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The Influence of Visitors on Heritage Conservation: The Case of the Church of San Juan del Hospital, Valencia, Spain

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Abstract: One of the greatest challenges in heritage management is to find a balance between the demands of visitor access and heritage conservation. The income generated prevents decay and benefits the conservation of buildings. At the same time, cultural tourism can accelerate the deterioration of buildings from increased use and an increase in agents harmful to conservation. This unique research analyses the influence of building use at San Juan del Hospital, the oldest church in the city of Valencia. Its architectural characteristics and the climate of the city mean that visits to the building put the conservation of its heritage assets at risk. Monitoring data from the summer months were put into a digital twin generated from a heritage building information model (HBIM), and the modelling of visitor numbers and the impact on indoor environmental quality was conducted. Monitoring and simulations confirmed that visitor numbers need to be reduced or mechanical conditioning systems need to be installed to prevent damage to the heritage artefacts within the building. This research provides building managers with information to make informed decisions about the preventive maintenance of heritage buildings. This research also demonstrates for the first time the value of using monitoring and a digital twin for conservation management.

Keywords: heritage; carbon dioxide; tourist capacity; heritage conservation; preventive maintenance

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1. Introduction

The preservation of heritage has proven to be one of the most important factors in reinforcing a sense of belonging to the places where people live [1]. Heritage buildings often become centres of attraction and generators of activity in the urban fabric when they are used properly [2]. However, heritage buildings and their artefacts, such as artwork, can be damaged when the demand for visits starts to overwhelm the management capacity of the authorities in charge of the buildings. At the beginning of the 21st century, the World Tourism Organization (UNWTO) had detected an increase in so-called cultural tourism [3]. In 2017, it accounted for 39% of the total [4]. This increase in visitors to places that are part of the historical and cultural heritage can lead to situations that are far from sustainable, negatively impacting visitor comfort and having a detrimental effect on the conservation of the property and its artefacts. This worries the authorities and is a cause for discussion that regularly appears in the press [5]. This situation usually manifests in maintenance challenges caused by daily interaction of people with the building fabric and its contents, leading to deterioration and damage of the building and its historic artefacts [6–9].

This is particularly pertinent to religious buildings where there it is necessary to balance the needs of worshipers with the need to generate income from visitors to pay for maintenance and conservation work [10,11]. This requires a sensitive and inclusive approach to the management of heritage buildings and the precious artefacts they contain to ensure the conservation and preservation of cultural heritage for future generations.

This needs to be achieved while maintaining physical and thermal comfort for all building users without negatively impacting the cultural assets [12]. To do so requires a sensitive maintenance strategy and use of management tools that are based on the thermal and hygrothermal characteristics of the building and how visitor numbers impact the internal environmental quality. The challenge is further complicated by the impact of climate change on buildings and the impact this is also having on building interiors and artefacts [13–16].

In southern Spain, there is a rich cultural and architectural history to be found in heritage buildings and the artefacts that they contain. Building managers need to establish a management process within the framework advocated in the National Preventive Conservation Plan approved in 2011 by the Institute of Cultural Heritage of Spain (IPCE). Its objectives include research into conservation methods and techniques, the definition of criteria and working methods, and the coordination of actions. All this should be achieved through the "promotion of initiatives materialized in studies that allow the definition and development of methodologies and management models" [17]. Under this strategy, preventive conservation plans have been launched for important monuments such as the Theatre, Amphitheatre, and House of Mithraeum in the archaeological complex of Mérida; the Cathedral of Santiago de Compostela; and the Alhambra in Granada. The development of these plans has also led to the subsequent preparation of the "Guide for the preparation and implementation of preventive conservation plans" [18]. This guide proposes a working method that allows for an adequate focus on and analysis of the problems of conservation of cultural assets and facilitates the design and implementation of procedures for the preservation of heritage. It establishes four stages or phases of work: (1) identification of the source of the risk; (2) description of the deterioration process and its effect; (3) indication of the objects in the collection or parts of the property that are vulnerable to such risks; and (4) identification of the level of protection against risks.

This research focuses on identifying the origin of the risk found in the public use of the building and the deterioration that can be caused. To achieve this, a case study building, the church of San Juan of the Hospital de Valencia, Spain, was used. High temperatures and relative humidity, in addition to the high concentrations of CO_2 caused by visitors to the church, have a negative impact on the coating materials and paints located in the church. This church can be considered as representative of buildings with similar architectural characteristics that are subject to a similar level of use without analysing the consequences for the protected elements that may be inadvertently generated by visitors. This research evaluates the influence of visitors on the indoor environmental conditions of the church, with the aim of defining the necessary strategies to ensure its future maintenance. This research on the influence of visitors can help generate predictive strategies and should help with the conservation and maintenance of buildings with heritage value in the face of the risk of excess visitors from a predictive, preventive and corrective point of view.

1.1. Background

The term conservation refers to the definition agreed at the XXV ICOM General Assembly in Shanghai in November 2009: "all those measures and actions that aim to avoid or minimise future deterioration or loss. They are carried out on the context or area surrounding the property, or more frequently on a group of goods regardless of their age or condition. These measures and actions are indirect, as they do not interfere with the materials and structures of the goods. They do not, therefore, change their appearance." [19].

The conservation of heritage buildings that contain works of art requires stable conditions of humidity, temperature, and CO_2 concentrations. This may be difficult to achieve without the help of mechanical conditioning systems, which consume energy and may have a high impact in the building architecture and its protected assets. The importance of data monitoring and collection for the control of internal environmental conditions has been demonstrated [20], and more recently, the value of generating digital repositories in which to host data to inform decision-making processes has been proven [21–24]. There is a general agreement that the conditions for the conservation of heritage assets should be set between 18 °C and 22 °C, between 45% and 65% relative humidity, and below 500 ppm for CO_2 concentration [25–27]. The concentration of CO_2 begins to affect people from 1000 ppm and is deemed to be uncomfortable from 1500 ppm [28].

Preventive maintenance plans (PMPs) provide the motivation to collect building performance data, from which it is possible to evaluate the current conditions within buildings, and the stress to which they are subjected. PMPs allow the design of conservation strategies to ensure targeted maintenance of artefacts and they can also contribute to the wellbeing of the people who use the building because the internal environment is better controlled [29]. To support PMPs, the use of strategies based on heritage building information modelling (HBIM) allows centralisation of information that, applied to historic buildings, becomes repositories where geometric, constructive, and historical information can be collected, facilitating collaborative work and the exchange of coordinated information between multidisciplinary teams [30–33]. This strategy supports what was stated in the Amsterdam Congress held in 1975, where it was agreed that architectures and historical sites require more prudent tools and operational practices to guide each intervention on cultural heritage from a global point of view [34].

