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The impact of tourism on the conservation and IAQ of cultural heritage: The case of the Monastery of Jerónimos (Portugal)

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ABSTRACT

Cultural heritage plays a crucial role in modern societies as a symbol of their past and as a way to safeguard their identity in a continuously changing world. Interest in cultural tourism has been growing significantly, and in 2015 it was estimated that it was responsible for 40% of European tourism.

Cultural tourism can be a major contribution to the economy of each country, as well as a potential vehicle in facilitating the preservation of cultural heritage if properly managed. However, the high number of visitors will contribute to higher humidity and CO_2, disrupting the historic climate, and can constitute a real risk for the conservation and indoor air quality. COVID-19 has slowed tourist routes around the world, and this reflection period can be used to assess the sustainability of mass tourism.

This paper intends to evaluate the impact of tourism on one of the most emblematic Portuguese monuments, the Monastery of Jerónimos, a UNESCO World Heritage building located in Lisbon. For this purpose, a simulation model of the Monastery was developed with the software WUFI®Plus and validated against the real data. The impact of visitors was evaluated according to the past occupancy, and a forecast for 2027 was performed, analysing the risks for conservation and indoor air quality. It was possible to conclude that even for the current data there was already a risk of fungi proliferation, and that any of the future considered scenarios increases this risk and contributes to the degradation of the indoor air quality.

1. Introduction

Cultural heritage plays a crucial role in modern societies as a symbol of their past and as a way to keep their identity safe in the future. Its conservation is a challenge to ensure cultural diversity in a continuously changing world [1,2]. Cultural heritage represents not only one of the most important facets that embodies the identity, traditions and practices of a country, particularly with the significance of its evolution throughout history, but also an integral part of modern life, since it stimulates the economy, especially due to the touristic activity [3].

Since most world heritage sites are touristic locations, their cultural value becomes an important indicator in enhancing an intercultural dialogue based on cultural diversity that enriches visitors from different parts of the world. Accordingly, tourism can be a major contribution to the economy of each country, as well as a potential vehicle in facilitating the preservation of cultural heritage if properly managed [1].

Europe has some of the most extraordinary examples of cultural heritage in the world. Although the impact of cultural heritage on the economy of the states is not yet fully known, there is some evidence to prove its importance. In 2015, a European report has recognised that cultural tourism accounts for around 40% of European tourism, representing a key economic sector with high growth potential [4].

A Eurobarometer report [5] reinforces the importance of cultural heritage for the European Union (EU) based on 27 881 surveys, reporting that 84% of Europeans consider cultural heritage to be important to them personally and 90% believe it is important for their country. This study also concluded that 82% of Europeans are proud of the monuments or historical sites, works of art or traditions of their region or country.

Despite the potential of tourism for heritage and economic issues, its management must be considered by all stakeholders, since excessive tourism can jeopardise the physical integrity and significance of heritage as evidenced by the International Cultural Tourism Charter first presented in 1999 by ICOMOS [1]. Since then, several documents have been published defending sustainability as a way to preserve cultural heritage and addressing the interrelationship between tourism and cultural heritage, as mentioned in Ref. [2,6–9]. Additionally, the UN's Agenda 2030 and Sustainable Development Goals (SDGs), ratified by 193 countries in

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2015 [10], incorporated a new global framework for sustainable development for the next 15 years, and for the first time, within the sustainable development goals, there is an explicit cultural heritage target to strengthen efforts to protect and safeguard the world's cultural and natural heritage.

In fact, the interest in cultural heritage is not only an opportunity but also a threat to the conservation of buildings and collections, to the visitors' comfort and to their sustainability. The increasing number of visitors acts as a disruptive factor affecting the stability of the indoor climate and compromising the conservation and comfort, since they release heat, water vapour and carbon dioxide in addition to the transport of exterior pollutants [11,12].

In air-conditioned buildings, such as museums or other important buildings, this can lead to an increasing energy demand and degradation phenomena in the envelope, since ancient buildings are usually characterised by poor hygrothermal behaviour [13]. On the other hand, in naturally ventilated and unheated buildings, as is the case of most of the churches and monasteries in southern Europe, the high number of visitors will contribute to higher humidity and CO_2, since the ventilation does not follow the increase of internal loads.

Within the EC-project 'Assessment of environmental risk related to unsound use of technologies and mass tourism' (ENV4-CT95-0088), Camuffo et al. [12] published one of the reference works in this field. Among other subjects, the influence of mass tourism in four European museums (Correr Museum, Venice, Italy; Kunsthistorisches Museum, Vienna, Austria; Royal Museum of Fine Arts Antwerp, Belgium; Sainsbury Centre for Visual Arts, Norwich, United Kingdom) was studied. The authors concluded that despite the positive impact that tourism has on the economy, it poses some risks for artworks, since visitors are responsible for transporting pollutants, water vapour, CO_2 and heat emissions that cause disruption to the conditions that cannot be overcome even with powerful HVAC systems. It is possible to find other studies that relate the impact of visitors on conservation or on the indoor climate, such as the work carried out at Royal Museum of Fine Arts (Antwerp, Belgium) [14] and the papers about the Scrovegni Chapel (Padova, Italy) [15,16] or about the Casa di Diana [17].

Despite this evidence, only 37% of Europeans believed that the growing tourism can be a threat to heritage conservation [5]. At present, the importance of sustainable tourism and cultural heritage has been highlighted, notably in 2017 the United Nations International Year of Sustainable Tourism for Development [18] with greater understanding among people and awareness of the value of heritage, thus contributing to its preservation [19]; and in 2018 the European Year of Cultural Heritage [20] with the slogan "Our heritage: where the past meets the future" with the aim of encouraging the search for new ways of celebrating and preserving heritage and encouraging people to discover European cultural heritage and to strengthen the sense of belonging to a common European area.

Despite the current pandemic, COVID-19 has slowed tourist routes around the world, and this period of reflection seems to be the ideal time to evaluate the impact of tourism on the conservation, comfort and sustainability with the aim of enabling careful management of the heritage in the future.

This paper intends to evaluate the impact of tourism on one of the most emblematic Portuguese monuments, the Monastery of Jerónimos, a UNESCO World Heritage building located in Lisbon. For this purpose, a simulation model of the Monastery was developed with the software WUFI®Plus and validated against the real data. Then, the impact of visitors was evaluated according to the past occupancy rates, and a forecast for 2027 was performed, analysing the risks for conservation and indoor air quality.

2. The cultural heritage tourism in Portugal

Global political uncertainty and terrorism have triggered a decrease in the touristic demand in some traditional destinations, and other countries like Portugal have emerged, where the tourism revenues grew faster than the economy for eight consecutive years, achieving a growth of about 20% from 2016 to 2017 and a direct impact of 7.8% in the Gross Domestic Product (GDP) [21,22]. Currently, due to COVID-19, tourism has slowed down, and it is difficult to predict what will happen in the near future. However, there is no reason to think that the situation will not resume once the pandemic is controlled.

The increase in general tourism has also contributed to the increasing interest in the Portuguese cultural heritage that incorporates more than 450 buildings classified as national monuments [23]. With regard to cultural tourism, according to the Portuguese Directorate-General for Cultural Heritage, the number of visitors increased by 55% from 2010 to 2016, where foreigners represented 70% of the total visitors.

The Monastery of Jerónimos is one of the most evident cases of the increasing interest in the Portuguese heritage, with an increase of 154% in the number of visitors from about 460 000 in 2005 to over 1 M in 2017, resulting in an average annual growth of 11%/year over the last 5 years [24]. These numbers refer to the cloister of the Monastery. However, the Monastery also includes a majestic church in which visitors' entrance is neither controlled nor paid and where the number of visitors was estimated as 3 times that of the cloister, representing a total of more than 3 million visitors in 2017. The evolution of the number of visitors in the church and the distribution between national and foreign visitors can be seen in Fig. 1. Between 2005 and 2017, the foreign visitors made up 92% of the total.

Relating the total number of nights spent in Portugal with the number of visits in the Monastery, the presence of a direct relationship between 2012 and 2017 was noted, as shown in Fig. 2. During this period, one visit to the Monastery was registered for each 22 nights spent in Portugal. This conclusion reinforces the growth tendency verified in the visits to the Monastery during the last years and the future scenarios.

