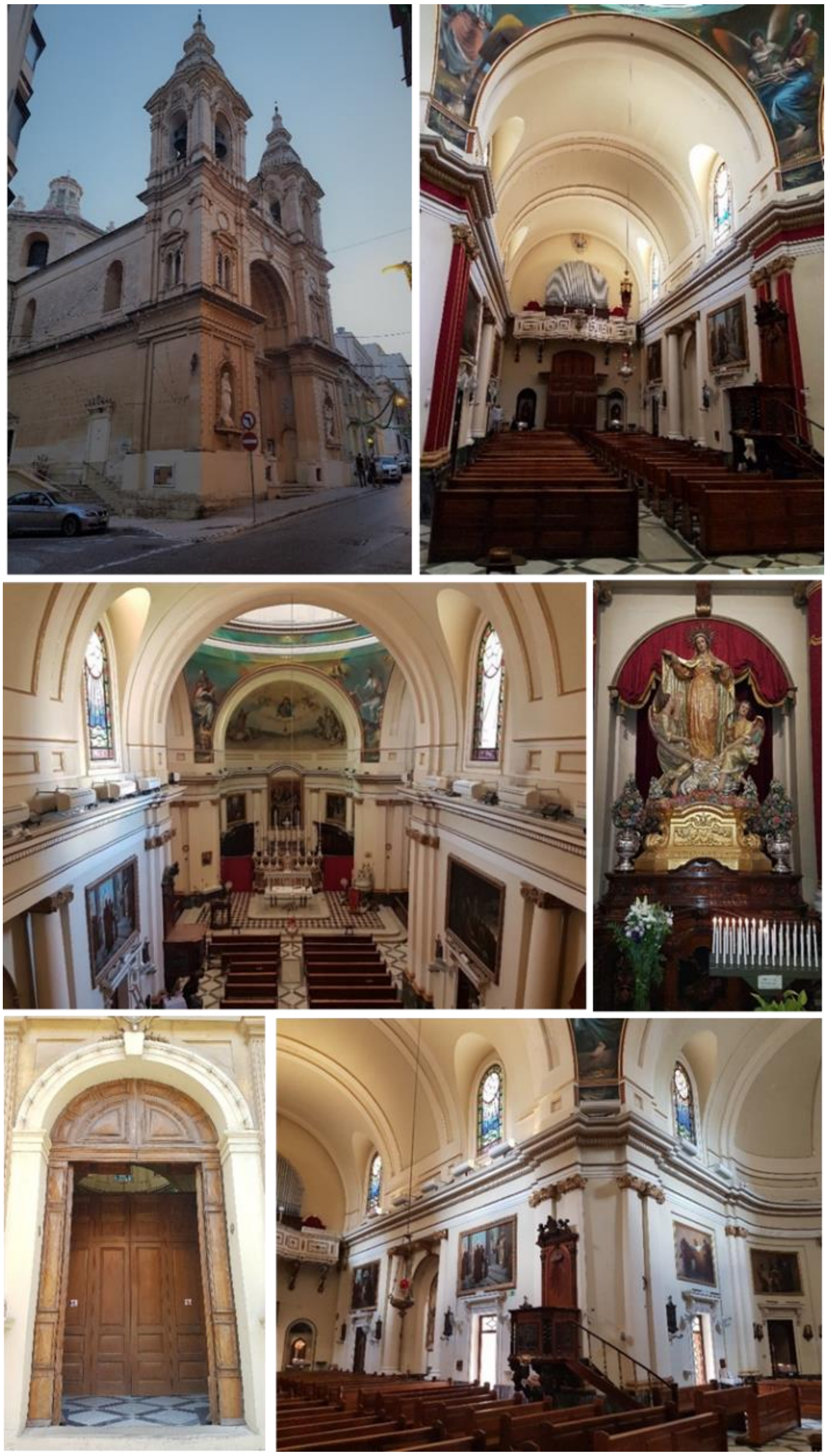


Figure 18: Our Lady Star of the Sea, Stella Maris Parish Church, Sliema. Photographs by author RCV (2018)

2.4 St. Joseph Parish Church, Msida

After Msida was established as a parish in 1867, the Immaculate Conception Old Church, which is still standing today, functioned as the Parish Church for a number of years. The current Parish Church was constructed in the late 19th century, on the design of local architect Andrea Grima, with a style resembling the conventional baroque churches that were popular at the time. A vaulted ceiling and dome structure made of globigerina limestone blocks are supported mostly by load-bearing masonry walls (refer to Figure 19). The construction of this church was brought to completion by 1889. The architecture is traditional and is in the shape of a three-aisled Latin Cross, which was the most popular design for parish churches in Malta at that time. The façade is made up of many bays, with belltowers in the proper proportions atop the two outer bays.

Figure 19: St. Joseph Parish Church, Msida. Photographs by author RCV (2018-2020)

2.5 Santa Venera Parish Church, Santa Venera

The Santa Venera Parish Church was built in phases between 1954 and 2005, however the structure is currently unfinished since it lacks bell towers and exterior finishing. On April 19, 1956, work on the church's Romanesque Revival (Neo-Romanesque) plans officially began. The crypt was finished as a temporary church by June 1967 after excavation work. Building at Santa Venera was stopped as a result of this and the Order of the Brothers of the Blessed Virgin Mary of Mount Carmel's (Carmelites) construction of three other churches in Malta. Architect (Perit) Louis A. Naudi was commissioned to complete the construction on the crypt's twentieth anniversary with help from Godwin Aquilina and Lino Bartolo. The initial concept was revised by Rabat-based architect Guzeppi Galea, and Attard Bros. Co. Ltd. carried out the construction works. The building process primarily uses reinforced precast planks supported on load-bearing masonry walls. The foundation stone was placed on October 6, 1990, and the project was finished fifteen years later, with architect (Perit) Innocent Centorrino overseeing the last operations (refer to Figure 20). On July 17, 2005, the structure was blessed and made available for veneration [82].

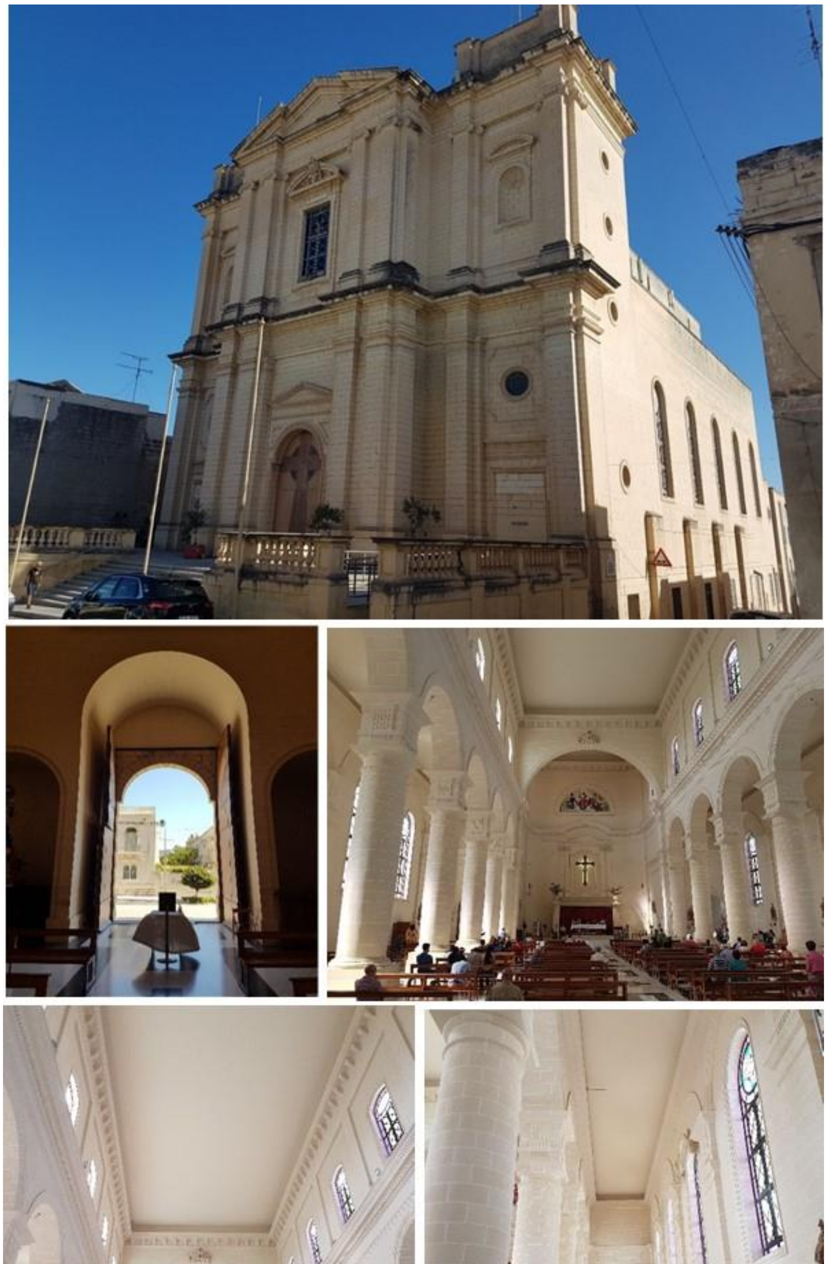


Figure 20: Santa Venera Parish Church, Santa Venera. Photographs by author RCV (2018-21).

2.6 Our Lady of Mount Carmel Parish Church, Fgura

The Parish Church of Fgura was constructed in the latter half of the 20th century (1988), and on February 1, 1990, it was dedicated to Our Lady of Mount Carmel. It was the brainchild of structural engineer (Perit) Godfrey Azzopardi and architect (Perit) Victor Muscat Inglott. This church is one of the most inventive and daring reinforced concrete constructions on the Island. It is constructed in a contemporary, post-Vatican II Council style (refer to Figure 21). Its layout is square, and a concrete shell construction that is symmetrical around both axes cover the top. Concrete serves as the primary structural component of the building, and the shape of the building rather than its sheer mass gives it strength. The structure appears to be floating due to its pyramidal external design and four triangle openings on each of its four sides.

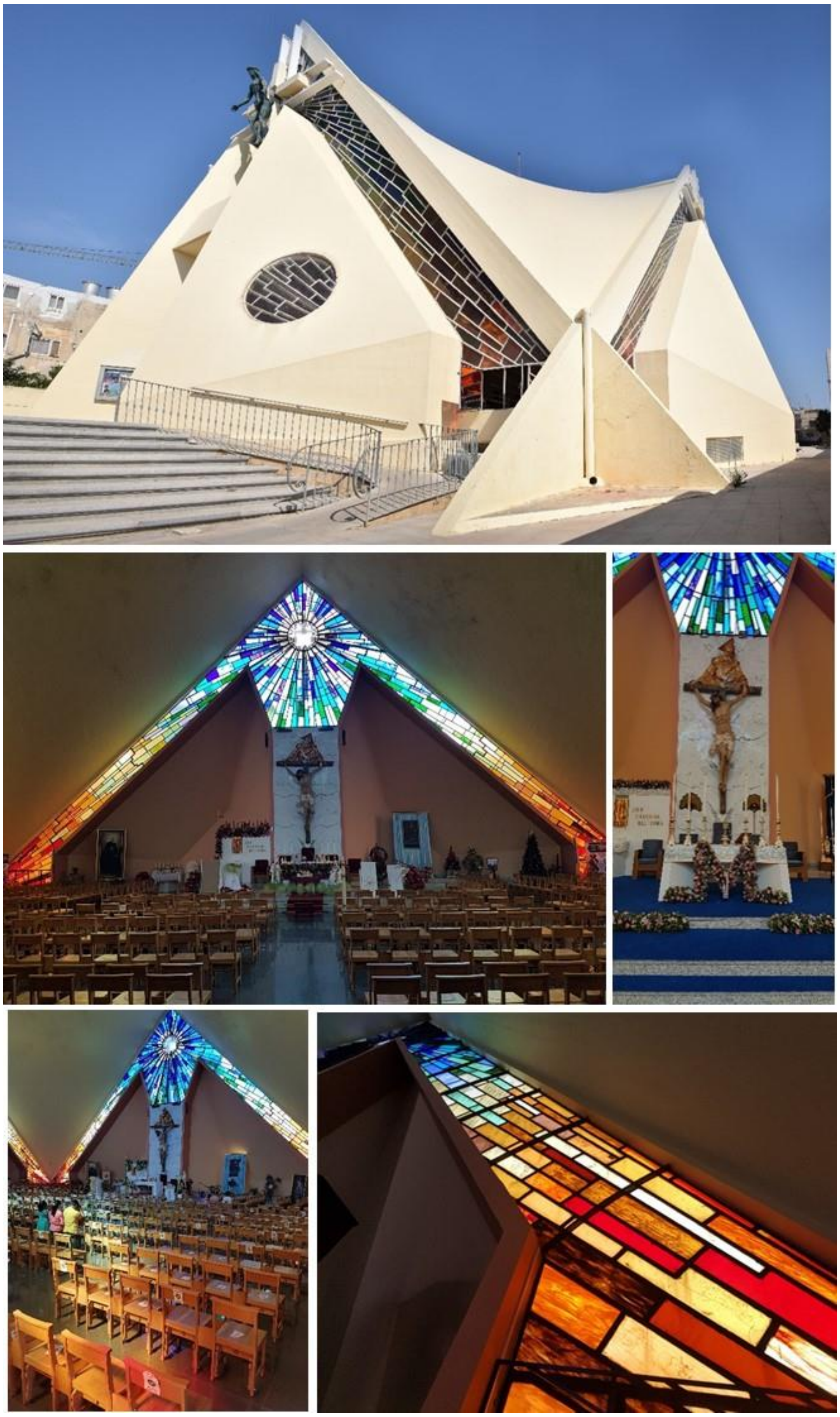


Figure 21: Our Lady of Mount Carmel Parish Church, Fgura. Photographs by author RCV (2018-21).

2.7 Construction Methodology and Local Distinctiveness

The Maltese Islands can be distinguished by their sedimentary geology and strategic location in the centre of the Mediterranean. With the whole capital city of Valletta and the megalithic ancient Temples being designated as World Heritage monuments by UNESCO, "franka" (as known in Maltese) or "softstone" is by far the most common local construction material. The Oligo-Miocene "soft limestones" found widespread in the Mediterranean Basin include the Globigerina Limestone Formation. It is the most prevalent formation in the Maltese Islands and is made up of a medium to fine-grained stone that is yellow to greyish and predominately composed of planktonic foraminifera (Globigerina) [83]. The Lower Globigerina Limestone, Middle Globigerina Limestone, and Upper Globigerina Limestone are the three components of this Globigerina Limestone Formation (refer to Figure 22), and two phosphatic hardgrounds separate them [84]. The oldest element, Lower Globigerina Limestone, has long served as the primary construction material in Malta.

