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Master in Civil Engineering

Indoor climate management on cultural heritage buildings:

Climate control strategies, cultural heritage management and hygrothermal rehabilitation

A thesis submitted for the degree of Doctor of Philosophy in Civil Engineering

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To my family

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ABSTRACT

Cultural heritage plays a major role in modern societies as a symbol of their past and as a way to safe keep their identity for future generation. Its protection and conservation are a challenge to ensure the cultural diversity in a continuously changing world.

Heritage buildings such as palaces, churches or monasteries are often used to display collections trying to combine the patrimonial and architectural value of the building with the artistic interest of the collections. This combination of interests, while returning some buildings back to society, may also pose some risk to their conservation due to pressures caused by high visitor flows and high levels of climate control. Nowadays, one of the greatest challenges for the cultural heritage is to achieve a compromise between conservation, sustainability and comfort. However, this balance has been difficult to achieve, since conservation and comfort require tight climate control, which is difficult to achieve in historic buildings with large volumes and high thermal transmittance.

This thesis aims to cover a wide range of situations that interfere with the indoor climate of the heritage, namely at the level of its monitoring and analysis, risk-analysis, discussion of the various climate control strategies and the capacity of buildings to comply with them. The impact of the visitors on the conservation and the influence of the envelope in the energetic rehabilitation were also investigated. Methods of statistical analysis and risk quantification, a climate control strategy and an energy optimization methodology were proposed.

The use of the climatic data from the Jeronimos Monastery (MJ), the church of São Cristóvão and National Museum of Ancient Art (NMAA) and the use of a simulation model of the MJ allowed to conclude the difficulty of the heritage buildings to comply with tight climate ranges. A high potential for reducing energy consumption was achieved through the application of dynamic climate control strategies without jeopardizing the conservation, and a new methodology was proposed and validated. The use of the MJ simulation model allowed to conclude that the current number of visitors already raises conservation risks and that, even in the most pragmatic scenario, it will contribute to the degradation of the air quality by 2027.

The simulation of a generic room of the NMAA for 15 European cities has made it possible to conclude that it is not possible to standardize the rehabilitation solutions since energy needs depend on the location. Finally, it was concluded that the focus on climate control strategies has a great potential for cost reduction and that in temperate climates of the southern Europe the improvement of thermal transmittance has a reduced effect on the building's response

Keywords: Cultural heritage, climate control strategies, preventive conservation, rehabilitation, simulation, energy reduction

RESUMO

O património cultural edificado tem um papel preponderante nas sociedades actuais contribuindo para a preservação da sua identidade e tradições. A sua protecção e conservação constituem um desafio para garantir a diversidade cultural num mundo em constante transformação.

Edifícios antigos como palácios, igrejas ou mosteiros são frequentemente utilizados para expor colecções com o objectivo de conjugar o seu valor patrimonial e arquitectónico com o valor artístico das colecções. Apesar de devolver alguns edifícios devolutos à sociedade, esta combinação de interesses pode também constituir um risco à sua conservação devido às pressões causadas por elevados fluxos de visitantes e níveis de controlo climático exigentes. Um dos maiores desafios actuais para o património é alcançar um compromisso entre conservação, sustentabilidade e conforto. Os volumes e transmitâncias térmicas elevados que caracterizam os edifícios históricos associados a níveis de controlo climático apertado constituem, porém, um entrave na procura deste equilíbrio.

Nesta tese pretendeu-se cobrir uma gama alargada de situações que interferem com o clima interior do património, nomeadamente ao nível da sua monitorização e análise, análise de risco, discussão das várias estratégias de controlo climático e capacidade dos edifícios para cumpri-las. Também o impacto dos visitantes na conservação e a influência da envolvente na reabilitação energética foram investigados. Propuseram-se métodos de análise estatística e de quantificação de risco, uma estratégia de controlo climático e uma metodologia de optimização energética.

A utilização dos dados climáticos recolhidos no Mosteiro dos Jerónimos (MJ), Igreja de São Cristóvão e Museu Nacional de Arte Antiga (MNAA) e a utilização de um modelo de simulação do MJ permitiram concluir a dificuldade dos edifícios patrimoniais em cumprir níveis de climatização apertados. Verificou-se um elevado potencial de redução do consumo energético através da aplicação de estratégias de controlo climático dinâmicas sem prejuízo das necessidades de conservação, tendo-se proposto e validado uma nova metodologia. A utilização do modelo de simulação do MJ permitiu concluir que o número actual de visitantes suscita já riscos à conservação e que, até o cenário de crescimento mais pragmático, contribuirá para a degradação da qualidade do ar num horizonte a médio prazo - até 2027.

A simulação de um modelo genérico do MNAA para 15 cidades europeias permitiu concluir a impossibilidade de padronizar soluções de reabilitação uma vez que as necessidades energéticas variam de forma pronunciada em função da localização. Finalmente, concluiu-se que o foco nas estratégias de controlo climático tem grande potencial de redução de custos e que em climas temperados do sul da europa a melhoria das transmitâncias térmicas tem um efeito reduzido no comportamento dos edifícios.

Palavras chave: Património cultural, controlo climático, conservação preventiva, reabilitação, simulação, consumo energético

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LIST OF SYMBOLS AND ABBREVIATIONS

Roman-letter notations

Symbol	Description	Units
a	Response factor	[-]
ACH	Air Change Rate	[h^{-1}]
c	Specific Heat	[J/kg.K]
C_a	Annual energy Costs	[€/m^2]
C_c	Carbon costs	[€/m^2]
Cg	Net Present Value	[€/m^2]
CO_2	Carbon dioxide	[ppm]
CV(RMSE)	Coefficient of variation of the root mean square error	[%]
d	Thickness	[m]
e	Water vapour pressure	[hPa]
E_a	Activation energy	[J/mol]
eLM	Equivalent lifetime multiplier	[-]
f	Energy Inflation Rate	[%]
LIM	Lowest Isopleth for mould	[-]
LM	Lifetime multiplier	[-]
MRF	Mould Risk Factor	[-]
NMBE	Normalized Mean Bias Error	[%]
p	Number of years from the starting period	[years]
PD	Percentage of dissatisfied people	[%]
PI	Performance Index	[%]
PMV	Predicted Mean Vote	[-]
q	Airflow	[m^3/h]
R	Gas constant	[8.314 J/mol.K]
R	Thermal Resistance	[m^2.ºC/W]
r	Real Discount Rate	[%]
R^2	Coefficient of Determination	[-]

Symbol	Description	Units
R_d	Discount Factor	[-]
RH	Relative humidity	[%]
R_{si}	Thermal Resistance of the Interior Surface	[m^2.ºC/W]
R_{se}	Thermal Resistance of the exterior Surface	[m^2.ºC/W]
$SHGC$	Solar Heat Gain Coefficient	[-]
T	Temperature	[ºC]
t	Time	[s]
$T_{e,ref}$	Outdoor reference temperature estimated as a 7-day exponentially weighed temperature	[ºC]
$T_{si,eff}$	Effective interior surface temperature	[ºC]
$T_{si,eff}$	Interior Surface Temperature	[ºC]
U	Thermal transmittance of opaque elements	[W/m^2.ºC]
U_w	Thermal transmittance of windows	[W/m^2.ºC]

Greek-letter notations

Symbol	Description	Units
Δe	Internal Water Vapour Pressure Excess	[hPa]
λ	Thermal conductivity	[W/m.K]
ρ	Density	[kg/m^3]
$\tau_{response}$	Response Time	[s]

Abbreviations and Acronyms

Abbreviation	Description
AAMD	Association of Directors of Art Museums
AIC	American Institute for Conservation
AICCM	Australian Institute for the Conservation of Cultural Materials
ASHRAE	American Society of Heating and Air-conditioning Engineers
ASTM	American Society for Testing and Materials
ATG	Adaptive Temperature Guidelines
BSI	British Standard Institute

Abbreviation	Description
CCI	Canadian Conservation Institute
DEC	Department of Civil Engineering
EN	European Standard
EU	European Union
FCT	Faculty of Sciences and Technology
GDP	Gross Domestic Product
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
ICOM	International Council of Museums
IIC	International Institute of Conservation
IPI	Image Permanence Institute
ISO	International Organization for Standardization
NMAA	National Museum of Ancient Art of Lisbon
PAS	Publicly Available Specification
SC	Scenario
SCATs	European Project Smart Controls and Thermal Comfort
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNI	Italian Standard
UNL	NOVA University of Lisbon
USA	United States of America
UV	Ultraviolet Radiation
AAMD	Association of Directors of Art Museums

1. Introduction

1.1. General overview

Cultural heritage plays a crucial role in modern societies as symbols of their past and as a way to preserve their identity in the future. Its conservation is a challenge to ensure the cultural diversity in a continuously changing world [1,2]. Cultural heritage represents not only one of the most important facets that embody 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 the touristic activity [3].

Europe has some of the most extraordinary examples of cultural heritage in the world. The recently published Eurobarometer report [4] reinforces the importance of cultural heritage for the EU. In a study based on 27881 surveys, 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.

The use of historic buildings to house museums, galleries or other public uses is increasingly frequent, bringing together the intrinsic value of the collections with the historical and architectural values of the building. However, the interest in built heritage also threatens the conservation of buildings and objects, the comfort of visitors and environmental and economic sustainability. The pressures caused by the requirements of comfort and conservation, especially in the case of museums that take advantage of the heritage value of the building to enhance the cultural interest of the collections [5,6], together with the increased rates of water vapour production and carbon dioxide emissions directly attributable to visitors and the poor hygrothermal response that usually characterizes historic buildings [7] require an in-depth study of indoor climatic conditions. At present one of the greatest challenges in the management of built cultural heritage is to find a balance between conservation, comfort and energy [8] since, by definition, comfort and especially conservation require tight ranges of temperature and relative humidity [9-11].

Museum climate control guidelines often assume tight intervals as safe for conservation - usually for historical reasons and with no scientific basis. The set-point of 20 °C for the temperature and 50% for the relative humidity [9], for example, has been widely used by conservators around the world for a long time and, although apparently defined without scientific basis, the truth is that it is still used in many cases. The widespread use of these intervals began at a particular moment in history boosted by technological advances and the emergence of powerful climate systems in a period where energy efficiency was not a prevailing theme and energy was at a low cost [9,12,13]. These historic ranges are so demanding that even in temperate climates they can only be achieved with powerful climate control systems.

This problem is most strikingly evident in historic buildings which often have a poor hygrothermal response. These buildings are usually characterized by thick walls with a high capacity to store heat, which gives them a great efficiency in damping and delaying thermal cycles. In temperate climates, this behaviour leads to a great thermal balance in short periods that is usually only disturbed by external factors such as artificial heating, lighting or human presence. Despite the thermal inertia the outer envelope of old buildings is usually characterized by high thermal transmission coefficients that trigger high energy consumptions and can cause surface condensations.

In addition to preventive conservation, environmental and economic concerns have also increased and highlight the need to make a more efficient use of resources with a constant search for energy reduction. The building sector, which accounts for about 40% of total energy consumption in Europe [14] is obviously not an exception. The EU has taken energy efficiency as an urgent necessity and has developed some ambitious directives, although they do not include cultural heritage buildings given their specific needs and requirements [11,15].