From these centralised repositories it is possible to develop digital twins (DTs) that allow simulations to be prepared to support maintenance strategies. These simulations are traditionally focused on energy and environmental improvements [35], but also allow, among other actions, researchers to evaluate the influence of people on the use of buildings as one of the contradictory factors in the process of heritage conservation. Appropriate use of a building contributes to its conservation, but, at the same time, large visitor numbers can generate conditions that result in the deterioration of the cultural assets that compose it.

Cultural tourism monopolises general attention because it has the effect of re-valuing heritage. In particular, the income generated from cultural tourism boosts the local and national economy. However, tourism can also be harmful if a coherent policy is not followed. Thus, it is necessary to establish protocols that address the establishment of a balance between marketing and visitor planning, and the conservation and maintenance of the heritage asset. This can be achieved by taking measures aimed at preventive conservation in preference to active conservation, since it is preferable to conserve rather than restore or renovate [36]. Preventive conservation originated mainly in museums and archaeological parks [37]; however, it has been established in the maintenance and protection of heritage buildings.

In this sense, there are different studies that address the evaluation of the influence of tourism as a preventive strategy. The analysis of the carrying capacity of resources [38], as well as the detection of tourist movements using smart technologies (DSTs), allows for improved management and planning [39]. Likewise, the challenge of making public visits and the conservation of the property compatible is highlighted in our research, so that tourist saturation does not compromise the preservation of a building's identity values.

In 2003, ICOMOS published a document entitled "Principles for the analysis, conservation and restoration of architectural heritage structures", where it established the actions related to the preventive maintenance of the built heritage (analysis, diagnosis, therapy, and control). In this way, preventive conservation is consolidated as a strategy against traditional "curative methods" by focusing on the causes of damages. In this sense, all countries have policies and procedures that contribute to the implementation of measures to adequately protect their historic monuments. Various organisations also dedicate their efforts to the preventive conservation of monuments. This is the case of the Monumentenwatch (Belgium) [40], which carries out systematic inspections of historic buildings [41]. In the same vein, the PRECOMOS UNESCO Chair establishes strategies for the preventive conservation of built heritage, including up to nine agents of deterioration [42,43].

In 2011, ICOMOS published its Guidance on Heritage Impact Assessment (HIA) for Cultural World Heritage Properties. This tool was developed to identify and evaluate the anthropogenic impacts over the cultural heritage, with the aim arriving at a sustainable balance between heritage conservation and societal development. The use of this HIA tool has been widely tested by researchers with valuable results [44]. However, there are some examples of research that criticises the approach of the HIA, as it is considered that it is focused on preservation rather than on conservation. This may guide heritage managers to frame results that result in deficient building management. Building managers are recommended to resort to alternatives to have a more global vision of the evaluation of a historic building [45].

In this sense, interest in preventive conservation and in understanding the factors that condition the conservation of heritage has generated several lines of research. There is research that proposes the use of non-destructive testing (NDT) for the diagnosis of heritage buildings, proving to be one of the most sustainable approaches in the field of preventative conservation [46]. This approach is supported by other researchers that based their interest in developing preventive conservation strategies based on new technologies such as the Internet of Things (IoT) [47] and digital databases [48,49]. In the same vein, research has been carried out on the mechanical behaviour of historic structures and the evaluation of their anticipated useful life using non-destructive techniques [50–54]. Integration of data into 3D models has also been studied, which has made it possible to draw a series of conclusions about the possible threats to stability, contributing to the development of a methodology for the preservation and conservation of historic monuments [55–59]. These interventions are based on the periodic control and maintenance of buildings, which requires the review of the state of the structural and functional elements and the state of conservation of the materials [60]. For example, stone materials can be altered by the environment that surrounds them in such a way that the presence of atmospheric oxygen favours oxidation processes and humidity favours hydration and dissolution processes [61]. In the same way, paintings and murals are part of the artefacts that may form the historical heritage, and which must also receive preventive maintenance [62]. Building managers must try to avoid more costly actions that have their origin, for example, in the appearance of efflorescence due to condensation [25]. Currently, most authors agree on five causes of damage: environmental, polluting, biological, constructive, and anthropogenic. In this research, we focus on the environmental causes generated by visitors, given that the impact of activity and human development has been scarcely addressed by researchers to date.

Currently, environmental controls tend to be carried out through networks of sensors that collaborate efficiently in preventive conservation [63]. Monitoring makes it possible to detect damage in its initial state, facilitating the need for intervention and maintenance. Monitoring has advanced the understanding of building pathology, primarily through the placement of sensors in heritage buildings, which is of great benefit for the preservation and planning of actions [20].

Wireless sensor networks have become one of the most promising technologies in the field of preventative conservation because they offer data flexibly and autonomously in time and space [64]. However, the different reactions of the different materials that make up a heritage building increase the complexity of the study [65]. This is why new sensors are emerging that respond to various situations that may arise. The CERVITRUM research group (Institute of History, CSIC) has patented chemical sensors capable of evaluating the pH of the air with the aim of knowing the real potential for degradation of cultural assets [66]. All these initiatives are, in essence, systematic automated control actions that detect problems in time, allowing short and medium-term interventions to be carried out according to a set of indicators. However, it is not only the environmental conditions inside that must be monitored, but also the external climatic conditions and the ability of the walls (building fabric) to withstand these conditions [67]. For this reason, it is necessary to know the evolution of the heritage asset's construction to understand the effects that the climate and the indoor environment can have on the building and its artefacts [68].

1.2. Digital Twins and Building Conservation

The evolution of technology is enabling a more efficient use of data collected from sensors. The establishment of the field of building performance simulations as a predictive tool is making it possible to better predict what is going to happen in the future and what corrective measures should be adopted to avoid damage to precious artefacts. It is possible to trace the development in the field of simulation and its relationship to data collection from buildings from the 1960s, confirming its value for decision making in the different phases of a building's lifecycle [69]. Among the new tools developed for the preventive maintenance of heritage are digital twins (DTs), which are virtual representations designed to accurately reflect a physical object. DTs can assist in the preventative maintenance process by allowing adjustments to be made based on simulations that draw on monitoring data. This technology is now being implemented in the management of buildings. DTs can be part of preventative maintenance plans (PMPs) developed for asset management and are often based on models developed with HBIM technologies. This makes it possible to generate dynamic models that enable changes in the decision-making process once the data collected by the physical twin have been analysed.

