The assessment of environmental conditioning techniques and its energy performance in historic churches located in Mediterranean climate.

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Abstract

The historical buildings have a specific approach regarding energy performance and indoor microclimate. However, the implementation the energy efficiency in historical buildings are limited, because the materials, the structure, geometry or artworks preservation do not allow an enhancement of the microclimate parameters or energy performance.

The main aim of this work is to study the use of environmental conditioning techniques in a historic building and its impact on artworks preservation before the refurbishment project. This study describe experimental research to carry out on the church of Nuestra Señora de la Merced, an example of an historic building in a Mediterranean climate. The building was monitored and measured to validate numerical codes using Design Builder version 4.7.027 and EnergyPlus 8.3.

Software building models allowed evaluating the implantation of different environmental techniques passive, active and combined in the church in order to conserve and preserve artworks. This work concluded that the use of passive environmental techniques do not completely eliminate mechanical risk or the bio-deterioration that are part of the movable heritage. Proposals for the use of active systems and their combination with passive techniques improve the initial preservation of artworks and decrease the risk of biological degradation. Although energy consumption is high due to the large size and thermal inertia, consumption is considerably reduced when active and passive systems are combined.

Keywords: Hygrothermal building simulation, energy efficiency, modelling, HVAC, historic buildings, mechanical degradation.

1. Research aims

This research is a part of a broader project [1] run by the University Institute of Architecture and Building Science and Seville University to discover the indoor environmental behaviour in Spanish churches located in southern of Spain. This study is developing a method to predict the impact of the implantation of environmental conditioning techniques on the preservation of artworks, user thermal comfort and energy consumption in historic buildings before the refurbishment project. This case of study describe the criterions for modelling historical building with monitoring data –a validated simulation model- and its potential and limits to predict the indoor hygrothermal behaviour.

2. Introduction

The historic churches, have particular characteristics regarding building energy performance behaviour modelling. These building are excluded from minimum energy requirement and energy performance certification [2]. On the other hand, churches are a building museum itself and have valuables artworks that require the maintenance of an adequate indoor microclimate for its preservation and use, achieved by HVAC systems.

These maintain a suitable indoor climate for the building and collection, as well as generate a comfortable indoor climate for users, but have high energy consumption [3].

In order to conserve the artworks in the building the indoor climate must minimize the ageing and degradation of the materials to be preserved [4]. This process depends on the materials and the type of degradation. In the case of materials, the most important climate parameter is often relative humidity, as high humidity encourages the growth of microorganisms which make use of organic bonds or cause damage by secreting acids. Relative humidity must be below 65% in order to ensure the prevention of organic infestations. Changes in temperature are equally problematic, as they generate stress and deterioration in material, salt crystallization, etc. in turn damaging this material depending on its vulnerability [5].

Indoor climate is an important factor in preserving the fabric of buildings and their artworks and some European Standards are the result of the need to reflect the special characteristics of these places [6-7]. In terms of preservation, an ideal solution would be to maintain suitable environmental conditions over a constant period. However, in practice, the costs for this operation hypothesis would be far too high for the institutions in charge of these buildings. This is why air conditioning systems in most churches tend to be used for very limited periods of time, coinciding with occupation during occasional events [8].

In a reference to the most used active systems in Europe, the radiant floors, infrared radiation heating, thermal pews, etc. are more common [3]. However, these systems do not resolve the problems arising in the Mediterranean climate in the warmer months. The use of active environmental conditioning systems such as HVAC (Heating, ventilation, air-conditioning and cooling) is common in Spanish churches [9]. Moreover, no reference has been made to cooling or ventilation in warm climate regions where some studies have identified problems in terms of preservation in these buildings [10-11].