Despite all efforts, the energy reduction has not yet reached the desired values [16]. European Union (EU) has taken energy efficiency as an urgent need and developed some ambitious directives aiming at energy reduction in the building sector, from which it is possible to highlight the 2010/31/CE [14], demanding and binding on new buildings or common rehabilitations but not encompassing most historical buildings given their needs and specificities, namely the risk of loss of identity and historical quality by invasive interventions. The Directive 2012/27/EU [17] was more ambitious and established that all member states of the EU should rehabilitate 3% of the constructed area of the air-conditioned buildings they own. Despite these directives, the evolution of energy consumption in the services sector, including museums, has not followed the global trend, with a 23% increase in final energy consumption between 2000 and 2016 in the EU28; in Portugal, for example, the increase was even more significant and reached a value of 39%.

Despite all the developments in the design of new buildings and rehabilitation, the rehabilitation of classified buildings is not obvious and impossible to standardize. The use of passive techniques for climate control is an important and proven solution [13,15], however the interventions in classified buildings require a special care [18] due to the impossibility of altering the original architecture under penalty of loss of identity and authenticity [19,20].

1.2. Climate in museums

The concerns about environmental and economic sustainability are increasing nowadays, and museums have not been insensitive to this issue. The general trend seems to assume less demanding climate control strategies and accept some risk, as discussed in refs. [21,22]. Nevertheless, global consensus is still far from reaching and in many cases stringent set-points with no scientific justification are still in use. It is important to reflect on the origins of preventive conservation to understand the choice of the climate control strategies.

The installation of a central system at the Boston Museum of Fine Arts in 1908 was one of the first attempts to efficiently control the indoor climate in museums. After an experimental period of two years, the target 55-60 % for the relative humidity was proposed. Despite this numerical conclusion, the report written by the project manager, Mr. McCabe, did not present any information about tests or results that gave rise to this target. Despite this target not being scientifically justified, it began to appear frequently in later recommendations and played a prominent role in the evolution of preventive conservation science [23-25]. For the Cleveland Museum of Art, for example, a safe target between 50 and 55 % RH was established in 1930 [25].

The war periods in Europe played a key role in raising awareness of the behaviour of collections and the evolution of preventive conservation. During the First World War, collections were transferred to underground tunnels in Grand Britain and Germany. Despite the installation of heating systems, at the end of the war, it was found that the storage conditions caused damage to the British Museum's collection. This conclusion evidenced the need to increase the scientific knowledge about the response of the artefacts to the climate and led to the creation of new research laboratories [26]. At the same time, meetings between conservators and other museum professionals also highlighted the need to define scientific methodologies to guide the choice of the ideal climate [27].

The first International Conference for the Study of Scientific Methods for the Examination and Preservation of Works of Art was held in 1930. Ten years later, a panel of international experts including Harold Plenderleith and George Stout published the "Manual on the Conservation of Paintings." This manual reflected about the set-point of 60-65% RH, arguing that in many climates it may easily achieved and that in temperate climates the value of 60% RH is the easiest to maintain [28].

In 1936, Coremans (the head of the Central Laboratory of Belgian National Museums) published an article attesting that several experiments carried out in several places allowed to obtain ideal values for temperature and relative humidity very close to 60ºF (16ºC) and 60 % RH, but arguing that these values were not viable in European museums during the summer. However, the values of 60 °F and 60% RH came to play an important role in the European bibliography since that moment [24].

In 1942, Rawlins (scientist of the British Museum) reinforced this idea by publishing a paper in which he stated that relative humidity is the most important parameter for conservation and the temperature should be chosen to contribute to the maintenance of ideal RH values. The author noted the impossibility of advancing a single value of temperature for all cases, mentioning however that the values of 60 °F (16°C) and 60% RH can be considered for most of the objects [24].

Paradoxically the Second World War was of paramount importance in the history of preventive conservation. With the beginning of the war the collection of the National Gallery (London) composed of about 2000 paintings was evacuated and stored in the slate quarry of Manod, Wales. Brick shelters were built, and a heating system was installed to keep the temperature at 63°F (17°C) and the relative humidity at 58% RH to protect the collection. This target of 58% RH was originated from previous studies developed by the National Gallery researchers who concluded that the average annual equilibrium moisture content for different pieces of wood within the gallery was about 11% corresponding to an RH of 58 % [23]. The works of art survived the war in very good condition [28], however when the war ended and the artefacts returned to the uncontrolled environment of the National Gallery several damages were detected [23,24]. These events contributed to the "cult" around the 58% RH. Thus, following a recommendation from the Weaver Committee of 1947, an air conditioning system was installed in the museum in 1950 [29]. Despite the air conditioning system, some difficulties were found to maintain the desired set-point due to the poor thermal response of the building.

In 1949, George Stout defended the concept of "long-range conservation" at the American Association of Museum's Congress in Chicago. Stout further warned against the impossibility of quantifying the cost of neglect compared with the costs associated with a constant care and protection, noting that continuous care saves money and maintains the integrity of objects. Stout stressed that caring for a collection is not only about occasional repairs and that it is necessary to improve knowledge about the true state of the object that is subject to degradation in order to maintain its integrity [28]. A year later, a large group of international researchers including George Stout began a new project that would become known as the International Institute for the Conservation of Historic and Artistic Works which was based on the need to carry out a preventive conservation of the collections.

In 1960, Harold Plenderleith and Paul Philippot published the results of a 1955 survey of the

International Council of Museums (ICOM) on the effects of climate on the conservation of museum objects [28,30]. The report entitled "Climatology and Conservation in Museums" considered a “safety zone” for relative humidity between 50 and 60% RH, arguing that sudden fluctuations of RH should be avoided. The authors stated that the safety of an object depends on its history and the conditions in which it was acclimatized, since even a climate assumed as ideal can accelerate the degradation phenomena if the object was exposed for several years to different conditions [28].

With the widespread use of these stringent targets, damages related to surface condensations has begun to appear particularly in cold climates. The imposition of high temperature on buildings with low thermal resistance walls made condensations a reality and contributed to the increasing degradation of artefacts placed in their vicinity [31]. In 1964, Richard S. Buck opposed this approach, arguing that the stringent intervals were virtually unattainable in old buildings in the USA. Buck proposed the use of a lower limit for temperature in winter and a wider relative humidity range between 45-65% RH [32].

In 1967 the first conference organized by the International Institute of Conservation (IIC) on climatology in museums was held in London. In the preface of the proceedings, the concept of preventive conservation is defined as the science that study the effect of the indoor climate on the objects and the attenuation of the effects of aging processes, stating that, like medicine, more than the cure, the primary goal should be related with the prevention [28].

In 1978 Garry Thomson, a scientific advisor of the National Gallery of London, made a great advance in this area with the publication of the book "The Museum Environment". Thomson addressed the issue in a different way, prioritizing collections in detriment of the visitor’ comfort and addressing the characteristics of the indoor climate according to a set of factors that had never been considered together, namely light, pollution, relative humidity and temperature. Thomson stated that controlling relative humidity in a museum is far more important than temperature [33]. He mentioned that the climate specifications for museums used until that moment were more linked to the air conditioning equipment capacity than with the real needs of the materials that were not yet sufficiently known. His work constituted a complete and critical evaluation of the scientific evidences available so far. In addition, the author argued the importance of considering the type of collection and the regional climate as determining factors in the choice of the indoor climate control strategy. The author also defended the use of simple and reliable systems with lower energy consumption, as well as anticipating the future problems related with sustainability. However, this idea was abandoned in the succeeding decades with the incessant search for an ideal value and for a climate as stable as possible jeopardizing the energy demand [33].

In 1986 Thomson published the second edition of his book [33], where the author introduced slight changes including two classes for climate control in museums. The first class is suitable for large national museums, old or new, and all new buildings to house important museums. The second class was designed to avoid major hazards and keep costs under control by setting fewer demanding intervals that would avoid major improvements in the building envelope. This less demanding class can be applied to buildings with fewer needs, such as churches. The two classes can be seen in Table 1.1. Thomson also defined a range of mean values for different climates and types of objects as shown in Table 1.2.

Table 1.1. Climate control classes defined by Garry Thomson [33]

Class	Temperature (ºC)	Relative humidity (%)
Class 1(1)(2)	Winter: 19 ± 1 ºC Summer: up to 24 ± 1 ºC	50 ± 5 % or 55 ± 5 %(3)
Class 2	Should be reasonably constant to stabilise RH	40 - 70

(1) The temperature must be controlled to control RH, but the level is dictated by human comfort. For fuel economy different winter and summer levels are suggested;

(2) In storage areas or buildings closed to the public in winter, the temperature can be allowed to fall, but not to the point where condensation may occur on cold or unventilated surfaces. A lower limit of 10ºC is suggested;

(3) The level may be fixed higher or lower, but for mixed collections should be in the range 45 – 60 %. Special exhibits may require special conditions.

Table 1.2. Choice of RH level according to climate [33]

65 %	Acceptable for mixed collections in the humid tropics. Too high, however, to ensure the stability of iron and chloride-containing bronzes. Air circulation is very important.
55 %	Widely recommended for paintings, furniture and wooden sculpture in Europe, and satisfactory for mixed collections. May cause condensation and frosting difficulties in old buildings, especially in inland areas of Europe and the northern parts of North America.
45 – 50 %	A compromise for mixed collections and where condensation may be a problem. May well be the best level for textiles and paper exposed to light.
40 – 45 %	Ideal for metal-only collections. Acceptable for museums in arid zones exhibiting local material.

Note: International exhibits and loans require international agreement on RH levels, and introduce a bias toward the median levels 50-55% RH

This recommendation was over-simplified in the following years, being rigidly presented as the standard pair 20ºC/50% RH for museums, usually named as the "magic numbers" since there was no scientific data to support them [34]. Its implementation occurred at a time when the energy costs were not a problem and there was a belief that the more stable the climate, the better for the collections. This adoption was a sharp setback in the results presented so far and still remains in use in several museums around the world.

Between 1979 and 1999 a great evolution of the paradigm was found and several studies from the

Smithsonian Institute in the USA and the Canadian Conservation Institute (CCI) were published arguing that the "optimum" temperature and relative humidity targets should be defined according to the collection response. The imposition of narrow temperature fluctuations and absolute values defined based on human comfort needs to be criticized as they imply exaggerated energy consumptions. In the years prior to the Ottawa Congress of 1994, temperature and relative humidity values were defined by most private or public institutions in a somewhat arbitrary manner and considered valid for all situations, regardless their location and climate history to which the collections survived [35].

In 1993 Stefan Michalski published an important work that contributed to the change of approach, where he argued that in general the most severe risks lie beyond the relative humidity range of 25 to 75% RH [36,37]. With this work, the author sought to understand the real impact of climate on the collections and to establish maximum limits and permissible fluctuations to minimize the risks of degradation. Michalski argued that the values of temperature and relative humidity should neither be too high nor too low and fluctuations around the mean values depend not only on the type of material but also on the risk one is willing to take.

In 1994 at the Ottawa Congress of the International Conservation Institute, David Erhardt and Marion Mecklenburg from the Smithsonian Institution concluded that there is no an ideal relative humidity value for museums, but values and ranges that minimize some degradation phenomena. The authors argued that extreme values and rapid fluctuations or large variations of relative humidity should be avoided. Within a certain range, as the 30-60% RH, the higher value tends to minimize the physical damage, while the lowest value tends to minimize chemical reactions [35,38]. As regards temperature, the two researchers concluded that this parameter should be defined according to human comfort, except for special cases of long-term storage [39]. Researchers such as Erhardt, Mecklenburg, Tumosa and Michalski argued that artefacts can survive to larger fluctuations that have been accepted in the past and they contributed decisively to changing the climate control approaches.