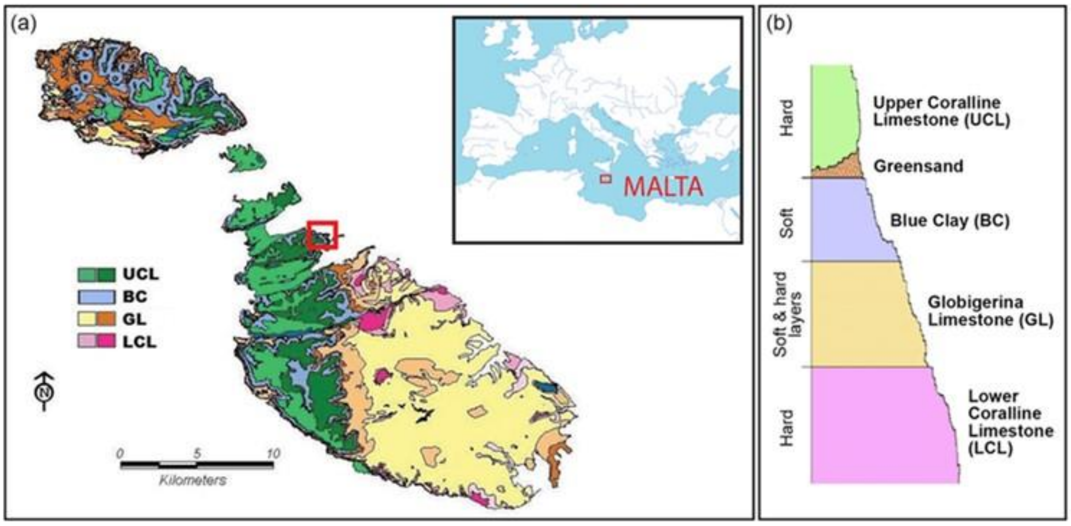


Figure 22: Geological map of the Maltese Islands.

The two primary porous and fissured limestone formations are the Globigerina-Lower Coralline Limestone and the Upper Coralline Limestone. The Blue Clay formation, which is occasionally covered by the Greensand formation, is a relatively thin layer of clayey and marly material that separates them. The Globigerina Limestone only serves as an aquifer locally, where it is heavily fractured, while the Upper and Lower Coralline Limestones are thought to serve as aquifer rocks [85].

Presently, the construction industry in Malta is facing severe challenges with respect to supply of good quality limestone for specific applications. The concern that natural resources, such as land and stone, are finite, is a tangible problem. In recent years, Malta has grappled with the problem of disposing of construction waste, with the industry also facing changes due to Malta's traditional Franka (Globigerina Limestone), increasingly becoming a scarce resource. Nevertheless, the Maltese limestone is still shaping the architecture of the islands even where churches are concerned. For the past six years, stonework (including intricate works) has been ongoing at the back of the Parish Church of Our Lady of Loreto in the village of Għajnsielem on the sister island of Gozo (refer to Figure 23). The foundation stone of this Roman Catholic neo-gothic parish church was laid on 14 September 1924 on the design of architect Ugo Mallia; nevertheless, the church was not completed until the mid-1970s due to a number of interruptions, with the sacristies never completed at all. During this period of report these two sacristies are being built in limestone on either side at the back of Għajnsielem parish church (refer to Figure 24).

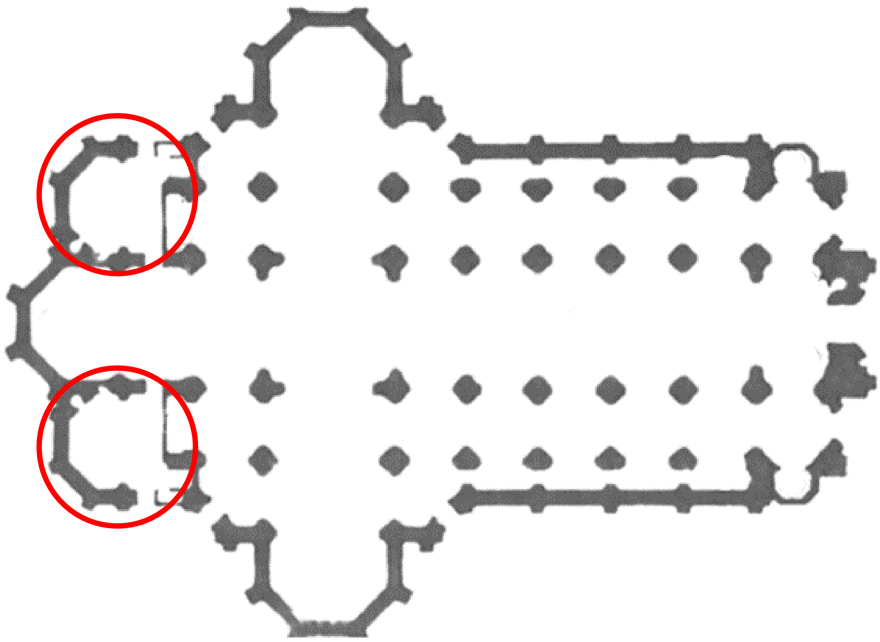


Figure 23: Plan of the Parish Church of Our Lady of Loreto in the village of Għajnsielem, Gozo.

Figure 24: Ghajnsielem Parish Church (Gozo, Malta). Photographs by author RCV (2022)

Given the extensive use of Globigerina Limestone in Maltese human culture, the Executive Committee of the International Union of Geological Sciences (IUGS), through its Heritage Stones Sub-commission (HSS), led by Prof. Dolores Pereira of the University of Salamanca (Spain), has approved the designation of Maltese Globigerina Limestone in 2019 as a Global Heritage Stone Resource (GHSR) [86].

2.8 Masonry to Concrete Structures

With the fusion of mass and tension found in the arch and arcade, it is perhaps not surprising that reinforced concrete became with time used for building contemporary churches. The idea of reinforced concrete as a frame construction, capable of bridging great spans and window openings because it worked in tension as well as compression, was a boon for factory construction, but its decorative potential was also proven in church architecture. This was brought with the Ateliers d'Art Sacré, an artistic movement based in Paris in the first half of the 20th century, that united artists, architects, and craftsmen to bring art that was aesthetically challenging as well as devotional into churches [87–90]. In Malta too, concrete pre-cast slabs for roofing and mass concrete structures were introduced in the 20th century. Reinforced concrete had an important role in the Roman Catholic churches built in the post-war years. Apart from Our Lady of Mount Carmel Fgura Parish Church, considered in this thesis as one of the RBs, other extraordinary uses of reinforced concrete for religious buildings in Malta are portrayed in St. Francis of Assisi Qawra Parish Church, in San Pawl il-Bahar (refer to Figure 25), and the Convent & Sanctuary Church of St. Therese of Lisieux, in Birkirkara (refer to Figure 26).

Figure 25: St. Francis of Assisi Qawra Parish Church, San Pawl il-Bahar. Photograph by author RCV (2021).

Figure 26: The Convent & Sanctuary Church of St. Therese of Lisieux, Birkirkara.

2.9 Onsite Measurements and Logging Systems

To address the performance of selected reference buildings, measurements of air temperature (T) and relative humidity (RH) with data loggers were conducted in various locations, 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).

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

Dual channel digital air humidity and temperature sensors (HOBO data loggers) were placed along the main nave at a height that corresponds the actual environment that churchgoers encountered while avoiding the impact of radiating sources and air movement, in order to acquire representative climatic data. At intervals of five minutes, the loggers recorded the indoor and outdoor temperature T (°C) and air humidity RH (%), with data being gathered on a monthly basis. The recorded data were wirelessly transferred to mobile devices using Onset's HOBO MX1101 data recorders using Bluetooth Low Energy (BLE) technology and tabulated in excel format [91]. After any data outliers were removed, recorded values were then converted from 5-minute intervals to the corresponding mean hourly values.

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.

2.10 Adaptive Comfort Model

Standards for thermal comfort in use are either based on heat balance or adaptable models. Both the Adaptive Comfort Model and the Heat Balance Model (PMV/PPD Model) are included in the EN 16798-1 standard. According to EN 16798-1 [92], the adaptive comfort model should be used for buildings without mechanical cooling, whereas the PMV/PPD Model is appropriate for structures that are mechanically heated and/or cooled (naturally ventilated).

The PMV/PPD Model is a heat balance model which investigates thermal physiology while assuming precisely analysed factors such as activity level, clothing's thermal resistance, air temperature, mean radiant temperature, relative air velocity, and ambient air's water vapour pressure [93]. This paradigm assumes that inhabitants are unable to adjust to their surroundings and that comfort levels are constant (i.e., regardless of external influences like outside temperature).

The adaptive model, on the other hand, explores the dynamic link between occupants and their general settings based on the idea that individuals often respond to changes that cause pain by looking for ways to increase their level of comfort [94]. Physiological, psychological, and behavioural changes are all part of this adaptation concurrently [95,96]. Because of this, the adaptable model, especially in naturally ventilated buildings, offers greater flexibility in matching ideal inside temperatures with outdoor environment. Therefore, adaptive standards are considered as more suitable for promoting comfort in low energy buildings [97–100]. As a function of the exponential weighted running mean of the external temperature, the EN 16798-1 Adaptive Comfort Model offers appropriate inside temperature limitations [94,101,102].

In view of the above, the EN 16798-1 Adaptive Comfort Model is the model deemed most significant for this study since all five RBs are being considered in their free running state, with Balzan and Sliema Parish Churches being mechanically cooled only intermittently during the summer period. The association between the operating comfort temperature and the air temperature was deemed sufficient to conduct a comparative analysis of the five selected churches and assess their degree of comfort during the years under investigation because EN 16798-1 is based on the operative comfort temperature. This correlation was examined through comparison studies of the information gathered from the three sensors along the main nave of the respective RBs, confirming that air temperature alone can be a reliable indicator of thermal comfort in areas with low air velocity and where air temperature and mean radiant temperature may be comparable. The Adaptive Model deemed also fitting as occupants are flexible in how they dress in response to interior and/or outdoor temperature conditions, and that the buildings are primarily used for human occupancy engaging in sedentary activities. Figure 27 shows the link between the operating comfort temperature and the outside running mean temperature that EN 16798-1 adopted.

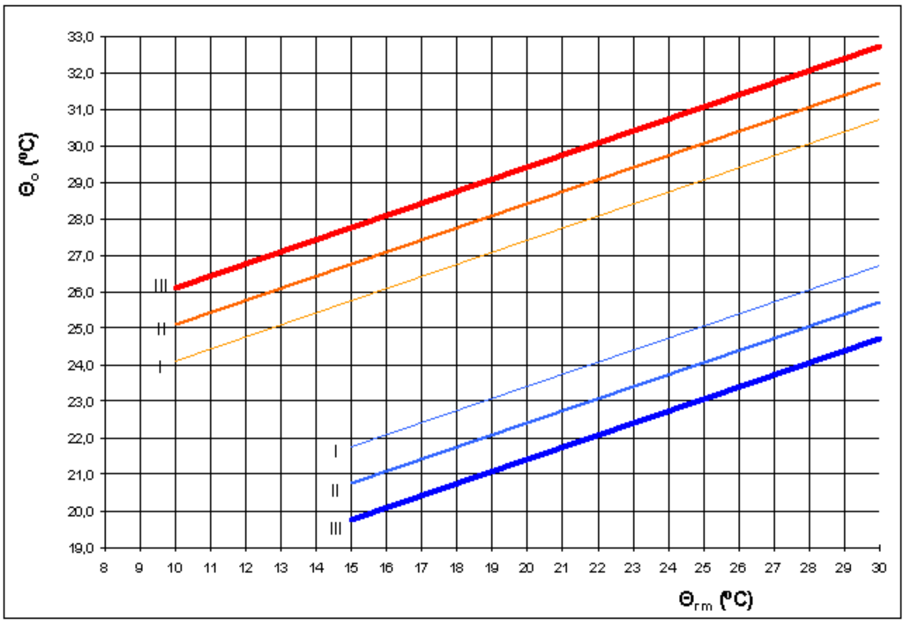


Figure 27 - Design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially weighted running mean of the outdoor temperature.

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: $\Theta_o = 0.33\Theta_{rm} + 18.8 + 2$ (1)

lower limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 - 3$ (2)

Category II upper limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 + 3$ (3)

lower limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 - 4$ (4)

Category III upper limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 + 4$ (5)

lower limit: $\Theta_o = 0.33\ \Theta_{rm} + 18.8 - 5$ (6)

where;

Θ_o = indoor operative temperature, °C

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

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

According to three separate categories based on the occupants' degree of expectations (refer to Figure 27), the model offers comfort limits. Church buildings have been assigned to category III level, which represents a reasonable yet acceptable standard of expectation. Table 4 provides a description of how the EN 16798-1 categories I through IV are applicable.

Table 4: Description of the applicability of the categories used (EN 15251)

Category	Description
I	High comfort levels to be used in sensitive areas such as in operating theatres, hospital wards and around vulnerable persons
II	Appropriate comfort levels for new and renovated buildings
III	Acceptable comfort levels for existing buildings
IV	Marginal comfort levels to be exceptionally used in areas with limited occupancy.

The outside mean temperature was calculated using the method shown below in accordance with EN 16798-1, and the results were extrapolated into the category III formulas:

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

where;

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

Θ_{ed-1} = daily mean outdoor air temperature for previous day

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

Θ_{ed-i} = daily mean outdoor air temperature for the i-th previous day

2.11 Recruitment Method, Study Population and Survey Design

Surveys with sample parishioners were conducted in each RB throughout the height of the harsh weather seasons of summer (representing May to September) and winter (representing November to March) when the microclimate was being observed. To provide a fair representation of the whole population, the data were gathered using the cluster sampling approach, in which respondents were picked with an equal chance [103]. In the summer, 60 people from each RB were questioned, totalling to 300 participants, and in the winter, another 300 participants were surveyed. Thus, a maximum margin of error of 4% is guaranteed adopting a 95% confidence interval for the study sample of 600 individuals (291 men and 309 women with a mean age of 49.31 years and a standard deviation of 16.778 years).

A 7-point Likert scale was used in the survey to ask participants about their current thermal state (CTS) within the church, with 1 denoting the "hot" extreme and 7 denoting the "extremely cold" extreme [104]. According to Hawkes' findings [105], the subject feels thermally comfortable at the "neutral" position, denoted by the number 0 on the Likert scale. On the other hand, S. Shahzad et al. (2018) concluded that additional measurements, such as thermal preference [106], may be required in addition to CTS to thoroughly analyse the users' thermal comfort. Nevertheless, it must be noted that the latter research focused on the use of the neutral thermal feeling in office buildings, where people spend an average of eight hours each day at work, a large amount of time compared to the circa 45 minutes that people spend in churches. Therefore, the parishioners' CTS provides useful information for assessing the thermal comfort of the RBs. The TSS also asked about participants' attendance patterns and times, whether they had ever changed churches as a result of uncomfortable temperatures, whether they had ever missed a Sunday prayer service because of extreme temperatures, and how to identify uncomfortable conditions and offer solutions [107]. Every participant's pertinent personal information, such as age, gender, and attire, was also recorded.