Environmental conditioning methods for churches were mainly designed to meet economic and thermal comfort requirements, with little consideration for conservation issues [12]. Although these systems first appeared in the 1960s and 1970s in Spain, regulation was not introduced until December 2012. Many Spanish churches in temperate climates have been equipped with environmental conditioning systems previously used in northern Europe [13-14]. The systems in most of these buildings are old and underperform, whereas when active systems are used in these large buildings, the energy consumption is high so that the use of these systems is rapidly abandoned [8].

To preserve monumental buildings and artworks have to be developed a method for predicting the indoor environment. In this context, simulation software are a very useful tool for calculating environmental conditions and energy consumption in buildings prior to interventions as it makes it possible to predict the behaviour of the different climate conditioning systems and installations. These calculations for this specific type of building are not always accurate, given that the software is geared towards the evaluation of other more modern buildings. Monitoring and real measurements are therefore needed to validate and contrast the results obtained from simulations [15]. Simulation models with behaviour close to reality [16] are generated using onsite measurements.

3. Methodology

3.1 Case study description

The church of Nuestra Señora de la Merced was built in the seventeenth century on the site of a convent which disappeared at the time of the Napoleonic invasion in Morón de la Frontera (Seville, Spain). This historic building was selected for this study because most of its imagery is part of the characteristic protected movable heritage of the town. As seen in Fig. 1 the church has a Latin–cross floor plan and features thick masonry and brick walls with high thermal inertia. The height of the central nave is 11 m above ground level. The building is currently used as a church and houses a valuable collection of paintings and an altarpiece.

Fig.1: The monumental buildings analysed in this study, church of Nuestra Señora de la Merced (Lat. 37.07º, longitude -5.26º). Top right: cross-section Below left: Façade Below right: Ground floor, position sensors. (S=sensor, h= height)

3.2 Monitoring

Hygrothermal conditions were monitored to understand part of the natural microclimate of this historic building in a Mediterranean climate. A wide variety of measurements of outdoor and indoor climate conditions air temperature (T) and relative humidity (RH) were recorded in the nave of church at fifteen-minute intervals for a year. In order to obtain representative climate data, combined digital air humidity and temperature sensors (USB data loggers) were placed at the best possible locations avoiding the influence of radiating sources, air flow through door openings, and heat loss through external walls or the barrel vault. Therefore, point measurement campaigns were carried out beforehand and the sensors were located on the longitudinal wall with an orientation between southeast and southwest. Sensors were placed on the southeast and southwest walls at the height of a seated person (1.10m) and at a height of 8.5 metres in order to observe thermal stratification at this height (see fig. 1). In addition, outdoor air temperature, RH, wind and pressure were measured at nearby Morón de la Frontera meteorological station.

3.3 Computational modelling

Simulation model have been generated to reproduce the interior space of the church, its exterior, constructive conditions and materials. The software used has been Design Builder version 4.7.027, with EnergyPlus 8.3. This program uses the EnergyPlus [17]. calculation engine, developed by the U.S Department of Energy (DOE) to simulate heat transfer processes, climatization systems and other factor relating to energy consumption in buildings. The model of the church consists of two areas: the nave on the ground floor and the roof of the barrel vault (see Fig. 2)

Fig. 2: Design builder model and different areas in the church

This research particularly focused on the indoor environment of the church. For this, a simulation model was created using recent meteorological data files from the weather station and the physical properties of materials, “U” values as shown in table 1. The physical properties of this building were defined by the catalogue of building materials of the Spanish Technical Code of Building (CTE) [18].

Building part	Material	*U values* (W/ m^2 K)
External wall	Brick, concrete and masonry	0.83
Barrel vault	Plasterwork, natural stone, wooden construction and concrete	1.96
Roof attic	Arab tiles, concrete, wooden beams	1.78
Floor	Marble, concrete, natural stone and sand	2.27
Windows	Double glazing	1.71

Table 1: Physical properties of building materials. Thermal transmittance

3.4 Validation model

The literature review show the absence of generally accepted methodology for the validation models. However, some authors define validation methodologies based on the manual adjustment of the models [19], while others base them on a multi-stage guided procedure [20-21]. Figure 3 shows a comparison of the indoor air temperature, indoor air relative humidity and indoor absolute humidity between the simulation model and on-site measurement for the church. The figure show that Design Builder was able to generate an adequate prediction of the air temperature, RH and absolute humidity: the maximum difference between measured and simulated values were approximately ±2 ºC for temperature, ± 10% for RH and ±3 g/m^3 for absolute humidity.