In 1998, Dario Camuffo published the first edition of the book "Microclimate for Cultural Heritage" addressing the effects of the variability of the interior microclimate on buildings, monuments and other cultural objects. The first part of this book is devoted to the theory applied to climate and presents the basic concepts of classical thermodynamics, kinetics and statistics that are necessary for the diagnosis and conservation of cultural heritage. The second part is dedicated to the practical use, highlighting the importance of the climate monitoring and adequate methods for its implementation, presenting some common mistakes that should be avoided [40]. The team led by Dario Camuffo carried out several important studies in the first decade of this millennium, from which it is possible to highlight some studies carried out in Italy, Austria, Belgium and United Kingdom [41-43]. Dario Camuffo was a staunch supporter of the concept of acclimatization that would serve as a basis for several guidelines, such as the Italian standard UNI 10969 [44] and later the European Standard EN 15757 [45]. Some critics have countered this theory since physical damage can be cumulative and even fluctuations that do not exceed historical levels can contribute to the degradation of collections [46].

In 1999 the Italian standard UNI 10829 was published [47] after the paradigm on climate control has undergone important changes. Always bearing in mind the concern to ensure the correct conservation of materials, a quest for a unique value was abandoned, seeking sustainable intervals based on the materials requirements. In this sense, some indicative values were recommended to limit seasonal variations and daily cycles to reduce the degradation risks. Some examples can be found in Table 1.3.

Table 1.3. Annual and daily limits for temperature and relative humidity for some artefacts according to the UNI 10829 [47]

Material	T [°C]	Daily T span [°C]	RH [%]	Daily RH span [%]
Cardboard artefacts	18 - 22	1.5	40 - 55	6
Textiles, curtains, rugs, religious costumes, materials made from natural fibres	19 - 24	1.5	30 - 50	6
Clothing and artefacts in leather	19 - 24	1.5	45 - 60	6
Canvas paintings, oil paintings, tempera and gouache	19 - 24	1.5	40 - 55	6
Paper or parchment archives, papyrus, manuscripts, printed books, stamp collections	13 - 18	1.5	50 - 60	5
Binding in leather or parchment	19 - 24	1.5	45 - 55	6
Polychromatic wooden sculptures, painted wood, wooden clocks, wooden musical instruments	19 - 24	1.5	50 - 60	4
Unpainted wooden sculptures carvings, basketwork and wood panels	19 - 24	1.5	45 - 60	4
Stone, rocks and minerals	19 - 24	-	40 - 60	6
Wall paintings, frescoes	10 - 24	-	55 - 65	-
Ivory, horns, collections of shells, bones	19 - 24	1.5	40 - 60	6

In the same year, a chapter dedicated to museums, libraries and archives was published in the handbook of the American Society of Heating and Air-Conditioning Engineers, Inc – ASHRAE [48]. This chapter has become part of later versions of this handbook. This specification defines several climatic classes to limit the degradation risks of the materials, focusing on mechanical, biological and chemical damages. This method was a great change from the past since it allows the existence of less stringent bands and presents different targets according to the requirements of the collections and the building limitations. The different classes and the respective limits of temperature and relative humidity can be seen in Table 1.4. The specification can be applied in the design phase, when it is desired to define the indoor climate conditions (ideal intervals), as well as in the microclimatic classification of museums in service, as later observed in several scientific works [35,49].

The new millennium increased the discussion on sustainability, also supported by the strong economic crisis that has been experienced globally. To reduce costs and the ecological footprint, several experts in the field of preventive conservation have advocated the use of less stringent set-points, as defended in several international meetings [21,22].

Table 1.4. Temperature and Relative Humidity specifications according to the ASHRAE specification [48]

Source	Setpoint	Seasonal cycle	Short-term fluctuation	Notes
ASHRAE (1999/ 2007)	T: 15ºC - 25ºC; RH: 50% (or historic annual average for permanent collections)	T: ±5ºC; RH: No	T: ±2ºC; RH: ±5%	Class AA – No risk of mechanical damage to most artefacts and paintings. Some metal and minerals may degrade if 50% RH exceeds a critical relative humidity. Chemically unstable objects unusable within decades.
		T: +5/-10ºC; RH: ±10%	T: ±2ºC; RH: ±5%	Class A - Small risk of mechanical damage to high vulnerability artefacts; no mechanical risk for most artefacts, paintings, photographs and books. Chemically unstable objects unusable within decades.
		T: +5/ -10ºC; RH: No	T: ±2ºC; RH: ±10%	
		T: Up 10ºC; <30ºC; RH: ±10%	T: ±5ºC; RH: ±10%	Class B - Moderate risk of mechanical damage to high vulnerability artefacts; tiny risk for most paintings, most photographs, some artefacts, some books; no risk to many artefacts and most books. Chemically unstable within decades, less if routinely at 30ºC, but cold winter periods double life.
		T rarely > 30ºC; usually < 25ºC; RH: 25 a 75 %		Class C - High risk of mechanical damage to high vulnerability artefacts; moderate risk for most paintings
		RH: <75%		Class D - High risk of immediate or cumulative mechanical damage to most artefacts and paintings

In 2007, Stefan Michalski participated at a meeting organized by the Getty Conservation Institute and addressed the concept of "proofed fluctuations" firstly introduced by him in 1993 [37]. Michalski argued that if the past fluctuations did not cause a significant damage to the collections, there is no reason to expect an increased risk in the future if the past fluctuations are not be exceeded [50].

In 2010 the European standard EN 15757 - Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials [45] was published. The publication of this standard intended to provide a methodology to limit the mechanical damage in organic hygroscopic materials based on the past climate. This methodology is based on the concept of acclimatization, according to which hygroscopic materials when exposed over a long period (more than a year) to certain conditions of temperature and relative humidity, can suffer cracking and irreversible deformations to adapt to the new conditions and to reach a new equilibrium. Throughout this adaptation process, the material loses its initial elasticity and the capacity to re-adapt to new conditions [45]. This method allows calculating safety ranges throughout the year instead of setting a constant target.

In order to overcome the difficulty of choosing ideal set-points for each type of artefact, this standard proposes a statistical method based on the historical microclimate to limit mechanical damage in organic hygroscopic materials. This approach allows more flexible ranges of temperature and relative humidity than the most of set-points frequently found in the international literature, which may lead to a balance between conservation and energy consumption [45]. The methodology is summarized in Table 1.5.

Table 1.5. Description of the EN 15757 methodology [45]

Source	Setpoint	Seasonal cycle	Short-term fluctuation	Notes
EN 15757 (2010)	T: No specification; RH: Historic yearly average	Historic seasonal cycle*	T: No specification; RH: ±10% or target range calculated from the historical data** (the higher range)	* This cycle is obtained by calculating a moving average of 30 days, centred on the current value.
				** The short-term fluctuations are calculated as a difference between a current RH reading and a moving average. The target range is obtained by adding the 7th and 93rd percentiles of the short-term fluctuations in the seasonal cycle.

In 2012, the British Standard Institute (BSI) published a specification called "Publicly Available Specification (PAS 198 - Specification for environmental conditions for cultural collections)" [51]. This project specifies the requirements for the definition of storage, exposure or loan environment conditions to prevent rapid deterioration and to avoid irreversible damage. These requirements for environmental conditions, in particular for temperature, relative humidity, lighting and pollution, consider a more weighted use of energy. It applies to all types and sizes of cultural collections held by individual collectors and all types of organizations, such as archives, libraries and museums, public or private.

In advocating the use of less stringent climate control strategies, a set of interim guidelines were issued in 2008 at the National Conference of Museum Managers and later by the Bizot Group in 2009, as well as by the American Institute for Conservation (AIC), the Association of Directors of Art Museums (AAMD) by the Australian Institute for the Conservation of Cultural Materials (AICCM) [52]. These guidelines advocated the use of a range between 40-60% RH in order to relieve the pressures imposed on HVAC systems and to maintain the collections safety.

Despite the current trend and the opinion of a large part of the experts is to implement less demanding climate control strategies, there is still no global consensus on this approach. In some institutions, the targets used so far are maintained, as they guarantee the maintenance of conservation levels and not contributing to new risks.

The more sceptical sometimes question the advances of science, arguing that the needs of real and ancient paintings cannot be compared to the results obtained by numerical models or laboratory tests [34]. The Doerner Institut has been one of the most critical of this approach, arguing that "stable is safe" and that the science has not yet reached a point where it can clearly state which intervals are safe and that the laboratory results obtained so far cannot yet be generalized [53].

1.3. Research objectives and methodology

With the objective of overcoming the limitations highlighted in 1.1, the author aims to study the influence of climate control strategies on conservation and energy consumption, the influence of tourism on the preservation of cultural heritage and the impact of adequate rehabilitation interventions. It is possible to separate the main goals of the present thesis in three grand points:

1. What is the impact of the climate control strategy on conservation, comfort and energy consumption in cultural heritage?

   The use of climate control strategies with tight limits to ensure the conservation of artefacts is frequent, but in many cases it has no scientific basis. Over the last two decades, it has been argued that materials adapt to the climatic conditions in which they are stored through a phenomenon known as "acclimatization". Based on this concept a European standard (EN 15757 [45]) was published proposing a new method to define the target climate of historic buildings based on the typical climate that characterizes the building. Despite the novelty of this approach, the methodology was based on cold climates and has not yet been tested in temperate climates.

   In this thesis, the author intends to evaluate the impact of different climate control strategies in the conservation, comfort and energy consumption of cultural heritage buildings and after to propose and validate a statistical method to optimize in a sustainable way the indoor climate of these buildings.

   To support these goals, the microclimate data from the Church of São Cristóvão, the National Museum of Ancient Art (NMAA) of Lisbon and the Jeronimos Monastery also in Lisbon were used. The data from the Church of São Cristóvão was obtained by the author during his master dissertation and the data from the NMAA was furnished by the museum core.

   The microclimate data of the Jeronimos Monastery was obtained within the aim of this thesis. To overcome the frequent problems with sensor prices and their limitation in programming, the author proposed to develop and test a low-cost and open-source monitoring campaign based on the Arduino technology.

Following this goal, the author intends to use a method to quantify the risk of degradation based on damage functions present in the bibliography to quantify the real effect of different climate control strategies on the preservation of buildings and collections. With the analysis of a set of climate control strategies frequently used in the field of preventive conservation, it is intended to analyse the impact of each of them on conservation and to verify if it is really necessary to use tight climatic control intervals.

2. What is the impact of cultural tourism for the conservation of the buildings and the health and comfort of the visitors?

   Cultural tourism has been increasing in Europe, which has given rise to several threats to cultural heritage. In spite of the economic value that the increasing number of visitors, it is necessary to consider the conditions of conservation of the buildings and collections and the comfort and health of the visitors themselves. In Portugal, this phenomenon has been evidenced mainly in buildings such as churches, palaces or monasteries, which are usually characterized by a deficient hygrothermal response, with low ventilation rates and no air conditioning system. The exacerbated increase in the number of visitors to the same level of ventilation contributes to the increased concentrations of water vapour and CO_2 that lead to increased risk of degradation and health.

   In this thesis, it is intended to evaluate the effect of tourism at Jeronimos Monastery. For this goal, an hygrothermal simulation model of the monastery was developed in the WUFI®Plus software and validated against the microclimate parameters recorded within the aim of this thesis.

   Based on the statistical analysis of the number of visitors in Portuguese monuments and the general tourism in the last years, several growth scenarios were defined.

   To quantify the real impact of tourism in conservation of the cultural heritage and in the health and comfort of visitors, a classification method based on published studies was used.

