Effects of future climate change on the preservation of artworks, thermal comfort and energy consumption in historic buildings

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ABSTRACT

Climate change will affect the indoor temperature of historic buildings, impacting the preservation of artworks and the thermal comfort of users, and possibly leading to increased energy consumption. This research proposes a method for assessing the impact of climate change on the preservation of artworks, thermal comfort, and energy consumption. An experimental method was followed, combining analytical formulations, on-site measurements, and HVAC systems in order to identify the adequate hygrothermal parameters for historic buildings. The climate change scenario predicted for 2050 was based on projected temperature variation. The case studies were Baroque churches, historic buildings located in the south of Europe. Data obtained from a monitoring campaign carried out in these churches was used to validate dynamic simulation models. The churches analysed showed an increase in cooling demand and a decrease in heating demand. Furthermore, in order to ensure human comfort and the preservation of artworks, it was necessary to implement active systems in operation for 12-hour periods. These results suggest an energy overconsumption, as the energy consumption for human comfort and artwork preservation was 50% higher than the energy consumption of active systems for the preservation of valuable historic objects. In addition, the annual energy consumption decreases for future scenarios for 2050 in the case of artwork preservation and thermal comfort, but increases by almost 15% for the preservation of works of art due to higher level relative humidity.

Before historic buildings can be adapted, it is essential to understand the influence of the future climate on their design, construction, and environmental conditions.

KEYWORDS

Climate Change, Heritage, Artwork preservation, Simulation, Thermal comfort

1. Introduction

Historic buildings were originally designed taking into consideration local conditions and environment. However, technicians do not take this, or the properties and hygrothermal behaviour of the materials, into account. To overcome this problem, dynamic simulation tools are currently being used in historical buildings to investigate hygrothermal performance to gain an in-depth understanding of their microclimate and to propose strategies for the preservation of works of art and thermal comfort [1]. There are certain limitations to the use of these tools in historic buildings, including the lack of information on the input parameters and their calculation limits for describing the specific geometric characteristics [2].

In Europe, specifically Italy, leading studies show the feasibility of maintaining the building's heritage values, while achieving significant improvements in energy efficiency and thermal comfort by using these tools. [3]. Even so, there is a wide range of solutions determined by the location and specific constructive features of each building. The interior microclimate and energy performance analyses of these spaces require personalized methodologies. [4].

Some notable studies were carried out at the Palazzo Gallenga Stuart, in the city centre of Perugia, Italy, applying a methodology to improve the sustainability of the building, based on the integration of renewable technologies. The implementation of cold tiles and geothermal heat pump systems can lead to savings of up to 67% in current energy consumption [5]. Another study, in a state-of-the-art museum in Amsterdam, the Netherlands, shows savings of around 77% thanks to the use of different slogan strategies, considering degradation damage and thermal comfort in their research [6].

At times the interventions proposed in these cases cannot be carried out due to the heritage value of the architectural elements or the visual impact upon it. Currently, this is one of the main challenges in historic buildings, and it has been observed that there is considerable potential for a reduction in energy consumption, a although in some countries this is still perceived as a cultural risk, as the preservation principles that regulate their treatment could interfere with renovation plans [7].

In the last decade, the issue of energy efficiency in historic buildings has become increasingly important given that almost a quarter of the existing building stock is made up of historic buildings and there is a need to improve their energy efficiency. [8]. The world´s leading climate scientists have warned that there are just 10 years left to ensure global warming is kept below a maximum of 1.5 ºC. Beyond this point, even half a degree will significantly worsen the risk of drought, floods, extreme heat, and poverty for hundreds of millions of people [9]. A 0.5-5 ºC increase in temperature is estimated for the period 2081-2100 [10]. In the case of southern Spain, temperatures will increase noticeably during the summer, as some studies illustrate [11].

Climate change is one of the most critical global challenges of our time and models are currently being developed for future climate projections [12]. For example, as part of the Climate for Culture project studies were carried out to calculate the impact of climate change for the indoor ambient of European historic buildings in Italy, Germany, England, Romania, Sweden, and the Netherlands [13]. Several types of historic buildings from different periods in different climate zones with different uses were researched. Some of these studies showed an increase in temperatures which in turn increased cooling energy demand and reduced heating energy demand [14].

Although these investigations yield data and solutions applicable to other buildings, buildings of great importance should be subject to detailed case studies that provide insight into their state of preservation, indoor climatic conditions, and requirements for preventive preservation strategies. Crucially, climate change will affect indoor comfort conditions, which is problematic as discomfort conditions are currently found in most historic buildings [15]. Nowadays, most churches are equipped to improve thermal comfort and the preservation of artworks as well as incorporating new requirements. However, the conflicting needs of these objectives mean that the balance between preservation, occupant comfort, and energy efficiency is hard to strike [16].

The current literature includes very few studies on the effects of climate change on the environmental conditioning of historic buildings [6], although numerous studies analyse the consequences of climate change on new constructions [17]. Most of these studies are linked to the consequences of increased rainfall and rising sea levels and analyse the damage caused to movable heritage by increased environmental humidity, especially in northern European countries [14].

European legislation is promoting the use of renewable energy, the regeneration of historic buildings, research on energy efficiency, and the reduction of CO_2 emissions [18]. However, historic buildings are exempt from this legislation and consequently these energy constraints do not currently apply to them. These spaces are characterized by large volumes of air and construction systems with high thermal inertia, so that in the not-too-distant future, it will be necessary to incorporate renewable technologies to improve indoor environmental conditions.

Although the main factors causing extensive damage to historic built environments are temperature increase and relative and absolute humidity, these factors cannot be attributed solely to climate change [1]. It is important to determine the impact of these threats to artworks and to develop suitable preservation strategies. Equally, the annual 80% increase in demand observed in historic buildings is further proof of the pressing need for strategies for improving energy efficiency in buildings [5].

While the studies mentioned above focused on energy consumption and the preservation of works of art, thermal comfort will also be evaluated in this case.

The objective of this study is to propose a method to evaluate the impact of climate change inside religious historical spaces and its impact on thermal comfort, the preservation of artworks, and energy consumption.This analysis focuses on the environmental consequences of the 2050 climate change scenario. This research was developed in various phases, using monitoring and simulation models to assess and quantify the environmental parameters of these historic buildings, taking into consideration the combined implementation of various environmental techniques - heating, ventilation and air conditioning (HVAC).

The document is organized as follows: Section 2 describes the methodology, case studies, and simulation models. Section 3 provides the results and Section 4 presents a discussion with conclusions.