The Portuguese Government carried out an analysis of the impact of tourism in the country and defined a growth strategy entitled "Tourism Strategy 2027" [27]. In this report, published in 2017 [27], a great emphasis was given to the role of tourism in Portugal's economic growth. The Portuguese Government predicted three scenarios for the number of nights spent until 2027. The worst scenario predicts a growth of 3.1%/year that approaches the average growth rate of 3.2%/year verified between 2005 and 2015. The Portuguese government has set a growth target of 4.2%/year to 2027, believing that this is the most plausible one. In addition to these two rates, the effect of a more optimistic growth scenario was analysed, considering a rate of 6.1%/year that approaches the average growth rate verified between 2012 and 2017.

Considering the three scenarios of tourism growth presented by the Portuguese government and the average growth rate of visitors at the Monastery of 11%/year during the last 5 years, the number of annual visitors until 2027 was estimated, as can be seen in Fig. 3.

Fig. 1. Visitors at the church of the Monastery of Jerónimos [24].

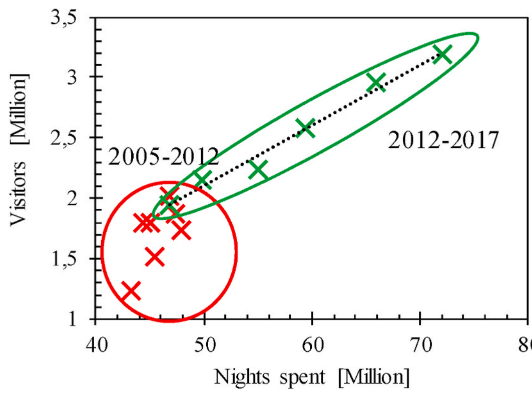

Fig. 2. Relationship between the total nights spent in Portugal and the visits to the Monastery of Jerónimos [25,26].

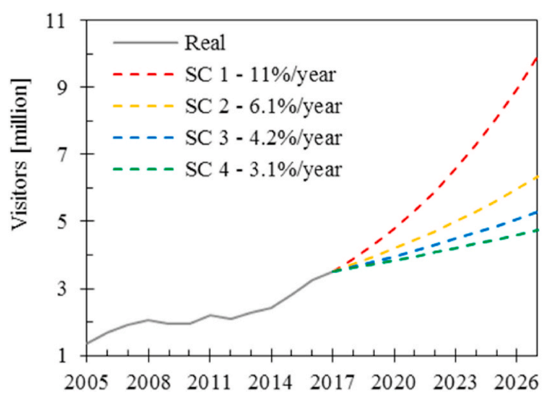

Fig. 3. The increasing visitors' scenarios in the Monastery of Jerónimos.

3. Methodology

3.1. General considerations

Mass tourism can have a negative impact on the conservation of buildings and artefacts and on the health and comfort of visitors. As regards the Monastery of Jerónimos, respiratory, cardiovascular and nausea problems are regularly reported in the days of higher influx according to unpublished Monastery Directorate reports. These reports make it possible to question the sustainability of current and future tourism and highlight the need to analyse several future scenarios and to study the indoor climate to define a safe strategy that will safeguard the heritage for future generations.

A recent paper published by Silva et al. [28] describes a complete climate monitoring campaign carried out for more than a year in the Monastery of Jerónimos. The authors characterised the indoor climate in terms of temperature, relative humidity and CO_2, estimating the mean air change rate. Despite the effectiveness of the monitoring campaigns for microclimatic analysis, the resulting data do not allow to test other scenarios, either in terms of building refurbishment, changes in the internal gains or the impact of different climate control strategies. The use of properly validated simulation models is a useful tool to test various solutions and to support the decision-making process.

In this paper, the authors define the methodology to quantify the impact of the visitors using a validated simulation model developed with the software WUFI®Plus [29], testing various future scenarios. The authors begin by describing the growth of cultural tourism in Portugal and the future scenarios, presenting the building and the simulation model, addressing the risks for the conservation and the indoor air quality and finally simulating various scenarios to quantify the impact of visitors in the indoor climate.

The WUFI®Plus is a powerful tool to simulate the hygrothermal conditions of buildings, allowing to consider heat and moisture exchanges with the elements and exterior environment, considering internal loads and the impact of ventilation [30].

There are several internationally published cases reporting the simulation of buildings with this software [31,32], including cultural heritage buildings, including the chapel of ease St. Margaretha in Germany [33], the National Museum in Krakow [34], or the church of São Cristóvão in Portugal [35].

3.2. Case study

3.2.1. Building geometry and construction elements

The Monastery of Jerónimos is one of the most emblematic monuments of Portugal, built in the 16th century, classified as national monument in 1907 and listed as World Cultural Heritage in 1983 by UNESCO [28]. The church is west–east oriented and presents a Latin cross configuration. Inside, the church is composed by a nave, a crossing, two transepts at south and north, a main chapel and a high choir. The model was designed in accordance with the blueprints provided by the Monastery Directorate and confirmed by on-site measurements. The church is 90 m in length, 23 m in width at the nave and 50 m at the transepts and has an average height of 24 m [28], as can be seen in Fig. 4a) and b). The church has a net area of around 2015 m^2, with about 1245 m^2 for the touristic route, 615 m^2 exclusively for religious celebrations and the remaining area for the altar and other religious spaces.

The church is composed by thick walls of limestone of varying thickness according to the orientation: about 2 m on the south wall and 2.5 m on the east and west walls; at north, two parallel walls separating a staircase present an average thickness of 1 m each [28]. The model geometry can be seen in Fig. 4 c).

The slab has about 0.2 m of limestone directly discharging the structural loads into the soil. The walls are made with two masonry layers of limestone, each 0.2 m thick, and the remaining space is filled with clay soil. This technique was widely used at the time [36]. The windows represent about 1% of the total floor area. The ceiling has limestone vaults and masonry over the top to support the roof. The thermal characteristics are based on Portuguese databases [36,37]. A summary of the construction features can be seen in Table 1.

3.2.2. Internal gains and ventilation

From September 2017 to August 2018, it is estimated that 3.25 M people visited the church, with main attendance in summer. The monthly and daily occupancy profiles can be seen in Fig. 5 and Fig. 6, respectively [28]. Usually the visits take 10–15 min. A typical duration of 10 min was assumed. The church is open to visits from Tuesday to Sunday from 10:00 h to 17:30 h between April and October and from 10:00 h to 18:30 h between May and September. Religious celebrations are held at 9:30 h and 19:00 h from Monday to Saturday, and at 9:00 h, 10:30 h and 19:00 h on Sunday and Holy Days.

For human occupancy, an average metabolic rate of 1.4 met was estimated assuming that the visitors spend 40% of the time walking calmly (1.7 met — walking about [39]) and 60% of the time stopped to observe the building and the artefacts (1.2 met — standing, relaxed [39]). Considering that 1 met corresponds to 58.2 W/m^2 and assuming a body area of 1.8 m^2 for an average male adult [39], it is possible to obtain the rate of energy produced per occupant. Since the released heat varies according to gender and age, a group divided equally among men, women and children was assumed. Considering that the amount of heat released by women is 85% that of men, and for children the percentage is 75% [40], an average value of 127 W/visitor was obtained.

The total rate of heat gain was divided into sensible and latent heat based on the polynomial equation used by the EnergyPlus software [41] as a function of the total gain and ambient temperature numerically calculated from (Eq. (1)) to fit the data published in Ref. [42]. A mean indoor temperature of 19.8 °C was considered in accordance with the