3. May the thermal rehabilitation be the solution for the energetic and economic sustainability of museums?

   Cultural heritage plays an important role in society, not only in cultural terms but also in the economy due to its touristic interest. European Union (EU) has taken energy efficiency as an urgent need and has developed some ambitious directives aiming at the reduction of energy consumptions in the building sector. The author proposes to study the effect of the thermal rehabilitation and the climate control strategies at the energy consumption of museums aiming the attest the energetic and economic impact of several scenarios and contributes for the decision-making process in the museum management.

Within this goal, a simulation model of a generic room of the National Museum of Ancient Art was developed with the WUFI®Plus software. The model was simulated for 15 different European cities aiming to demonstrate the different necessities according the local climate and the impossibility of standardizing rehabilitation scenarios.

Aiming to evaluate several scenarios for Lisbon, a sensitivity study testing two climate control strategies, four scenarios of thermal transmittance for the opaque envelope, four scenarios of thermal transmittance for the windows and four solar heat gain coefficient scenarios were simulated performing a total of 128 simulations.

Despite the energy analysis is useful for decision making, it says little or nothing about the economic return of each solution. Thus, the author intended to apply the optimal cost methodology for two distinct economic evolution scenarios to test which solutions are economically viable. In total, 144 combinations were tested.

1.4. Research structure

The document has the followed structure:

- ✓ Chapter 1 – Introduction
- ✓ Chapter 2 - The impact of the climate control strategies on the conservation, comfort and sustainability of cultural heritage buildings
- ✓ Chapter 3 - The impact of mass tourism on the conservation and visitors' comfort in the Jeronimos Monastery, Lisbon (Portugal)
- ✓ Chapter 4 - A statistical methodology to define a sustainable climate control strategy for cultural heritage buildings in temperate climates
- ✓ Chapter 5 - A sequential process to assess and optimize the indoor climate of the Nacional Museum of Ancient Art of Lisbon
- ✓ Chapter 6 - Sustainable rehabilitation of museums
- ✓ Chapter 7 – Conclusions and future work

1.5. Contributions

Up to the present date the following papers were published or submitted for publication:

Scopus indexed journals

H.E. Silva, G.B.A. Coelho, F.M.A. Henriques, Climate monitoring in World Heritage List buildings with low-cost data loggers: the case of the Jerónimos Monastery in Lisbon (Portugal), Journal of Building Engineering (accepted for publication on October 26, 2019 – In production).

G.B.A. Coelho, H.E. Silva, F.M.A. Henriques, Impact of climate change on the conservation of cultural heritage, Journal of Global Warming (accepted for publication on August 5, 2019 – In production).

G.B.A. Coelho, H.E. Silva, F.M.A. Henriques, Calibrated hygrothermal simulation models for historical buildings, Building and Environment. 142 (2018) 439–450. doi:10.1016/j.buildenv.2018.06.034.

H.E. Silva, F.M.A. Henriques, T.A.S. Henriques, G. Coelho, A sequential process to assess and optimize the indoor climate in museums, Building and Environment. 104 (2016) 21–34. doi:10.1016/j.buildenv.2016.04.023.

H.E. Silva, F.M.A. Henriques, Hygrothermal analysis of historic buildings: Statistical methodologies and their applicability in temperate climates, Structural Survey. 34 (2016) 12–23. doi:10.1108/SS-07-2015-0030.

H.E. Silva, F.M.A. Henriques, Preventive conservation of historic buildings in temperate climates. The importance of a risk-based analysis on the decision-making process, Energy and Buildings. 107 (2015) 26–36. doi:10.1016/j.enbuild.2015.07.067

H.E. Silva, F.M.A. Henriques, Microclimatic analysis of historic buildings: A new methodology for temperate climates, Building and Environment. 82 (2014) 381–387. doi:10.1016/j.buildenv.2014.09.005.

Other journals

H.E Silva, F.M.A. Henriques, T.A.S. Henriques, G. Coelho, A análise climática na conservação e optimização energética em edifícios históricos: o caso do Museu Nacional de Arte Antiga, Construção Magazine. 79 (2017) 10-14.

H.E Silva, F.M.A. Henriques, Análise Microclimática de um edifício histórico em clima temperado: limites sustentáveis para a correta conservação dos materiais, Ambiente Construído. 15(2) (2015) 65-77. doi:10.1590/s1678-86212015000200014

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Conferences

G.B.A. Coelho, H.E. Silva, F.M.A. Henriques, Development of a three-dimensional hygrothermal model of a historic building in WUFI®Plus vs EnergyPlus, in: Central European Symposium on Building Physics (CESBP), 2-5 September 2019, Prague, Czech Republic.

H.E. Silva, G.B.A. Coelho, B. Rocha, F.M.A. Henriques, Impacto dos visitantes na conservação do património cultural em Portugal, accepted for presentation in Contrução 2018 – Reabilitar e construir de forma sustentável, which will be held between 21 to 23 November 2018 at FEUP, Oporto.

H.E Silva, F.M.A. Henriques, Hygrothermal analysis of historic buildings – Statistical methodologies and their applicability in temperate climates, in *1st International Symposium on Building Pathology* (ISBP-2015, Faculty of Engineering – University of Oporto, Oporto, Portugal, 24-27 Mars, 2015.

H.E Silva, F.M.A. Henriques, Análise e classificação microclimática de edifícios históricos: Capela das Albertas, Museu Nacional da Arte Antiga (Lisboa), in *5ª Conferência sobre Patologia e Reabilitação de Edifícios*, Patorreb 2015, Oporto, Portugal, 26-28 Mars 2015.

Technical reports

H.E. Silva, F.M.A. Henriques, T.A.S. Henriques, Avaliação do clima interior no Museu Nacional de Arte Antiga, Technical report 1.16 DEC/FCT/UNL for the Nacional Museum of Ancient Art of Lisbon, Caparica, January 2016.

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2. The impact of the climate control strategies on the conservation, comfort and sustainability of cultural heritage buildings

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H.E. Silva, F.M.A. Henriques, T.A.S. Henriques, G. Coelho, A sequential process to assess and optimize the indoor climate in museums, Building and Environment. 104 (2016) 21–34. doi:10.1016/j.buildenv.2016.04.023.

2.1. Introduction

Historic buildings assume a fundamental role in modern societies, being a symbol of their past, and often used as museums or galleries, bringing together the value of their collections and the history behind the building.

The artefacts that constitute the collections react to temperature and relative humidity, which can induce degradation phenomena, namely mechanical, biological and chemical [1]. To avoid the inherent risks and to guarantee a proper conservation it is common to use tight limits of temperature (T) and relative humidity (RH).

Throughout history, the guidelines were not always based on scientific works, and sometimes the set-points were defined according to experience and observation of the response of objects. The set-point of 20ºC for T and 50% for RH, for example, was widely used by conservators for a long time, apparently with no scientific explanation, but the truth is that it is still used in several cases [2]. These limits were defined in a particular moment where the energy efficiency was still not a problem due to the low cost of energy, and where the risk-based analysis was not extensively used [2-4]. These targets, even in temperate climates, can only be achieved using HVAC systems.

It is important to consider that historic buildings often show a particular hygrothermal response. These buildings, usually with thick walls and a small percentage of transparent surfaces when compared to the opaque envelope, present a large capacity to store heat, showing a great effectiveness in damping and delaying thermal cycles. In temperate climates, this behaviour leads to a great thermal equilibrium in short-periods, disturbed only by the presence of disrupting factors such as artificial heating, lighting or human presence [5]. However, their envelope is usually composed of materials with high thermal conductivities, which do not react positively to tight targets of temperature. If the limitations of the envelope are ignored, the consequences may not be positive, with the possibility of surface condensations, for example [6,7].

The knowledge about these subjects is improving and the most recent trends show a higher flexibility, according to developments in the materials science [8]. The experience obtained along the time has shown that in some cases the collections have survived positively, even when exposed to less demanding targets. The ASHRAE specification [9] is a good example, defining five classes and allowing some fluctuations without compromising the collections. The European Standard EN 15757 is another good example, where it was defined as a dynamic method to limit the mechanical degradation of organic hygroscopic materials [10].

The implementation of tight limits has another worrisome consequence: the high-energy consumption needed to keep the buildings at the desired levels. Nowadays, one of the biggest challenges in historic buildings, such as museums, is to reach an equilibrium between the conservation requirements and the energy economy [4,7], as it is evidenced in the recent British specification PAS 198 [11], where the targets are defined according to the collection needs, trying also to achieve energy economy without jeopardizing conservation.

Monitoring the indoor climate in buildings with no climate control can be a useful tool to understand the natural behaviour of these buildings and to define a climate control strategy that can balance conservation, comfort and energy. Despite the importance of the monitoring campaigns, it is necessary to carry out a careful and objective analysis of the data to draw clear conclusions about the microclimatic behaviour and the real risk of degradation.

The methodology used in this chapter combines long-term monitoring, a statistical and a risk-based analysis aiming to characterize the indoor climate of cultural heritage buildings. The climate data recorded during more than a year in the Church of São Cristóvão in Lisbon was used to evaluate the response of the building and collections. The implementation of the targets defined by the EN 15757, PAS 198 and the historic set-point of 20ºC and 50% were also evaluated.

2.2. Methodology

2.2.1. General considerations

For a better understanding and evaluation of the strengths and weaknesses of the cultural heritage buildings, a microclimatic analysis is indispensable to verify the interactions between the interior and exterior climates, the influence of the thermal inertia and to check the air stratification, the disrupting factors and to assess the degradation risks. This section intends to present a set of tools that allows to standardize in a certain way the microclimatic analysis and increase the robustness of the conclusions.

2.2.2. Statistical analysis

To facilitate the analysis of the microclimatic behaviour and to complement the graphical analysis, a general statistical analysis of the temperature, relative humidity and the water vapour pressure for the interior and exterior of the buildings was carried out.

Sometimes it may be necessary to smooth the data. Throughout the monitoring, extreme values of temperature and relative humidity can occur that do not necessarily correspond to reality for several reasons, such as energy fails. However, it is impractical to analyse manually each point. Therefore, it is proposed to smooth the data by excluding 1% of the highest positive and negative extremes (safe area: from 0.5 º to 99.5 percentiles) as made by Martens [6].

It has been considered that it makes no sense to present the temperature with more than one decimal and that the relative humidity should be rounded to the unit since the uncertainty of the sensors does not justify a higher precision.

The temperature (T) and the relative humidity (RH) were obtained directly, while the water vapour pressure (e) was calculated by eq. (2.1) respecting the formulation presented in the standard EN 16242 [12]:

$$e = 0.06112 \times 10^{\frac{7.65 \cdot T}{243.12+T}} \times RH\ (hPa) \tag{2.1}$$

where *e* is the water vapour pressure (hPa), RH is the relative humidity (%) and T is the air temperature (°C).

In a second phase, several statistical operations were used to parameterize the data: the annual average, the 2nd, 10th, 90th and 98th percentiles, the seasonal (monthly) cycles and the short-term fluctuations.

The determination of the seasonal cycle was carried out based on the methodology described in the European standard EN 15757 [10]. The seasonal cycle is obtained from the calculation of a 30-day moving average centred on the desired value, considering the records of the 15 days before and the 15 days after the value under analysis:

$$\bar{X}_{moving,i} = \frac{1}{n+1} \cdot \sum_{i-0.5 \cdot n}^{i+0.5 \cdot n} X_i \tag{2.2}$$

where $\bar{X}_{moving,i}$ is the 30-days moving average centred at the point *i*, *X* is the *T* (°C), *RH* (%) or *e* (hPa), *n* is the number of records during the 30 days and *i* is the centre point.