2. Methodology

The methodology of this research, based on on-site experimental methods combining on-site measurements and computer-simulated analytical formulations to predict the indoor environment of churches, is presented in this section. The on-site measurements are used to generate simulation models for real buildings, which are then validated (See Appendix A) .

This method was applied to several churches, most of them declared Asset of Cultural Interest and covered by Spanish Law 14/2007 of November 26 on the Historic heritage of Andalusia [19]. As no work is therefore allowed on the skins or elements of these buildings, active techniques to guarantee the preservation of artworks and comfort conditions were studied.

2.1 Case study buildings

The churches of St. Francis of Assisi (SF), St. Merced (M) and St. Victoria (V) are located in the province of Seville, in southern Spain, in a Mediterranean climate. These 16th- and 17th-century religious spaces are classed as Assets of Cultural Interest (Figure. 1).

Figure 1. Floor plan of churches 1) St. Francis of Assisi 2) St. Merced 3) St. Victoria

These churches present a single rectangular nave, although a Latin cross plan is found in the case of the church of St Merced. The main building materials are masonry and brick, with single-glazed windows. The thick walls (1-1.20 m) provide high thermal mass, and Figure 2 shows the thermal transmittance values of the building envelope. These historic buildings house a wide range of artworks, including sculptures and wooden altarpieces.

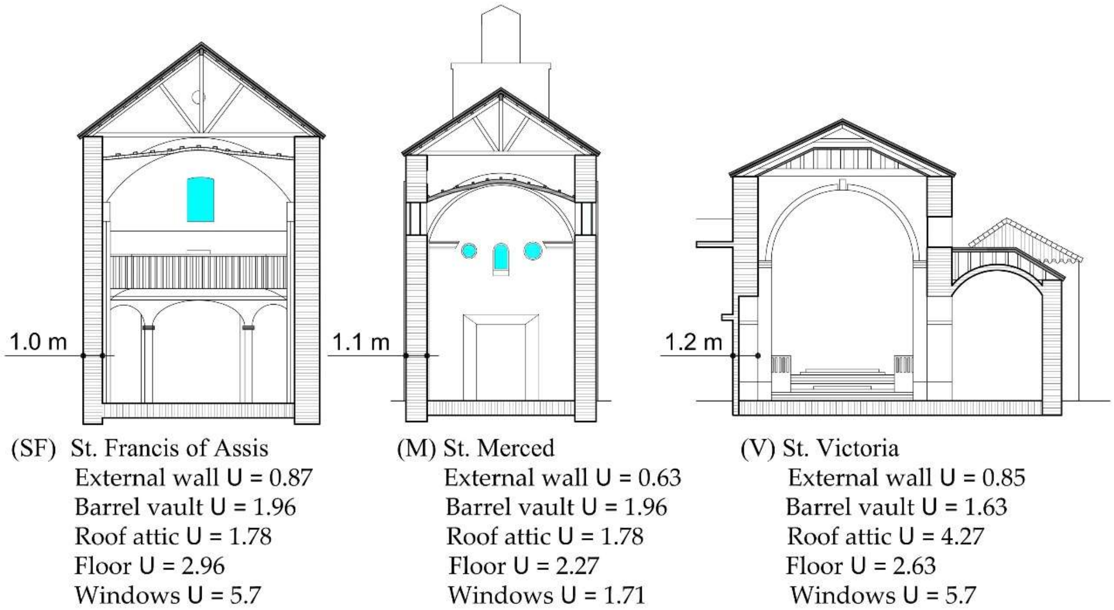

Figure 2. Physical properties of the buildings. Thermal transmittance *U (*W /m^2 K)

2.2 Measurements and computational modelling

USB data logger sensors were used to measure simultaneous parameters such as temperature (T), relative humidity (RH), and absolute humidity (AH). These measurements were carried out in the churches for all of 2018. The logger measures air temperature in a range of -35 to 80 ºC with an accuracy of ±3 ºC and resolution of 0.03 ºC. Relative humidity is in a range of 0-100% and accuracy is ±2%, with a resolution of 0.05%. These loggers were placed at the best possible location avoiding the influence of radiation sources, air flow through door openings, and loss through external walls or the barrel vault. Sensors were placed on the southeast and southwest walls at the height of a seated person (1.10 m) and at a height of 8 m in order to observe thermal stratification. Measurements for outdoor wind, global radiation, cloud cover, T, RH, and pressure were obtained from a meteorological station near the churches.

DesignBuilder Version 6.1.3.008 [20] was used to generate simulation models reproducing the exterior, interior, materials, and constructive details of the churches (Table 1) and to simulate indoor environmental conditions. This program uses the Energyplus 8.9 calculation engine, developed by the US Department of Energy [21], and Matlab version 2017 [22] was used to evaluate PMV (Predicted Mean Vote) and PPD (Predicted percentage of dissatisfied) results following Fanger [23] and current regulations. In this case, clothing insulation was assumed to be outerwear worn indoors.

The monitored data for this one-year period were used to validate the simulation models (See Appendix A). The on-site results and simulation model values were compared and evaluated using statistical measurement indicators, following the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 14-2014 [24] Hourly Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Square Error (CV(RMSE) [25].

The model validated in this research was used to evaluate artwork preservation, human comfort, and energy consumption under the climate conditions predicted for the year 2050. The original climate data file was modified taking into account climate change for the year 2050 and the result was compared with the current situation. CCWorldWeatherGen software created by researchers at the University of Southampton was used to modify climate data [26]. The scenario selected for this research was A2 as it was the most hostile, according to the Intergovernmental Panel on Climate Change (IPCC) Hadley Center Coupled Model Version 3 (HadCM3) [11]. Figure 3 shows a comparison of the average hourly indoor temperature and average hourly relative humidity of the church of St. Francis of Assisi in 2018 and 2050.

The average temperature increases by between 1ºC in the coldest months and 3ºC in the hottest months. As expected, the average relative humidity in the hottest months mostly falls by around 5-10%, but increases in the coldest months by around 3-5%.