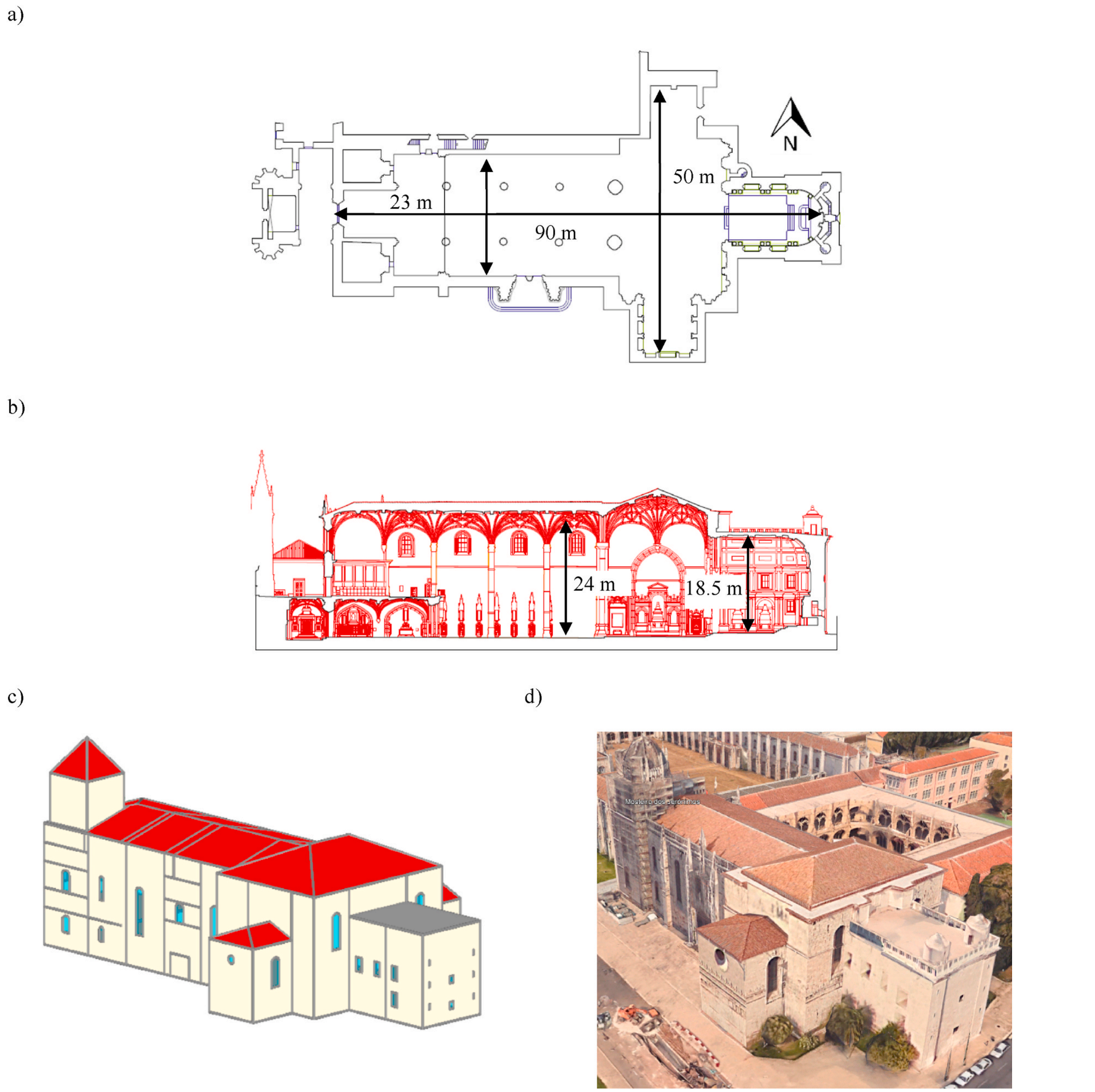

Fig. 4. Building geometry: a) horizontal plan (adapted from Ref. [28]); b) longitudinal cross-section from west to east (adapted from Ref. [38]); c) model geometry in WUFI®Plus; and d) exterior view (from Google Earth).

Table 1
Thermal properties of the building elements [36,37].

Building component	Materials	d [m]	λ [W/m.K]	ρ [kg/m^3]	C [J/kg.K]	U [W/m^2.°C]	Surface mass [kg/m^2]
Walls	Limestone	0.20	2.3	2400	850	0.57 to 1.3	1860 to 4110
Outside → Inside	Clay soil	0.60–2.10	1.5	1500	880		
	Limestone	0.20	2.3	2400	850		
Ceiling	Lime mortar	0.15	0.7	1785	850	2.0	748
Outside → Inside	Limestone	0.20	2.3	2400	850		
Floor	Limestone	0.20	2.3	2400	850	3.9	480
Windows	Wooden single-glazed window frames			U_w = 5.1 W/m^2.K		SHGC = 0.85	

mean value obtained in the building along the monitoring campaign [28], resulting in 89 W of sensible gain (60% emitted by radiation and 40% by convection [40]) and 38 W of latent gain.

$$\begin{aligned} S = {} & 6.461927 + 0.946892\cdot M + 0.0000255737\cdot M^2 + 7.139322\cdot T \\ & -0.0627909\cdot T\cdot M + 0.0000589172\cdot T\cdot M^2 - 0.198550\cdot T^2 \\ & +0.000940018\cdot T^2\cdot M - 0.00000149532\cdot T^2\cdot M^2 \end{aligned} \quad \text{(Eq. 1)}$$

where S is the sensible gain (W), M is the total gain (metabolic rate) (W),

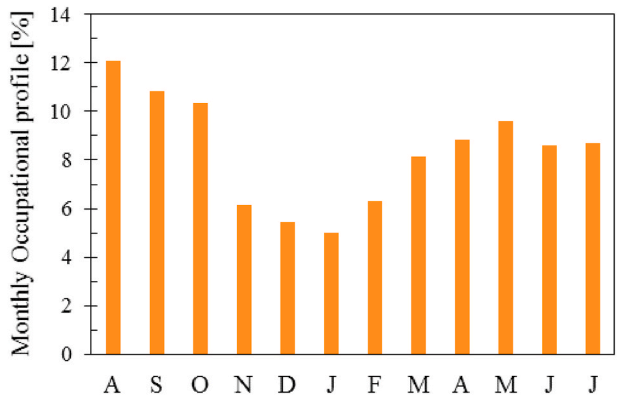

Fig. 5. Monthly occupational profile from August 2017 to July 2018 [28].

and T is the air temperature (°C).

The water vapour production rate of 61 g/h was obtained through the ratio between the latent gain and the value corresponding to the water evaporation enthalpy [43]:

$$\dot{m}_{w,vap} = \frac{L}{\Delta h_{vap}} \cdot 3600 = \frac{M - S}{\Delta h_{vap}} \cdot 3600 \qquad \text{(Eq. 2)}$$

where $\dot{m}_{w,vap}$ is the water vapour generation rate per person (g/h), L is the latent gain (W), M is the total gain (metabolic rate) (W), S is the sensible gain (W), and Δh_{vap} means the water specific evaporation enthalpy (2257 J/g [43]).

The CO_2 generation rate per person was obtained from (Eq. (3)) [44]:

$$V_{CO2} = \frac{0.00276 \cdot A_D \cdot met \cdot 3.6}{(0.23 \cdot RQ + 0.77)} \cdot RQ \qquad \text{(Eq. 3)}$$

where V_{CO2} is the CO_2 generation rate per person (m^3/h), met is the metabolic rate (met), here assumed as 1.4 met, A_D is the body surface area — an average value of 1.56 m^2 was adopted for a group equally divided among men, women and children, and RQ is the respiratory quotient that returns the ratio between the rate of CO_2 generation with the consumed oxygen and it equals 0.83 for an average adult in a sedentary activity. Thus, a CO_2 generation rate of 0.01872 m^3/h·person was obtained. At 21 °C and 1 atm, this value can be converted to 34 g/h [45].

It was considered that the church lighting is guaranteed by halogen and tungsten lamps. In a simplified way, a constant illuminance of 100 lux was admitted for the whole main room as made in Ref. [35], assuming that 50% of the lighting is guaranteed by halogen lamps with a luminous efficacy of 20 lm/W and the remaining 50% by tungsten lamps with a luminous efficacy of 15 lm/W [13]. The lighting power density was calculated by dividing the illuminance by the luminous efficacy, which results in a value of 5.8 W/m^2. In accordance with [46,47], the emitted heat by tungsten and halogen lamps can be divided into 30% radiant heat and 70% convective heat.

Regarding ventilation, Silva et al. [28] estimated an average air change rate of 0.13 h^{-1} for the church using the *concentration decay method* [44,48,49]. This ventilation rate agrees with others published in international papers addressing the same type of buildings [50–54].

3.2.3. *Weather data*

A weather file generated by the EnergyPlus Weather Converter [55] and based on the outdoor air temperature and water vapour pressure recorded in the tower of the church and the atmospheric pressure, wind direction and velocity, rain and global radiation data provided by the Portuguese Institute for Sea and Atmosphere (IPMA) for the Geofisico weather station (located at 1.4 km from the church) were used.

For the simulated year, from September 2017 to August 2018, Lisbon was characterised by an average temperature of 17 °C, with maximum and minimum values of 37.4 °C and 6.8 °C, respectively. As regards the relative humidity, average, maximum and minimum values of 67%, 100% and 18% were found.