In addition to the graphical representation of the seasonal cycle ($\Delta_{seasonal}$), also the maximum seasonal amplitude was quantified by subtracting the minimum value to the maximum for each of the parameters under analysis:

$$\Delta_{seasonal} = max(\bar{X}_{moving,i}) - min(\bar{X}_{moving,i}) \tag{2.3}$$

Typical short-term fluctuations were obtained as the 7th and 93rd percentiles of the difference between the measured climatic parameter and the 30-day moving average value for that time throughout the year.

Additionally, the internal water vapour pressure excess parameter was used. This parameter represents the differential between the interior and exterior water vapour pressure [13]. High values increase the risk of surface condensation and mould germination and may indicate an inadequate ventilation and/or an occupancy too high for that particular ventilation. Low values show that the room is well ventilated and that the existence of pathologies related to humidity may be justified by other factor as those related with the external climate, evidencing the need to heat and/or to dehumidify the space, or with other problems such as infiltrations or rising damp. This parameter can be obtained from the equation (2.4):

$$\Delta e = e_i - e_e \tag{2.4}$$

where Δe is the internal water vapour pressure excess (hPa), e_i is the interior water vapour pressure (hPa) and e_e is the exterior water vapour pressure (hPa). The results can be presented as monthly our annual averages.

2.2.3. Performance Index

Museums are usually equipped with air conditioning systems to control temperature and relative humidity and to limit the risks of loss of the collections, often using stringent targets that lead to large energy consumptions. Despite this, sometimes the targets are not kept due to the ineffectiveness of the HVAC system or by possible limitations of the building envelope.

To assess the compliance of the imposed targets the method defined and tested by Corgnati et al. [14,15] named as "Performance Index" was used. This index expresses the percentage of time in which the measured parameters are within the reference target. This approach can easily be used to evaluate the performance of the HVAC system and its ability to keep the hygrothermal parameters within the imposed limits. It is important to consider that this index does not evaluate the damage risks, but only the effectiveness of the climate control system. For buildings with no HVAC system, this method can be used to evaluate the natural capacity of the building to meet the desired setpoints.

The graphical representation of the method facilitates the analysis of the climate and the diagnosis of possible problems, allowing to identify the situations that require major concerns, as can be seen in Figure 2.1. The analysis of the effectiveness of the HVAC system should be based on the setpoints imposed to the system. To analyse the possibility of controlling the climate in naturally ventilated buildings, these limits must come from the literature related to the subject and should be duly justified.

The climate is classified as “too hot” if the measured temperature exceeds the maximum allowable value, and “too cold” if the measured temperature is lower than the lowest limit. As regards relative humidity, the climate is classified as “too humid” when the measured value is higher than the upper limit and as “too dry” when the measured value is lower than the lowest limit. The requirements are met if both the temperature and relative humidity are between the minimum and maximum targets (a range defined as "OK"). For example, if both the temperature and relative humidity exceed the respective upper limits, then the climate is considered "Too humid and too hot".

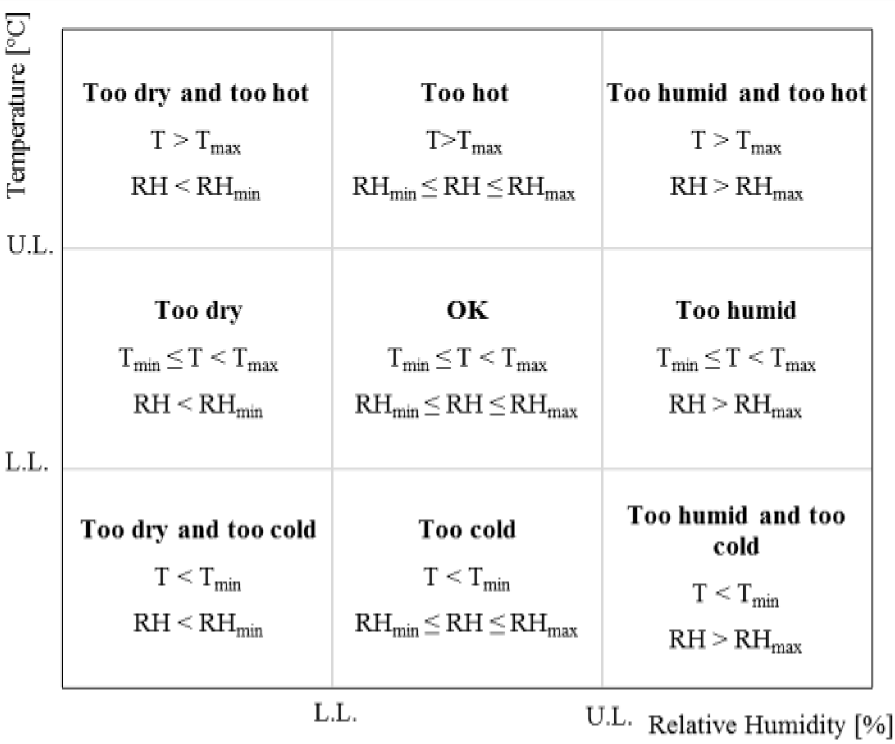


Figure 2.1. Performance index (adapted from [16]): U.L. – upper limit; L.L. – lower limit

2.2.4. Risk-assessment

For several years the conservation science theories were based on tight limits of temperature and relative humidity, assuming that any discrepancies would cause deterioration. Nowadays a new consensus seems to be reached leading to a higher resilience of the collections to microclimate fluctuations. New standards, guidelines and risk-assessment methods based on laboratory tests are emerging, as those used in the current thesis. Despite these advances, some experts argue that the actual approaches, although less demanding, remain too conservative [17]. The rationale being that if some materials of permanent expositions have survived for years to environmental changes, even before the proliferation of the HVAC systems in indoor climates only controlled by the building envelope, what is the reason not to survive in the present days?

It is known that temperature and relative humidity have a direct influence on the degradation of the collections. Often the analysis is simply qualitative since it is not always easy to quantify the damage associated to a certain fluctuation. In this section, a set of tools based on laboratory and numerical studies present in the bibliography was presented to facilitate the risk evaluation and to support the optimization process.

2.2.4.1. <u>Mechanical degradation</u>

The fluctuations of T and RH originate changes in the equilibrium moisture content of organic hygroscopic materials that can lead to important degradation phenomena. It is possible to find some targets in the bibliography aiming to limit this phenomenon, but a risk-based analysis applied to each case is indispensable.

The temperature does not usually appear as a key factor for conservation. For example, hide glues can survive to fluctuations from -29ºC to + 32ºC without plastic deformations. However, it is known that some materials such as acrylics, alkyds and oil paints when exposed to low temperatures become brittle. If the temperature of the glass transition (12.8ºC for the acrylics) is respected, the risks of mechanical degradation due the T-fluctuations remain very low [18].

The mechanical damage in organic hygroscopic materials, as wooden objects, is a real problem, since the RH fluctuations are directly linked to dimensional changes. If the movement is not restrained the object can change freely, but if it is restrained, as in objects composed by different layers or when different moisture gradients are present, high tensions are created and damage can occur. Dimensional changes are directly influenced by the changes in the moisture equilibrium of the materials, that fluctuate in accordance with the relative humidity (although not instantaneously). Usually, the objects do not respond immediately to the air fluctuations; often the equilibrium is reached after several hours, days or even weeks [16] and depends on the adsorption/desorption characteristics of the materials. It is important to analyse the response time for each material, considering that the core and the surface layers do not respond at the same time. In this point, a set of damage functions based on the response of the material were used, according to the response-times defined in Table 2.1.

These damage functions are only valid for undamaged artefacts, since damaged surface layers may increase the velocity of the interactions between the objects and the environment, decreasing their response times and, consequently, underestimating the climate influence.

Table 2.1. Time and type of response for painted panels, furniture and sculptures [16]

Artefact	Type of response	Response time
Painted Panel	Surface response just under oil paint	4.3 days
	Full response of the entire panel	26 days
Furniture	Full response	40 days
Sculptures	Surface response	10 hours
	Sub-surface response causing maximum stresses	15 days

To obtain the equivalent relative humidity of the materials for each moment, respecting their response times, equation (2.1) defined by Martens [16] should be used:

$$RH_{response,i} = \frac{a \cdot RH_i + a^2 \cdot RH_{i-1} + a^3 \cdot RH_{i-2} + a^4 \cdot RH_{i-3} + ... + a^n \cdot RH_{i+1-n}}{\frac{a}{(1-a)}} \quad (2.1)$$

where $RH_{response,i}$ is the RH equivalent to the moisture content of the object in each moment obtained from the response factor *a* which is calculated from the equation (2.2):

$$a = e^{\frac{-3 \cdot \Delta t}{\tau_{response}}} \quad (2.2)$$

where Δt is the interval between 2 successive records [s] and $\tau_{response}$ the response time [s].

Painted panels

To evaluate the mechanical risk-damage in painted panels, two different methods were used: one defined by Mecklenburg *et al.* [19] to evaluate the wooden substrate, and another defined by Bratasz *et al.* [20] to evaluate the response of the pictorial layer.

The research published by Mecklenburg *et al.* [19], where the authors assessed the climate-induced mechanical damage of some materials of painted panels, is a good example of how it is possible to evaluate the mechanical degradation in function of RH fluctuations. The allowable RH fluctuations that do not lead to plastic deformations of the base materials (for the cottonwood) is shown in Figure 2.2.a. This method, based on the yield strain criterion, considers a yield strain of 0.004, a conservative value since 0.0055 is the yield strain generally assumed for most of the old woods. To apply this method in a dynamic form, it was considered the hypothesis that the internal restrictions change due to RH fluctuations, considering the values corresponding to the full-response of the material in the x-axis and the surface response in the y-axis as considered in the ref. [16].

In the literature about the pictorial layer it was shown that the lag in the response between the gesso and the unrestrained wooden substrate corresponds to the worst scenario for the pictorial layer, due to the higher responsivity of the wood in relation to the gesso layer. The yield strain of gesso limits all the system, since its admissible strain in elastic response is lower than that verified by the hide glue and paint [19,20].

The allowable magnitudes of RH for which gesso can survive without damage were determined by cyclic tests with sinusoidal fluctuations around the 50% RH by Bratasz *et al.* [20]. The allowable fluctuations were derived from the duration of the cycle, the thickness of the panel and the moisture diffusion configuration, i.e., if the diffusion takes place on both sides or only on one, simulating the effect of a pictorial layer completely impermeable to moisture flow. It was concluded that in the worst case, only fluctuations with amplitudes higher than 14% RH can lead to the failure of the pictorial layer [20]. In addition to the RH, it was also found that temperature plays an important role in the failure by fatigue. The risk is lower for temperatures of 5°C than for 20 ºC [20]. The allowable fluctuations according to their duration for two moisture diffusion configurations and two different temperatures can be seen in Figure 2.2.b.

Sculptures

Despite the effectiveness of the method presented by Mecklenburg *et al.* [19] for the painted wood, it was based on some simplifications that compromise their application on more elaborated objects and where the moisture gradient from the core to the surface is important, as is the case of sculptures. Moreover, this method does not consider the influence of the cycles, considering only the full response of the materials. Accordingly, Jakieła *et al*. [21] have modulated the instantaneous and daily hygrothermal response of lime wood cylinders.

This method considers the influence of the moisture gradient from the inner to the surface of the objects instead of considering its full-response. Modulating the response of lime wood cylinders subjected to instantaneous and daily fluctuations, the allowable RH fluctuations to maintain the sculptures in safety were determined. The fluctuations of moisture content assume a fundamental role in the mechanical response of the objects, i.e., for example, when the surface is drying, the core remains with higher moisture content, resulting in high tensions. The stresses decrease when the moisture content of the core is closer to the one of the surfaces.