Fig. 3: Comparisons of the indoor temperature, relative humidity and absolute humidity, measured and simulated. Histogram of hourly: a) T residual (ºC), b) RH residuals (%), c) AH residual g/m^3

The hourly residual values were of under 1 ºC temperature and 1.5 g/m3 absolute humidity for 95% of the time and less than 5% relative humidity for 90 % of the time. T, RH and AH residual hourly, with the majority of results around 0-0.3 ºC in the case of T, 0-4% in the case of RH and 0-0.8g/m^3.

3.4 Environmental conditioning techniques

The different environmental conditioning techniques were simulated after validating the model. These were based on a previous field study of Spanish churches, where the passive and active techniques most used in Mediterranean climate were established.

Three groups of techniques - passive, active and combined - were evaluated. Passive techniques are actions on the constructive elements of the thermal envelope of the church: openings, roof, façade walls, and floor. Active techniques consist in installing cold-heat HVAC systems in the building, with or without damp control, using different systems and technology. Nowadays, most of the active techniques in historic buildings are old systems with high energy consumption, and owners choose not to use these for the sake of economy. Therefore, these hypotheses study systems more efficiently, improving their COP (coefficient of performance) and EER (energy efficiency Ratio).

Finally, the third group is a simultaneous combination of passive and active techniques used to ascertain the energy savings when passive and active techniques were combined. Table 1 shows that the physical properties of the church refer to original environmental conditions (HOEC) and table 2 shows the case hypotheses considered for the church of Nuestra Señora de la Merced.

HVAC systems were simulated in different operation modes: 24 hours (continuous), 12 hours (daytime) and occasional use (hypothesis for religious celebrations held in the church).

HYPOTHESIS	Description	CONTROL	
		T	HR
Passive	H0: Change of double-glazing from single-glazing (*U windows= 5.69)*	NO	NO
	H1: Increased thermal insulation in the barrel vault (*U barrel v.= 0.80)*	NO	NO
	H2: Increased thermal insulation in blank walls *(U wall= 0.63)*	NO	NO
	H3: Addition of thermal insulation to flooring *(U floor= 1.40)*	NO	NO
	H4: H1+H2 (*U barrel v.= 0.80, U wall= 0.63)*	NO	NO
	H5: H1+H3 (*U barrel v.= 0.80, U floor= 1.40)*	NO	NO
	H6: H1+H2+H3 (*U barrel v.= 0.80, U wall= 0.63, U floor= 1.40)*	NO	NO
Active (HVAC)	H7: Full air autonomous system (heating + cooling) (Fan component of constant volume, a DX cooling coil (Capacity 23.4 kW) a DX heating coil (Capacity 25.4 kW)).	YES	NO
	H8: Air handling unit (AHU) (heating + cooling) (Fan component with variable volume, a chilled water cooling coil (condenser type) and heating coil hot water (Capacity 24.9 kW). Boiler provides hot water (nominal thermal efficiency 1).	YES	NO
	H9: AHU (heating + cooling) + humidifier (Fan component with variable volume, a DX cooling coil, a heating coil (capacity 40 kW) hot water (boiler provides hot water and electric steam humidifier).	YES	YES
	H10: AHU (cooling) + humidifier + radiators (heating) (Fan component with variable volume, a DX cooling coil, a heating coil (capacity 40 kW) hot water (boiler provides hot water), electric steam humidifier and hot water convector (radiators).	YES	YES
	H11: AHU (cooling) + humidifier + radiant flooring (heating) (Fan component with variable volume, a DX cooling coil, a heating coil (capacity 40 kW) 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
	H12: Ventilation (Fan component (variable volume). Efficiency 1	NO	NO
	H13: Ventilation + humidifier (Fan component (variable volume) and humidifier). Efficiency 1	NO	YES(*)
Combined (Passive + active)	H14: (H9 + H3) AHU+ humidifier+ insulated flooring	YES	YES
	H15: (H10+H3) AHU+ humidifier+ radiators+ insulated flooring	YES	YES
	H16: (H9+H5) AHU+ humidifier+ insulated vault+ walls	YES	YES
	H17: (H10+H5) AHU+ humidifier+ radiators+ vault+ walls	YES	YES
	H18: (H11+H5) AHU+ humidifier+ radiant flooring+ vault+ walls	YES	YES
	H19: (H9 + H6) AHU+ humidifier+ vault+ wall+ flooring	YES	YES
	H20: (H10 + H6) AHU+ humidifier+ radiators+ vault+ walls + flooring	YES	YES
	H21: (H11 + H6) AHU+ humidifier + radiant flooring + vault+ walls + flooring	YES	YES
	H22: (H13 + H6) Ventilation + humidifier+ vault + walls + flooring	NO	YES(*)