DTs have begun to be applied in heritage buildings and historic sites by way of case study research. This has demonstrated that the use of data from sensors and digital twins can help to safeguard the integrity of heritage assets by acting in a preventative way [70]. Digital technologies offer many opportunities for creating a virtual replica of heritage objects, from which it is possible to explore scenarios and hence adopt an informed approach to the preservation and protection of heritage. With these tools, qualitative and quantitative indicators of the current condition of heritage can be defined and validated in an interdisciplinary framework [71].

The first experiences in the development of DTs have their origin in purely geometric representations that were born from LIDAR and that allowed for a better experience of the protected building while guaranteeing it was not deteriorated by visits [72]. However, it has been shown that a DT applied to HBIM allows access to different layers of information to properly document the building and directly involve the owner in the process of preserving the historical legacy [73]. There are experiences in the use of DTs for heritage conservation with the aim of improving interior conditions in historic buildings. In these investigations, through HBIM, it has been possible to develop computational fluid dynamics (CFD) to evaluate the amount of ventilation needed and reduce the equipment needed to condition a historic site [26]. At the same time, the use of DTs supported by HBIM strategies has made it possible to integrate both technologies into a decision support system based on artificial intelligence (in this case machine learning techniques) for the management of museum collections in historical architectures [74]. There are also experiences in the use of DTs for the conservation of cultural artefacts [75].

1.3. Digital Twins and User Capacity

Among the factors that can be modelled in a DT is building user capacity. Controlling the number of people who visit a property and who have an influence on its indoor environmental quality, especially humidity, temperature, and CO_2, can help to resolve the challenge posed by excessive tourist visits and resulting damage to the heritage they are visiting. This is one of the future challenges for the management of heritage tourism that institutions in Spain are proposing [76].

There are examples of visitor control in cities and monuments around the world, such as in Barcelona through the Check Barcelona App, in the Albaycin in Granada through visitor counting cameras, Teotihuacán (Mexico), Pompeii (Italy), or Machu Pichu (Peru). In addition, there are initiatives in monumental landmarks such as the Alhambra in Granada, Notre Dame in Paris, and the Sagrada Familia in Barcelona. Similarly, large archaeological sites and museums such as the Louvre, the Vatican Museums, and the Uffici Gallery have implemented capacity regulation systems to prevent damage from visitors. This demonstrates the need for research that aims at a rational use of heritage based on knowledge of building performance, the influence of visitors on its conservation, and the use of new technologies. It also confirms the need for these technological developments to support the decision-making process. It is a very young technology and no consolidated strategies have been found, making it necessary to work with case studies [77], as is the approach adopted in this research.

2. Materials and Methods

The focus of this research is the evaluation of the interior environmental conditions in the church of San Juan of the Hospital de Valencia, described below. The methodology comprised the monitoring of the church under its usual operating conditions in the summer months and the use of building simulations using a digital twin to evaluate the impact of visitors to the church. A monitoring system was designed to collect the necessary information for evaluation of the building's situation and allow improvements to be proposed based on the performance data. The monitoring data comprised humidity, temperature, and CO_2 concentrations. These data were combined with the visitor capacity of the building. Once the origin of the situations that put heritage conservation at risk had been detected, strategies based on new technologies were proposed to mitigate the impact on the fabric and artefacts. This was achieved by proposing conservation scenarios in a digital twin based on a heritage BIM (HBIM) and the data collected via the monitoring campaign. From this, it was possible to propose preventative maintenance and conservation strategies for the church to ensure the preservation of its artefacts for future generations. This is described in greater detail in the sections that follow.

2.1. San Juan del Hospital

The Church of San Juan del Hospital is in the city of Valencia, Spain. It was chosen as a case study building because it is a good example of heritage that must be preserved, and the church has a high rate of visits throughout the year. San Juan del Hospital is part of an architectural complex that originally consisted of the monks' residence, hospital, cemetery, and temple. It was built in the mid-thirteenth century by the Order of St. John of the Hospital of Jerusalem. It is located next to the Xerea gate of the Arab wall and was a strategic place for the defence of the city. It was the first church consecrated in Valencia after the cathedral in 1238. Only the church and part of the cemetery remain of the original complex. The cemetery is a unique architectural element because it is walled with arcosoliums on its perimeter, and a small funerary chapel on a tumulus located in its centre (Figure 1).

San Juan del Hospital is the oldest church in Valencia city. It began as a small Romanesque church to which three bays were added at the end of the thirteenth century, and which remain today. The two doors of the Romanesque church have been preserved and the paintings have been recently restored (Figure 2). The side chapels located between buttresses on the gospel side were added in the 15th century. The first of these was made by Pere Balaguer, designerof the well-known Serranos' Towers, the gate of the Christian wall and symbol of the city. On the side of the epistle, the side chapels are enclosed with thin stone walls (15 cm) due to the subsequent construction of cemetery arches on the outside. The large number of archaeological remains found in the subsoil of the cemetery area has led to the creation of a museum that is in adjoining rooms. Under this complex are the remains of the different cities that have developed since the Roman era when the city was founded (138 B.C.): the Visigoths from the 5th century to 714, the Arabs (714–1238), and the Christians from 1238 to the present day.

The church has a single nave with chapels between the buttresses (Figure 3). The main nave is characterised by the small size of its openings to the outside, with only three openings that coincide with the three access doors: one faces the north courtyard, another faces the south courtyard, and a third acts as the main access located in the west part of the nave.

Figure 1. View of the south courtyard, where the cemetery is located, with the chapel on the left and the arcosoliums and the South Romanesque doorway behind.

Figure 2. Picture of the art of the chapel of San Miguel Arcángel.

In terms of natural lighting, the windows located in the presbytery are made of alabaster. The church has a lighting system based on fixed projectors. It does not have interior air conditioning equipment, although portable fans are used in the summer for the comfort of the visitors to the church (Figure 4).