The allowable RH fluctuations according to the variations from the core (x-axis) to the surface (y-axis) are shown in the Figure 2.2.c for a step fluctuation of RH. It was decided to use this approach instead of the daily fluctuation since it is the more adverse and conservative scenario.

Furniture

For furniture the results obtained by Bratasz et al. [22] in a study about the dimensional response of a lacquered wooden box were used. The response of the wooden support and the lacquer were analysed, considering the restrictions of movements in the box caused by its own construction, and the restraints of the lacquer in the interface with the wooden support. According to the yield strain criterion, it was possible to define the allowable RH fluctuations that do not compromise the mechanical response both for the wooden structure as for the lacquer layer, as it is possible to see in Figure 2.2.d. As in [16] the x-axis corresponds to the annual average and the full response to the y-axis.

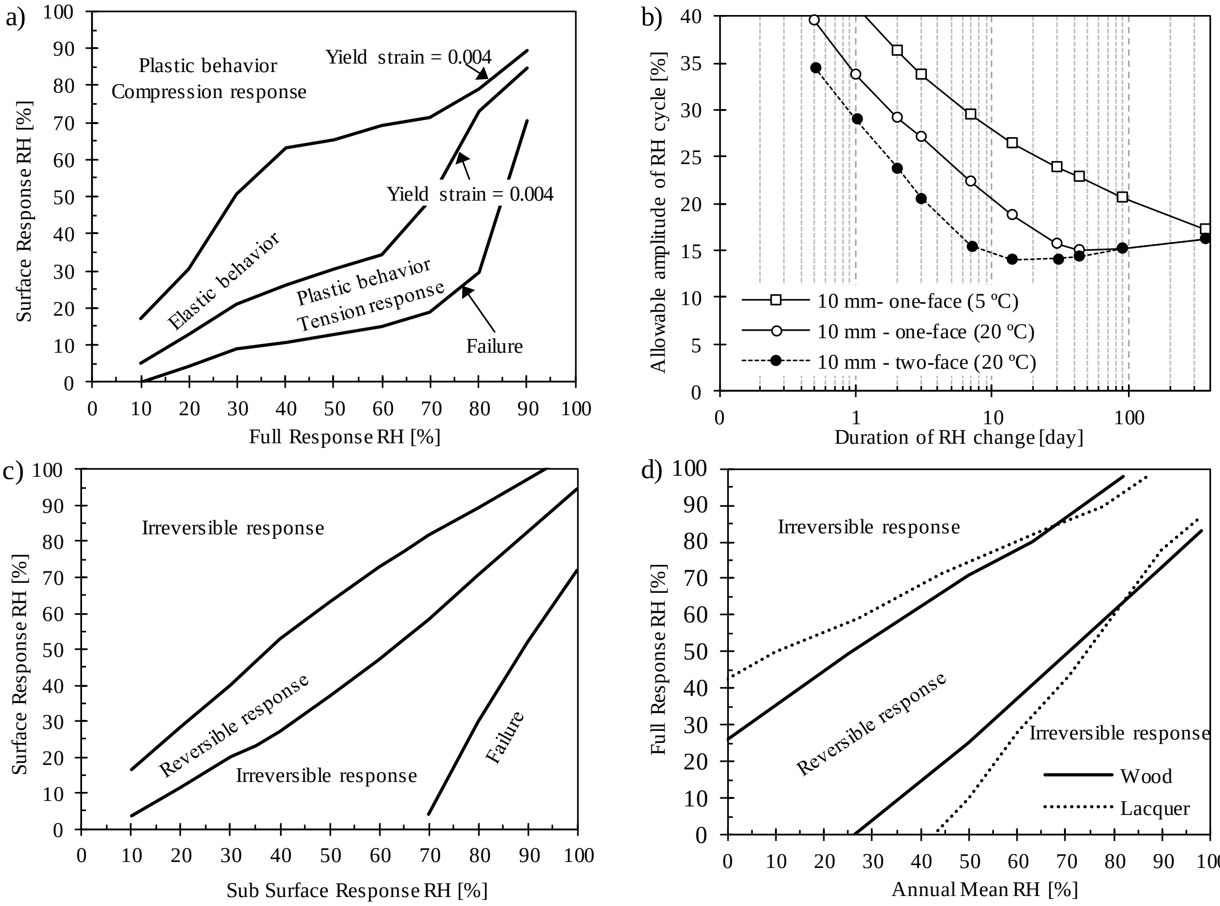


Figure 2.2. Mechanical risk-assessment: a) wooden substrate of painted panels [19]; b) pictorial layer of painted panels [20]; c) sculptures [21]; d) furniture [22]

2.2.4.2. Biological degradation

The biological degradation is directly linked to the mould growth and is considered a major cause of degradation in museums all over the world, denouncing the presence of high values of relative humidity [16]. The development of microorganisms has some negative impacts in visual terms and create conditions for the deposition of particulates, which can change some parameters as sorptivity, therefore changing the hygrometric equilibrium processes of the materials.

In addition to the problems that mould brings to the buildings and collections, it is important not to neglect the risks for human health. Some reports of respiratory problems may occur, along with allergies, nausea, shortness of breath, and vomiting associated to the presence of moulds [23,24] which have a toxic metabolic activity and release mycotoxins and volatile organic components. Even if it is sometimes possible to use biocides to mitigate the problem, it is of common sense that the only definitive solution of the problem is to avoid the hygrothermal conditions that can contribute to their germination.

Usually values below 60% RH are assumed to prevent the mould germination, while values above 75% RH constitute a real risk [16]. However, there are other factors that contribute for mould germination, namely the type of the substrate, the nutrient availability or the existence of prior contamination.

Several authors have studied this theme, and the isopleth method defined by Sedlbauer [25] has generated a great consensus on the preventive conservation field as can be assessed in the refs. [22,26-28]. The method was developed according to three grand lines: temperature, relative humidity and the substrate quality, which must coexist along a certain time to allow the mould germination and the mycelium growth. For the definition of this method, Sedlbauer carried out an extensive literature review collecting data of about 200 species of fungi frequently present in buildings. The information on minimum, maximum and ideal conditions of temperature and relative humidity for spore germination and mycelium growth were collected separately [29].

A graphical method was developed with the creation of several diagrams (usually named as isopleth diagrams) for different classes. In these diagrams, the lower curve LIM (Minimum Isopleth for Mould) represents the minimum conditions for mould germination and it is often used for the design of indoor conditions since if the RH remains below the LIM for a certain T, the mould risk can be neglected.

The method considers four different types of substrate, which seek to recreate surfaces susceptible to fungal attack in buildings [29]: Category 0: ideal medium; Category I: biologically recyclable construction materials; Category II: biologically hazardous building materials; and Category III - building materials which are neither degradable nor contain nutrients. The isopleth diagrams for the category I and II can be seen in Figure 2.3.

The isopleth method was developed based on data obtained in steady-state conditions [25], which has been pointed out as one of the major limitations of the model [30] since it does not allow to evaluate the influence of the periods in which the relative humidity is lower than a certain isopleth. It should be considered that the model is divided into two components: germination and growth, in which growth only takes place after the germination has occurred. Thus, as indicated in the diagrams, it is necessary that a certain isopleth is exceeded continuously for the period associated therewith, after which the growth of the mycelium begins if the hygrothermal conditions so corroborate.

In this thesis the concept of mould risk factor (MRF), as defined in the ref. [31], was adopted to obtain more conclusive results. To determine the MRF, it was assumed that for each reading above a certain isopleth the counter would start. The MRF is obtained by summing the reciprocal of the time needed to the germination for each point above the isopleth. In cases where the data were recorded for every 10 minutes, each reading above the isopleth of 16 days, for example, is pondered as 1/(16 x 24 x 6) [29,31]. The result of a running sum allows the computation of the global MFR. If the MRF equals the unit, the conditions for germination are met. The biological degradation is a frequent risk in old buildings, not only directly on the objects but also on the interior surfaces. Since the analysis should be conducted for the surface conditions, it was considered that the object responds instantaneously to the air fluctuations.

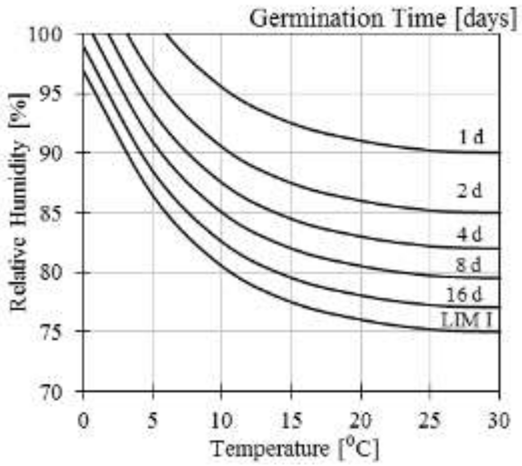
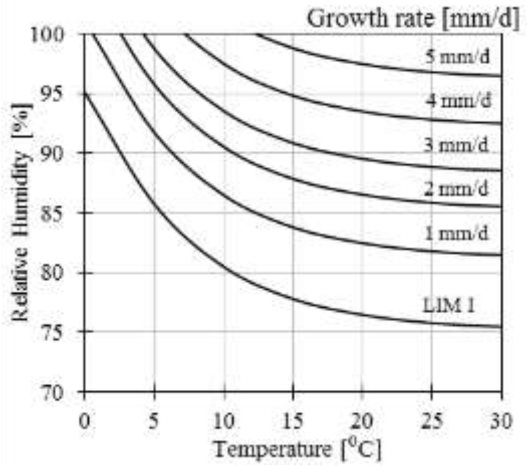
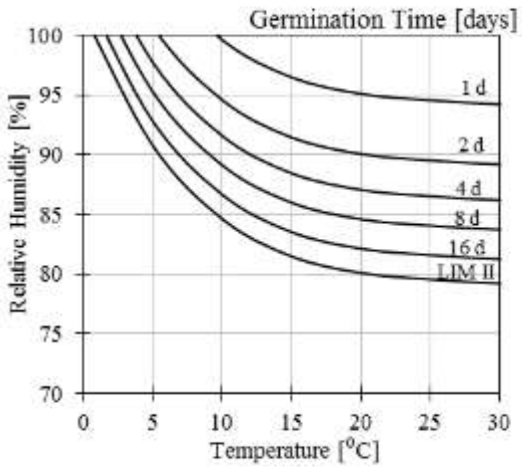
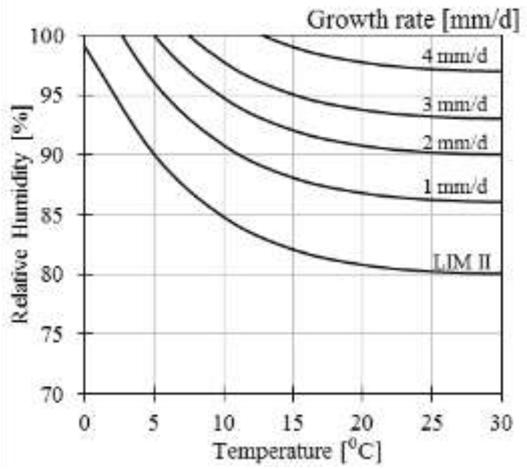
<table>
<tr><th>Substrate type</th><th>Spore germination</th><th>Mycelial growth</th></tr>
<tr><td>I</td><td></td><td></td></tr>
<tr><td>II</td><td></td><td></td></tr>
</table>

Figure 2.3. Isopleth method of Sedlbauer for the substrate types I and II [25]

The use of the MRF allows adapting the original stationary method in a dynamic model. Despite this innovation, the accounting of the influence of points with unfavourable conditions for mould germination is not unanimous. Sedlbauer [25] argued that spores can survive to unfavourable conditions and resume the growth after this period. So, the sum for MRF should be continuous over the period under review where unfavourable points do not contribute to the sum but also do not imply a restart, as exemplified in the refs. [29,32]. This approach is also followed by an analogous method used by Image Permanence Institute (IPI) [31] and by Silva et al. in [27] and [28]. Other authors argue that the sum should not be continuous and should restart whenever the conditions are unfavourable, as defended by Martens [16].