Table 2: Study hypotheses. (*) System without dehumidification control. *U values (*$W/ m^2 K$)

The use of active (HVAC) systems was programmed to reach acceptable indoor conditions both in terms of human comfort and for the conservation of goods. The indoor conditions for ensuring thermal comfort for people and a rational use of energy are established in the current Regulations on Thermal Installations in Buildings (RITE) [22]. (table 3). The requirements for ensuring conservation are included in UNE-EN-15759-1 [6], UNE-EN 15758 [23], ASHRAE [24].

COMFORT (RITE)	T	RH
Winter	21-23ºC	40-50%
Summer	23-25 ºC	45-60%
Preservation		
Winter	10-20 ºC	30-65%
Summer	20-30 ºC	30-60%

Table 3: Indoor design conditions

Given that both sources present different ranges of variables, the values used for the simulation of operating conditions are intermediate and close to or in compliance with both requirements (table 4).

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

Table 4: Ranges established for the active conditioning systems

4. Results and discussion

4.1 Passive environmental techniques.

This section shows the percentage of time over a year, analysed by season, when temperature variations (T) and relative humidity (RH) can cause mechanical damage, biological deterioration, and thermal discomfort among church occupants.

Mechanical deterioration is related to the amount of water absorbed by organic materials or thermal expansion in inorganic materials, especially metals. The item changes size and shape, leading to cracking, etc. This change is connected with changes in RH, and to a lesser extent T, when the environment fluctuates. This happens when ΔT ≥ 2ºC according to ASHRAE [24] and ΔRH ≥ 10% according to EN 15757 [7]. Biological deterioration is damage caused by living organisms such as insects, bacteria, and mould. Relative humidity and temperature levels determine whether these organisms flourish, as is the case when T and RH are in the growth range of fungi, T> 20ºC and RH> 65%. Given the complexity of thermal comfort, methods studied to date are only approximate. The method used in this study to predict the general thermal sensation and degree of discomfort is defined in EN-ISO 7730 [25], and a limitation of thermal comfort is proposed in a range of sensations from neutral to slightly cool, corresponding to the Predicted Mean Vote (PMV) between +1 and -1. Matlab was used to calculate PMV and Predicted percentage of dissatisfied (PPD) values following Fanger.

In this case study the use of passive techniques worsens the original condition in the analysis and assessment of the results relating to mechanical degradation. In addition, the environmental conditions worsen in relation to the deviation of HR. The results for spring, summer and autumn are poorer than the original conditions (HOEC), especially when the building envelope is thermally insulated. Although the high risk of biological degradation does not exist in winter for any hypothesis, in spring and summer the risk is at its highest.