2.12 DesignBuilder Simulation Model

Computer simulations for this study's purposes make use of DesignBuilder Software [108]. This program, an expanded user interface to Energy Plus, is a typical building modelling tool that gives access to all of the most often used simulation functions, including those for renewable energy sources, building fabric, thermal mass, glazing, and shading.

The full geometry of the churches under consideration was created in AutoCAD, and their respective building envelope characterisation, occupancy schedules, and lighting fixtures were modelled to resemble an accurate representation as possible of the true building and the respective indoor environment in order to generate an accurate and precise 3D model in the DesignBuilder.

The software was verified to have an acceptable margin of error between the output of the simulated interior temperature simulation and the observed data. The '2018 Weather File' obtained from the Malta International Airport (MIA) was installed within the DesignBuilder application, and a yearly simulation was conducted. The predicted hourly data of the inside mean air temperature were compared to the actual indoor hourly average observed temperature for 2018. The hourly simulated data and the hourly measured values were then contrasted. Using the appropriate Weather File for each year (2018, 2019 and 2020), this procedure was performed for all three years.

Based on EnergyPlus estimates, the DesignBuilder program developed the typical weeks for all four seasons and the design weeks for both the summer and winter seasons [109]. Comparison between typical and design conditions were conducted for the different seasons.

CHAPTER 3: SCIENTIFIC PUBLICATIONS

The findings of this study are important to evaluate the ability of current building envelopes in providing thermal comfort while decreasing energy waste. This study further enables an in-depth understanding of the effectiveness of proposed materials/installations that can be used for zero energy buildings (ZEBs) and give the opportunity to transform such majestic buildings to best-practice examples that the whole community may benefit from by adopting them in their own dwellings and places of work.

3.1 Complementary Paper

In the complementary paper entitled "Monitoring Indoor Temperatures of Places of Worship: A First Step Towards Energy Sustainability (ESSE'18)," five representative churches in Malta, ranging from sizable and modest baroque structures to more modern structures, are investigated to determine their current indoor climate conditions during the winter. In order to identify and assess the severity of comfort concerns in these buildings, analysis of measured temperature and humidity was conducted (refer to Figures 28 and 29). According to preliminary findings, the thermal mass of buildings proved crucial in regulating internal temperature in such free-running structures. Whilst baroque churches enjoyed a relatively stable indoor temperature, the interior temperature of the selected representative more contemporary concrete church, displayed extensive diurnal swings that surpassed the comfortable thresholds.

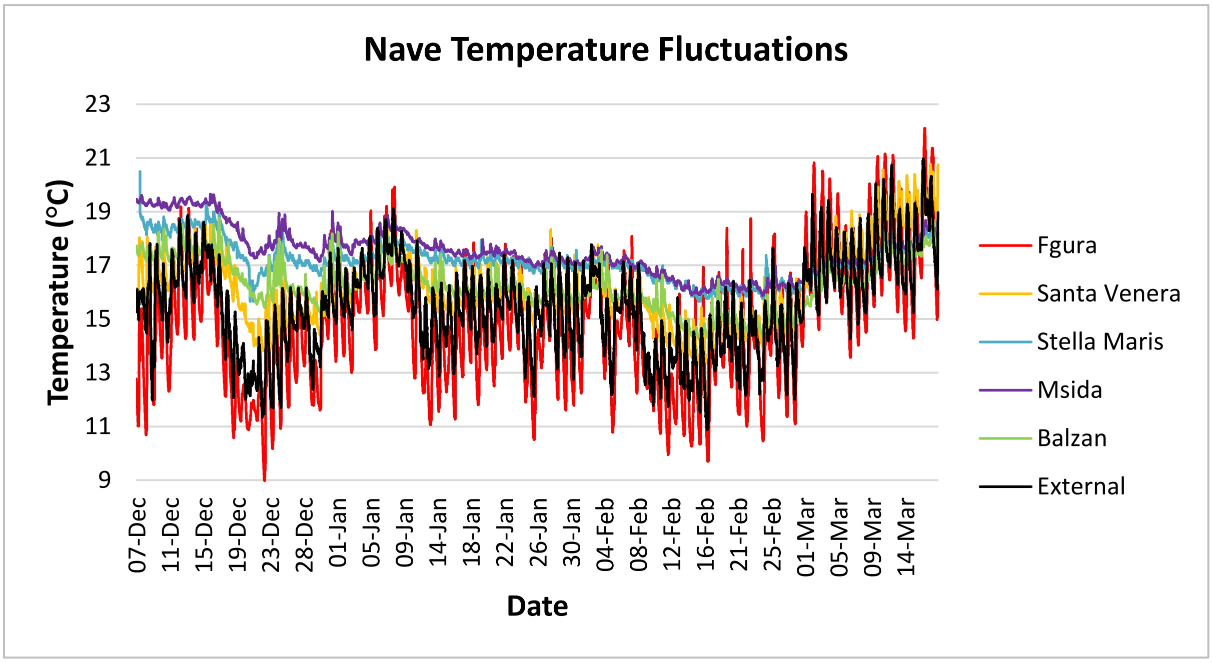


Figure 28 - Comparative Analysis of Nave Temperature (T °C) Fluctuations of the five churches under study.

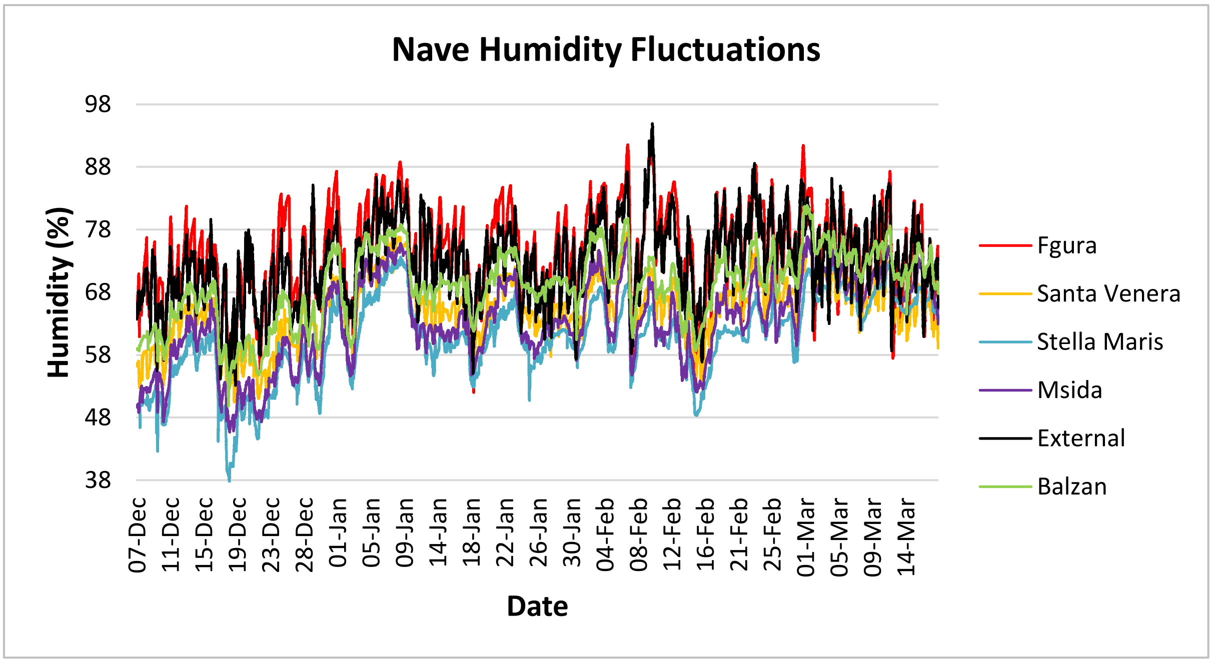


Figure 29 - Comparative Analysis of Nave Humidity (RH %) Fluctuations of the five churches under study.

The baroque churches under consideration feature substantial globigerina limestone walls. The wall's thickness provides strong thermal insulation, preventing the inside temperature from being impacted by the building's daily/hourly temperature changes. Additionally, the hygroscopic building fabric buffer the RH as it absorbs and desorbs moisture from the air, as long as the air within the church is not rapidly exchanged with the outside air [110]. On the contrary, modern churches such as that of Fgura exhibited low temperature and high relative humidity for the measured period in winter, and both parameters are considered to go out of the comfort zone. Due to these phenomena and supporting results from this study, one must promote passive control methods and, concurrently ensure that the environment has no impact on the structure and objects decorating our churches.

As most of the historic structures on the island fit the category of baroque churches, the results from the complementary paper were indeed a real eye-opener to those present at the Engineering Sustainability & Sustainable Energy 2018 (ESSE ’18) conference organised by the Chamber of Engineers in collaboration with the Institute for Sustainable Energy of the University of Malta. All professional stakeholders present acknowledged that considerable opportunity exists to leverage the benefits of energy-efficient retrofitting. This prompted further studies to explore future strategies for creating a sustainable future in a world experiencing energy difficulties.

The information in this paper is based on scientific data gathered to reveal the efficacy of temperature control recommendations that result from a confluence of human comfort needs, a paucity of science, a substantial number of assumptions, and an unfortunate propensity to generalize to a single rigid target. There are still a lot of unknowns in the examination of temperature-related dangers. Such presumptions must be contested in an era of growing concern over the prudent use of our planet's resources. The question becomes, where and how should one focus temperature control efforts, and why?

Sustainable cities call for sustainable solutions, but this study highlights how increasingly unsustainable more modern churches are. This emphasizes the value of adhering to current standards and certification throughout the entire building development life cycle as well as the use of techniques and technologies in the effort to renovate and retrofit buildings in order to significantly reduce energy consumption while maintaining an acceptable level of comfort.

Malta is obliged under the Energy Efficiency Directive to establish national building renovation policies, including eco-refurbishing public structures, many of which have historical significance. Although restoration of historic structures is gaining popularity in Malta, the significance of energy-efficient renovation is yet largely unexplored, and thus an in-depth study, utilising the EN 16798-1 adaptive comfort model was taken up, the outcome of which is portrayed in Scientific Article No.1.

3.2 Scientific Article No.1

Scientific Article No.1 entitled *'A study of thermal comfort in naturally ventilated churches in a Mediterranean climate';* published by Energy & Buildings Journal [2], conducts a comparative analysis of the five selected churches to determine their respective level of indoor thermal comfort throughout the year (2018) using the EN 16798-1 adaptive comfort model with category III comfort limits. In this research, the adaptive comfort model was adopted, as opposed to the PMV/PPD model, as it provides more flexibility on the optimal indoor temperature conditions when compared with the outdoor ambient temperature, particularly in natural ventilated churches. In addition, this model is founded on the hypothesis that occupants within naturally ventilated buildings attain thermal comfort within a wider range of indoor temperatures when compared with occupants within HVAC controlled environments. In fact, over the past 20 years, it has been established that there was a shift from heat-balance based thermal comfort models towards adaptive comfort models [111]. In this case, since the environments within the RBs had low air velocities and provided that the mean radiant temperature and the air temperature recorded similar readings, the latter was considered as a sufficient indicator of thermal comfort. Moreover, category 3 was chosen as the optimal limits of comfort which is termed as "an acceptable, moderate level of expectation and may be used for existing buildings" [92].

Monitoring of indoor and outdoor temperatures and humidity, using HOBO calibrated sensors located along the main nave and situated at a defined height which corresponds to the level of the occupants, was conducted for all five RBs simultaneously for the year 2018. The fiveminute interval readings were transposed to hourly values, and an analysis of the design and typical weeks across all four seasons was conducted.

From the analyses conducted it was determined that the thermal mass of buildings have a significant influence in managing indoor temperature in these free-running structures. The Baroque churches demonstrated to have an overall high thermal mass when compared to the mid-20th century neo-Romanesque style architecture, and late 20th century (post Vatican Council II style) contemporary architecture, resulting in a steadier indoor temperature in Baroque churches as compared to higher fluctuations in temperature for the more recent architectural styles. An extract of the results for all five RBs are graphically interpreted in Figures 30 to 34. The behaviour portrayed between the Baroque and the contemporary churches is mainly attributed to the lack of overall thermal mass of the contemporary buildings and higher solar gains through glazed elements, providing minimal "inertia" against external temperature fluctuations. The fundamental difference lies within the building envelope, which is composed primarily of masonry blocks (high thermal mass) having walls that are between 1.5 and 2 meters thick for the Baroque churches. This results in minimal heat transfer (U-value) across the building, which prevents fluctuations in the inside temperature. Furthermore, as compared to the more contemporary construction methodologies, the proportion of glazing to wall area in Baroque churches is negligible, making up only 3% of the entire external surface area of the church.

Results also highlighted that out of the two contemporary churches, the Santa Venera parish church exhibited the highest internal temperatures on average. This is due to the fact that the absolute total area of glazing is higher in Santa Venera parish church, even though the Fgura Parish Church has a higher percentage of glazing. Glass by itself has a very low thermal mass value, but it also lets solar radiation to flow through, hence causes the indoor space to overheat, especially in the summer. Thus, the indoor ambiance is aggravated 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. In addition, amongst the churches under study, Santa Venera parish church is the only one whereby the *antiporta* (that is a door placed behind the main door to create a small porch) is missing, which results in natural infiltration causing induced significant fluctuations in the indoor environmental conditions during service hours.

The results achieved in Scientific Article No.1 give a sound indication (status quo) of the condition during the period of report vis-à-vis the thermal comfort (or rather the lack of it) in five naturally ventilated RBs in Malta when contrasted to EN 16798-1 Category 3. Though for Baroque Churches, both design and typical weeks in summer generally recorded temperatures within the comfort limits, the application of mechanical cooling was still being sought. This anomaly prompted further investigation and a Qualitative Analysis of worshipers' and pastors' perception of indoor comfort, by means of questionnaires, was conducted. The outcome of this qualitative research is portrayed in Scientific Article No.2.