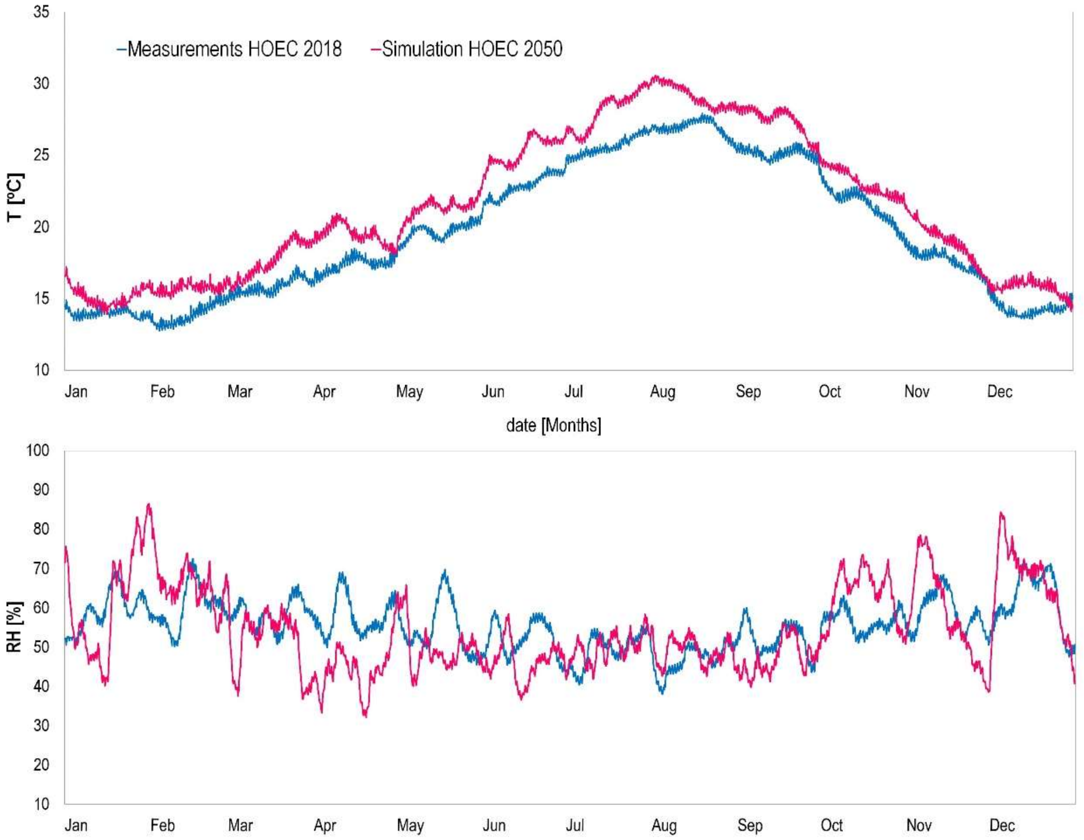

Figure 3. Church of St. Francis of Assisi in Original environmental conditions (HOEC) 2018 and in HOEC 2050 a) Comparison of average hourly indoor Temperatures b) Comparison of average hourly indoor Relative Humidity.

These models were used to simulate environmental conditioning systems (Table 1). The consequences of environmental conditioning on preservation, thermal comfort, and energy consumption were evaluated for HOEC 2018 and HOEC 2050 scenarios, and the results compared.

Mechanical and biological deterioration were evaluated for the preservation of artworks. Mechanical deterioration is linked to thermal expansion in inorganic materials or to the amount of water usually absorbed by organic materials. When the environment fluctuates, these changes result from variations in relative humidity and, to a lesser extent, temperature. According to ASHRAE [27] this occurs when the temperature increase (ΔT) is higher than 2 ºC or when the relative humidity increase (ΔRH) is higher than 10%, according to EN 15757 [28]

In the case of biodeterioration, air temperature and relative humidity ranges were established when T and RH were in the growth level for the analysis of biological degradation. T>20 °C and RH > 65% can encourage the appearance of insects [29].

Finally, EN-ISO 7730 was applied to determine the human comfort range [23]. A thermal comfort limitation was present with a (PMV) between +1 and -1, a range from neutral sensation to slightly cool.

This research studies different active systems with a performance coefficient (COP=3.5) to improve environmental conditions in summer and winter. For radiant flooring and radiators a condensing boiler with a performance coefficient of 109% was used. Table 1 shows the different systems considered for the churches.

Table 1. Study hypotheses (H). HOEC, HVAC, Air handling unit (AHU).

HYPOTHESIS	Description	CONTROL	
		T	RH
HOEC 2018	Original environmental conditions 2018	NO	NO
HOEC 2050	Original environmental conditions 2050	NO	NO
Active (HVAC)	H1: AHU (heating + cooling) +ventilation + humidifier Fan component with variable volume, a DX cooling coil, a heating coil hot water (boiler provides hot water and electric steam humidifier)	YES	YES
	H2: AHU (heating + cooling) + ventilation + humidifier + radiators (heating) Fan component with variable volume, a DX cooling coil, a heating coil hot water (boiler provides hot water), electric steam humidifier and hot water convector (radiators).	YES	YES
	H3: AHU (heating +cooling) + ventilation + humidifier + radiant flooring (heating) Fan component with variable volume, a DX cooling coil, a heating coil hot water (boiler provides hot water), electric steam humidifier) and heated floor (hot water is circulated through the floor surfaces of the zone) (radiant flooring).	YES	YES
	H4: Ventilation + humidifier + dehumidification Fan component and humidifier	NO	YES

The hypothesis of original environmental conditions refers to current conditions in the church in the year 2018 and future environmental conditions for the year 2050. H4 (Ventilation + humidifier + dehumidification) was studied to compare the results of the active techniques used for the preservation of artworks and thermal comfort (H1, H2, and H3) and those only used for the preservation of heritage (H4).

HVAC systems with 12-hour operation modes (daytime) were simulated as previous studies[30] considered this to be the best option for thermal comfort, preservation, and energy consumption.

The active systems (HVAC) were programmed to reach adequate indoor conditions both for the preservation of artworks and to ensure human comfort. The indoor conditions to guarantee thermal comfort for use of energy and people are established in the current Regulations on Thermal Installations in Buildings (RTIB) [31]. The legislation for ensuring preservation is included in EN-15759-1 [32], EN- 15758 [33] and ASHRAE [27] (See Table 2 and table 3)

Table 2. Conditions of indoor design

Thermal comfort (RTIB)	T	RH
Winter	21 -23ºC	40-50%
Summer	23- 25 ° C	45-60%
Preservation		
Winter	10-20 ° C	30-65%
Summer	20-30 ° C	30-60%

Table 3: T, RH values established for the active techniques

Autumn	Winter	Spring	Summer
23 ºC	20 ºC	23 ºC	25 ºC
45-65%	45-65%	45-65%	45-65%

3. Results and discussion

The three churches were simulated for different environmental conditioning strategies and under HOEC 2018 and HOEC 2050. The results obtained in this study are shown below in various sections. Section 3.1 shows the analysis of weather data for 2018 and 2050, Section 3.2 the results of biological degradation, Section 3.3 Mechanical degradation, Section 3.4 Thermal comfort, and finally, Section 3.5 the HVAC energy consumption results.