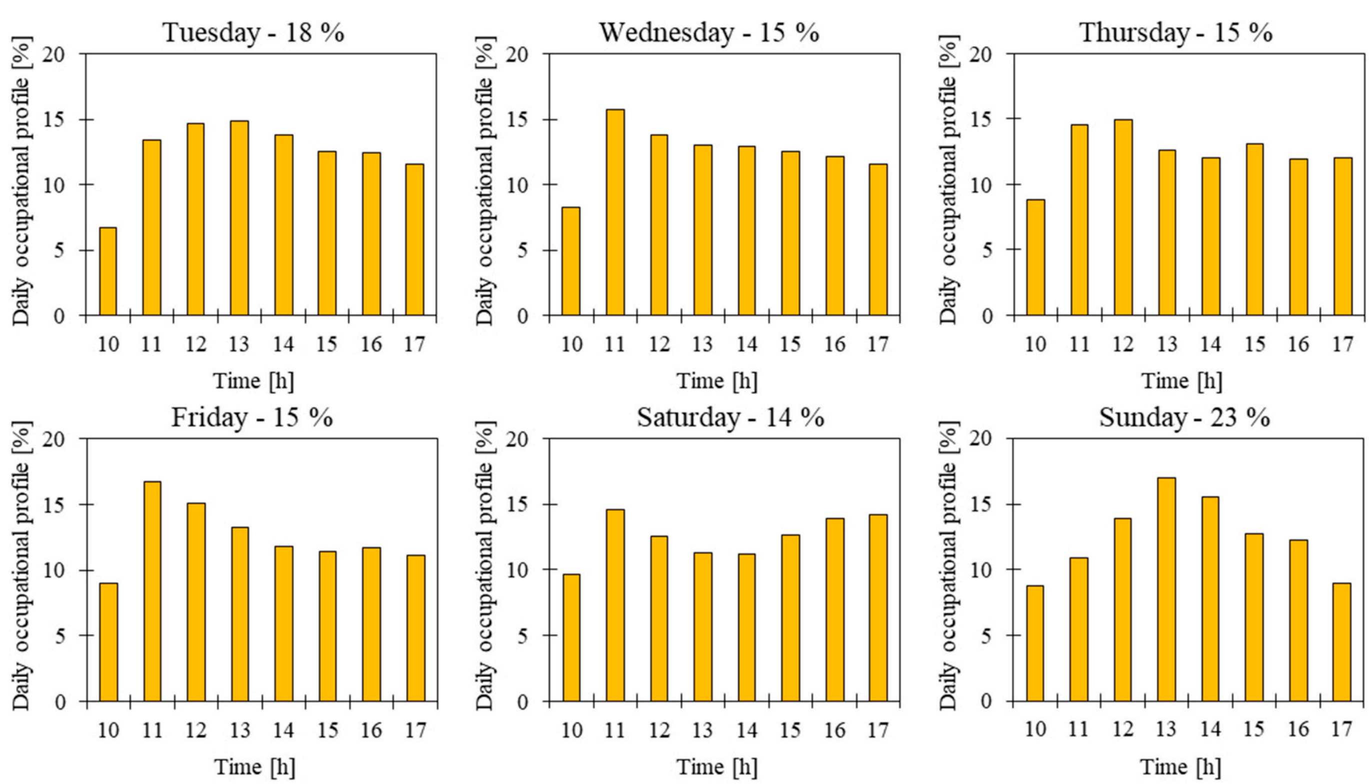

Fig. 6. Daily occupational profile [28].

3.3. Model validation and statistical analysis

The use of simulation models can be useful for testing various scenarios; however, models must represent the reality in a faithful way, otherwise the results can induce mistakes by decision-makers. The use of statistical indices published in the international literature and used in several papers (such as those presented in Ref. [56–61]) can contribute to the model validation and to ensure the robustness of the results.

The simulation model was validated against the recorded data obtained from a complete monitoring campaign carried out by Silva et al. [28]. A graphical comparison was made considering the real and simulated data of temperature and relative humidity for a whole year. A brief statistical analysis comparing the annual average, maximum, minimum, 2nd, 10th, 25th, 50th, 75th, 90th and 98th percentiles was made.

In addition, to guarantee the model robustness, three other statistical indices were used, namely the coefficient of determination (R^2), the normalised mean bias error (*NMBE*) and the coefficient of variation of the root mean square error (*CVRMSE*). The model is validated if the R^2 is higher than 0.75 [61] and the *NMBE* and *CVRMSE* are lower than 5% and 20%, respectively [61].

The R^2, which describes the correlation between the measured and simulated values, can be calculated from the equation:

$$R^2 = \left(\frac{\sum_{i=1}^{N} \left(X_{i,meas} - \overline{X_{meas}} \right) \cdot \left(X_{i,sim} - \overline{X_{sim}} \right)}{\sqrt{\sum_{i=1}^{N} \left(X_{i,meas} - \overline{X_{meas}} \right)^2 \cdot \sum_{i=1}^{N} \left(X_{i,sim} - \overline{X_{sim}} \right)^2}} \right)^2 \quad \text{(Eq. 4)}$$

NMBE expresses the general normalised mean error and shows the influence of smaller errors [56]. It can be calculated from the equation:

$$NMBE = 100 \cdot \frac{\sum_{i=1}^{N} \left(X_{i,meas} - X_{i,sim} \right)}{\overline{X_{meas}} \cdot (n-1)} \quad \text{(Eq. 5)}$$

CVRMSE demonstrates how the model fits the measured data, overcoming possible compensation mistakes of the *NMBE*, and it shows the influence of the higher errors [56]:

$$CVRMSE = 100 \cdot \frac{\sqrt{\frac{\sum_{i=1}^{N} \left(X_{i,meas} - X_{i,sim} \right)^2}{(n-1)}}}{\overline{X_{meas}}} \quad \text{(Eq. 6)}$$

3.4. Climate characterisation

3.4.1. Risk assessment

To assess the impact of visitors and indoor climate on conservation, the method published by Mecklenburg et al. [62] was used, based on the yield strain criterion, to assess the mechanical risk for the base layer of painted panels; to assess the risk of loss due to mechanical action in sculptures, the method published by Jakieła et al. [63] was selected. Since the objects do not respond instantly to climatic fluctuations, the response time of the collections was taken into account, as presented by Martens [64].

At the same time, it was considered pertinent to analyse the biological risk associated to the mould germination through the use of the isopleth method published by Sedlbauer [65,66]. This method considers, among others, the quality of the substrate, the relative humidity, the temperature and the exposure time necessary for mould germination.

To facilitate the analysis, the concept of *MRF* (mould risk factor) was used, which quantifies the time in which the pair *T* and *RH* is above a certain isopleth. The global *MRF* is achieved by a running sum of the instantaneous *MRF* for each isopleth. Comparing the coefficient achieved for each one, the highest *MRF* should be adopted. For a generic isopleth, the *MRF* is obtained from the following equation:

$$MRF = \sum_{i}^{a} MRF_i \quad \text{(Eq. 7)}$$

$$MRF_i = 0 \text{ if } f(T) < \text{isopleth } (t)$$
$$MRF_i = 1/(isopleth(t) \cdot RF \cdot 24) \text{ if } f(T) \geq \text{isopleth } (t)$$

where MFR_i is the instantaneous mould risk factor, $isopleth(t)$ is the germination time corresponding to a certain isopleth (days), *RF* means the recorded frequency (records per hour), $f(T)$ means the pair *T* and *RH*, and *a* means the total data points. A low risk was considered for *MRF* values between 0 and 0.5, a potential risk was considered for *MRF* values up to 1, and a high risk was considered for *MRF* values above 1.

Since the spores can survive to unfavourable conditions and resume the growth afterwards, a continuous *MRF* sum was considered, where unfavourable points do not contribute to the *MRF* but also do not imply the restart of the process [65–68].

It was decided to apply the method to the surface conditions of the north wall, since it is less exposed to solar radiation and has a greater risk of mould germination. Since the wall is made up of limestone elements that recently underwent a conservation intervention, the isopleths defined by Sedlbauer for substrate type II were adopted, as shown in Fig. 7. The mycelium growth occurs only after mould germination if the climatic conditions are favourable, that is, an *MRF* greater than 1 is a necessary condition for the mycelium growth, but it is not a sufficient condition. The complete description of the application of these methods to cultural heritage can be found in the references [38,64,69–72].

3.4.2. Indoor air quality — IAQ

The definition of the IAQ in terms of comfort is based on the perception of the occupants of a certain space; however, the human sensitivity to pollutants and discomfort vary according to several factors [73,74]. This sensation is influenced by the emission of CO_2 and other gases and odours emitted by the occupants and by the building itself, its components and air conditioning systems [75]. IAQ is assessed by humans according to the combination of smell and perception of irritation obtained through the nasal mucosae and the eyes. The perception of comfort also depends on subjective factors, as the expectancy level or cultural adaption.