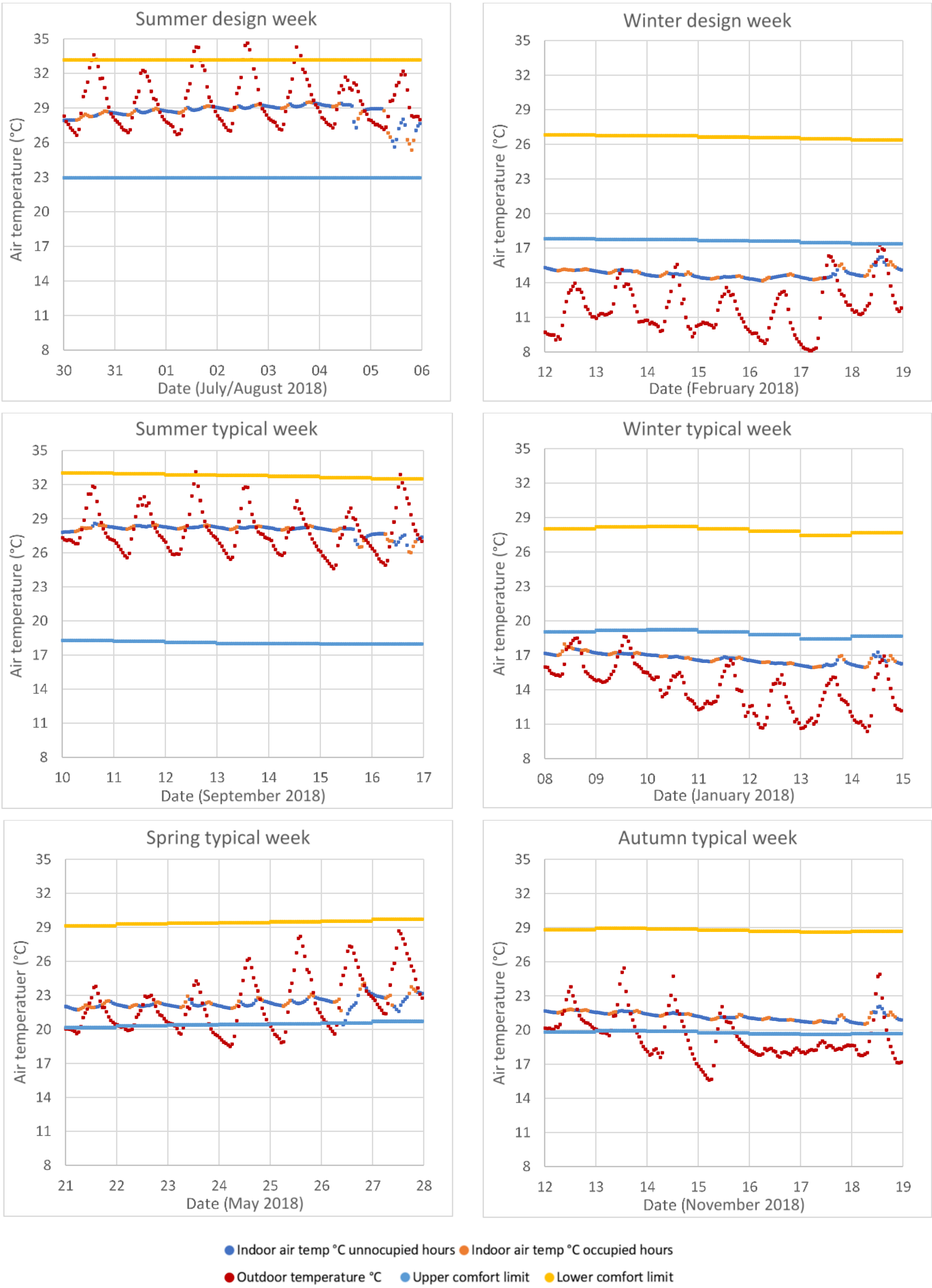


Figure 30 - Balzan – The Annunciation Parish Church – EN 16798-1 Category 3 Comfort Analysis

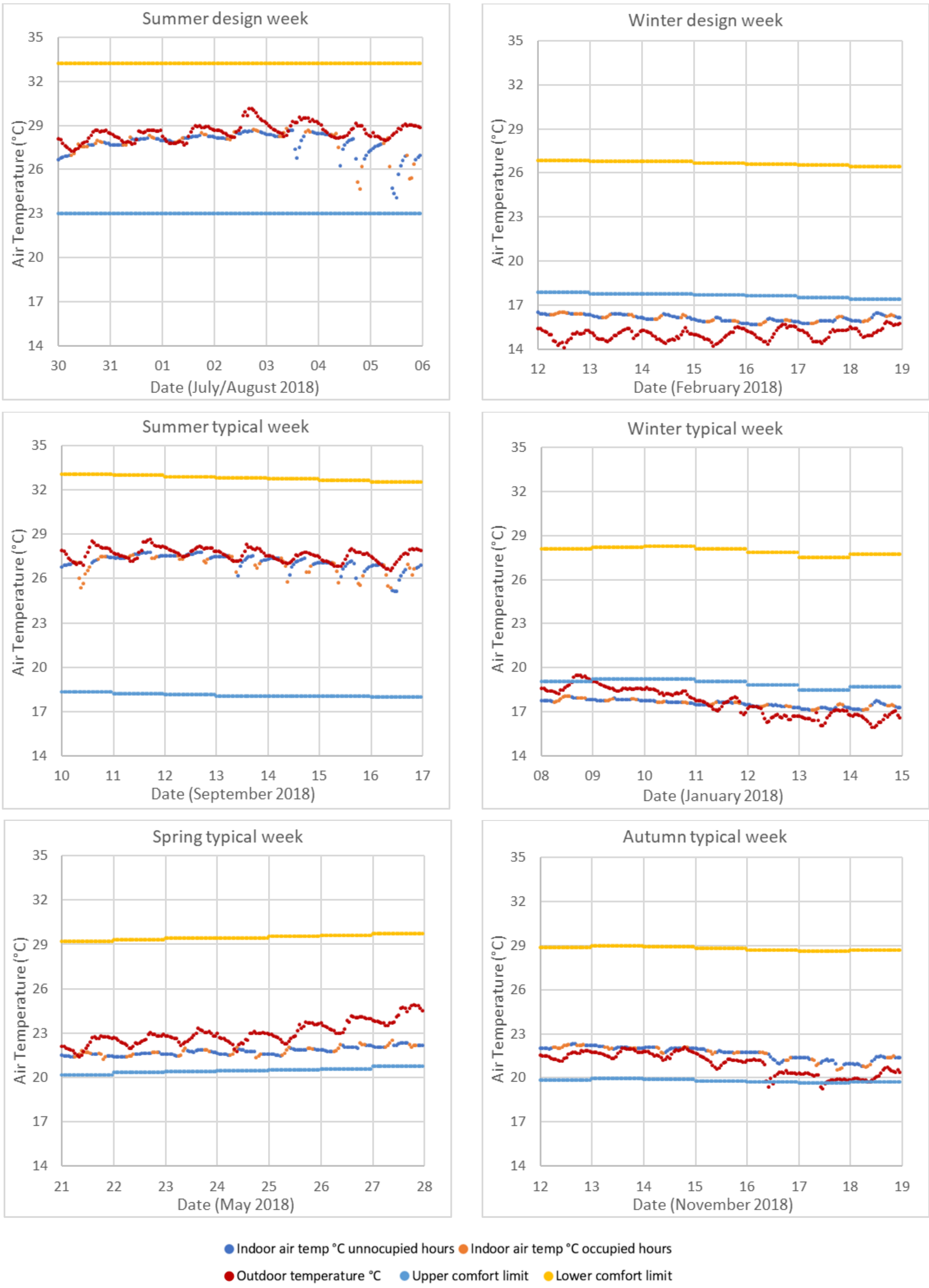


Figure 31: Stella Maris Parish Church – EN 16798-1 Category 3 Comfort Analysis.

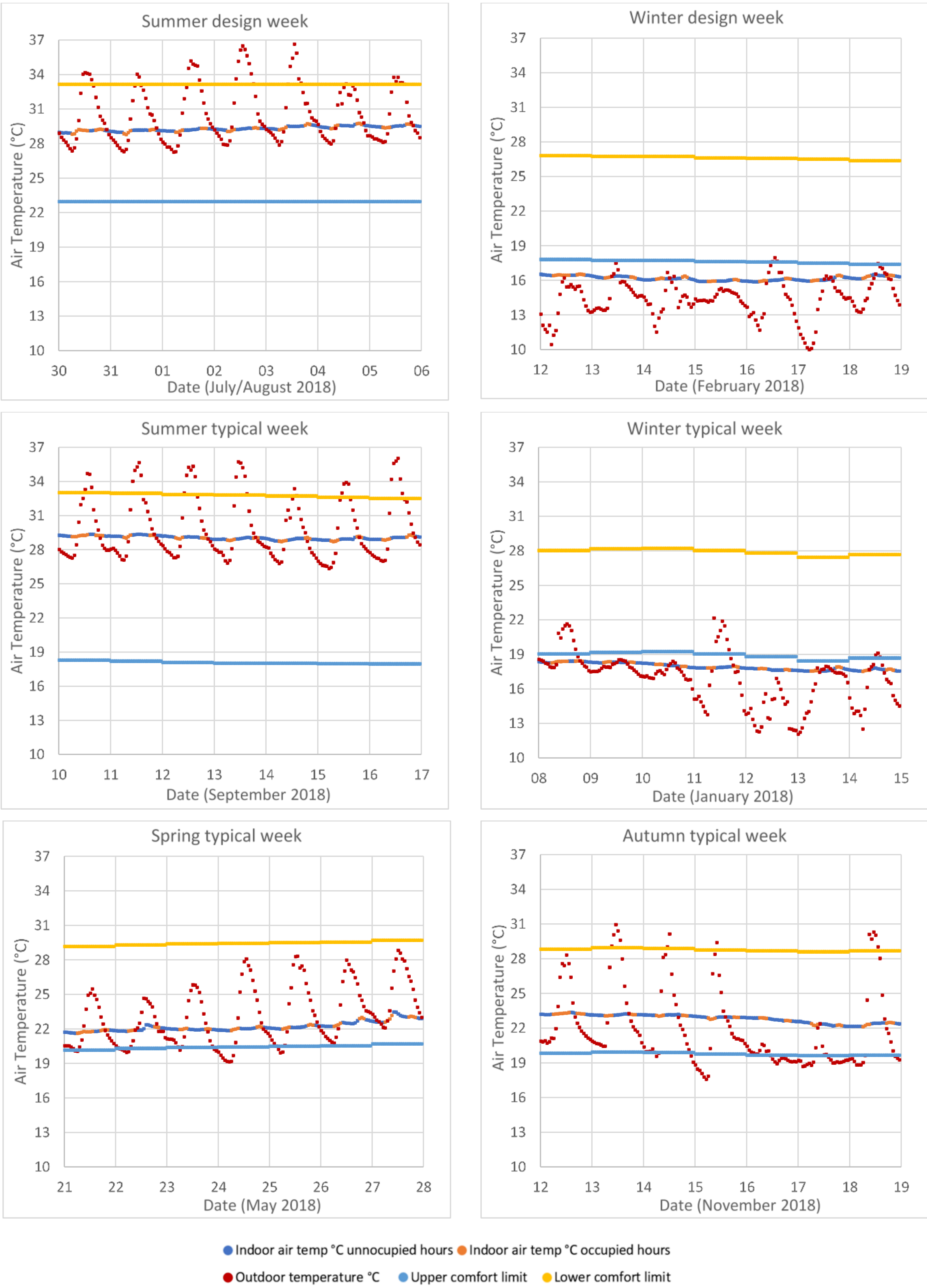


Figure 32 - Msida – St. Joseph Parish Church – EN 16798-1 Category 3 Comfort Analysis

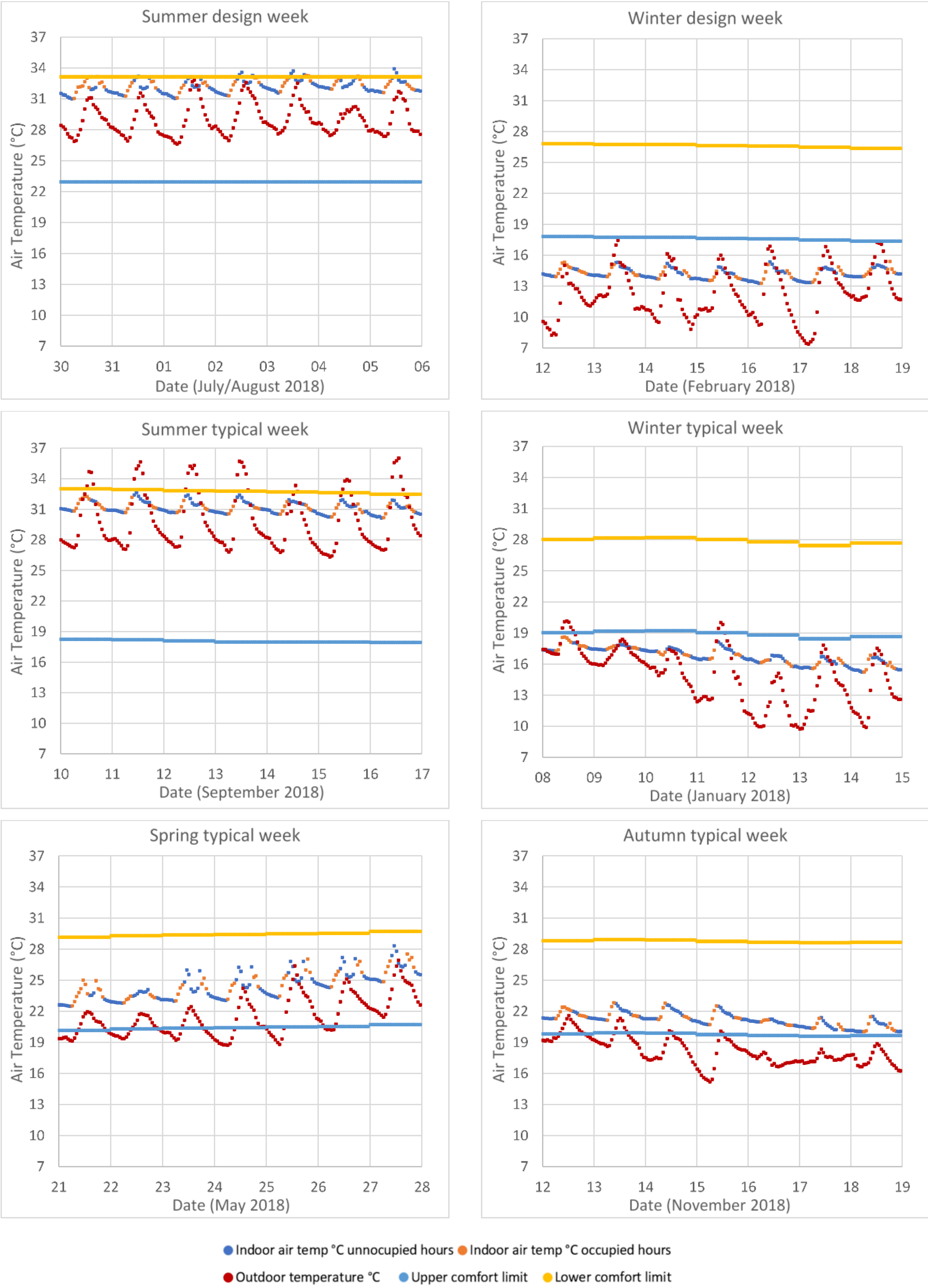


Figure 33 - Santa Venera – Santa Venera Parish Church – EN 16798-1 Category 3 Comfort Analysis