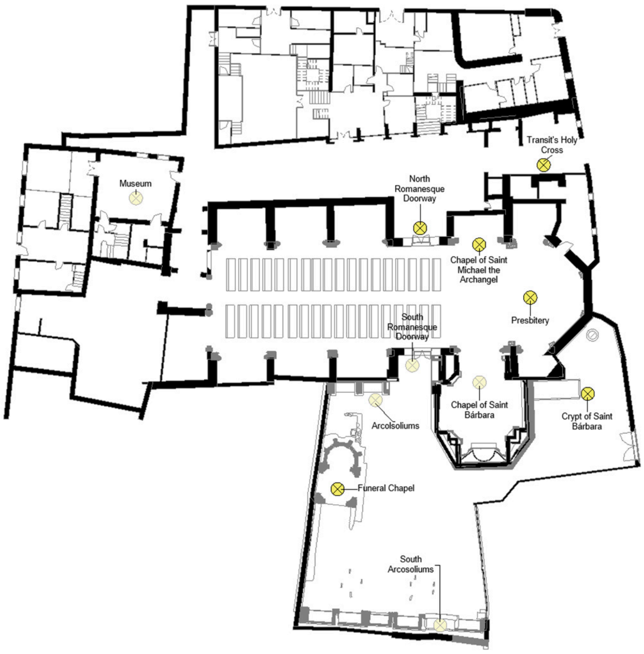


Figure 3. Plan of the church.

Figure 4. Image of the church interior.

The importance of the heritage, together with the large number of religious activities that take place in this church, make it a focus of attraction, both for parishioners and cultural tourists. The influx of visitors has a double aspect: the dissemination and knowledge of a monument of great singularity and heritage value and the deterioration of its beautiful Romanesque paintings and the degradation of the stone of its walls due to excessive environmental pollution.

Since 1997, the church has had a master plan for its conservation. This document established the programming of a series of intervention projects aimed at the conservation of the monument. These recovery and maintenance actions were carried out from 2002 to 2018. At present, the temple and the complex have an HBIM on which the information produced by the different agents involved in its conservation and documentation is being implemented. This system confirms what other researchers have said about the usefulness of these repositories in heritage management [30].

Currently, the complex is in a good state of conservation, with a maintenance monitoring plan for the rehabilitation actions carried out and a continuing recovery plan for the pending areas. The main damage is caused by the excessive humidity inside the church due to both capillarity and condensation. The former comes from the outside of the enclosures, especially the north and south façades, and the latter via thermal transmission in the vault of the nave of the temple and the chapels on the south side, which have a flat roof.

The main source of income for the church comes from visitors and worshipers who make use of the church from a tourist and religious point of view. The influx of visitors (tourists) guarantees a revenue stream that is mostly reinvested in the maintenance of the building.

2.2. Building Monitoring

As part of the preventive conservation strategy, a monitoring system was installed in the church. Six Testo 160 IAQ sensors were installed: three at the bottom of the church main nave walls at 1 m high and three at the top of the gothic arches at 4 m high. The sensors were distributed throughout the church floor, alternately, on both sides of the main nave. These sensors are autonomous and wireless and collect data on relative humidity, indoor temperature, atmospheric pressure, and CO_2 concentration every 15 min. These data have been collected continuously since the installation of the sensors. Calibration of the sensors is carried out periodically by comparing their readings with those taken through a portable Testo 435-2 sensor. The precision of the measuring equipment is shown in Table 1.

Table 1. Summary of measuring instruments and their characteristics.

	Model	Measuring Range	Accuracy
Humidity/temperature/CO_2 probe	Testo 435-2	−20–+70 °C +10–+100% HR 0–+10,000 ppm CO_2	±0.3 °C ±2% HR ±75 ppm CO_2
Humidity/temperature/CO_2 DataLogger	Testo 160 IAQ	0–+50 °C 0–+100% HR 0–+5000 ppm CO_2	±0.5 °C ±2% HR ±50 ppm CO_2

The data were compared with meteorological data (external temperature and relative humidity) of the city of Valencia, which was collected by the Spanish Meteorological Agency at the meteorological station closest to the church [78].

Because the summer of 2023 was the hottest since records began in the city of Valencia, and because the temperatures and relative humidity reached inside the church have been very high, it was decided to use the monitoring data that covered this period (1 May to 31 October). The monitoring information was transmitted to a processing system and applied to the digital twin of the church. During this period, visitor numbers were counted with the aim of defining patterns and of understanding how visitors affect the behaviour of the building and impact the conditions of the heritage assets. The church has a capacity of approximately 230 people, which is only reached during large celebrations, such as weddings.

3. Results

3.1. Analysis of the Data Obtained by Monitoring

During the study period, a total of 103,680 readings were taken for each of the analysed parameters. An hourly analysis was carried out to understand the global behaviour of the church, analysing the data every 15 min in the most detailed analyses. The results obtained from monitoring can be seen in Figure 5. The church tends to stabilise the temperature variations that occur outside, and an ascending pattern is exhibited, reaching the maximum indoor temperature during the month of August. The temperature inside the church is above the maximum temperatures collected outside from 1 May to 10 June, from 28 August to 26 September, and from 19 October to 30 October. During the study period, outdoor air temperatures in Valencia city were between 13 and 38 degrees Celsius, with temperatures inside the church between 23 and 30 degrees. The internal temperature starts to drop through the night, although this drop does not occur fast enough to ensure a comfortable internal temperature at the beginning of the next day. At the start of the day, the energy released from the stone structure, the solar gain from the windows of the presbytery, and the heat from the visitors (to a lesser extent) cause the temperature to rise again, usually from a higher starting temperature than the previous day.

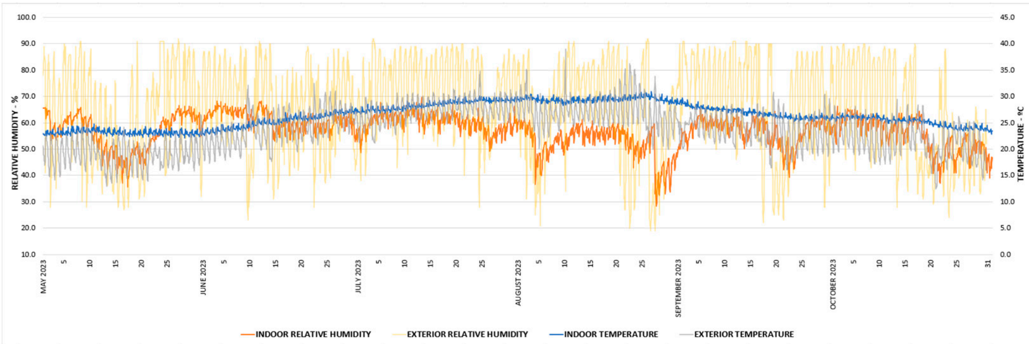


Figure 5. Complete monitoring of the Church of San Juan del Hospital: indoor temperature, outdoor temperature, indoor RH, and outdoor RH.