3.1 Weather data

The results on the consequences of climate change can be seen in figure 4, with a considerable variation in temperature. Average temperature increases to 21 ºC, with a minimum temperature of -0.6ºC in March and a maximum temperature of 49 ºC in July. In the case of outdoor relative humidity, the values decrease by around 4-13% in the hottest months and 1-3% in the coldest months. Relative humidity increases by around 5% only in the months of October and February compared to the current situation.

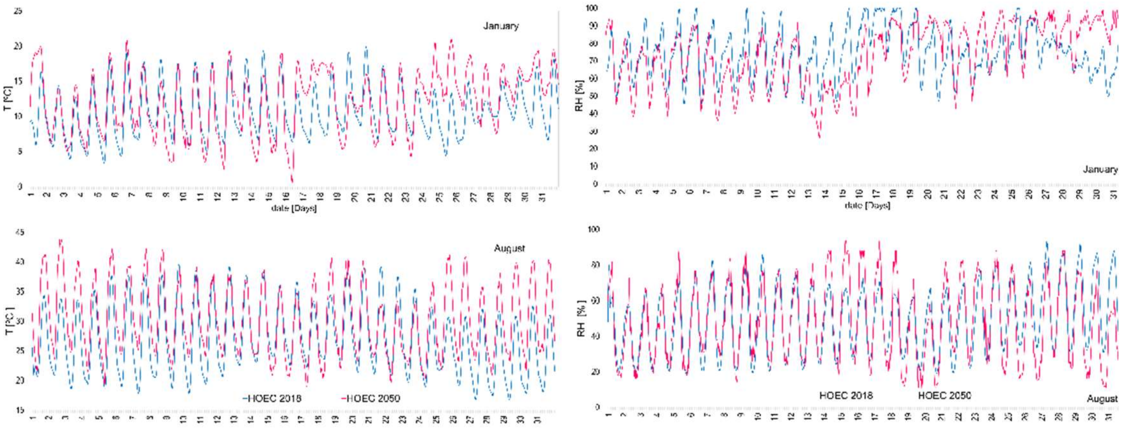

Figure 4. Climate values for outdoor temperature and outdoor relative humidity

in HOEC 2018 and HOEC 2050

This increase in temperature leads to higher energy consumption in summer, but this consumption decreases in winter.

Temperature values were studied to establish the indoor temperature of the spaces analysed as seen in table 3.

Figure 5 shows the quartiles, median, maximum, and minimum for the average operative temperature (OT) data in different seasons contemplating both HOEC 2018 and HOEC 2050. These data show a dispersion of temperature values with respect to the median during summer and autumn, and a lower dispersion for temperature values in winter and spring. An increase in temperature is observed in HOEC 2050.

According to these data, the difference in the median average OT of HOEC 2018 with respect to the values according to regulatory requirements (Table 3) is 6ºC in winter and spring and 1ºC in autumn. In the case of HOEC 2050, this difference drops to 4ºC in winter and spring, but increases to 3ºC in summer. The median average OT is 28ºC

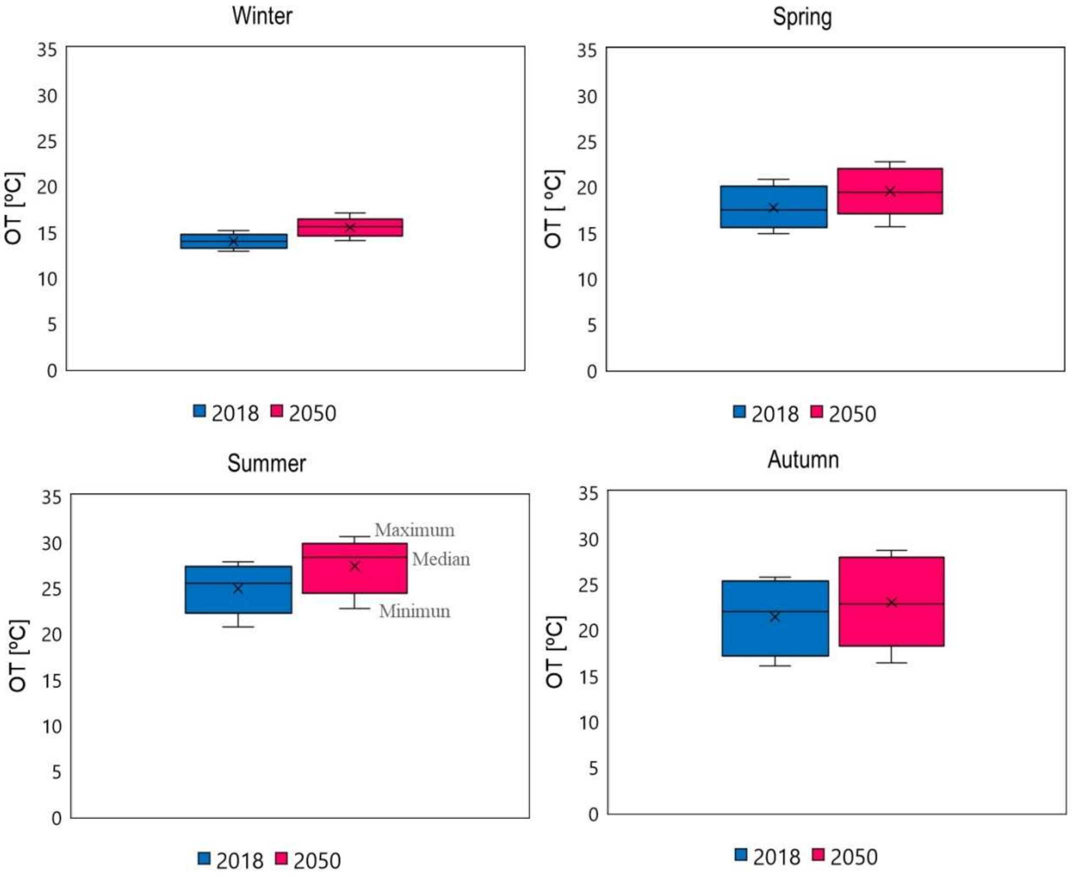

Figure 5. Average operative temperature HOEC 2018 (blue) and HOEC 2050 (pink). The quartile, median, maximum, and minimum temperature points divide sorted datasets into four equal groups (by temperature data count), each representing a fourth of the temperature data distributed sample.