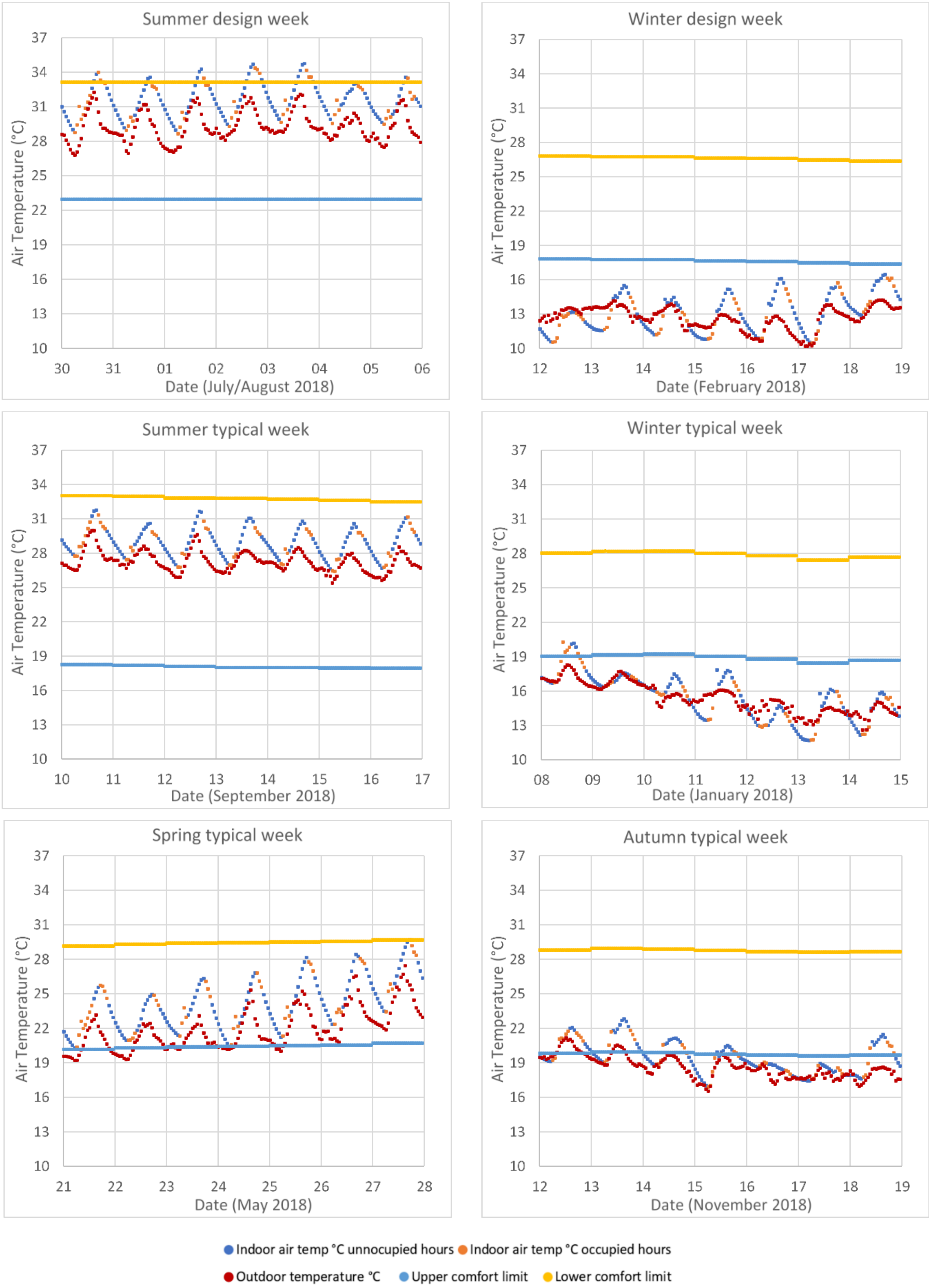


Figure 34 - Fgura – Our Lady of Mount Carmel Parish Church – EN 16798-1 Category 3 Comfort Analysis.

3.3 Scientific Article No. 2

Thermal Comfort in Places of Worship within a Mediterranean Climate, Scientific Article No.2, published by Sustainability Journal [2], looks at the correlation between the actual EN 16798-1 thermal comfort levels and the anticipated thermal comfort of visitors in the five representative parish churches during 2018. This is accomplished through statistical analysis of both quantitative research based on indoor measurable data and qualitative research based on replies to questionnaires from churchgoers. Thermal sensation surveys were used to collect statistical data as well as scientific data on temperature and relative humidity for this analysis (TSSs). The data gathered further provide first-hand information about how churchgoers adjust their behaviours and thermal sensations to the complex environment within the respective churches.

The scientific information was acquired through monitoring of 5-minute interval readings of the inside air temperature in each parish church during the year 2018 and converting those readings to hourly values. Line graphs were used to illustrate data in respect to EN 16798-1 comfort limits. The statistical data, on the other hand, was gathered through a field study on thermal comfort assessment conducted in all five representative churches in both summer and winter during the peak period of extreme weather. This assessment of thermal comfort in churches was based on the responses to a questionnaire survey (refer to Table 5), which was administered concurrently in both Maltese and English.

Table 5: Questionnaire survey (English version)

THERMAL ENVIRONMENT SURVEY

This survey is part of a study to evaluate the current thermal conditions of the selected building. We appreciate your feedback in this evaluation. Please tick at the square box where applicable.

1. Gender
   a) Male: ☐
   b) Female: ☐
2. Age: _______
3. How many years have you been attending this church?
   a) 6 months ☐
   b) 1 year ☐
   c) More than 1 year ☐
4. How would you describe your typical level of thermal comfort in this church during summer?
   a) Hot ☐
   b) Warm ☐
   c) Slightly Warm ☐
   d) Neutral ☐
   e) Slightly Cool ☐
   f) Cool ☐
   g) Cold ☐
5. Why do you think the church has this ambient? What do you suggest to make the church more comfortable?

   ____

   ____

   ____

6. Occupant's Clothing

   Please refer to the Table below. Place a check mark next to the articles of clothing that you are currently wearing as you fill out this sheet. If you are wearing articles of clothing not listed in the table, please enter them into the space provided below.

   Clothing Ensembles

Trousers/skirt/dress, short sleeve shirt /T-shirt	
Trousers/skirt/dress, long sleeve shirt	
Trousers/skirt/dress, long sleeve shirt plus jacket	
Trousers/skirt/dress, vest, long sleeve shirt plus jacket/coat	
Trousers/skirt/dress, vest, long sleeve shirt plus long sleeve sweater	
Trousers/skirt/dress, vest, long sleeve shirt plus long sleeve sweater plus jacket/coat	
Other; specify	

7. Do you attend mass:
   a) Early Morning: 6 - 8
   b) Midday: 9 - 12
   c) Evening: 6 – 8
8. Did you ever change the church where you usually attend specifically because of uncomfortable temperatures inside?
   a) Yes
   b) No

If yes, which church did you go to?

____

9. Have you ever missed Holy Mass because the church is too hot or too cold? If yes
   a) Less than 5 times
   b) Less than 10 times
   c) More than 10 times
   d) Never
10. If you are dissatisfied, how would you best describe the source of your discomfort (check all that apply)
    a) Too much air movement
    b) Not enough air movement
    c) Incoming sun
    d) Drafts from windows
    e) Drafts from vents
    f) Hot-cold surrounding surfaces (floor, ceiling, walls or windows)
    g) Heating/cooling system inefficient
    h) Uneven temperature (some parts always hot while others always cold)
    i) Other. Please describe:

    ____

    ____

    ____

11. Please feel free to include any other remarks with respect to indoor comfort in your church

    ____

    ____

    ____

    ____

    ____

    ____

Thank you for participation.

This survey is intended to provide an assessment of the thermal comfort. Answers to these survey questions provide an indication as to the performance of the buildings heating, ventilation and air-conditioning systems while providing direction for making improvements to systems in an attempt to provide a continual comfortable environment for building occupants.

This survey provided an assessment of the thermal comfort provided by these buildings to its occupants. Answers to these survey questions provide an indication as to the performance of the buildings' ambient conditions and first-hand information from churchgoers on their perception. This survey was divided into four sections.

- Section 1 – Individual information.
- Section 2 – Ambient Conditions & Level of Comfort.
- Section 3 – Occupant's Clothing.
- Section 4 – Occupant's Remarks.

Data was gathered using the cluster sampling approach, in which each responder had an equal chance of being selected, resulting in a fair representation of the whole population. To provide a fair representation of the entire population, the data was gathered using the cluster sampling approach, in which respondents were chosen with an equal chance [38]. In summer, 60 participants were surveyed from each RB, totalling to 300 participants, and in the winter, another 300 participants. As a result, there were 600 participants in the overall study population (291 men and 309 women, with an average age of 49.31 years and a standard deviation of 16.778 years), which ensures a maximum margin of error of 4% when assuming a 95% confidence interval.

From the data gathered, several statistical studies were conducted to determine the relationship between the actual thermal comfort levels measured in accordance with the EN 16798-1 standard and those anticipated by the parishioners. Each test, given a significance threshold of 0.05 [112], resulted in one of two hypothesis: the null hypothesis or the alternative hypothesis. The null hypothesis (which states that there is no correlation between the two categorical variables), mean that the two categorical variables are independent. The converse is specified by the alternative hypothesis, i.e. that the two categorical variables are not independent.

The key finding of this study show that there is a significant correlation between the actual thermal comfort levels measured accordance to EN 16798-1 standard portrayed in paper 1, and the expected thermal comfort experienced by churchgoers in the majority of the parish churches under review. Figure 35 shows a bar graph representing comfort levels in the different parish churches in both summer and winter. This information determines that the thermal comfort performance hierarchy of the church structures support the findings established in the first published scientific article.

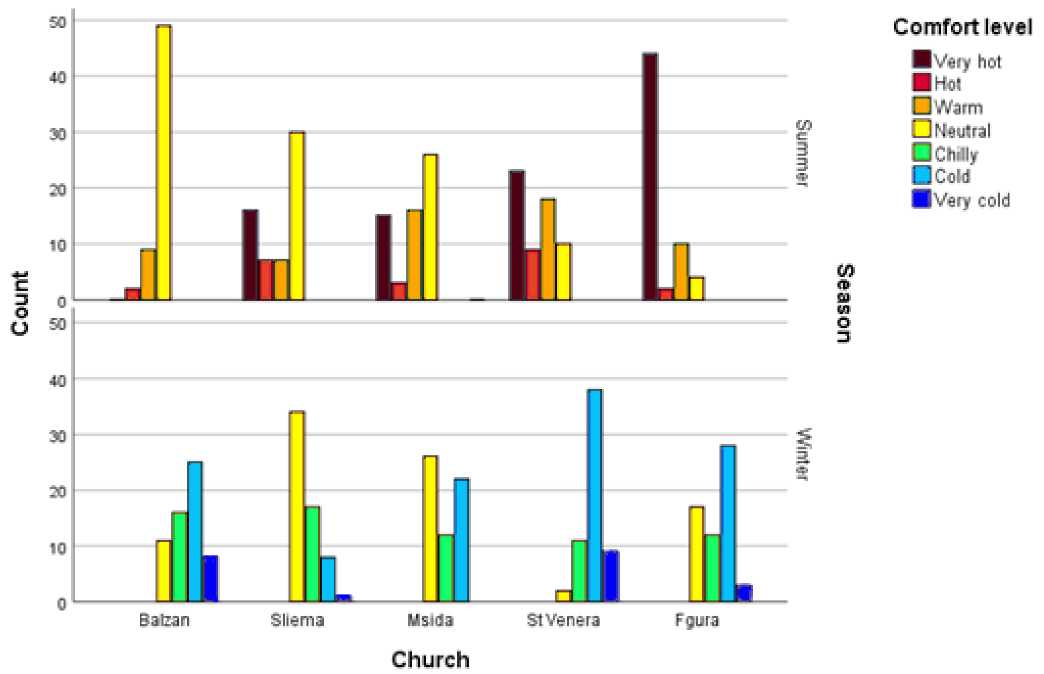


Figure 35: Bar graph representing different comfort levels in the different parish churches in summer and winter.

Other results assessed in this paper regarding the physiological factors (gender) show that females tolerated higher temperatures when compared to men with 45% and 35% respectively (refer to Figure 36). This outcome is in line with the results established by Y. Zhai et al. who mentioned that females are more satisfied in warmer temperatures than men [113]. In addition, this is further supported with the results attained in the study conducted by B. Kingma who concluded that females prefer warmer temperatures than men [114].

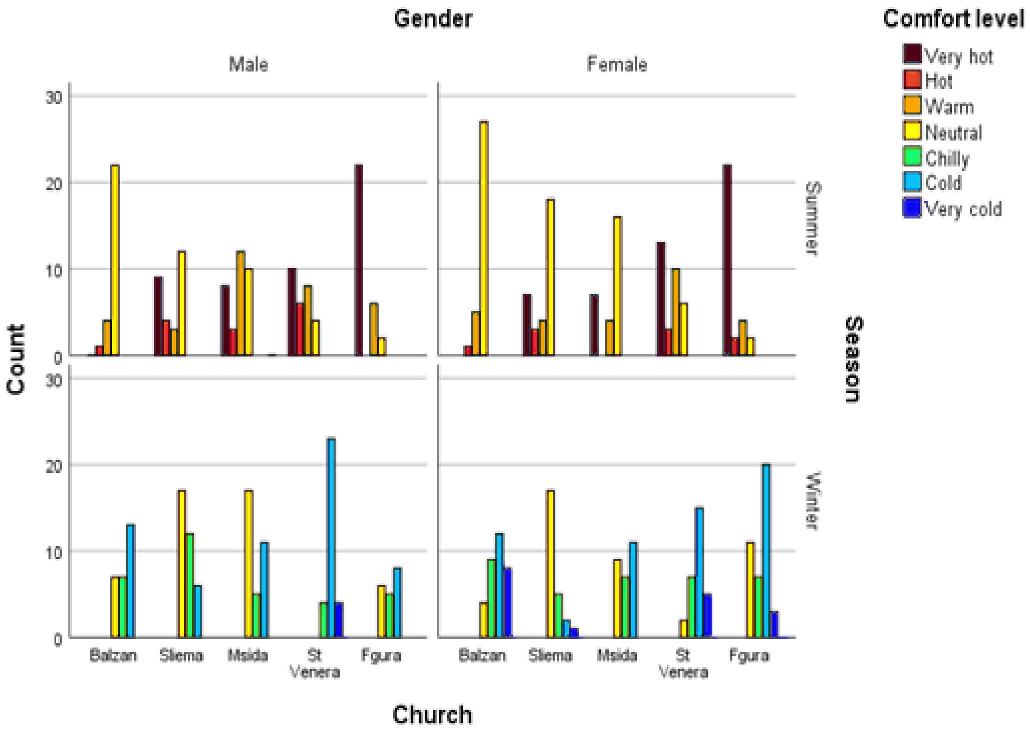


Figure 36 - Bar graph representing the difference in comfort levels between males and females in the different parish churches in summer and winter.