The variation in relative humidity inside the church was smaller in range when compared to outside measurements. The relative humidity in the church was between 50% and 70%, while outside, the city recorded a humidity between 25% and 90%. In this case, there was a small increase in the relative humidity, but the church, as with the temperature, does not reproduce the external trend. The church reproduces the pattern of ups and downs in outdoor relative humidity but is not able to increase and decrease the percentage at the same rate as is shown outside. This limitation in the variation in relative humidity, which has its origin in a lack of ventilation, has a positive and a negative side. The positive side is that the church does not reflect the extreme values that are collected outside, but on the other hand, it does not reflect the decreases that occur in the external climate and that can be beneficial for the conservation of heritage.

A more detailed analysis of the church's behaviour can be seen in Figures 6 and 7, which show interior monitoring data during the period between 13 July and 27 July. These figures show a comparison of the interior conditions of the church in terms of temperature, relative humidity, CO_2 concentration, and visitor capacity and the exterior conditions.

External variations in temperature only affect interior temperatures positively, and the church is not able to reduce outdoor temperature during the night period, in which the outside temperatures drop, as shown in Figure 6. It should be noted that in this period, the outside temperature in the city of Valencia did not fall below 25 °C, an unusual situation according to the geographical location of the city and the official climate records.

The third variable monitored was the concentration of CO_2 inside the church. In this case, a comparison must be made with the visitor capacity as there is a direct relationship between the concentration of CO_2 in the church and the number of visitors. As it can be seen in Figure 7, the attendance of people for tourist visits or religious services generates an immediate increase in the concentration of CO_2, and the church may need up to 20 h to recover the levels prior to the activity in the highest cases. Comparing the temperature and humidity with the visitor capacity, the influx of people has a minimal effect on the temperature, while slightly increasing the relative humidity. Taking the week of 21–27 August 2023 as an example, Figure 8, higher concentrations of CO_2 are reached due to the number of services with a large influx of people attending them; it is shown that CO_2 concentrations reach the limit close to 1500 ppm. CO_2, together with a temperature close to 30 °C and a relative humidity between 60% and 70%, creates interior environmental conditions that are considerably different from those needed for heritage conservation and which create uncomfortable conditions for visitors.

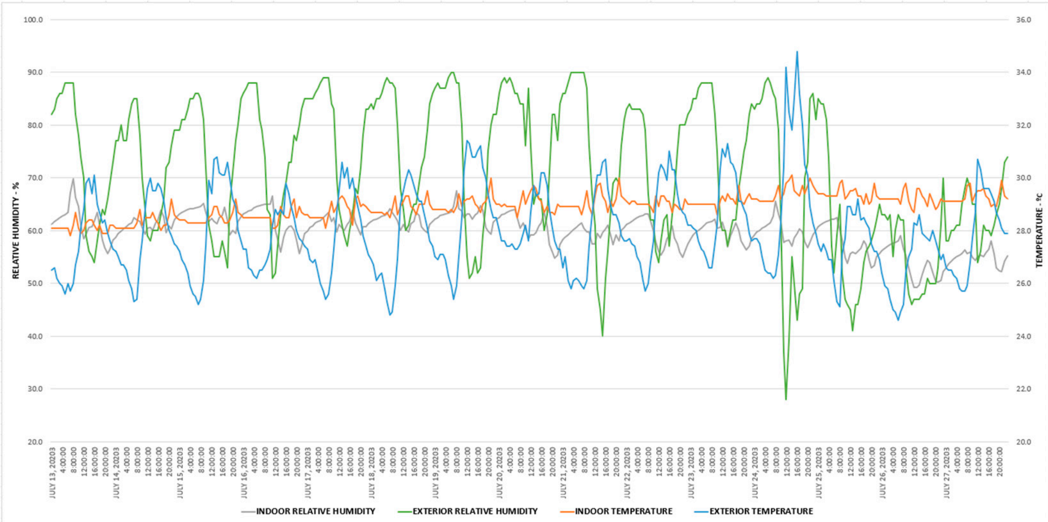


Figure 6. Monitoring of the indoor temperature, outdoor temperature, indoor RH, and outdoor RH.

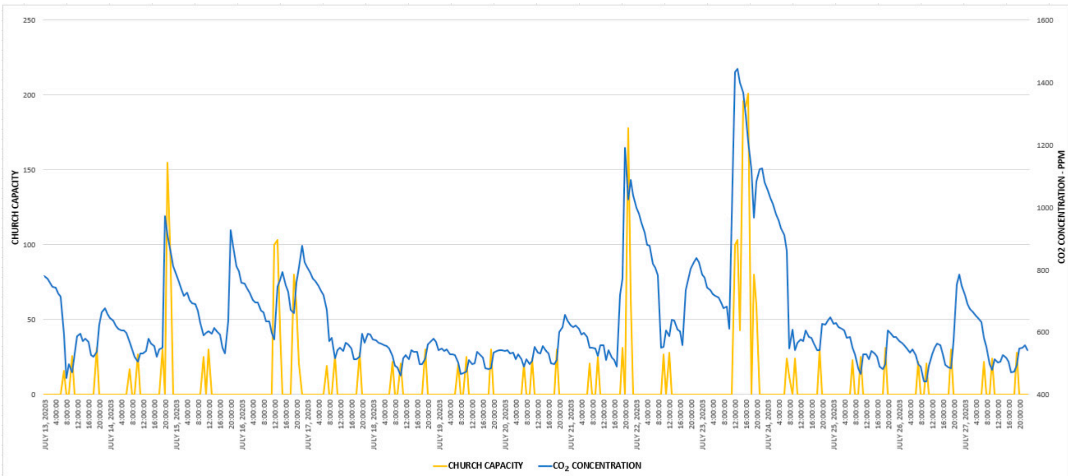


Figure 7. Comparison between CO_2 concentration and visitor capacity.

In Figure 9, the church behaviour on 26 August can be seen in detail. The indoor temperature was between 29.5 and 30.6 degrees Celsius, while the relative humidity was between 48.8 and 60.3%. The indoor environmental conditions were in contrast with the outdoor conditions. The temperature ranged between 23.9 and 31.4 degrees Celsius. A relative humidity between 62 and 91% was recorded. The relationship between capacity and CO_2 concentration and the time that the church needs to return to the previous CO_2 levels after the activity that generated it has finished can also be seen in the figure.

An analysis of the data obtained from monitoring confirms that the church does not benefit from external thermal changes and cannot reduce the interior temperature during drops in exterior temperatures. This same situation is reproduced with relative humidity, although on some occasions, this could be considered beneficial because the levels that occurred in the city were higher than those in the building. At the same time, it is noted that visitors have a significant influence on the concentration of CO_2 and that the CO_2 cannot be dissipated at the same rate as it is produced. The data also show that the interior conditions are far from ideal for heritage conservation. The indoor temperature and relative humidity are outside the acceptable thresholds, and the influx of visitors generates CO_2 concentrations that are considered harmful to the maintenance of buildings and negatively impact the health of visitors.