To evaluate and predict the comfort sensation, several tests were carried out in climate-controlled chambers and in occupied buildings. The impact of odours in the perceived IAQ was firstly investigated by Yaglou in 1936 with studies in chambers ventilated with outdoor fresh air at different rates, in which the occupants evaluated the IAQ according to their perception by using different scales, including a scale of odour intensity [76]. These results have been the basis of standards and guidelines of ventilation for more than 50 years.

These tests were replicated in the 1980s and 1990s by using more modern conditions and a larger number of individuals. Tests carried out in Europe [77,78], USA [79] and Japan [80] showed a strong correlation that validated the methods and results of the various laboratories. These studies were based on the answers of office workers and university students from USA, Denmark and Japan with modern personal hygiene habits.

The European results [77,78] form the basis of several international documents, such as the ASHRAE 62.1 [81] and the recent published EN 16798-1 [82]. From these results, a relationship between the percentage of dissatisfied people and the concentration of indoor CO_2 was established, which proved to be a good indicator to evaluate the IAQ, since while people are releasing CO_2 they are also releasing odours. Usually, a CO_2 concentration of about 650 ppm above the external value [44,83], representing 20% of dissatisfied people, is used to evaluate the IAQ, as mentioned by the standard ASTM D-6245 [44]. Although there are other methods to access the IAQ, with different limits or even with different categories depending on the level of expectation, it was considered that the limit of 650 ppm is adequate for the present analysis that aims to compare the impact of various scenarios.

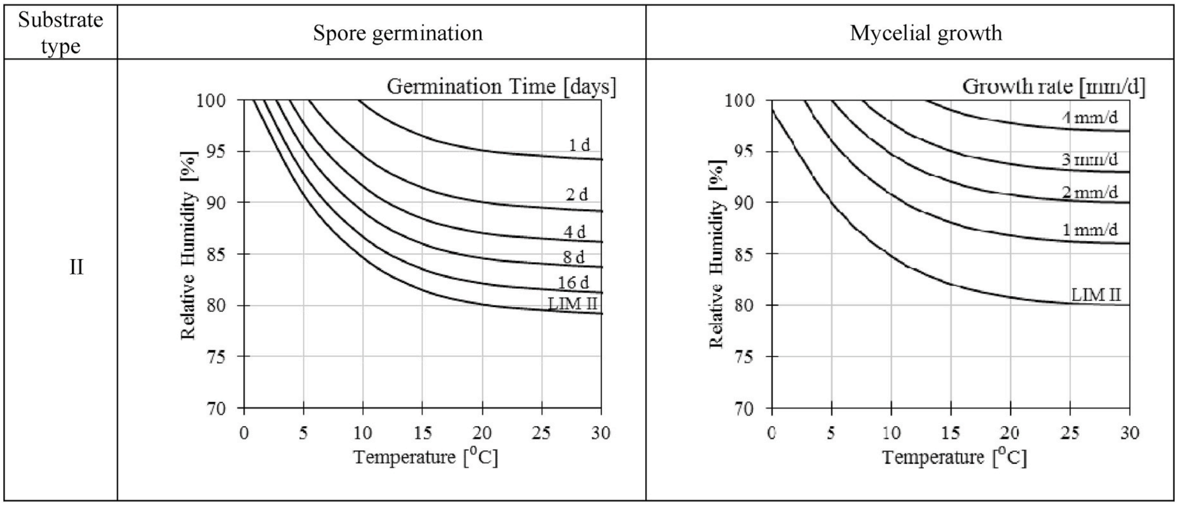

Fig. 7. Isopleth method of Sedlebauer for the substrate type II [65].

In addition to comfort issues, IAQ should ensure a low risk to the occupant's health. The effects of IAQ on humans may be acute and of short duration (such as ocular irritations) or develop over a longer period (such as cancer) [84]. To reduce health risks, maximum concentrations and exposure times for each pollutant should be defined according to their specificities. In this analysis, only CO_2 was considered.

3.5. Methodology to access the impact of tourism on conservation

According the data presented in chapter 2, it was decided to simulate six scenarios: the first one, taken as the reference case, considering the presence of people only during the religious celebrations, and following the annual visitors registered in 2005, 2008, 2015 and 2017. For the future, four different increasing visitors' scenarios were considered: 11%/year; 6.1%/year, 4.2%/year and 3.1%/year, as shown in Fig. 3. The different scenarios to simulate can be found in Table 2.

4. Results

4.1. Model validation

The global comparison of the recorded values and those simulated, regarding temperature and relative humidity, can be seen in Fig. 8. The visible gaps in the figure correspond to periods in which the external data logger had technical problems. In general, it is possible to observe that the simulated values follow the trend of the real data.

The annual averages, the maximum and minimum extremes and the 2nd, 25th, 50th, 75th and 98th percentiles for the measured and simulated data can be seen in Table 3. Regarding the temperature, the following differences were obtained: 0.3 °C between the measured and the simulated annual average, 0.3 °C for the maximum values and 0.7 °C for the minimum values. The percentile analysis reinforces the greatest proximity between the measured and simulated values during the summer. Regarding the relative humidity, differences of 1% RH for the annual average, 1% RH for the maximum and 2% RH for the minimum values were obtained.

Table 2
Occupancy rates to simulate.

Sim	Year	Annual visitors, Million				
		Real	SC 1	SC 2	SC 3	SC 4
1	Reference case	0	-	-	-	-
2	2005	1.4	-	-	-	-
3	2008	2.0	-	-	-	-
4	2015	2.8	-	-	-	-
5	2017	3.5	-	-	-	-
6	2027	-	9.9	6.3	5.3	4.8

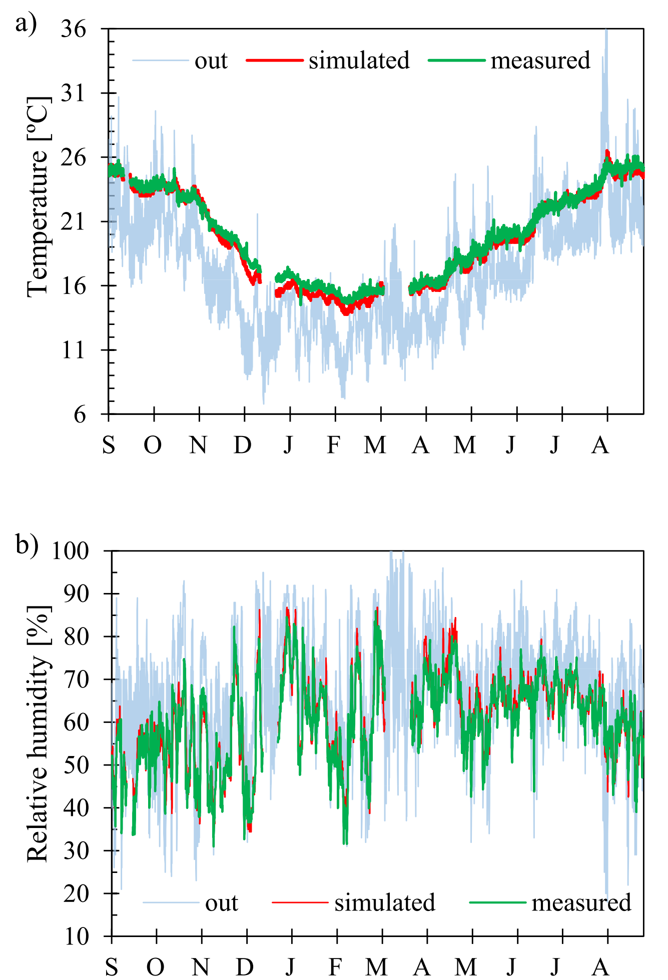

Fig. 8. Comparison between the simulated and the measured climate data: a) temperature and b) relative humidity.

Table 3
Comparison between the measured and simulation values.

Variable	Situation	Mean	Max	Min	Percentiles					R^2	NMBE [%]	CVRMSE [%]
					2°	25°	50°	75°	98°			
T [°C]	Meas	20	26.2	14.5	15.0	16.5	19.9	23.3	25.4	0.99	2.0	2.5
	Sim	19.7	26.5	13.8	14.4	16.0	19.5	23.0	25.3			
RH [%]	Meas	60	86	31	38	53	61	67	79	0.88	4.4	6.0
	Sim	61	87	33	39	54	62	68	81			

The sensors used have an uncertainty of ±0.2 °C for the temperature and a typical uncertainty of ±2% RH for the relative humidity [28]. Considering the uncertainty of the indoor and outdoor sensors, it is possible to see that in most of this statistical analysis the obtained differences fall within the error of the sensors, concluding that in general the results converge with the reality.