Below are the results obtained from the heat balance of the churches for HOEC 2018 and HOEC 2050. In this case, the floor and walls present the highest values, with gains increasing noticeably in the summer of 2050. In summer, HOEC 2050 will increase floor losses by 50-60% and wall gains by 60-70%. (See Figure 6). Likewise, it is important to analyse why the main losses occur through the floors, followed by walls and cover. Previous studies have shown that the use of passive techniques such as the application of insulation to floors, walls and roofs did not benefit the preservation of works of art or thermal comfort. In this case therefore, as previously mentioned, only active conditioning techniques [30] are studied. Furthermore, the current protected status of the churches meant that actions on their roof or walls were not possible. This is a decisive factor when choosing the types of active systems, in this case underfloor heating, radiators and AHU.

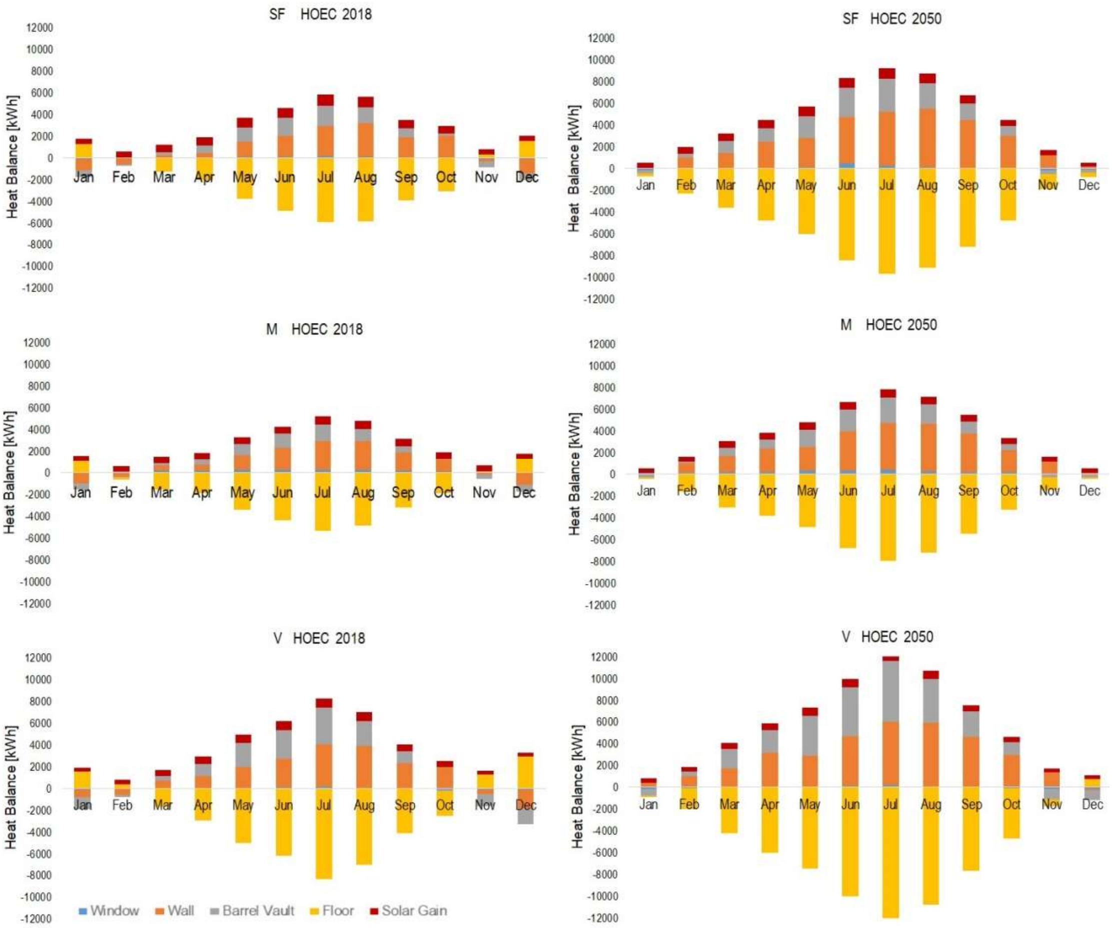

Figure 6. Heat Balance (kWh) in HOEC 2018 and HOEC 2050 (SF, M, V)

3.2 Biological degradation

In order to establish biological degradation, the hygrothermal conditions of the unheated religious space for HOEC 2018 and 2050 were evaluated to ascertain whether they encourage biological degradation. No risk of biological degradation exists when temperature values are 10-20 °C and relative humidity is below 65%. There is a low risk of biological degradation with temperature values of 10-20 °C and relative humidity above 65% or temperature above 20 °C and RH below 65%. However, this risk is high with temperatures above 20 °C and relative humidity above 65% [29]. Table 4 presents the time percentage for each situation and strategy.

In warmer months, such as in spring and summer, HOEC 2018 shows a high risk 25-30% of the time and 5-12% of the time respectively. The scenario for HOEC 2050 presents higher biological deterioration in autumn 12- 27% of the time, although the hygrothermal conditions are excellent for preservation throughout the year.

Table 4. Time percentage with risk of biological degeneration in HOEC 2018 and HOEC 2050, H1-H4 Active (HVAC). A (Autumn), W (Winter), Sp (Spring), S (Summer)

		HOEC 2018			HOEC 2050			H1-H4
SEASON	CHURC	T 10-20 ºC RH≤65%	T 10-20ºC RH≥65% T≥20ºC RH≤65%	T≥20 ºC RH≥65%	T 10-20 ºC RH≤65%	T 10-20ºC RH≥65% T≥20ºC RH≤65%	T≥20 ºC ºRH≥65%	
		NO RISK	LOW	HIGH	NO RISK	LOW	HIGH	NO RISK
A	SF	19%	80%	**15%**	70%	6%	**24%**	100%

	M	24%	74%	2%	88%	0%	**12%**	100%
	V	14%	81%	5%	60%	13%	**27%**	100%
W	SF	23%	77%	0%	58%	40%	2%	100%
	M	25%	75%	0%	52%	46%	2%	100%
	V	13%	87%	0%	63%	34%	3%	100%
Sp	SF	15%	55%	**30%**	97%	1%	2%	100%
	M	20%	73%	**7%**	96%	2%	2%	100%
	V	6%	69%	**25%**	97%	2%	1%	100%
S	SF	0%	88%	**12%**	99%	1%	0%	100%
	M	0%	98%	2%	100%	0%	0%	100%
	V	14%	81%	5%	100%	0%	0%	100%

Some studies based on isopleth models determine fungal growth and its growth rate [34]. The growth of fungi depends on the type of material, in some cases it occurs after eight days of exposure and in others after sixteen to T of 15ºC and RH higher than 83%. The scenario for HOEC 2050 presents some days in January and February with T between 15-17ºC and RH above 70% (see Figure 3). However, these environmental parameters are only observed for four continuous days.