It is known that under certain hygrothermal conditions spores do not survive. If this happens, the count for the MRF must restart, and a new growth occurs only if the MRF reaches the 1-value [29,31]. However, once again there is no consensus on the conditions required for fungus death. According to the method used by IPI [31], the mycelium dies if exposed to 24 h or more under adverse conditions, although it does not specify which are the conditions. Martens [16] considered a period of one month with relative humidities lower than or equal to 55% RH to lead to fungal death.

In this thesis an update to the method presented in [28] is made. The use of a continuous sum was maintained to calculate the MRF, as used in the refs. [29,31,32]. However, the mycelium death was assumed if exposed during 30 days or more to relative humidities equal or less than 55% RH.

It should be noted that the method must be applied for the substrate types I and II. If there are some doubts, the category I must be used. In theoretical terms the germination time over the LIM I and LIM II isopleths are infinite [33], but the numerical use of the method implies the adoption of a finite number for those isopleths. A germination time of 150 days for LIM I and 35 days for LIM II were adopted in accordance with the ref. [34], as referred also in ref. [25].

To increase the robustness of the method and to overcome a limitation that has been pointed out [30], interpolations between the various isopleths were made. For Category I, the following isopleths were used: 150, 116.5, 83, 49.5, 16, 14, 12, 10, 8, 7, 6, 5, 4, 3, 2 and 1 days. For Category II the following isopleths were used: 35, 30.25, 25.5, 20.75, 16, 14, 12, 10, 8, 7, 6, 5, 4, 3, 2 and 1 days. With respect to mycelial growth, rates of 0, 0.0625, 0.25 mm/d and hence spaced at 0.25 mm/d were considered as high as 5 mm/d.

2.2.4.3. Chemical degradation

The chemical degradation assumes an important role in the conservation science. The chemical degradation is more influenced by the temperature, contrary to what is verified on mechanical and biological degradation. Some phenomena as discolouration and embrittlement of paper, dye fading in old photographs and the loss of resistance in textiles are examples of chemical degradation [35,31]. It is difficult to reach a balance between chemical, mechanical and comfort needs, due to the necessity of low temperatures and relative humidities to guarantee a proper chemical conservation. However, a compromise should be possible to keep the risk of loss at an acceptable level.

Hydrolysis, one of the major manifestations of chemical degradation, is commonly characterized by Arrhenius equation [36,37], that allows the calculation of the degradation rate. Sometimes this equation is difficult to apply, which lead to the formulation of new approaches. The researchers of the Image Permanence Institute (IPI) developed some experiments and defined an empirical equation that allows estimating how long it is necessary for cellulose acetate to evidence significant signals of deterioration, as discolouration, embrittlement and other changes that involve a loss in appearance or functionality [35,31]. The IPI has established a value of 45 years as the minimum to guarantee a proper conservation. Equation (2.3) shows this estimator, denominated as *Preservation Index* [35]:

$$Preservation\ Index = \frac{e^{(95220-134.9\times RH)/(8.314\times(T+273.15)+0.0284\times RH-28.023}}{365} \tag{2.3}$$

with RH in % and T in degree Celsius.

However, it must be kept in mind that the method defined by the IPI is an empirical result based on specific data for cellulose acetate and it is therefore not possible to extrapolate the results to other materials. Therefore, it will be used only like a qualitative classification method.

In this thesis, a different method was used – the concept of Lifetime Multiplier [38]. This equation returns a multiplier factor that compares the real pair of T and RH with the conditions for the set-point of 20ºC;50% RH. This method does not allow a lifetime prevision, but only a comparison with the standard values, as can be seen:

$$LM_i = \left(\frac{50\%}{RH_i} \right)^{1.3} \times e^{\frac{E_a}{R} \times \left(\frac{1}{T_i + 273.15} - \frac{1}{293.15} \right)} \qquad (2.4)$$

where LM_i is the Lifetime multiplier at point i, E_a the activation energy [J/mol] – 70000 for the yellowing varnish and 100000 for degradation of cellulose [16,38], R is the gas constant (8.314 J/mol.K), T_i is the temperature at the point i [ºC], RH_i is the relative humidity at point i [%] and "i" is the data point in data series.

In order to facilitate the analysis and to evaluate the annual response, an equivalent Lifetime Multiplier is proposed returning a unique value and representing the influence of all year. Instead to the use of the arithmetic average, it was decided to calculate the equivalent value by the average of the reciprocal values of lifetime multiplier, increasing the influence of the points with worse conditions, as it was made by the IPI to calculate the Time Weighted Preservation Index [31,35]:

$$eLM = \frac{1}{\frac{1}{N} \times \sum_{i=1}^{N} \left(\frac{1}{LM_i} \right)} \qquad (2.5)$$

where the eLM is the equivalent lifetime multiplier and N is the number of data points.

As it was referred for the mechanical degradation, the objects do not reach the equilibrium from the environment instantaneously. According to the IPI, a running average of 24 h for T and of 30 days for RH [31] was used to obtain the response of the collections and to calculate the lifetime multiplier.

2.2.5. Thermal comfort

The evaluation of thermal comfort in the built cultural heritage is a complicated task since models are not specifically designed for their requirements and most of them were created to meet the needs of the occupants of offices, schools or residential buildings [27,39].

This problem has already been identified in some studies, where it is possible to highlight Silva et al. [27] who proposed an adaptation of the PMV model with the use of dynamic inputs or by Kramer et al. [26] that used an adaptive model defined for the Netherlands [40], or by Kramer et al. in [39] resorting to a model based on 1248 surveys carried out in the Hermitage museum of Amsterdam in 2015 [41] that allowed the definition of an adaptive model that until now seems to be the most suitable for museums, although it has not yet been validated for other climates.

The PMV model, which returns the Predicted Mean Vote of a large group of people, is based on the balance between the heat generated by the human body and the heat released to the environment. This method, of stationary genesis, was based on surveys and climatic analysis in offices of the USA and Europe. The method has a worldwide acceptance and is present in several reference documents such as the ISO 7730 [42], ASHRAE 55 [43] or EN 15251 [44]. It is a very complete tool and factors such as clothing, metabolic activity and climatic conditions are considered. However, it does not consider subjective factors such as the expectancy and adaptability of the people. It is expected that the level of expectation regarding thermal comfort of cultural heritage visitors will not be too high, as Jeong and Lee concluded [45]. In naturally ventilated buildings, as is the case of the most churches and monasteries in the southern Europe, the adaptability and expectancy may play a major role in the comfort sensation. The use of adaptative models appears as a useful tool for the indoor climate management of the cultural heritage and they can contribute to achieve a compromise between comfort and environmental and economic sustainability since these models allow the use of less demanding targets than those traditionally obtained through the use of the PMV model.

There are several adaptive models in the international literature, from which it is possible to highlight the model developed by Dear and Brager [46], the one published in standard EN 15251 [44] based on the European project Smart Controls and Thermal Comfort (SCATs) in which several field studies were carried out in five European countries - Portugal, United Kingdom, France, Sweden and Greece [47], the ATG [40] models developed in the Netherlands based on the study of Dear and Brager [46] and applied to museums by Kramer et al. [26] or a model recently published by Kramer et al. [41] based on 1248 surveys carried out in the Hermitage Museum of Amsterdam in 2015.

The adaptive model proposed by Matias [48] seems to be a reasonable tool to use in the Portuguese case. The model was supported by the results of an extensive fieldwork developed over about 2 years and covering 40 buildings, about 290 climate monitoring campaigns and approximately 2400 surveys. The novelty of this study was the use of several types of buildings, namely residential buildings (senior and conventional dwellings) and service buildings (university classrooms and offices) with and without air conditioning system spread throughout mainland Portugal.

The obtained results allowed to conclude that the sensation of thermal neutrality did not allow by itself to explain the thermal comfort. The author also verified that both the analytical and adaptive models present in the ASHRAE 55 [43], ISO 7730 [42] and EN 15251 [44] standards do not allow to explain the totality of the obtained results, pointing out also limitations to the application of the adaptive model present in the EN 15251 during the winter.

A strong correlation between the indoor temperature of comfort and a 7-day exponentially weighted outdoor temperature for naturally ventilated buildings (R = 0.97) was verified. Matias also found a strong relation for buildings with controlled indoor climate (R = 0.84). This fact can be justified by the persistence of some adaptive capacity, namely in terms of clothing and the control of shading elements.

Finally, Matias proposed an adaptive model for the Portuguese climate. The model is applicable for sedentary activities with metabolic rates between 1.0 and 1.3 met, clothing between 0.4 and 1.4 clo, air velocity between 0 and 0.6 m/s and the outdoor exponentially weighted temperature between 5 and 30 ºC and shows a fluctuation around temperature of neutrality (or in this case the comfort temperature) of ± 3 °C guaranteeing an acceptance level of 90%, such as the range presented for class II of the EN 15251 model. The author divides the comfort requirements into two different building-types: air-conditioned and naturally ventilated buildings. Despite Matias only presented the model for an acceptance level of 90%, in this thesis it was decided to present the model also for an acceptance level of 80%, with a fluctuation of ± 4 °C around the temperature of neutrality. This acceptance level is recommended by ASHRAE 55 for typical applications and by the EN 15251 for an acceptable/moderate level of expectation to be used in existing buildings, as is the case of the cultural heritage buildings. The model can be seen in Figure 2.4 and calculated from the equations present in Table 2.2.