Following the model validation, three other statistical parameters were used. Focusing the attention on the parameters R^2, *NMBE* and *CVRMSE* and comparing them with the limits frequently presented in the bibliography, it is possible to conclude that the model does represent the reality. Values of R^2 of 0.99 and 0.88 were obtained for the temperature and *RH*, respectively, all of them higher than the lowest admissible limit of 0.75. As regards the *NMBE*, values of 2.0% for temperature and 4.4% for the *RH* were obtained, complying with the maximum admissible limit of 5%. Finally, values of 2.5% for temperature and 6.0% for *RH* were obtained for the *CVRMSE*, complying with the maximum admissible limit of 20%.

4.2. *The impact of visitors on the indoor climate*

As mentioned above, the growing number of visitors inside buildings has a clear impact on the indoor climate. In naturally ventilated and large-volume buildings, such as the Monastery of Jerónimos, it is expected that ventilation will remain reasonably constant and will not accompany the increase in internal gains, contributing to the disruption of the indoor climate.

In Fig. 9 it is possible to find the results obtained for three distinct cases: a) the reference model — building closed to visitors; b) 3.5 M visitors per year, corresponding to 2017; and c) 9.9 M visitors per year. Despite the high volume and thermal inertia of the building, the impact of visitors on temperature and RH is evident, especially during summer when the largest flows occur.

The statistical analysis of the impact of visitors on temperature and relative humidity can be seen in Table 4 and Table 5, respectively. Focusing the analysis on temperature, it can be concluded that the annual mean shows an increase of 0.6 °C compared to the reference case and 0.4 °C compared to 2017 for the most optimistic growth scenario (SC 1). Regarding the extremes, the maximum temperature presents a value higher than the reference by 1.1 °C and 0.6 °C regarding the data for 2017. The minimum temperature also increases.

The differences referring to *RH* are higher. The presence of 9.9 M visitors per year contributes to the increase of the annual average in 8% *RH* compared to the reference case. In relation to the absolute minimum, there is an increase of 1% *RH*. The maximum value corresponds to an increase of 6% *RH* for the most burdensome case.

If the flow of visitors continues to grow at the pace of the recent years, it is expected that a number of visitors will reach around 9.9 M in 2027. For these conditions, the relative humidity will be between 43 and 89% *RH* during 96% of the time and between 52 and 81% RH during 80% of the year. The translation of the most frequent relative humidity range is clear, which can affect the conservation of the collections.

4.3. *The impact of visitors on conservation*

Previously, it was possible to observe that the growing number of visitors changes the internal microclimatic balance, especially in relation to *RH*. Thus, it was considered imperative to carry out a risk-based analysis of mechanical and biological degradation.

In order to study the impact of visitors on mechanical degradation, the use of the damage functions for the base layer of painted panels [62] and for the sculptures [63] was adopted. The risk-based analysis can be seen in Fig. 10: green — reference building without occupation; yellow — 1.4 M visitors per year (2005); blue — 3.5 M visitors per year (2017); purple — 5.3 M visitors (growth scenario 3 to 2027); and red — 9.9 M visitors (growth scenario 1 to 2027).

For the two methods, the lower black line limits the failure zone, the upper line and the middle line limit the safe zone in which the objects present an elastic response, and the remaining zones demonstrate a plastic response, where the yield strain was exceeded but not reaching the rupture. A more detailed description of the methods can be seen in Refs. [62–64].

This analysis emphasised the negative impact of the visitors on mechanical damage. Regarding the base layer of painted panels or sculptures, it can be seen that the elastic limit is exceeded in all cases, showing that the materials have already undergone irreversible deformations and an adaption to the past climate, that is, the artefacts are now acclimatised. However, the negative impact of visitors is still perceived. For the reference case, the elastic limit is exceeded in 9.2% of the time; for an occupancy of 1.4 M (2005), the limit is exceeded in 10.6% of the time; for an occupancy of 3.5 M (2017), the limit is exceeded in 13.6% of the time; and in 2027, for the occupancy predicted for the scenarios 3 and 1, the limit is exceeded in 15.6% and 25.1%, respectively. For sculptures,

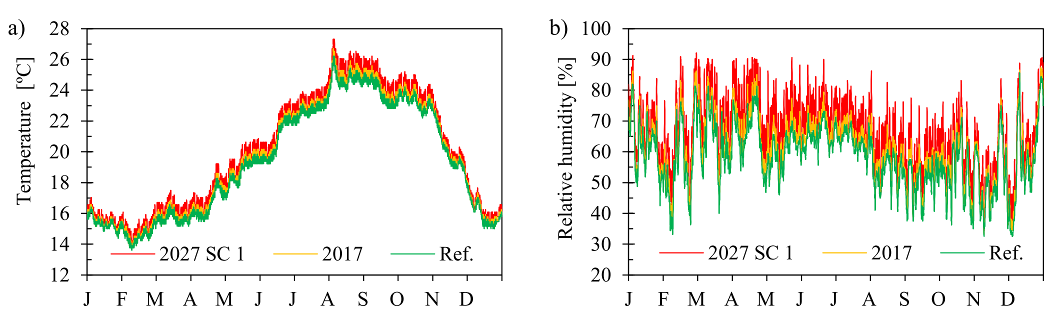

Fig. 9. Visitors impact on the indoor climate: a) temperature; b) relative humidity.

Table 4
Statistical analysis of the impact of visitors on the indoor temperature.

Visitors (Million)	Year/ scenario	Temperature [°C]						
		Mean	Max	Min	Percentiles			
					2°	10°	90°	98°
0	Reference	19.3	26.2	13.6	14.2	15.2	24.2	25.0
1.4	2005	19.4	26.4	13.8	14.2	15.2	24.4	25.1
2.0	2008	19.4	26.5	13.8	14.4	15.2	24.4	25.1
2.8	2015	19.5	26.5	13.8	14.4	15.2	24.5	25.3
3.5	2017	19.5	26.7	13.8	14.4	15.2	24.5	25.3
4.8	2027 (SC 4)	19.6	26.8	13.8	14.4	15.3	24.5	25.4
5.3	2027 (SC 3)	19.6	26.8	13.8	14.4	15.3	24.7	25.5
6.3	2027 (SC 2)	19.7	27.0	13.9	14.5	15.3	24.7	25.6
9.9	2027 (SC 1)	19.9	27.3	13.9	14.5	15.5	25.0	25.9

Table 5
Statistical analysis of the impact of visitors on the indoor relative humidity.

Visitors (Million)	Year/ scenario	Relative Humidity [%]						
		Mean	Max	Min	Percentiles			
					2°	10°	90°	98°
0	Reference	58	86	33	37	44	71	79
1.4	2005	59	86	33	38	46	72	80
2.0	2008	60	86	33	39	46	73	81
2.8	2015	61	87	33	39	46	73	81
3.5	2017	61	88	33	40	47	74	82
4.8	2027 (SC 4)	62	89	34	41	48	75	83
5.3	2027 (SC 3)	63	89	34	41	49	75	84
6.3	2027 (SC 2)	63	91	34	41	49	76	85
9.9	2027 (SC 1)	66	92	34	43	52	81	89

the same happens, but with lower differences: there is a maximum increase from 7.5% in the reference case to 11.2% in 2027 for the most optimistic scenario. Despite the risk of deformation, according to this method the risk of failure or cracking is low.

Regarding mechanical conservation, it is concluded that the materials have already undergone a process of acclimatisation, since even the natural climate of the building without occupation does not allow an elastic behaviour throughout the year. The increase in the number of visitors is not considered to have a significant impact on the mechanical safety of the collections. However, it is recommended that the current level of risk should not be exceeded. The implementation of some type of RH control can limit the risks and maintain the current state of conservation. In case of future restoration works, the strategy must be rethought, since the state of equilibrium of the materials will be changed.

In addition to the risk of mechanical degradation, the increase of *RH* also contributes to increase the risk of mould germination. The representation of the same five scenarios considered for the mechanical risk is plotted in the so-called isopleth diagram for substrate type II, as can be seen in Fig. 11 a. The impact of the increasing number of visitors is evident. However, the diagram analysis does not allow to conclude what the real risk is. Thus, the concept of mould risk factor (*MRF*) was used. A low risk was considered for *MRF* values between 0 and 0.5, a potential risk for *MRF* values up to 1 and a high risk for *MRF* values above 1. The analysis of Fig. 11 b allows a clear conclusion about the increasing risk of mould germination. For the reference case, the risk is low, with an average risk for the occupancy observed in 2005 and a high risk beyond 2017. In other words, it is concluded that the current occupancy already constitutes a real risk of mould germination at the surfaces. If the presence of pictures or furniture is considered, the risk increases [68]. This analysis allows to conclude that whatever the future scenario of visitor's growth, the safe limit for the mould germination ($MRF > 1$) will be exceeded.