In addition, analysis on age results mainly signified that older generations feel less thermally comfortable in cool temperatures than warmer temperatures when compared with the younger generations (refer to Figure 37). This is in line with the findings of Blatteis C.M et al, whereby it was established that older generations exhibit lower body temperatures, thus feeling more thermally comfortable in warmer temperatures [115].

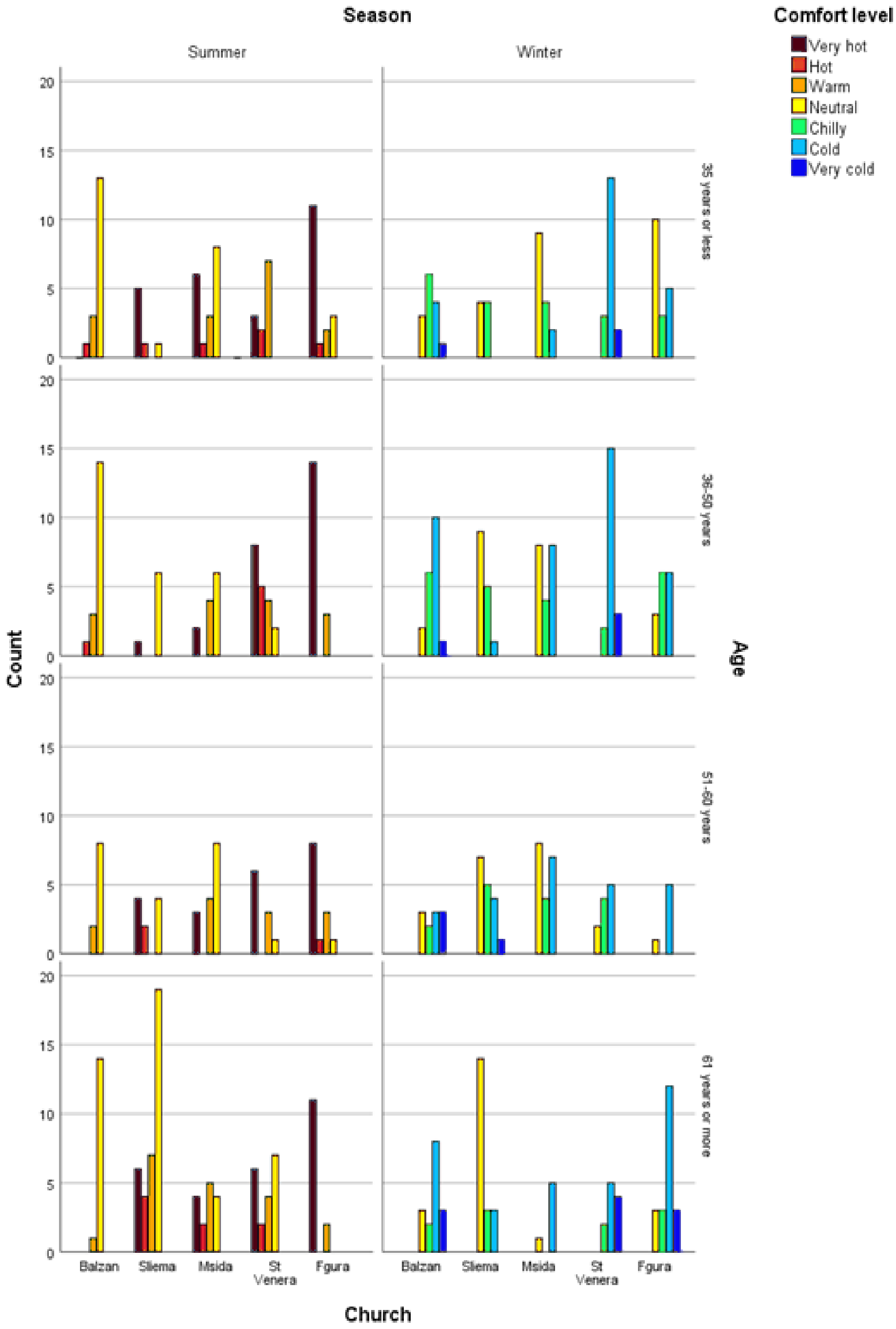


Figure 37 - Column graph representing the difference in comfort levels between the four different age groups in the different parish churches in both summer and winter.

Given that there is a significant correlation between the actual thermal comfort levels measured accordance to EN 16798-1 standard and the expected thermal comfort experienced by churchgoers in the majority of the parish churches under review, the findings of paper 2 reaffirmed the findings of paper 1. With results showing that generally baroque churches are deemed thermally comfortable according to both the EN standard and data gathered through questionnaires, the installation of ACs in baroque churches became even more questionable and the implementation of passive measures pronounced.

3.4 Scientific Article No. 3

Using DesignBuilder-EnergyPlus software, Scientific Article No. 3 Prioritising Passive Measures over Air Conditioning to Achieve Thermal Comfort in Mediterranean Baroque Churches, investigates the efficacy of selected passive measures in two free-running church buildings, namely that of Stella Maris Parish Church in Sliema and Our Lady of Mount Carmel Parish Church in Fgura. The major goal in this paper was to determine whether the implementation of passive design practices would improve the interior thermal comfort, whilst preventing the use of mechanical cooling, thus minimizing the energy consumption, and reduce carbon emissions.

For this study, the interpretation of the interior thermal comfort was measured in accordance with the same adaptive comfort model (EN 16798-1 standard) using the category 3 comfort limits. The quantification of such improvement in thermal comfort, if any, was determined through the reduction in the number of discomfort days. Moreover, the on-site data was also gathered through the continuation of the indoor and outdoor monitorisation of air temperature and relative humidity using the HOBO data loggers.

In order to assess the effect of the passive measures on the thermal comfort within the church buildings under study, a software simulation approach was adopted. The Designbuilder was the model of choice for this case. This software, which is an advanced user interface to Energy Plus, is a standard building modelling tool that gives access to all of the most frequently used simulation functions, including those for renewable energy sources, building fabric, thermal mass, glazing, and shading. Respective church building models were generated within this software and supplied with identical building envelope characterisation properties, occupancy schedules, and lighting fixtures to attain an accurate indoor environment of the true scenario. Both software models underwent a validation process to access whether the latter was attained. This was conducted by comparing the annual simulated indoor air temperature data with that measured for the particular year of the monitorisation period. In this case it was repeated for three consecutive years (2018, 2019 and 2020). In addition, the compiled weather files for the respective years were inputted in the software to enable an accurate comparison between the measured data and the simulated model for each year under consideration. The weather files were compiled using weather data from the Meteorological Office of the Malta International Airport (MIA) and solar radiation data from the Institute for Sustainable Energy of the University of Malta. The year 2019 was the optimal year providing the lowest margin of acceptable discrepancy between modelled data and actual temperatures monitored within the churches.

In this study, software modelling was used to simulate the summer design week, the summer typical week, the winter design week, and the winter typical week in 2019 for both churches under review. The design and typical weeks were automatically generated through the EnergyPlus configuration of data analysis. In this investigation, two passive measures gave rewarding results. The first was a 3mm coating of liquid white acrylic polymer paint applied to the roof, and the second was a layer of "EPS extruded polystyrene (standard)" applied in thicknesses of 5 and 10cm. Each passive measure was simulated individually to allow for comparison and evaluation of their own effectiveness and performance. Additionally, the relationship between the simulated indoor air temperature with and without PM in relation to the EN16798-1 category III comfort limits was established in each case using the adaptive comfort model, to evaluate and determine the level of comfort.

The application of the white acrylic polymer paint on the roofs proved to alleviate the indoor temperatures in both churches under study (refer to Figures 38 and 39), with its effectiveness being more pronounced during the summer period. This is attributed to the decrease in the solar absorbance at the roof surface.

The application of the EPS proved to be superior to the white acrylic polymer paint in terms of enhanced indoor comfort for the Sliema parish church. This is manifested through further decreased indoor temperatures during the summer period whilst also attaining higher indoor temperatures during the winter period thus exhibiting its beneficial performance not just for the summer period but throughout the full year. Results also established that the thickness of EPS application and the indoor temperature are not directly proportional with 50% increase in the EPS thickness exhibiting only a minor decrease in the indoor temperature. On the other hand, the white acrylic polymer paint proved to be superior to the EPS application for the Fgura parish church. This is attributed to the fact that the church, apart from having a low thermal mass, has a high percentage of glazing.

This study demonstrates that historic church buildings defeat expectations and, in general, outperform more modern church buildings. Historic church buildings were originally constructed to make advantage of passive design characteristics for internal comfort. In conclusion, as seen in Figures 38 to 41, data indicate that passive measures reduce extreme hot and low interior temperatures, creating a more pleasant environment.

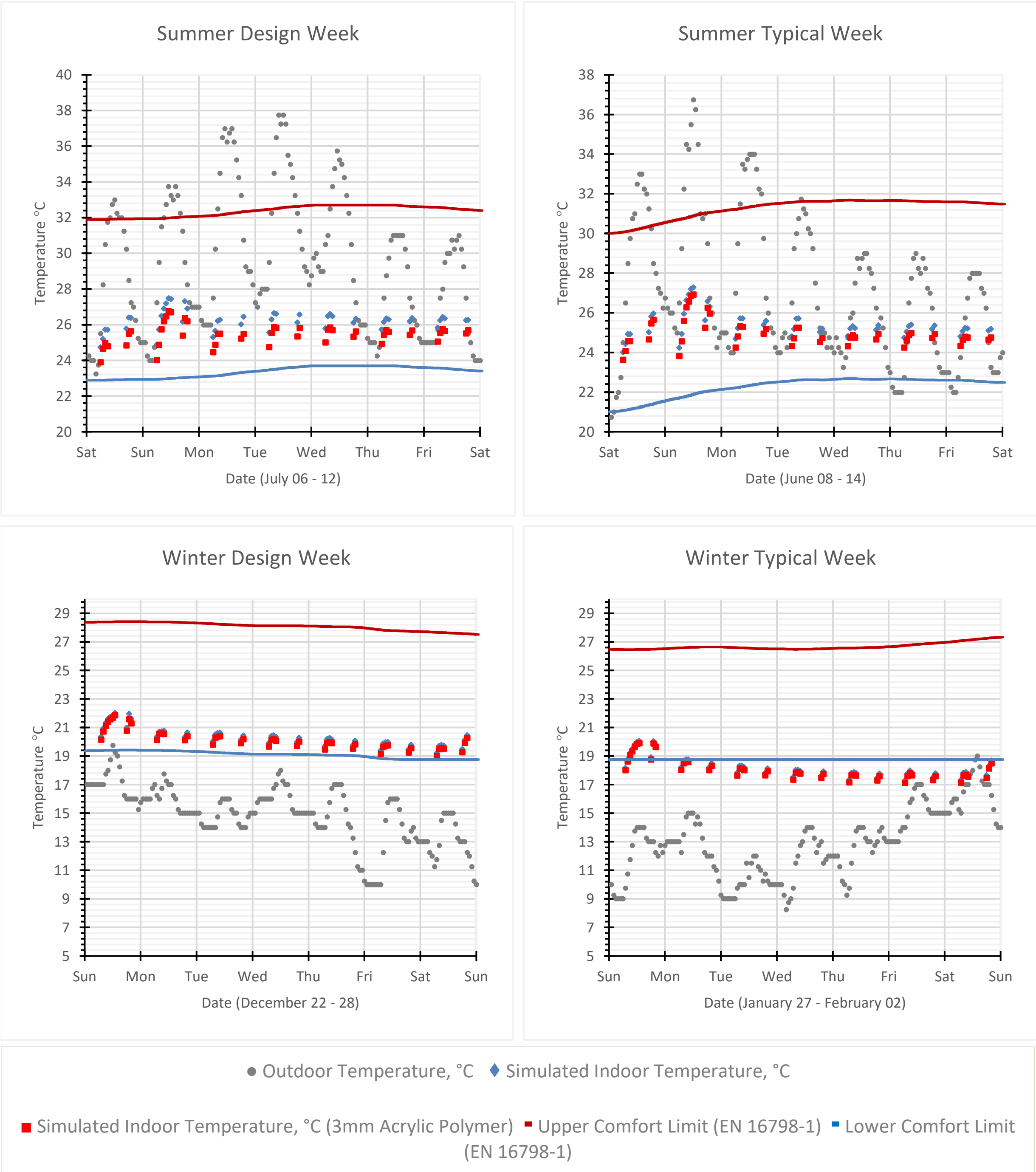


Figure 38 - Sliema Simulated Indoor Temperature including 3mm White Acrylic Polymer Paint (Occupied Hours).