According to the different study hypotheses the mechanical and biological degradation and the thermal comfort of the congregation worsens. The thermal comfort worsens especially in spring and summer, although improves in autumn. In winter the level of discomfort remains high.

To sum up, the different passive environmental techniques do not simultaneously resolve the problems of conserving heritage and the wellbeing of occupants.

4.2. Active and combined environmental techniques and energy consumption

The results for active and combined environmental techniques show that when the systems used control T and HR simultaneously and permanently (24h), the risk of heritage suffering mechanical deterioration disappears. However, the risk remains in cases with ventilation systems or systems which do not control HR, as in the case of H7, H8, H12, H13 and H22. As is to be expected, when equipment is in operation over shorter periods of time (12 h or depending on use) the risk remains for all cases.

Table 5 assesses the risk of bio-deterioration when using active systems and/or combining them with passive systems. The code used in the risk assessment is as follows: A means there is no risk of bio-deterioration; B represents an improvement of initial conditions still with risk; and finally, C represents a worsening of the initial situation.

The results show that when the systems use control temperature and humidity the risk of bio-deterioration disappears, providing these systems are active for a minimum of 12h a day. When operation depends on use, there is a general improvement over the initial conditions, although in spring there continues to be a minimum percentage of time where there is a higher risk of bio-deterioration for movable heritage.

			ACTIVE SYSTEMS							COMBINATION OF ACTIVE AND PASSIVE SYSTEMS								
Work	Season	HOEC	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21	H22
24h	W	0%	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	Sp	7%	**C** **9%**	**C** **13%**	A	A	A	**C** **18%**	A	A	A	A	A	A	A	A	A	A
	Sm	2%	**C** **4%**	**C** **61%**	A	A	A	**C** **18%**	A	A	A	A	A	A	A	A	A	A
	A	2%	**B** **1%**	**C** **14%**	A	A	A	**C** **6%**	A	A	A	A	A	A	A	A	A	A
12h	W	0%	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	Sp	7%	**C** **13%**	**C** **17%**	A	A	A	**C** **20%**	A	A	A	A	A	A	A	A	A	A
	Sm	2%	B 2%	**C** **49%**	A	A	A	**C** **25%**	A	A	A	A	A	A	A	A	A	A
	A	2%	B 1%	**C** **10%**	A	A	A	**C** **4%**	A	A	A	A	A	A	A	A	A	A
Use	W	0%	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	Sp	7%	**C** **20%**	**C** **14%**	B 5%	A	B 1%	**C** **20%**	A	B 2%	B 1%	B 2%	B 1%	B 2%	B 2%	B 2%	B 2%	B 1%
	Sm	2%	**C** **4%**	**C** **10%**	A	A	A	**C** **24%**	B 2%	A	A	A	A	A	A	A	A	B 1%
	A	2%	A	B 1%	A	A	A	B 1%	A	A	A	A	A	A	A	A	A	A

Table 5. Risk of bio-deterioration. **%** : data outside the range

A No risk **B** Improvement of initial conditions but still risk **C** Worsens initial risk

Finally, as regards the thermal comfort of users, when the systems are in use for 24 hours or 12 hours the church is comfortable 100% of the time in the case of all study hypotheses except those involving only ventilation of the church. For operation depending on use, the church ensures comfort conditions during the celebration of mass providing the systems (except ventilation systems) are switched on an hour before the event. However, operation depending on use does not guarantee occupants' comfort for the remaining hours of the day. This table shows how in the study hypotheses in which there is thermal insulation in the flooring (H14, H15, H16, H17, H18, H19, H20, H21, H22) thermal comfort decreases in summer. The lowest thermal discomfort occurs in autumn and the greatest in winter.