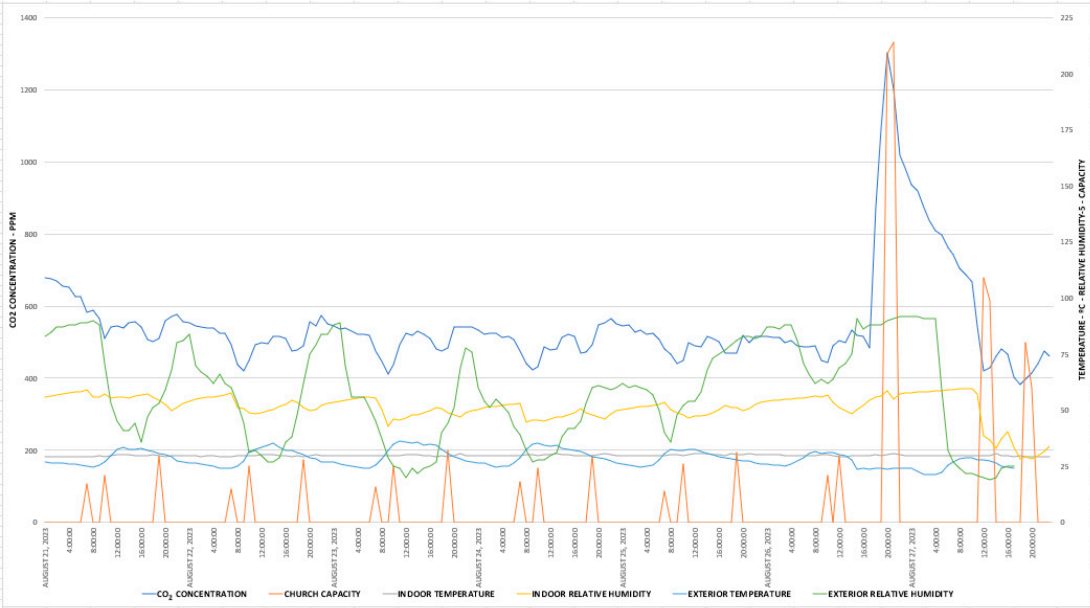


Figure 8. Comparison between indoor temperature, outdoor temperature, indoor RH, outdoor temperature, CO_2 concentration, and capacity (21–27 August).

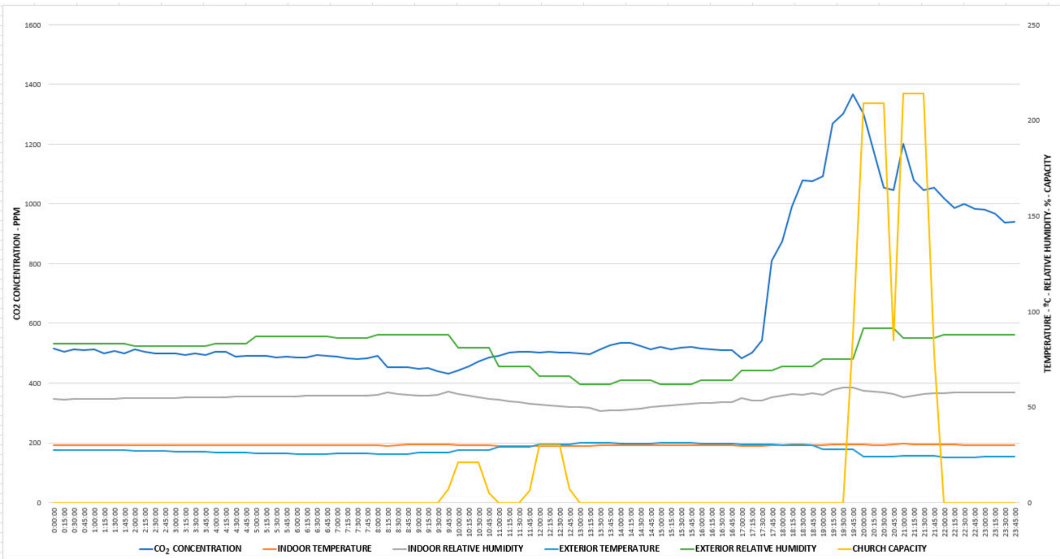
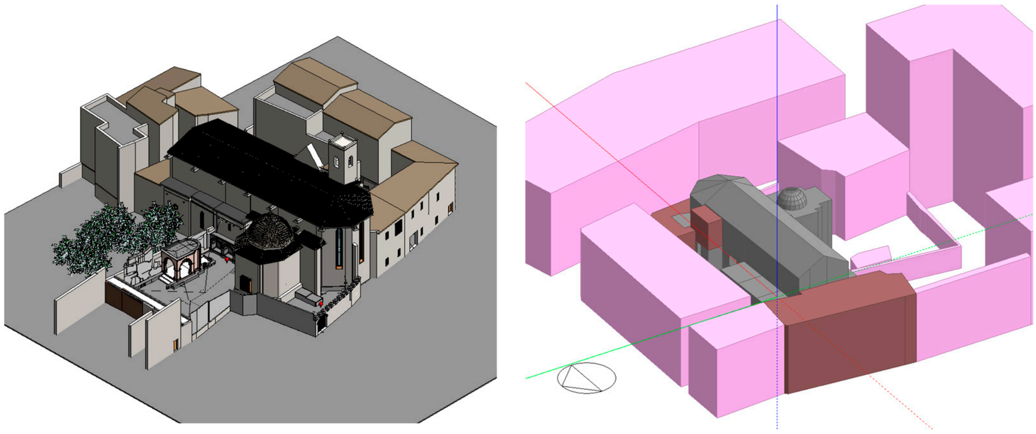


Figure 9. Comparison between indoor temperature, outdoor temperature, indoor RH, outdoor temperature, CO_2 concentration, and capacity (26 August).

3.2. Definition of Corrective Strategies Based on Simulations

The church has a master plan for its conservation. Among the actions included in this document is the drafting of a preventative maintenance plan that, since 2018, has featured an HBIM (Figure 10a) made in Autodesk Revit as a centralised repository of information that has proven its value in the process of conservation of the building [31–33]. From this HBIM, it was possible to generate a DT for the simulation of corrective strategies and to support decision-making processes. The DT was generated in DesignBuilder and exported to EnergyPlus (Figure 10b).