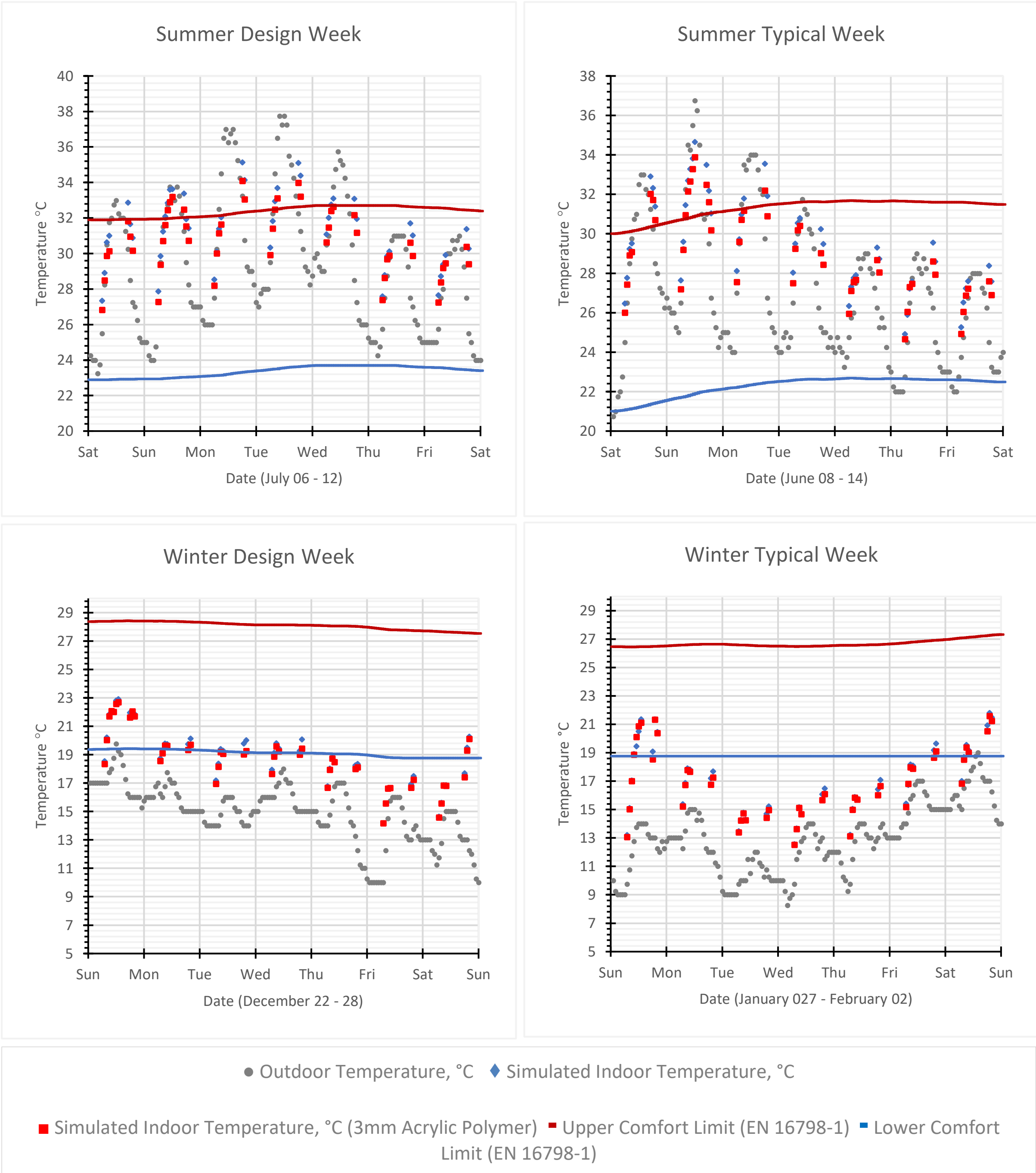


Figure 39: Fgura Simulated Indoor Temperature including 3mm White Acrylic Polymer Paint (Occupied Hours).

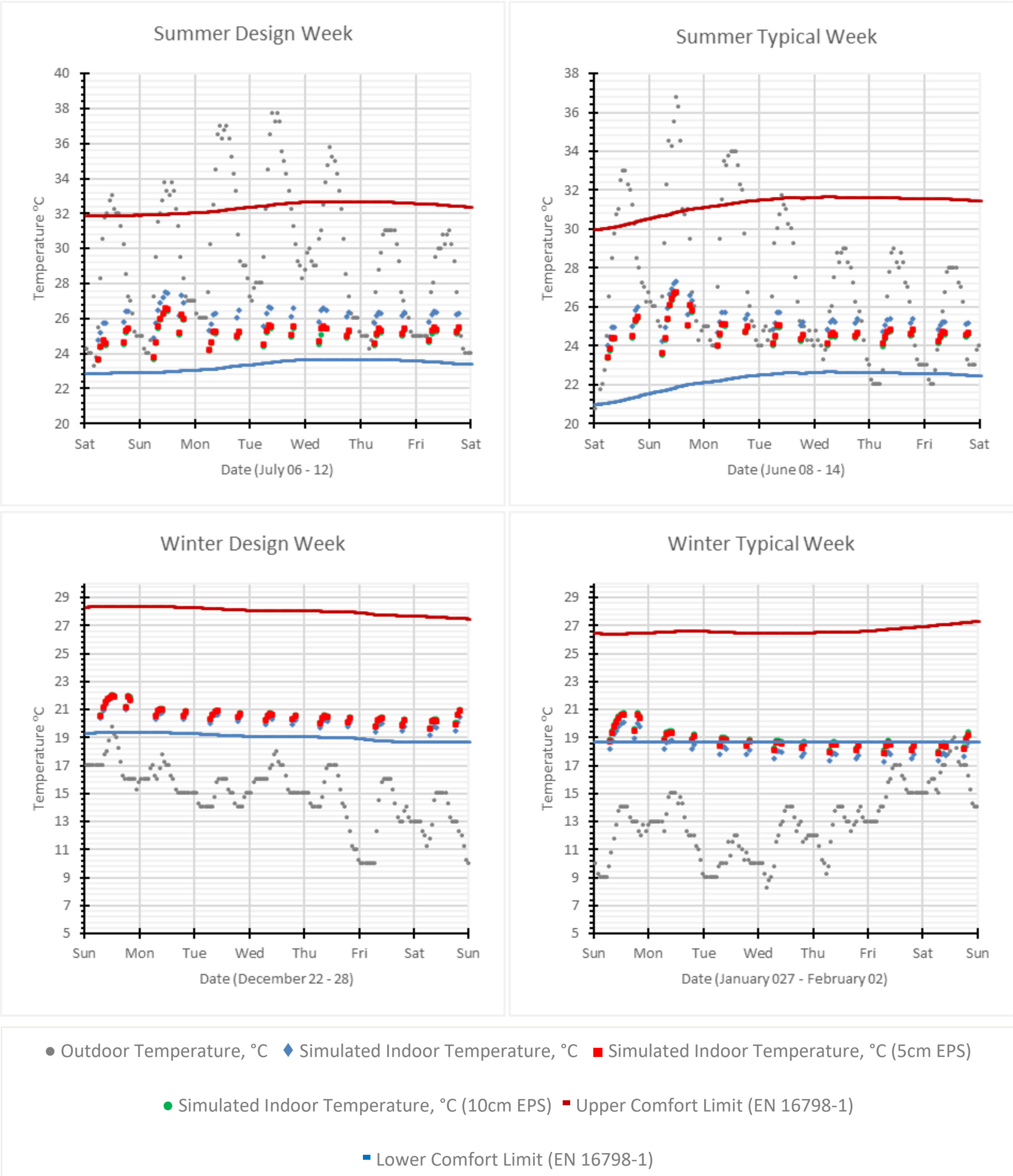


Figure 40 - Sliema Simulated Indoor Temperature including 5cm/10cm EPS Extruded Polystyrene (Occupied Hours)

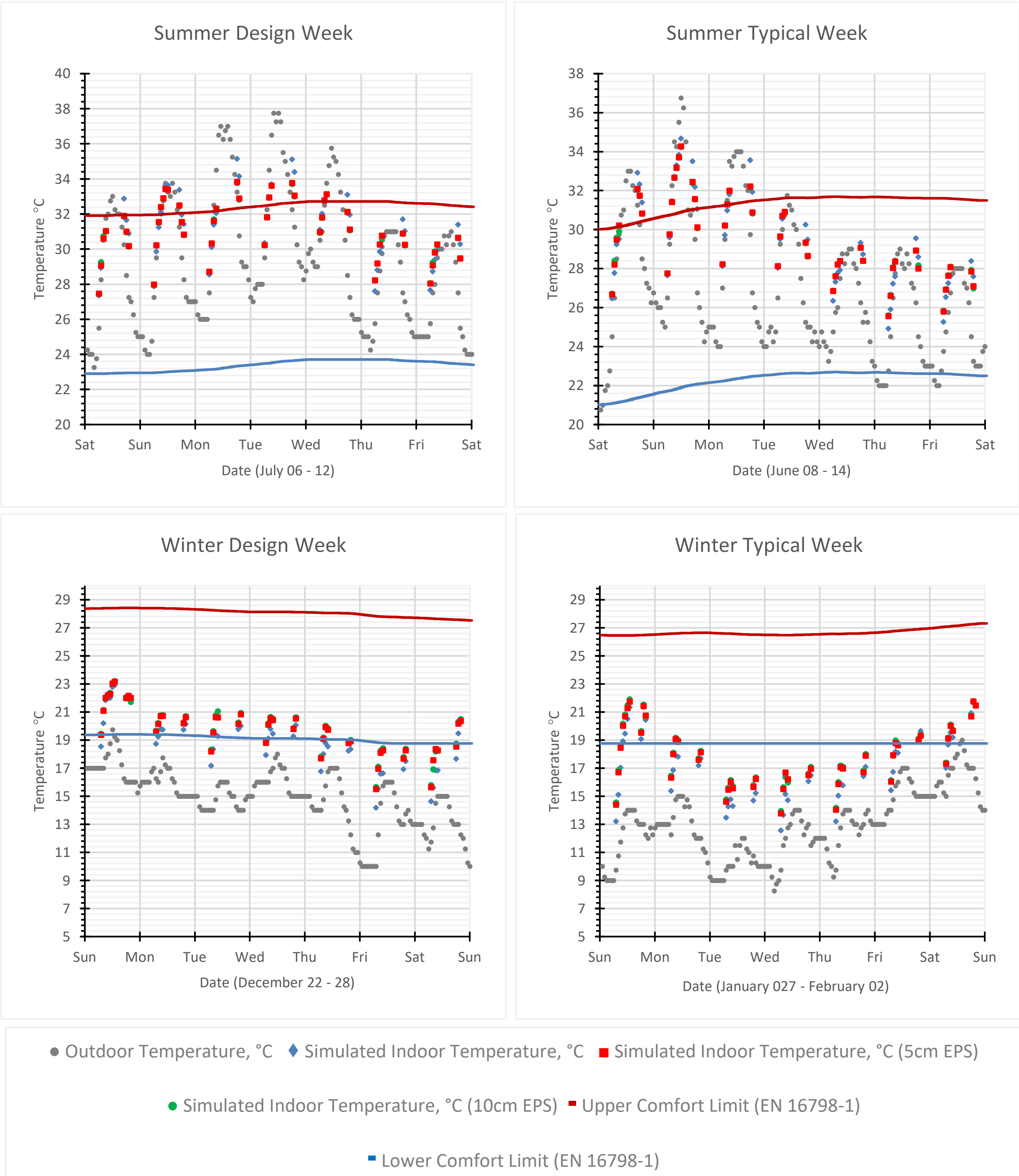


Figure 41 - Fgura Simulated Indoor Temperature including 5cm/10cm EPS Extruded Polystyrene (Occupied Hours)

CHAPTER 4: CONCLUSION AND FUTURE WORKS

4.1 Conclusion

This information provides further assurance to decision-making bodies in addressing carbon neutrality by 2050. This is in line with the 2030 National Energy and Climate Plan (NECP) which aims to achieve a sustainable infrastructure in favour of climate change abatement and mitigation. The thermal comfort demand for users in church buildings has increased exponentially over the past years and this was erroneously mitigated by quick solutions such as the introduction of heating and cooling systems, which could have detrimental effects on valuable artefacts such as paintings, frescoes and prestigious ornaments found within these buildings. Thus, prioritising passive measures as opposed to the conventional mechanical air-conditioning systems within such buildings is an important step towards safeguarding the macroclimate, whilst attaining a sustainable and comfortable indoor environment.

In conclusion, this research addressed the projected key questions in three scientific articles as follows:

Paper 1: To what extent are places of worship both traditionally and newly built conforming to indoor comfort levels in accordance with the EN16798-1 standard?

Paper 2: How do communities frequenting places of worship relate to the indoor comfort conditions for different seasons?

Paper 3: To what extent do passive building envelope measures and their prioritisation contribute towards improving the indoor building environment in places of worship and therefore avoiding the installation of mechanical air-conditioning systems?

This research highlights that modification of the indoor climate, with both passive and active measures, present complex conservation issues, and the understanding of the local limestone matrix, texture, and porosity, is imperative for informative decisions. Measures to prevent the highly fluctuating external climates alone from impacting the indoor climate is not necessarily a solution to address indoor comfort. Subjecting the building fabric and indoor climate to changes may give rise to unpredicted complications. This study shows that historic church structures outperform expectations than more modern church buildings. Historic church buildings were initially constructed to make use of passive design techniques for internal comfort. The local architectural typology was created through many years of practice with the intention of giving building inhabitants a comfortable interior space. Therefore, the heritage building typology provides enormous possibilities for lowering energy consumption, maintaining balanced environmental conditions for artifacts, and meeting occupant comfort standards. Despite this, there is a perception that churches do not offer comfortable interior environments for building occupants, and a new trend has emerged where the criteria to improve thermal comfort have been restricted to a paper exercise to determine what size air conditioner is necessary to address the cooling capacity. This, to the detriment of needless retrofits that impair the historic building's structural integrity and adorned artefacts. This study further highlights the present situation whereby when faced with the decision of implementing passive energy-efficient measures, nature is viewed as secondary while the installation of ACs is viewed as essential.

Attempts to promote thermal comfort primarily by cooling within inhabited buildings while achieving acceptable quality energy efficiency have been a key challenge on an island located within a Mediterranean environment, with scorching temperatures dominating much of the year. This study shows that considering passive measures in free-running buildings give advantageous results. It is not appropriate to prioritise occupant thermal comfort within historical and prestigious buildings using un-justified mechanical systems at the expense of jeopardising the integrity of the artefacts historical value. Though it is becoming the norm to overlook low-cost, low-energy, passive solutions for naturally ventilated structures in the pursuit of a single technical solution, this is not sustainable. The findings of this study demonstrate that passive measures may be used in churches, even though each church in Malta has distinct and unique issues. In summary:

- Implementing solar control techniques, such as painting roof surfaces with white solar-reflective paint to achieve a ‘cool roof’, can greatly reduce heat discomfort.

- Roof thermal insulation greatly enhances both indoor comfort and thermal performance.
- The use of certain PM is restricted by the architectural aesthetical values of heritage structures.
- Owing to PM, the heritage building typology has the capacity to preserve balanced indoor environmental conditions for artifacts and meet occupant comfort criteria.
- One can analyse the influence of phased exclusion of external climates and the proper humidity and temperature values required to address human comfort with a detailed understanding of local building construction techniques and building block characteristics.

Policymakers, architects, and engineers now have a greater understanding of how to put passive conservation techniques into practice that may be useful for their preventative conservation without compromising human comfort. As a result, one must promote passive control systems and, on a case-by-case basis, make the required modifications to increase Indoor Thermal Comfort.

The findings of this study are in line with the objectives proposed by the European Parliament, the Council and the European Commission in the 'Conference on the Future of Europe', in order to provide sufficient, affordable and sustainable energy [116]. It is obvious to everyone that the goals of the 2015 Paris Climate Summit cannot be achieved without significant and urgent changes in our way of life.

4.2 Future Works

Experts are warning that nowhere near enough is being done to ventilate public and private spaces across the world. Apart for thermal comfort, since the start of the COVID pandemic only a few countries have announced ventilation plans to improve indoor air quality. On the other hand, the recently published research in the British Medical Journal (BMJ), reported that people can infect each other when they are more than two metres apart [117]. In view of the above, further studies need to be taken up to improve ventilation in public buildings.