The main cause of biological deterioration with case studies HOEC 2018 and HOEC 2050 was the high RH level in autumn, spring, and summer, despite the fact that active use techniques control the RH level and there is no risk with this parameter.

Analysis of the data obtained in the simulations for the different strategies (H1 to H4) shows that the churches do not present biological degradation if active techniques are used.

3.3 Mechanical degradation

Figure 7 shows the average percentage of time where there is risk of mechanical damage due to the variation of air temperature and relative humidity in these churches. EN 15757 [28] establishes a maximum variation of 10% for RH and several deviation levels are set for the air temperature parameter: no risk (A) (limit ±2) and moderate risk (B) (limit ± 5 ºC) according to ASHRAE [27]. The use of active systems increases the percentage of time at risk of mechanical degradation due to temperature deviation to 10%.

The results were very similar for all three churches, and the values for the church of St. Francis of Assisi are as follows:

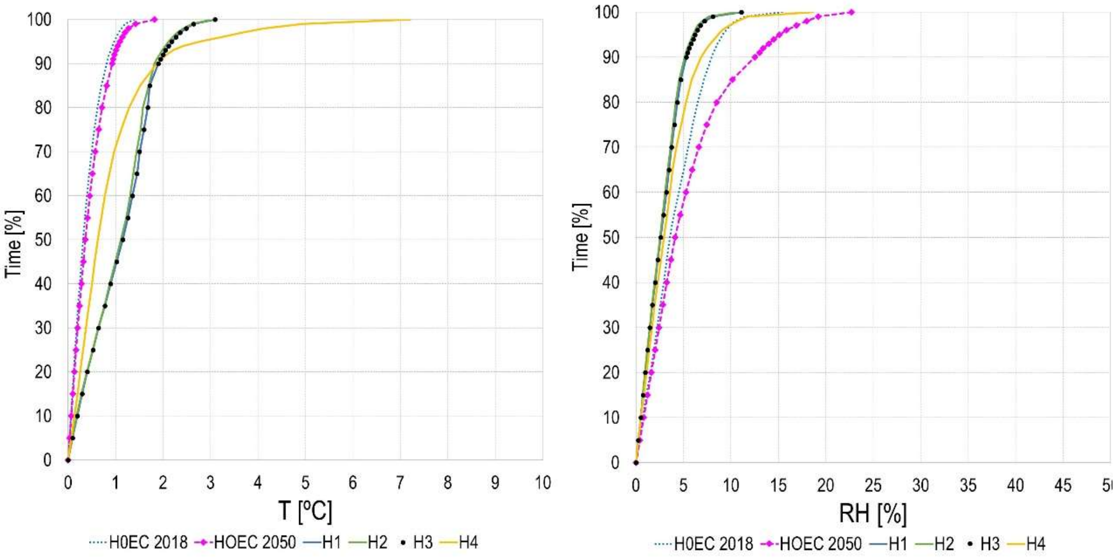

Figure 7. Risk of mechanical degeneration. a) Time percentage where deviation ranges are exceeded for T, no risk (limit 2ºC), and moderate risk (limit ±5) b) Time percentage where deviations for RH are exceeded (limit 10%).

Currently, RH deviation causes mechanical degradation 5-7% of the time. However this situation is expected to worsen with climate change, increasing to 12-15%. RH deviation is the parameter with the most influence on mechanical risk, so that all active system strategies are present 3% of the time, making them suited to the preservation of artworks. In the case of deviation in T, there is only a risk of mechanical degradation 8-10% of the time with strategies H1, H2, H3, and H4.

One of the problems with using ASHRAE's climate classifications is that when one of these is held for a period of time, it can cause damage to works of art. As proposed by ASHRAE, it would only be valid when the classification is fulfilled 100% of the time, which is not the case here.

In the churches analysed the protected works of art are wooden sculptures and altarpieces protected with varnish. Some studies indicate a panel painting experiences mechanical degradation at 4.3 days (surface response) and 26 days (sub-surface). In the case of wood this is 10 hours (surface) and 15 days (sub-surface) [34].

In the churches studied, climate class A is the most unfavourable and is exceeded 10% of the time, that is, 876 hours, 36 discontinuous days. Analysing the data, the maximum time exposed does not exceed 3 hours in any case. In future works, the artwork will be studied in further detail as in other research [35].

3.4 Thermal comfort

Figure 8 shows the percentage of hours of discomfort for the HOEC 2018 and 2050 scenarios without the use of active techniques. A comparison of the results shows that with climate change the percentage of discomfort is reduced 10-20% of the time during the cold months, although it increases 20-30% of the time during warmer months (Figure 8).

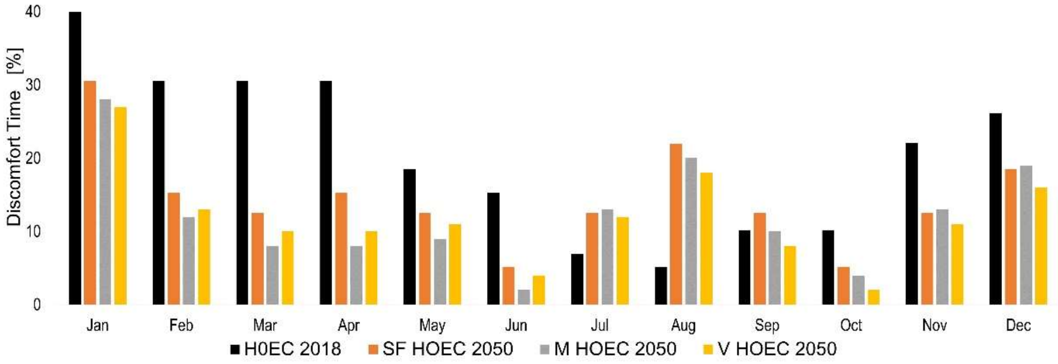

Figure 8. Time percentage in discomfort. H0EC 2018 and HOEC 2050 (SF, M, V)

The churches are conditioned for human comfort during 100% of the day when HVAC is in use for 12-hour periods with all the strategies studied. This is not the case for (H4) Ventilation + humidifier + dehumidification, where churches are in discomfort 30% of the time in winter, 20% of the time in summer, and 10-15% of the time in spring and autumn.

3.5 HVAC energy consumption

Energy consumption was recorded through the implementation of active environmental techniques (H1, H2, H3, and H4), ensuring the conditions for the preservation of artworks and human comfort in H1, H2, and H3. The implementation of these techniques leads to high energy consumption, caused partly by the large size and thermal inertia of the buildings.