Figure 4 presents a comparison of the energy consumption percentages of the different systems, as well as variations when passive environmental techniques are applied. From the analysis of these results it can be concluded that in order to reduce the consumption of active systems, the hypotheses offering the greatest energy savings are those in which interventions are carried out on all constructive elements.

Maximum consumption values are represented by the letter **M**. This indicator always corresponds to 24-hour operation in situations where passive techniques are not applied. 12-hour operation reduces maximum consumption by 27-50% and operation depending on use by around 90% (depending on individual cases).

When the use of systems is combined with passive techniques can be reduced by 5-14% in cases with 24-hour operation consumption; with 12-hour operation it is reduced by 10%; and in cases where operation depends on use by only 2%.

Figure 4: a) Risk of mechanical degradation. Percentage of time where deviation limits are exceeded for T ($\Delta T \geq 2ºC$) or RH ($\Delta RH \geq 10\%$). b) Annual energy consumption (kWh) and % of reduction in energy consumption due to the combined application of passive and active environmental techniques

5. Conclusions

In this study of the environmental conditions of the church of Nuestra Señora de la Merced in Morón (Seville) the standards of artwork preservation and thermal comfort were applied to a historic building. Several possible scenarios for heating and cooling systems in the unheated church were simulated. These standards were measured against the natural climate (obtained by monitoring the building) using a risk-based analysis (mechanical and biological degradation) and thermal comfort analysis. Important conclusions reached include:

- The in situ measurements of the church made it possible to evaluate and characterize hygrothermal conditioning. The thermal inertia in this building is high due to the thickness of its walls and the adjoining buildings decrease direct solar radiation on the church walls. Analysis shows a high risk of biological degradation in spring and summer, with high rainfall affecting the preservation of artworks and increasing this risk. Given the heavier rainfall in the first year of monitoring, and as the data percentage increases with risk, RH deviations had a greater incidence on the preservation of artworks.

- Ground temperature must be established to validate the hygrothermal simulation models for this case study as results are subject to change. Other research considers the floor (in contact with the ground) as adiabatic, but in this case the models with adiabatic floors could not be validated.

- The use of passive environmental techniques does not ensure comfort during the year, particularly in winter, spring and summer when users are not comfortable for 95%

and 40-35% of the time respectively. In addition, the use of these techniques does not fully eliminate mechanical risk or the bio-deterioration of materials of movable heritage. Any combinations which include insulated church flooring can have negative repercussions on occupants' thermal comfort during summer.

- The proposed use of active systems combined with passive techniques operating for 24- and 12-hour periods improves the initial preservation of artworks, reducing the risk of biological degradation. If the active system functions solely when the building is occupied (in use), the risk of bio-deterioration is present for about 2% of the time, particularly in spring. There is no mechanical damage to the artworks when the active systems are in operation for 24 hours, except in cases with ventilation systems or systems that do not control relative humidity. The churches are comfortable when the systems are in use for 24 hours or 12 hours, except with the hypotheses of ventilation. When not in operation the churches are not comfortable during the day and comfort is only ensured when the systems are switched on at least one hour before an event, such as the celebration of mass. Finally, when active techniques are applied in these spaces, energy consumption is high due to the large spatial volume and thermal inertia. According to energy saving requirements, the energy consumption for these types of buildings is limited to 45-48 kWh/m^2. However, although in these case studies (24 h, 12 h and use) the level of energy consumption is much higher, if the active and passive systems are combined consumption is reduced by 5-14% in systems that operate 24 hours, 10% in systems that operate 12 hours and finally, by 2% in systems with periodic operational use.

- In this case study, the combination of active systems with all the passive techniques (H19, H20 and H21) improved energy saving and resulted in less damage than other hypotheses.

- The results of Nuestra Señora de la Merced Church were compared with other churches with similar characteristics, but different geometries. We concluded that the most important elements in energy consumption were building volume, number of windows, roof type (energy consumption was lower in churches with barrel vaults). In these cases orientation was not important, since most of them had the same orientation and adjoining walls.

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