The construction methodology during the 17th to mid-18th century Baroque period entailed a roofing composition of a breathable ‘deffun’ layer consisting of various graded gravels (from coarse and large grains to smaller grains), followed by a lime layer with beaten crushed pottery (clay) powder over it, laid to falls. In view of the application of a more recent waterproofing non-breathable membrane, an in-depth study is highly recommended to analyse the long-term effect of converted breathable roofs to non-breathable applications.

Stained glass apertures have long been a traditional part of church architecture, and the window to wall ratio has drastically increased throughout the years. This to the detriment of increased direct solar radiation and heat gain. Shading will alleviate the problem in new construction, but many times retrofitting is not feasible. In light of this, further research needs to be carried out on ways and means to mitigate solar radiation where apertures are deemed to have a detrimental effect.

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APPENDICES

APPENDIX A - Complementary Paper

‘Monitoring Indoor Temperatures of Places of Worship: A First Step Towards Energy Sustainability Engineering Sustainability and Sustainable Energy’; (ESSE ’18) Conference organised by the Chamber of Engineers in collaboration with the Institute for Sustainable Energy of the University of Malta, St. Paul’s Bay, 8 May 2018, pp. 55-66, ISBN: 978-99957-853-2-1, https://www.um.edu.mt/library/oar/handle/123456789/30540

APPENDIX B - Scientific Article No. 1

‘A study of thermal comfort in naturally ventilated churches in a Mediterranean climate’; published by Energy & Buildings Journal, Volume 213, 2020, 109843, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2020.109843

APPENDIX C - Scientific Article No. 2

'Thermal Comfort in Places of Worship within a Mediterranean Climate'; published by Sustainability Journal 2021, 13, 7233, https://doi.org/10.3390/su13137233

APPENDIX D - Scientific Article No. 3

'Prioritising Passive Measures over Air Conditioning to Achieve Thermal Comfort in Mediterranean Baroque Churches" published by Sustainability Journal 2022, 14(14), 8261 https://doi.org/10.3390/su14148261

APPENDIX E - UV IV Conference Certificate

Certificate from the Coordinator of the Doctoral Program in Industrial Engineering from the University of Valladolid on successfully accomplishing IV Conference of Doctoral Students PD Industrial Engineering organized by the Academic Committee of the Doctoral Program in Industrial Engineering of the University of Valladolid, on 14 September 2017.

Escuela de Doctorado **Universidad** de **Valladolid**

El Coordinador del Programa de Doctorado en Ingeniería Industrial

de la Universidad de Valladolid

certifica que

ROBERT VELLA

ha superado la actividad formativa de carácter transversal

IV Jornada de Doctorandos PD Ingeniería Industrial

organizada por el Comité Académico del Programa de Doctorado en Ingeniería Industrial

de la Universidad de Valladolid, el día 14 de septiembre 2017, con una duración total de 10 h.

En Valladolid, a 13 de abril de 2018

APPENDIX F - Evaluation of the Academic Commission 2016-2022

Inscripción y seguimiento

Apellidos y nombre	VELLA , ROBERT
Plan	595 - Doctorado en Ingeniería Industrial
Decreto	RD 99/2011
Fecha máxima de depósito	17/05/2024

Curso académico	Descripción	Convocatoria	Evaluación	Observaciones	Fecha calificación	Documentación
2016/2017	Tutela Académica (primer año)	1	EVALUACION POSITIVA		21/09/2017	
2017/2018	Tutela Académica (segundo año)	1	EVALUACION POSITIVA	Tras examinar las Actividades y el Plan de InvestigaciÃ³n del doctorando, y a la vista de los informes de tutor y directores, se considera que dichas actividades y el plan son coherentes con el desarrollo de la tesis y con la adquisiciÃ³n de competencias, capacidades y destrezas previstas.	13/09/2018	
2018/2019	Tutela Académica (tercer año)	1	EVALUACION POSITIVA	Tras examinar las Actividades y el Plan de InvestigaciÃ³n del doctorando, y a la vista de los informes de tutor y directores, se considera que dichas actividades y el plan son coherentes con el desarrollo de la tesis y con la adquisiciÃ³n de competencias, capacidades y destrezas previstas.	12/09/2019	
2019/2020	Tutela Académica (cuarto año)	1	EVALUACION POSITIVA	Tras examinar las Actividades y el Plan de InvestigaciÃ³n del doctorando, y a la vista de los informes de tutor y directores, se considera que dichas actividades y el plan son coherentes con el desarrollo de la tesis y con la adquisiciÃ³n de competencias, capacidades y destrezas previstas.	17/09/2020	
2020/2021	Tutela Académica (quinto año)	1	EVALUACION POSITIVA	Tras examinar las Actividades y el Plan de InvestigaciÃ³n del doctorando, y a la vista de los informes de tutor y directores, se considera que dichas actividades y el plan son coherentes con el desarrollo de la tesis y con la adquisiciÃ³n de competencias, capacidades y destrezas previstas.	09/09/2021	
2021/2022	Tutela Académica (sexto año)	1	Sin calificación		-	

APPENDIX G - Main Seminars Participation

HOW TO INCREASE ENERGY EFFICIENCY IN THE MEDITERRANEAN'S BUILDINGS

IDEATION Workshop; November 2017

Climate-KIC supported by the European Institute of Innovation & Technology (EIT), an independent body of the European Union

ZEROCO2: PROMOTION OF NEAR ZERO CO2 EMISSION BUILDINGS DUE TO ENERGY USE

Interreg-Europe Project: ZeroCO2 Regional Conference; March 2018

Interreg-Europe in collaboration with the University of Malta

BUILD UP THE EUROPEAN PORTAL FOR ENERGY EFFICIENCY IN BUILDINGS

Building Sustainability Performance Seminar; June 2018

(contact@buildup.eu) - Seminar number: 849 987 080

MALTA ARCHITECTURE AND SPATIAL PLANNING

Planning for Liveable Places Conference; October 2018

Reinventing Places through Innovation Conference; November 2019

Malta Planning Authority

NEW CHALLENGES FOR GREEN BUILDINGS 2020

Technology for Business Seminar; October 2018

Malta Developers Association

NEW AND RENOVATED BUILDINGS ENERGY EFFICIENCY AND THEIR COMPLIANCE WITH TECHNICAL DOCUMENT F

The Building Envelope: M.E.E.R.E.A. Seminar; December 2018

Malta Energy Efficiency and Renewable Energies Association

SUSTAINABLE REGENERATION OF BUILT HERITAGE

A case study of the Presidential Palace - Workshop; April 2018 & January 2019

University of Bath in collaboration with the University of Malta

ENSURING AND SAFEGUARDING A HEALTH LIVING ENVIRONMENT

Looking ahead to 2050 Conference; March 2019

The Ministry for the Environment, Sustainable Development and Climate Change

RENOVATING HISTORIC BUILDINGS TOWARDS ZERO ENERGY

IEA SHC Solar Academy Seminar; January 2020

Solar Heating and Cooling Solar Academy in collaboration with the International Solar Energy Society

CHANGING THE GAME FOR A SUSTAINABLE BUILT ENVIRONMENT

Sustainable cities require Sustainable Solutions Seminar; May 2020

The Malta Group of Professional Engineering Institutions (MGPEI)

APPENDIX H - Curriculum Vitae

PERSONAL DETAILS

Date of birth
05/05/1969

Nationality
Maltese

ABOUT ME

Awards:

- Architectural Heritage Conservation Award
- Special Commendation as part of the Malta Architect Awards (2016)
- European Award for Architectural Heritage Intervention by the Association of Architects for the Defence and Intervention in Architectural Heritage (AADIPA0

AFFILIATIONS

Warrant No. 741

- Architects' Council of Europe (ACE)
- Commonwealth Architects Association (CAA)
- Union of Mediterranean Architects (UMAR)
- International Union of Architects (UIA)
- European Forum for Architectural Policies (EFAP)
- Malta Energy Efficiency and Renawable Energies Association (M.E.E.R.E.A.)

ROBERT VELLA

ARCHITECT & CIVIL ENGINEER EN (USA), B.E. & A. (HONS), A. & C.E.

RCV Architects 126/2 Independence Avenue , Mosta, MST9024, Malta

+356 27327865, +356 99804481

robertvella@rcvachitects.mt

WORK EXPERIENCE

PRIVATE ARCHITECTURAL PRACTICE
Oct 2016 - Present

Architect & Civil Engineer

Col. Perit Vella set up his own architectural firm under the name of RCV Architects with a design studio based on Independence Avenue in Mosta. Throughout his private practice in Architecture and Civil Engineering, between 2016 and 2022, Perit Vella was responsible for over 320 permitted applications, issuance of their specifications, direction, and supervision of works in terms of the Civil Code of the Laws of Malta. Furthermore, he was commissioned as site technical officer on various projects and tasked with project management to oversee through challenging projects, achieving pre-determined goals within strict timelines. Some of the most prominent works are listed below.

ARMED FORCES OF MALTA (AFM)
Feb 1989 - Oct 2016

Army Engineer Officer

Following a successful military career in both command and staff appointments, with honors achieved both locally and abroad, Col. Perit Robert Vella is decorated with the long and efficient service medal, awarded for long and meritorious service with the Armed Forces of Malta (AFM). Having retired from uniformed service as a Senior Engineer Officer in the rank of Colonel with 27 years of distinguished service, Col. Perit Vella now pursue a career as self-employed in the field of Architecture and Civil Engineering.

After joining the army through the officer cadet scheme in February 1989, he was commissioned at the Royal Military Academy Sandhurst in the United Kingdom. Following graduation he specialised in the field of military engineering, initially at 'Scuola del Genio' in Rome, Italy, and later, successfully completed and achieved the International Distinguished Graduate Award for exceeding course standards in the Army Engineer Officer Advanced Course at the US Engineer Center in Fort Leonard Wood, Missouri, USA. Throughout his service Col. Perit Vella further specialised in International Humanitarian Law, International Affairs, and as a United Nations Military Observer in Germany. He represented the Maltese Government in various fora, namely the 5 + 5 Defence Initiative to promote security in the Western Mediterranean.

Col. Perit Vella's organisational and managerial skills have reached their epitome as Commanding Officer 3 Regiment with over 300 men under his command and later on in his career as Head Property Management and Development Branch within HQ AFM. With the implementation of the EU External Borders Fund (EBF) Programme 2007-2013, Col. Perit Vella successfully served as Project Leader, Architect and Civil Engineer in four consecutive EU Infrastructural Projects and have overseen over others.

CORE COMPETENCIES

- Project Architect and Civil Engineer
- Project Management
- Site Technical Supervision
- Civil Engineering Design
- Cost Estimating and Surveying
- Structural Analysis
- Interior Design
- Restoration and Conservation

LANGUAGES

ENGLISH

MALTESE

ITALIAN

LINKS

Website :
http://www.instagram.com/rcvarchitects/

EDUCATION

UNIVERSITY OF VALLADOLID
Spain

Doctorate in Industrial Engineering
01/01/2017 - Present

UNIVERSITY OF MALTA
Malta, G.C.

Degree – Bachelors in Architecture and Civil Engineering (Honours)
01/10/2005 – 29/09/2009

US ARMY ENGINEERING SCHOOL
FLW Missouri - USA

Degree in Military Engineering (Distinguished Honours)
01/01/2003 – 17/09/2003

BUILDING REGULATION OFFICE
Malta, G.C.

Energy Performance Assessor of Buildings (Non-Dwellings)
23/05/2016

KEY PROJECTS

Hal Luqa/Hal Far
Mar 2014 - Jun 2016

Armed Forces of Malta

AFM Ground Support Facilities at Air Wing in Luqa (EBF2010/11/12), including the construction of three aircraft hangars, and at Maritime Squadron in Haywharf (EBF2012/13) to construct a Rapid Deployment Launching Facility.
- Estimated Project Cost: 20M
- Role: Project Leader, Project Manager, Architect & Civil Engineer

Hal Luqa
Oct 2021 - Apr 2023

Social Housing Project

Construction of a new residential housing block consisting of 46 social housing units in two three storey blocks with underlying garages for 50 car spaces at basement level.
- Estimated Construction Cost: 2.5M
- Role: Site Technical Officer, Architect & Civil Engineer.

Paola
Apr 2019 - Nov 2023

Primary Healthcare Southern Regional Hub

Construction of a new 5-story hospital over 18,500m2 built-up area.
- Estimated Construction Cost: 25M
- Role: Architect & Civil Engineer

Valletta
Apr 2021 - May 2023

Fast Ferry Passenger Terminal

Construction of a Passenger Terminal and Quay extension seaward for the operation of high-speed passenger ferries linking Xatt il-Barriera off Ta' Liesse, in Grand Harbour Valletta to Mgarr, Gozo.
- Estimated Project Cost: 6.5M
- Role: Architect & Civil Engineer

Tigne, Sliema
Mar 2022 - Aug 2023

Q3 Residential High-Rise Tower

Construction of a 17-storey tower with condominium ancillary facilities at ground floor, and 63 luxury residential apartments.
• https://lom-architecture.com/work/tigne-point
• Estimated Construction Cost: 12M
• Role: Architect & Civil Engineer

Valletta
Jan 2021 - Apr 2023

St John's Co-Cathedral Museum Project

Consolidation and construction works, including the rehabilitation of the existing areas within the basement level, the restoration of the Bartolott Crypt, the construction of a new Tapestry Chamber, and the construction of the Caravaggio Museum (ERDF.PA5.0109).
• Estimated Construciton Cost: 5M
• Role: Site Technical Officer

Valletta
May 2020 - Mar 2024

Palazzo Romegas, Boutique Hotel Project

Extensive Restoration works to convert dilapidated 18th Century palazzo into a 23-room boutique hotel, including restaurant at ground floor, vertical extension, pool deck and bar at roof level.
• Estimated Construction Cost: 4M
• Role: Site Technical Officer

Sliema
Mar 2022 - May 2023

Regina Hotel

Construction of a five-star hotel, with ancillary facilities, retail floor space and car parking facilities.
• Estimated Construction Cost: 10M
• Role: Site Technical Officer

Tigne, Sliema
Jun 2019 - Jun 2020

Fortina Project

Construction of a mixed-use development to include a 183-room 5-star hotel, 109 designer luxury apartments over fifteen floors, public open space, a sprawling retail area over two levels, an office block, parking facilities, spa, gym, lido, specialised dining areas /restaurants and conference facilities.
• Estimated Construciton Cost: 17M
• Role: Site Technical Officer

Qawra, St Paul's Bay
Feb 2020 - Jun 2022

Qawra Palace Hotel Extension Project

Construction of 2 additional floors on existing hotel, and lateral extension of hotel to accommodate additional 210 rooms, car parking facilities, multipurpose hall and restaurant facilities.
• Estimated Construction Cost: 8M
• Role: Site Technical Officer

Hal Far
Nov 2021 - Sep 2022

Malta Recycling Plant (BCRS)

Construction of a recycling plant and 331 reverse vending machines across Malta and Gozo, for the collection and recycling of single-use beverage containers.
• Estimated Project Cost: 17.2M
• Role: Project Manager