Figure 9 shows energy consumption for the original conditions and for the 2050 conditions using these techniques. The comparison of results for H1, H2, and H3 shows how the percentage of energy consumption will decrease by 15-20% during the colder months in 2050 in relation to HOEC 2018, while this percentage will increase by 25-30% during the summer months, and by 5-15% in autumn.

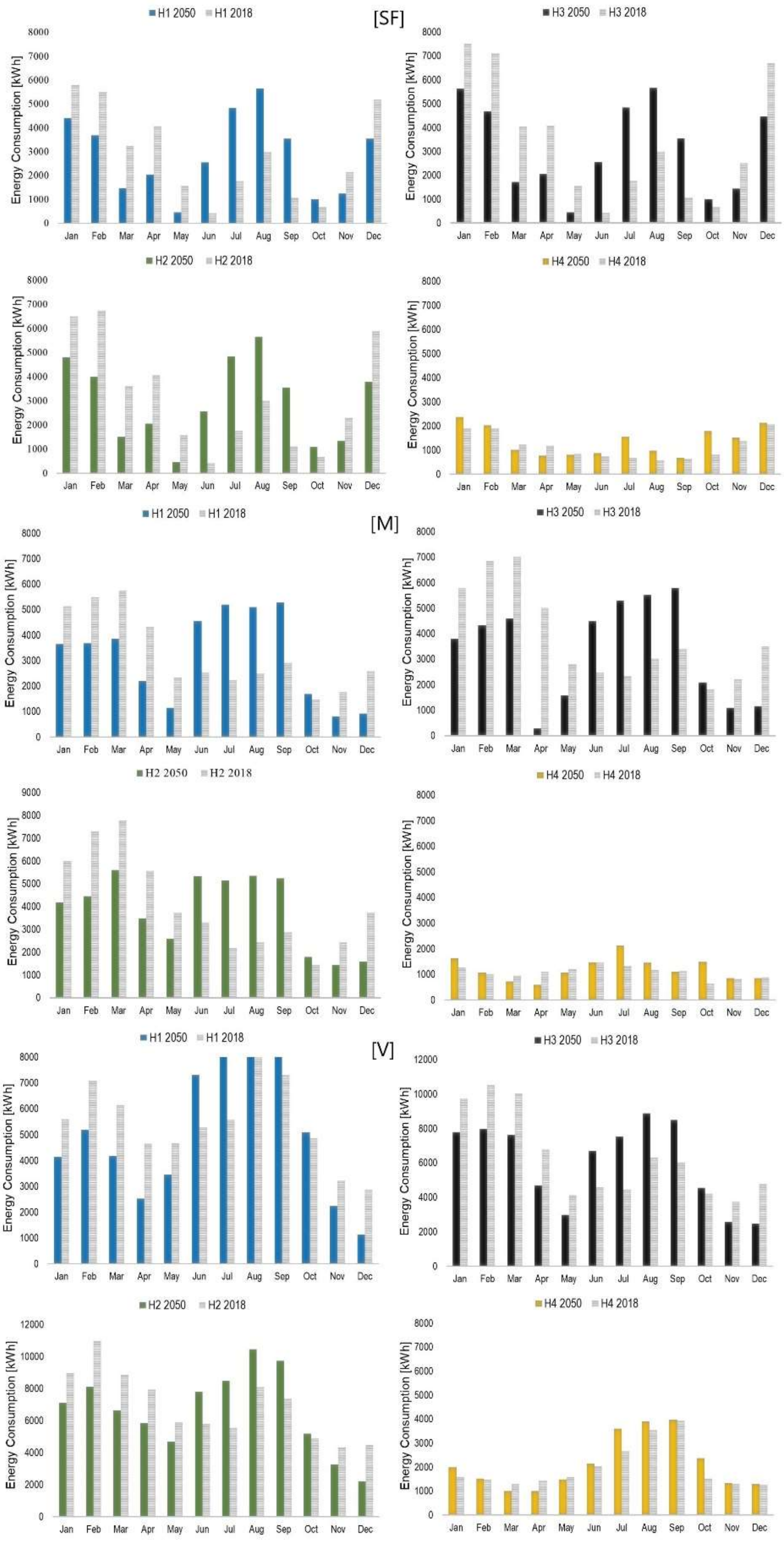

Figure 9. Energy consumption (kWh) of the different study hypotheses with the climate for 2018 and 2050 (SF, M, V)

The energy consumption for H4, an active technique designed for heritage preservation, decreases in the spring months, but increases by around 5-10% during the rest of the year.

Despite these differences, the total annual decrease in energy consumption is only between 1-3% (H1), 4-6 % (H2) and 4-12% (H3). In the case of H4, energy consumption increases by 9-15% for the 2050 scenario.

The energy consumption ranges are 98-177 kWh/m^2 (H1), 102-220 kWh/m^2 (H2), 109-200 kWh/m^2 (H3) and 47-71 kWh/m^2 (H4) per year. According to the Basic Energy Saving Document [37] if these were not protected buildings, energy consumption would be limited to 15-20 kWh/m^2 per year. As table 5 shows, the hypotheses which consider thermal comfort and preservation far exceed this consumption.

Table 5. Energy consumption (kWh/m^2) comparison for the climate in 2018 and 2050.

Churches		**H1**	**H2**	**H3**	**H4**
SF	2018	99	108	116	40
	2050	98 (-1%)	102 (-6%)	109 (-6%)	47 (+15%)
M	2018	116	145	137	39
	2050	113 (-2%)	137 (-5%)	120 (-12%)	43 (+10%)
V	2018	181	230	208	65
	2050	177 (-3%)	220 (-4%)	200 (-4%)	71 (+ 9%)

4. Conclusions

This study has shown the impact of climate change on the preservation of works of art, and thermal comfort and energy consumption in various churches. The methodology applied followed an experimental method combining analytical formulations, on-site measurements and HVAC systems to identify the adequate hygrothermal parameters for these buildings. The climate change scenario forecast for 2050 was based on projected temperature variations. The mechanical and biological deterioration was evaluated for the preservation of works of art according to EN 15757 [28] and ASHRAE [27]. EN-ISO 7730 [23] was applied to determine the human comfort range when wearing street clothing indoors. The indoor conditions to guarantee thermal comfort for use of energy and people are established in the current Regulations on Thermal Installations in Buildings (RTIB) [31]. The legislation for ensuring preservation is included in EN-15759-1 [32], EN- 15758 [34] and ASHRAE [27].