The evolution of the mould risk factor (*MRF*) and the mycelium growth according to the number of visitors can be seen in Fig. 12. For the occupancy of 2017, an *MRF* greater than 1 ($MRF = 1.07$) was obtained. In addition to the germination conditions, it was concluded that growth was also possible.

It is known that the indoor climate is heavily dependent on the exterior environment and one-year simulation may not be enough to define the maximum number of visitors. In fact, these results may not allow the proposal of a visitor's strategy, but they clearly confirm that there is a direct relationship between the number of visitors and the increased risk of fungal growth.

4.4. Indoor air quality

Visitors have a direct impact on the interior microclimate of the cultural heritage buildings and its conservation. An inappropriate occupancy can compromise the IAQ and consequently the comfort and health of the visitors. In naturally ventilated buildings, the problem of

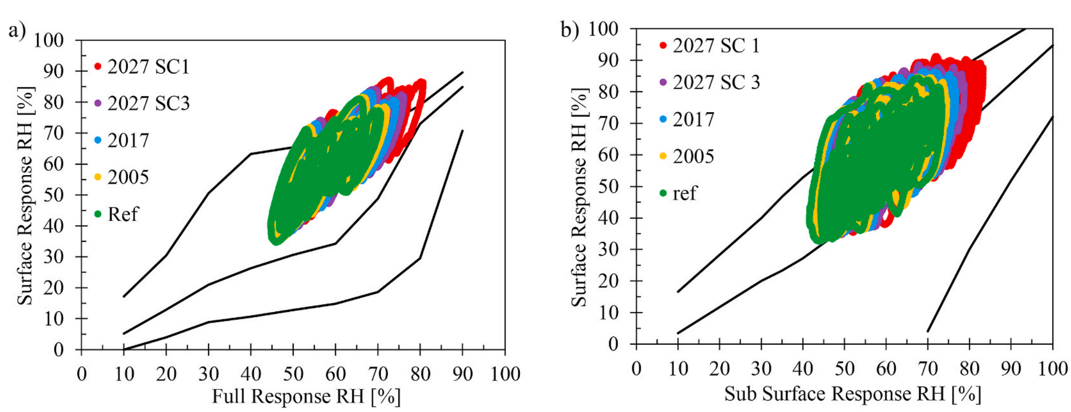

Fig. 10. Mechanical risk assessment: a) wooden substrate of painted panels; b) sculptures.

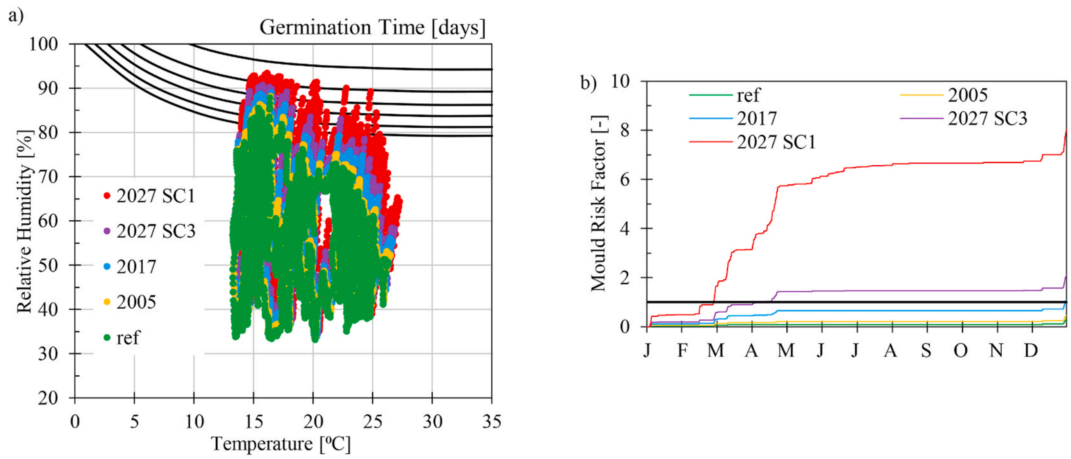

Fig. 11. Biological risk-assessment: a) representation of the data records on the northern surface on the isopleth diagram for the substrate type II; b) mould risk factor.

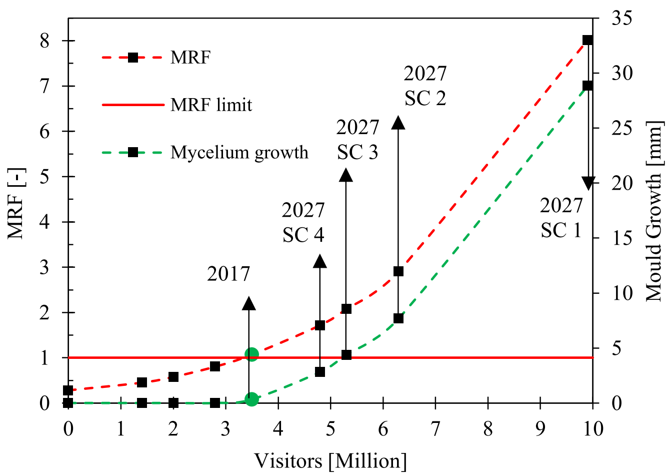

Fig. 12. Mould risk factor (*MRF*) and mycelium growth according the number of visitors.

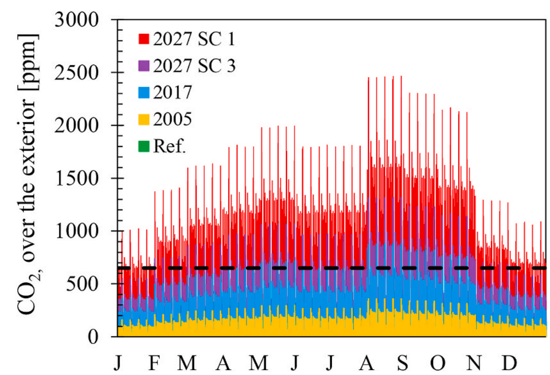

Fig. 13. CO_2 over the exterior according the number of visitors.

the relationship between ventilation and occupancy is of greater importance, since it is not possible to control ventilation accurately.

One of the major effects of occupants on indoor environment is related to the generation of odours and CO_2 that can compromise the comfort and in extreme cases even the health. In a naturally ventilated building with high volume and where only the doors are operable, it is impossible to increase the fresh air intake and the concentration of odours and CO_2 can create uncomfortable conditions.

The CO_2 concentration over the exterior throughout the year can be seen in Fig. 13, and the percentage of time in which the IAQ complies with the imposed limit and maximum CO_2 concentration over the exterior is presented in Fig. 14 for the global analysis, January and August.

The analysis of these figures makes it clear that tourism growth can bring indoor air quality to unwanted levels. As expected, the highest concentrations of CO_2 occur during summer. According to the simulated scenarios, up to 2 M visitors per year (corresponding to 2008) there were no problems related to the IAQ. The first problems, although slight, arose for the values of 2015 (2.8 M) and 2017 (3.5 M), where the limit of 650 ppm was exceeded in 1% and 2% of time, respectively.

The evolution of the air quality deterioration is evident, and even the scenario with more conservative growth gives rise to worrying values. Considering the 2027 horizon, scenario SC 4 (4.8 M) shows CO_2 values above desirable in 11% of the time. For scenario SC 3 (5.3 M), which is considered the most likely by the Portuguese government, the CO_2 limit is surpassed in 17% of the time, with a maximum value of 1318 ppm over the exterior. Considering the most optimistic scenario presented by the Portuguese government (scenario SC 2–6.3 M), the CO_2 limit is surpassed in 30% of the year, with a maximum value of 1577 ppm over the exterior.

In addition to these growth scenarios, a more optimistic growth scenario was also tested based on the average growth seen over the past 5 years in the Monastery and which allows a maximum number of 9.9 M visitors. This scenario shows even more worrying results, in which the limit of 650 ppm over the exterior is exceeded in 54% of the time and in which a maximum value of 2466 ppm over the exterior is reached.

Dividing the analysis into winter and summer, it appears that in the first case only the most optimistic scenario shows problems, without however exceeding a concentration of 1024 ppm above the exterior. When focusing on August, the picture is significantly different. The 2017 numbers show that the comfort limit has been exceeded in 10% of the time. Analysing the impact of future scenarios, it appears that the comfort limit is exceeded in 38% of the time for SC 4, in 47% for SC 3, in 55% for SC 2 and in 67% of time for SC 1.