(a) (b)

Figure 10. Digital building models: (**a**) HBIM; (**b**) digital twin.

The DT was validated with the data from the monitoring programme and the capacity monitoring. It provides a building performance model that is very close to the real building with minimum errors.

The validation of the digital twin was carried out in accordance with the provisions of the ASHRAE Guideline 14 standard for the calibration of simulation models of building behaviour through monitoring data [79]. This regulation is designed to, among other things, validate relative humidity and temperature data, but in this research, it was also used to calibrate the CO_2 concentration.

In accordance with what is indicated in this regulation, the normalised mean bias error (NMBE) and the coefficient of variation of the root mean square error (CV(RMSE)) were calculated hourly for each of the monitored parameters, all of them being below the limits set by the regulation. In this way, 4320 data taken hourly in situ for each of the parameters under monitoring could be compared with their DT counterparts, exhibiting the errors defined in Table 2 for each of the monitored parameters. Research is currently underway improve the validation of the digital twin to reduce the error between simulation and reality. However, the researchers are confident that these errors do not negatively impact the results reported in this article.

Table 2. Summary of NMBE and RMSE according to ASHRAE 14.

	Limit	CO_2, ppm	Temperature, °C	RH, %
Normalised Mean Bias Error (NMBE), %	±10	9.32	8.58	−8.76
Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), %	30	15.30	9.89	25.87

The simulations carried out with the DT focused on detecting which measures would be the most appropriate to improve the indoor environmental conditions of the church without resorting to mechanical conditioning systems.

The first simulation focused on a reduction in the visitor capacity in the church. As can be seen in Figure 11, to keep the church below 500 ppm, it is necessary to limit the capacity to below 5% of its maximum capacity. Considering that the church has a capacity of 230 people, this means that there could only be 11 people inside at any one time. This would mean that the church in its current condition would not be able to host large celebrations, putting the calendar of activities that it currently has at risk. As can be seen in the figure, the limitation of capacity has little impact on humidity or temperature. It is, therefore, necessary to concentrate on improving ventilation, given that even limiting the capacity to 5% of its maximum capacity, the church is at concentrations close to 500 ppm CO_2. Two new scenarios were designed in which ventilation is improved by (a) opening the three doors during the day and (b) opening the three doors at night (recognising that this option may have security implications).

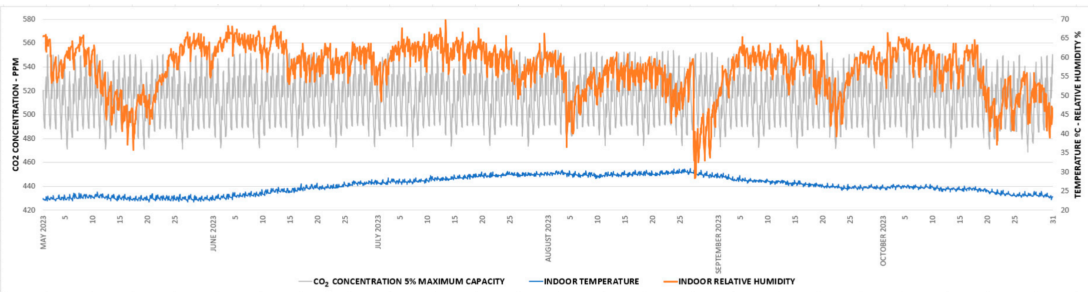


Figure 11. Comparison of indoor temperature, indoor relative temperature, and CO_2 concentration with capacity limited to 5% of the maximum.

Figure 12 shows that an increase in the ventilation of the church during the day improves the overall performance of the church from the point of view of CO_2 concentration, although it worsens the situation in terms of relative humidity. Opening the doors has hardly any effect on the interior temperature. However, CO_2 concentrations are above the maximum required at times when a large influx of visitors is reached, so this measure would only be effective if combined with a restriction on occupancy. The opening of the doors makes it possible to reach the extreme higher values of relative humidity that occur in Valencia during the study period with percentages close to 100%. At the same time, CO_2 concentrations close to 800 ppm appear, which, although lower than those reached with regular use, are still high.

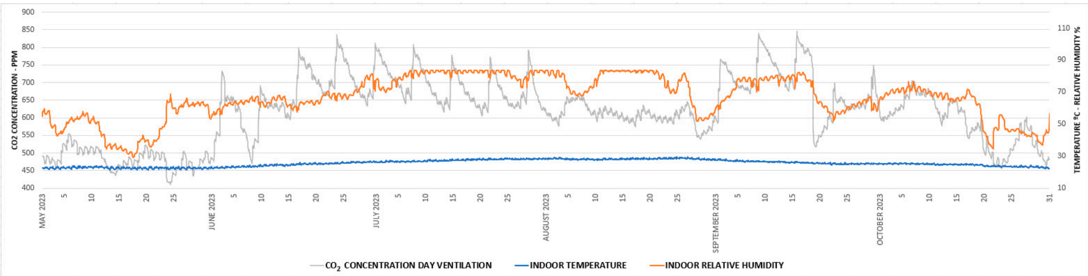


Figure 12. Comparison of indoor temperature, indoor relative temperature, and CO_2 concentration providing ventilation during day activities.

As an alternative to the daytime opening, a study of the influence of temperature and ventilation during the night was performed. During the study period, the outdoor night temperature drops, although not to the necessary limits, and at the same time, the relative humidity drops. As can be seen in Figure 13, greater nighttime ventilation generates a greater reduction in CO_2 concentrations after a religious event with many people. At the same time, it allows for an improvement in the indoor temperature. However, the relative humidity, as with the door open during the day, is more similar to the outdoor conditions. In this case, the decrease in the concentration of CO_2 occurs more quickly, although at times when there is a greater influx of visitors, the concentrations are still around 800 ppm. This means that the viability of this proposal is also reliant on a restriction in visitor numbers, like the previous one.

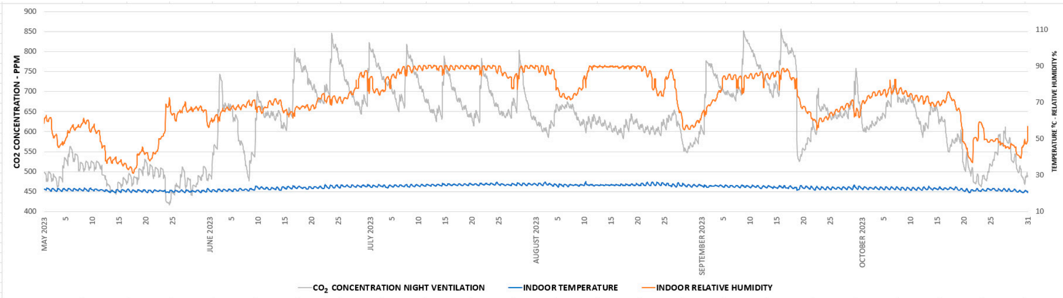


Figure 13. Comparison of indoor temperature, indoor relative temperature, and CO_2 concentration when providing ventilation during night.