The results for the outdoor temperature in the 2050 climate scenario show an increase in temperature throughout the year, especially in the hottest months. This increase in temperature in 2050, considerably increases the gains and losses in construction elements such as floors and walls, which have a larger built surface. Climate change considerably improves thermal comfort compared to the current situation throughout the year, except in the hottest months, where this situation worsens.

As expected, the application of active systems in these spaces makes churches comfortable during use, except for the system which only controls ventilation and RH.

Climate change increases the risk of mechanical degradation in works of art, compared to the current state. With the use of active systems, this situation improves, although there is a minimum percentage of risk. Despite this, the length of time that wooden works of art are continuously exposed in this environment does not exceed the stipulated time for superficial damage.

Climate change decreases energy consumption in winter, due to increased temperatures, but increases it during the summer months. However, annual energy consumption is lower in 2050 than in the current situation. In the case of active systems used solely to solve the problem of the preservation of works of art, energy consumption increases by around 10-15% due to the increase in RH levels with climate change.

The energy consumption of environmental techniques for the preservation of works of art is double that of the energy consumption for preservation and thermal comfort.

Out of the systems analysed, the one with the lowest consumption is the AHU with boiler, but in the case of AHU systems plus radiators or underfloor heating, future studies are recommended to analyse the stratification of T and RH in the church, using Computational Fluid Dynamic (CFD) studies. The lower areas warming of the churches is more suitable for preservation.

According to the results obtained, energy consumption is high in these heritage buildings. Europe faces the challenge of creating modern restoration and preservation requirements for better energy use and reduced carbon emissions, without compromising architectural heritage. Without this policy change, traditional buildings, which are now a valuable asset, will become a burden in the near future.

Future studies should evaluate the increase in energy incorporated into historic buildings. Climate change poses a challenge for historic buildings given the risk of increased interior overheating and moisture-related damage. Therefore, there is a pressing need to assess these risks and plan adaptation strategies for historic buildings. However, it is necessary to understand how the future climate will influence the design, construction and environmental conditions of these historic buildings before they can be adapted. Besides, it will be necessary to incorporate renewable technologies to improve indoor environmental conditions.

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Nomenclature

T Temperature [ºC]
RH Relative Humidity [%]
AH Absolute Humidity [Kg/m ^{3}]
U Thermal transmittance [W/m^2 K]
PMV Predicted Mean Vote
MBE Mean Bias Error
CV(RMSE).Coefficient of Variation of the Root Mean Square Error
HVAC Heating, Ventilating and Air Conditioning
AHU Air Handling Unit
RTIB Regulations on Thermal Installations in Buildings

Appendix A

Simulation Software

This appendix shows the simulation models of the churches, validated using in situ measurements. These models replicate the materials, spatial volume, geometry, urban environment, and climate of each building (Figure A.1). In order to validate these models the monitoring values and simulation data of RH, AH and T were compared. For example, Figure A.2 shows the data and results for interior average temperature. This comparison took into consideration all the environmental parameters over a year.
The simulation models were validated using indicators from U.S. Department of Energy M &V Guidelines [38] and ASHRAE 14-2014 [29]. These indicators were MBE (Mean Bias Error) (Eq. 1), Cv RMSE (Coefficient of variation of the Root Mean Square Error) (Eq. 2), describing the variation between mathematical models and measured data. The simulation model was validated when MBE hourly values were within ±10% and CvRMSE fell below 30%.

$$MBE\ (\%) = \frac{\sum_{i=1}^{Ni}(Mi-S\ )}{\sum_{i=1}^{Ni} Mi} * 100 \qquad (1)$$

$$(CV)RMSE(\%) = \frac{\sqrt{\sum_{i=1}^{Ni}\frac{(Mi-Si)2}{Ni}}}{\frac{1}{ni}\sum_{i=1}^{Ni} Mi} * 100 \qquad (2)$$

Where:
Mi measured data
Si simulated data
Ni number of records used for validation

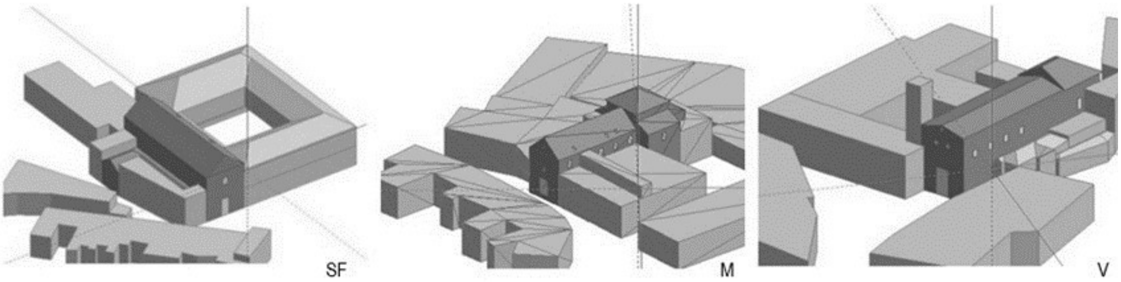

Figure A1. Simulation models. (SF), (M), (V)

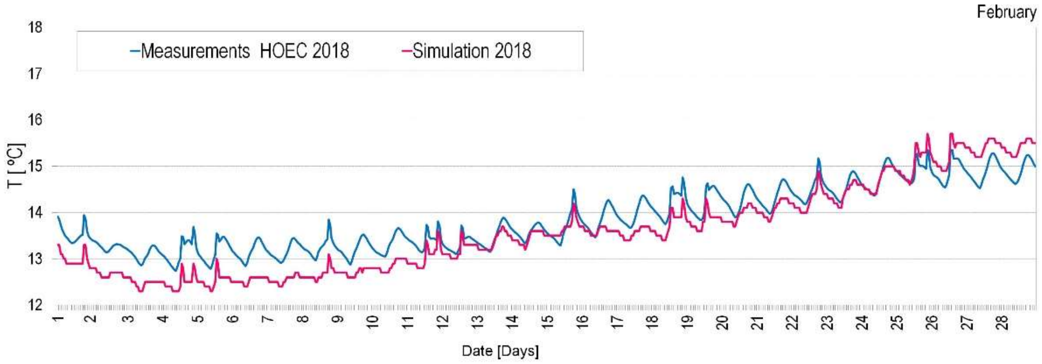

Figure A2. Example of validation in February. Church St. Francis of Assisi

	SF		M		V	
	MBE	CV(RMSE)	MBE	CV(RMSE)	MBE	CV(RMSE)
T	-0.20%	18%	-0.21%	19%	-0.10%	8%

RH	-0.24%	20 %	-0.25%	20 %	-0.30%	24%
AH	-0.27%	21%	-0.30%	21%	-0.30%	25%

Table A1: Result of the error indicators

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