4.5. A sustainable solution

The above results lead to conclude that a large number of visitors brings real dangers to biological degradation and indoor air quality. To reduce the risk of biological degradation, the amount of indoor moisture can be reduced by increasing ventilation, reducing moisture loads or by installing a dehumidification system. With regard to comfort, IAQ can be improved by increasing ventilation by installing mechanical equipment

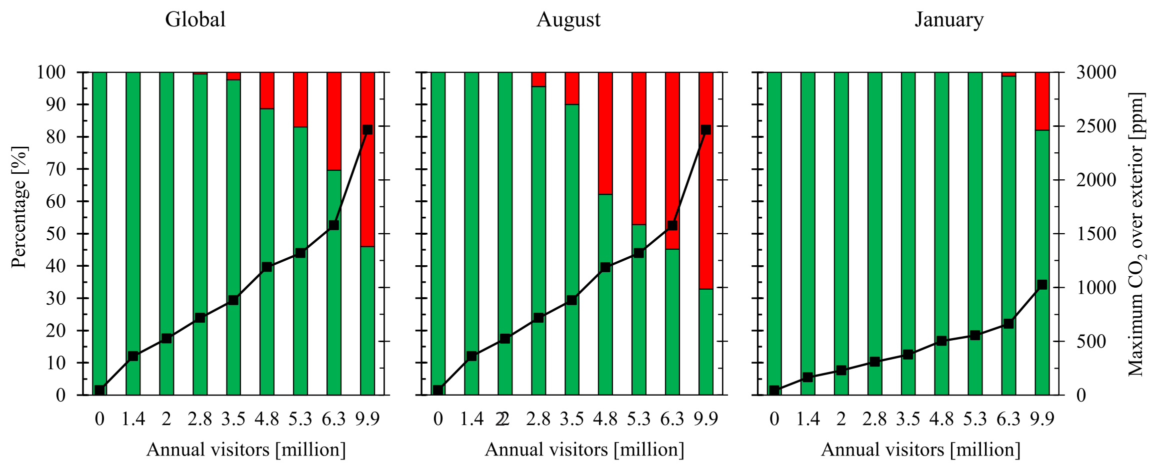

Fig. 14. Indoor air quality: percentage of time with the difference between the indoor and exterior CO_2 higher than 650 ppm (the red columns). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

or reducing the number of visitors.

It is important to take into account that this type of building is characterised by a historic microclimate to which the objects have been acclimatised. A change in the typical climate can have a catastrophic effect on the safety of artefacts, since they have lost their ability to adapt over the years [85]. The installation of an HVAC system can also have an unwanted visual impact on the heritage, in addition to the initial and operation costs.

Despite the current uncertainty at the global level due to the pandemic caused by COVID-19, future predictions made so far run the risk of deviating from reality. However, the recent past showed an increasing interest in cultural tourism that cannot be discouraged, as we do not know exactly what will happen, nor how long it will take us to overcome the current situation, but it is believed that recent trends may resume.

Despite the risks that tourism brings to cultural heritage, the financial results provided make it difficult to limit the number of visitors to the heritage except for a few exceptions where the evidence is well known. The need to limit the number of visitors to halt the progression of the pandemic allows us to reflect on the control of visitors in other periods as well.

Considering a maximum admissible difference of 650 ppm between the indoor and the outdoor concentrations of CO_2 and knowing the air change rate, the volume and the CO_2 generation rate per person, the maximum number of visitors can be estimated using a mass balance equation.

A steady-state mass balance equation can be used to obtain the maximum occupancy that guarantees the desirable indoor air quality level. Analysis in steady-state conditions does not consider the volume of the space, which affects the time necessary to reach the equilibrium conditions. This fact becomes especially relevant when CO_2 (or other pollutant) emission occurs during a limited period, in which case the steady-state equation overestimates the necessary airflow to keep the pollutant within the desired limits. Assuming a continuous occupancy during the opening hours, the use of a steady-state analysis was considered satisfactory [46]:

$$q_{tot} = \frac{n \cdot G_{CO2} \cdot 10^6}{\varepsilon_v \cdot (C_{CO2,i} - C_{CO2,e})} \quad \text{(Eq. 8)}$$

where q_{tot} is the total airflow (m^3/h), n the number of visitors (−), G_{CO2} is the emission rate of CO_2 (m^3/h), $C_{CO2,i}$ is the allowed indoor concentration of CO_2 (ppm), $C_{CO2,e}$ is the concentration of CO_2 in the exterior (ppm), and ε_v is the ventilation efficiency (−). For the current purposes, the assumption of a totally efficient ventilation was considered admissible.

The total airflow is obtained by multiplying the volume by the *ACH*: 49 039 m^3 by 0.13 h^{-1}. A CO_2 generation rate of 0.01872 m^3/h is considered according to the data presented in Section 3.2.2. It is thus concluded that the presence of 221 visitors simultaneously is the maximum admissible value that does not compromise the indoor air quality. As mentioned, this value is conservative since it was obtained under steady-state conditions. At first sight, this value can be considered hard to reach, but if we think that for example there are cruises that dock in Lisbon with capacity for more than 3000 people and that the Monastery of Jerónimos is one of the main points of tourist interest of the city, it can easily be seen that this limit can be largely exceeded.

From a theoretical point of view, if a constant occupancy profile would be possible, a maximum of 3.3 M of visitors is obtained. However, the Monastery Directorate should not limit the visits according to this value, since a constant occupancy profile is not expected. The only way to control the indoor air quality is based on the CO_2 demand. This method allows to consider the fluctuation in the *ACH* and control effectively the IAQ at each moment.

5. Conclusions

The increase in the tourist interest on the built cultural heritage can be a threat to its conservation and to the comfort and health of the visitors. In the case of the Monastery of Jerónimos, the increase in the number of visitors may raise some concerns, with a growth of 154% between 2005 and 2017. Recurrent complaints from visitors with headaches, indisposition, dizziness and other symptoms in periods of greater influx drew attention to possible problems related to an exaggerated number of visitors inside the building.

The 12-month indoor climate analysis between September 2017 and August 2018 was used to validate a dynamic simulation model and to test the impact of tourism on the conservation of the building and artefacts and on the comfort and health of visitors. The unoccupied building was simulated to obtain a reference model, and several past occupancy rates were used: 1.4 M visitors (2005), 2 M visitors (2008), 2.8 M visitors (2015) and 3.5 M visitors (2017).

Regarding conservation, it was concluded that there is a risk of irreversible deformations in the base layer of painted panels and sculptures for any of the simulated cases, even for the reference case (without visitors), but the risk rises with the visitors' increasing. The results regarding mould germination were more conclusive, with a great influence of the number of visitors to increase the risk. For the numbers of 2017, the risk is already present. Regarding air quality, it was noted that the first problems appeared in 2015, with CO_2 concentrations higher than the comfort limit during the periods of greatest occupancy

(1% of the time).

Despite these findings, there is no control plan for the number of entries. Nevertheless, future scenarios were also evaluated. Four growth scenarios were tested, three of them defined according to the projections proposed by the Tourism of Portugal and the fourth based on the average growth in the Monastery over the last 5 years. A short horizon was used until 2027 to avoid major errors since growth trends are volatile and can change according to several factors.

Each scenario has significantly increased the risk of mechanical and biological degradation. The indoor air quality can be severely deteriorated. For the slower growth scenario, visitors will experience discomfort in 11% of the time the church is open for visitors. In the fastest growing scenario, it was estimated that air quality will be unacceptable in 54% of the time.

Since it is not plausible to install climate control and mechanical ventilation systems in the building, the only solution to control the conservation and the indoor air quality is to limit the number of visitors. Although it is not possible to achieve a maximum limit of visitors for conservation purposes since there are several other influencing factors such as the external climate, it is clear that the increase in tourism contributes clearly to the degradation of the environmental conditions. As far as indoor air quality is concerned, the most plausible solution is to install CO_2 sensors inside and outside the building, preventing new visitors from entering whenever CO_2 concentration reaches undesired values. For the estimated ventilation conditions, a maximum instantaneous occupancy of 221 visitors was obtained, but this value should be used only as a reference, since it was obtained for stationary conditions (and ventilation may vary over time). Therefore, it is recommended to control the influx of visitors according to real-time CO_2 concentrations.

Declaration of competing interest

The authors whose names are listed immediately above certify that they have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript or non-financial interest such as personal or professional relationships, affiliations, knowledge or beliefs.

All authors have participated in the conception and design, analysis and interpretation of the data, drafting the article and revising it critically.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The Images that I have submitted to the journal for review are original, was taken by the stated authors, and has not been published elsewhere.

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