Since all simulations indicate that the building does not have enough openings for natural ventilation to lower the temperature, humidity, and CO_2 concentration levels, a calculation was made using mechanical ventilation. An indoor CO_2 concentration below 500 ppm could be achieved by means of a ventilation system that provides a flow rate of 0.5 renovations/h. To achieve this ventilation rate, it would be necessary to install two centrifugal fans with a power of 245 W that operate at 900 revolutions per minute. The renewed air must be distributed through a network of ducts so that the air enters gradually. The air inlet should have a section of 0.24 M2 that could be divided into four bars of 0.50×0.25 m^2 assuming a passage coefficient of 0.5. The size of these fans is small, at $565 \times 521 \times 508$ mm. However, the main issue of installing them comes from the impact of the needed wall perforations and the position of the air conducts over the protected walls.

To achieve a CO_2 concentration below 500 ppm, it would be necessary to have the fans working for 7180 h/year, which would use 2297 kWh. Considering the average price per kWh of electricity in Spain in 2023, which stands at 0.13 kWh without including taxes, this implies an annual energy cost of EUR 298 plus taxes. If it were considered necessary to reduce humidity and temperature, it would be necessary to install a dehumidifying and conditioning machine. This equipment of considerable size would need to operate 40% of the year, with a consumption of 29,784 kWh, generating a significantly higher cost of EUR 3871 plus taxes.

4. Discussion

The analysis of the results obtained from monitoring shows that the church is an airtight construction, and there is a significant need for ventilation. Due to its configuration and construction, the church demonstrates a high degree of thermal inertia, producing progressive heating throughout the research monitoring period. This warming is rooted in energy gains through the solid stone enclosures, solar gains through the chancel windows, and interior gains from lighting and visitors. However, the influence of visitors is less than other factors. These gains cannot be compensated for during the period of the day when temperatures drop, demonstrating the importance of thermal inertia in the study of this type of building.

From the point of view of relative humidity, the church also proves to be quite airtight, not having enough practicable openings to ventilate its interior. In normal use, the openings allow the interior of the church to differ from the extreme situations that occurred in Valencia during the period of study. Using the openings at different times of the day worsens the indoor humidity, bringing it closer to the conditions outside the church. This would also generate security problems, since more access points would have to be controlled than are currently used.

The concentration of CO_2 is the parameter most influenced by visitors to the church. The adoption of passive measures to improve ventilation by opening the operable elements of the building is totally ineffective, and it is therefore necessary to limit capacity to mitigate damage. Reducing the capacity to a maximum of 5% of the maximum occupancy to a maximum of 11 people is not practical. This would mean eliminating practically all activity within the building with the risk of abandonment that this entails. In addition, the income generated from visits and religious services, which is needed for the maintenance of the building, would be significantly reduced, making it unfeasible. To improve the indoor environmental quality of the church and guarantee the conservation of activities, income, and heritage, it would be necessary to adopt active conditioning systems. This would involve introducing ventilation systems that would have to be combined with dehumidification and cooling for a large part of the summer if the humidity and temperature were to be controlled. This has cost implications for the church and unless designed and installed with respect for the building's character, it could be visually intrusive. This would imply that in a Gothic building where the architectural value is found in the structure, dissonant elements would appear in the form of ducts for the diffusion of air conditioning, with a complicated relationship with the geometry of the church. These ducts would need to be placed in the upper part of the arches of the main nave to avoid excessive stratification of temperatures inside the building during the warm period of the year.

At the same time, the introduction of powerful conditioning equipment would require an upgrade of the electrical installations to support the necessary electrical consumption. Furthermore, a detailed study would be necessary to minimise the environmental impact of this new installation by introducing elements that generate clean energy, which could also increase the impact on the protected elements of the building.

5. Conclusions

This research confirms that there may be conflicts between regular use and tourist visits to heritage buildings. Excessive capacity can generate environmental situations that endanger the protected elements of these buildings. Limiting capacity can be a solution, but it can also be a risk because these buildings can fall into disuse and also lose one of their main sources of income for their maintenance. A balance needs to be found for each individual building and its context. The methodology followed in this research could be the starting point for the development of strategies that allow for the regulation of capacity in similar buildings where there is no adequate ventilation and where there are important limitations for the installation of conditioning systems.

Within these strategies, the monitoring of historic buildings is a valuable tool to understand the interior environmental quality and the behaviour of the building over time. This can help to detect situations that may put the conservation of their heritage assets at risk. The data obtained from the monitoring confirmed that the regular use of these buildings generates indoor environmental conditions that exceed the appropriate limits to ensure the conservation of paintings and other cultural artefacts. The research findings demonstrate that the architecture and construction help to achieve high levels of temperature, relative humidity, and CO_2 inside the church. The lack of operable openings limits natural ventilation to the interior, causing an inadequate indoor environmental quality, and the building does not take advantage of the drops in temperature and humidity that occur outside. This research shows that a reduction in capacity is necessary to improve indoor hygrothermal conditions and reduce the concentration of CO_2 to acceptable levels. The alternative is to install active ventilation and conditioning systems, the installation of which could clash with the architectural values of protected buildings and which will require electricity, hence negatively impacting the environmental impact of the church.

This research opens the debate on the responsible use of heritage by society. There are many buildings from the same period with a similar architectural configuration and with difficulties in ventilation that receive many visitors. Strategies must be developed to allow the use and at the same time the conservation of heritage while keeping the temperature, humidity, and carbon dioxide below the maximum levels. In this sense, this research also confirms that the use of new technologies, such as digital twins, with preventative maintenance plans helps to inform the decision-making process for building managers. Simulations based on actual data readings make it possible to design appropriate maintenance strategies, which include visitor control.

6. Future Research

The methodology followed in this research is currently being applied in two protected buildings in the city of Valencia. Both buildings have high visitor numbers due to cultural tourism, and both buildings face the same challenge of trying to balance visitor numbers with income and the protection of its cultural heritage. The monitoring of these buildings and resulting digital twins will be of considerable value to building managers and researchers as there will be an opportunity to further validate the methodology and narrow the gap between monitoring and simulations.

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