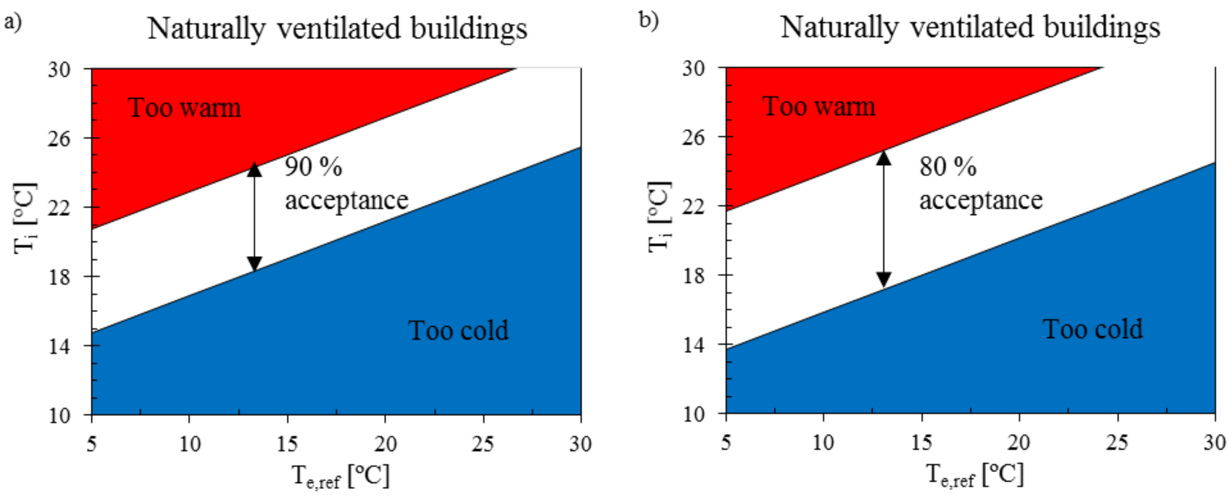


Figure 2.4. Adaptive model of thermal comfort assessment according to Matias: a) naturally ventilated buildings for an acceptance level of 90 %; b) naturally ventilated buildings for an acceptance level of 80 %; c) buildings with HVAC system for an acceptance level of 90 % and d) buildings with HVAC system for an acceptance level of 80 % [48]

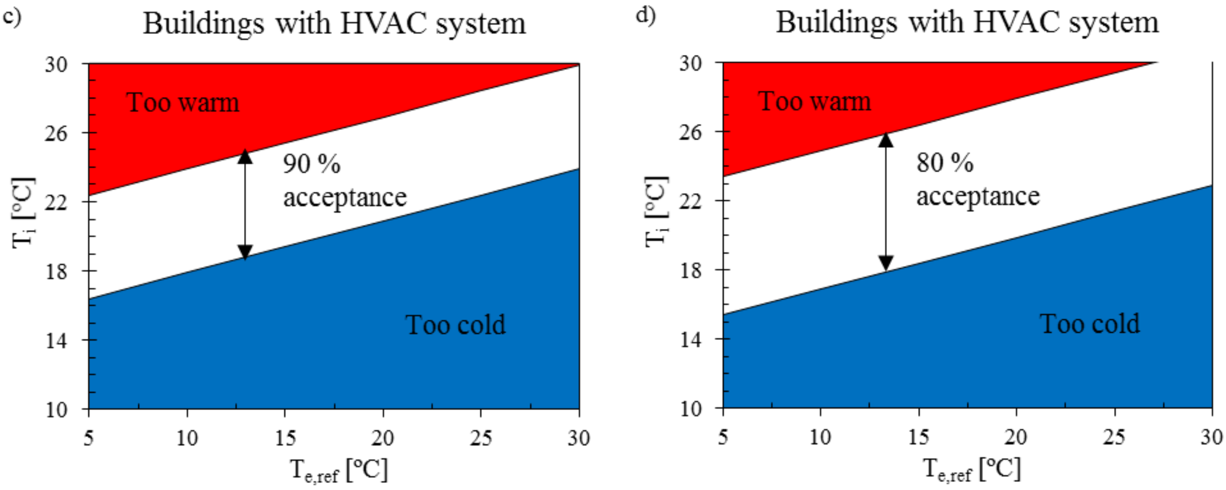


Figure 2.4 (continuation). Adaptive model of thermal comfort assessment according to Matias: a) naturally ventilated buildings for an acceptance level of 90 %; b) naturally ventilated buildings for an acceptance level of 80 %; c) buildings with HVAC system for an acceptance level of 90 % and d) buildings with HVAC system for an acceptance level of 80 % [48]

Table 2.2. Equations to obtain the targets defined by Matias for his adaptive model of thermal comfort [48]

Category	Target	
	90 % of acceptance	80 % of acceptance
HVAC	Upper limit: $0.30 \cdot T_{e,ref} + 20.9$	Upper limit: $0.30 \cdot T_{e,ref} + 21.9$
	Lower limit: $0.30 \cdot T_{e,ref} + 14.9$	Lower limit: $0.30 \cdot T_{e,ref} + 13.9$
NV	Upper limit: $0.43 \cdot T_{e,ref} + 18.6$	Upper limit: $0.43 \cdot T_{e,ref} + 19.6$
	Lower limit: $0.43 \cdot T_{e,ref} + 12.6$	Lower limit: $0.43 \cdot T_{e,ref} + 11.6$

The $T_{e,ref}$ is the reference outdoor temperature and it can be determined by:

$$T_{e,ref} = \frac{T_{e,i-1} + 0.8 \cdot T_{e,i-2} + 0.6 \cdot T_{e,i-3} + 0.5 \cdot T_{e,i-4} + 0.4 \cdot T_{e,i-5} + 0.3 \cdot T_{e,i-6} + 0.2 \cdot T_{e,i-7}}{3.8} \quad (2.6)$$

where $T_{e,i-1}$ is the arithmetic mean temperature of the day before that under analysis (24 h) and so on.

2.2.6. Global evaluation

Following the individual analysis described previously, it was decided to use a global classification method that may allow a better understanding of the global phenomena and an easier process for the comparison of results. This classification was strongly influenced on that presented by Martens [16] that defines three classes and evaluates the risk of chemical, biological and mechanical degradation. However, some changes were introduced highlighting the inclusion of a new parameter

(PI – Performance Index) and different criteria to evaluate the risk.

The classification system is divided in three categories, where 3 represents the ideal conditions and 1 the worst case and evaluates five different parameters: the hygrothermal building capacity – PI (Performance Index); the mechanical degradation of painted wood, sculptures and furniture; the biological degradation - MRF (mould risk factor) and the chemical degradation - eLM (equivalent lifetime multiplier). No weights were attributed to the parameters, neither a final classification, considering that each building or collection has specific needs.

For the mechanical risk of the base layer of painted panels and the sculptures a 3-point scale is proposed, where class 3 represents a perfect behaviour, always in the elastic region, while class 1 represents the failure obtained when the object is subjected to tension strengths. The middle zone of the scale – class 2 - shows a plastic response, but without reaching failure.

A 3-point scale is proposed to classify the damage-risk of the pictorial layer, where 3 correspond to an *ideal* response and 1 to a *high risk*. The absence of risk was considered for RH full-response fluctuations around the annual average lower than 14 %, not being necessary to proceed to other evaluations. For the other cases it is necessary to plot the data in the graph presented in Figure 2.2.b. For this purpose, it is necessary to fit sine curves to the full-response of the panels to obtain the amplitudes for different periods, beginning in 365 days and decreasing by √2 until 1 day [16]. If the full-response fluctuations are higher than 14 %, but the obtained amplitudes are always lower than the curve corresponding to the 1-face samples tested at 20 ºC, the response is included in class 2. If at least one amplitude is present behind this curve, a *potential risk* of class 1 must be considered.

To classify the furniture response a 3-point scale based on the classification applied to sculptures and wooden substrates of painted panels is proposed. An ideal response corresponding to class 3 was considered when the values of RH remain in the elastic region both for the box as for the lacquer. It was assumed a greater concern towards the box since the finishing layer can be more easily repaired. Thus, it was decided to classify the response with class 2 if the elastic limit of the box was maintained, even when the limit of the lacquer was not. It is considered a potential risk if both elastic limits are exceeded.

The concept of MRF, based on the research developed by Sedlbauer [25,29] was used to quantify the risk of biological activity and it was divided into 3-classes, influenced by the limits defined by the Image Permanence Institute [31]. Class 3 allows germination levels to be exceeded for short periods as long as MRF is lower than 0.5. Although germination may occur for MRF values greater than 1, this condition is necessary, but not sufficient. Thus, class 1 is assigned for cases where the MRF is greater than 1 and mycelial growth occurs. All other cases are confined to class 2, where the risk of mould germination is considerable, but its growth has not yet occurred.

For the evaluation of chemical risks, the concept eLM was used, relating the risks of a given ambience (characterized by T and RH) with the reference established for 20 ºC – 50% RH. For this purpose, a classification was defined considering that the perfect conditions of class 3 are obtained for eLM higher than 1. The worst scenario of class 1 was considered for eLM values lower than 0.75. A middle of reasonable risk was obtained for all other cases and classified as class 2. The definition of the intervals for each class was based on the classification of the Image Permanence Institute [31] and that proposed by Martens [16].

Finally, 3 classes for the Performance Index (PI) are proposed, representing the percentage of time in which the use of HVAC systems is not necessary or the percentage of time in which the imposed limits to the HVAC system complies. For class 3 (ideal) a range between 80 and 100 % was defined. The worst scenario of class 1 was defined for those cases in which the benchmarks do not comply at least 50 % of the time. All other cases should be included in class 2. A careful analysis should be made for classes 1 and 2 checking if the existing temperature/relative humidity targets are not too tight or if there are problems with the envelope that may lead to unnecessary heat losses.

Regarding thermal comfort, it was decided to count the percentage of time in which the reference band is fulfilled during the opening periods.

The classification model can be seen in a summary form in Table 2.3.

Table 2.3. Microclimatic classification according to the building response and the damage functions

Category		PI [%]	Painted wood	
			Base material	Pictorial layer
Ideal	3	]0.80;1]	Elastic	$\lvert RH_{full\ response} - RH_{annual\ average} \rvert < 14$ %
Possible risk	2	[50;80[	Plastic	$\lvert RH_{full\ response} - RH_{annual\ average} \rvert > 14$ %; A (period) < 10 mm two faces curve at 20ºC
Potential risk	1	<50	Failure	$\lvert RH_{full\ response} - RH_{annual\ average} \rvert > 14$ %; A (period) > 10 mm two faces curve at 20ºC
A (period): the amplitude of fitted sine curves for each given period				

Table 2.3 Microclimatic classification according to the building response and the damage functions (continuation)

Category		Sculptures	Furniture	MRF [-]	eLM [-]
Ideal	3	Elastic	Lacquer and wood in Elastic	<0.5	>1
Possible risks	2	Plastic	Wood in Elastic; lacquer in plastic	[0.5;1] with no mycelium growth	[0.75;1[
Potential risk	1	Failure	Lacquer and wood in Plastic	>1 with mycelium growth	<0.75

2.2.7. Case study

2.2.7.1. Site description

The Church of São Cristóvão is a national monument of Portugal located on the slopes of the São Jorge Castle (Lisbon – Portugal) under the influence of a Mediterranean climate with mild temperatures due to the proximity of the Atlantic Ocean. Lisbon has about 260 days of sunshine per year, an annual average of 17ºC of temperature, an annual precipitation of 725.8 mm and north prevailing winds [49].

The church was built in the early thirteenth century and maintained its original configuration until the sixteenth century when it was badly damaged by a fire. It suffered little damages with the 1755 earthquake that shook the entire waterfront of the city [28].

The building features thick walls, between 0.7 and 1 m, lined by limestone on the corners and lime mortar renders on the exterior and walls covered with gilded and painted panels in the interior surfaces. According to the Ref. [50], an average thermal resistance of 0.56 m^2.ºC/W can be considered for the exterior walls. The roof is made with ceramic tiles supported by timber frames. Inside, there is a rectangular nave with 144 m^2 and 13 m in height, with a flat ceiling. The church presents a sacristy to the north of the nave and a funeral room to the south. The wooden frames single glazing windows have a global area of about 45 m^2, which when compared to the 800 m^2 of external walls, provide a ratio of 5.6%. No artificial heating systems are available. The roof with no thermal insulation and a small mass appears as a weakness zone. The location of the church, its façade and the interior can be seen in Figure 2.5.

During the monitoring campaign, the church remained usually closed and received few visitors. It was open from Tuesday to Saturday between 17:00 and 19:30, with religious celebrations taking place at 18:30. On Sunday, it was open between 11:00 and 13:00, with a religious celebration at 12:00. On Monday it remained closed throughout the day.

2.2.7.2. Monitoring campaign

To understand the interior microclimatic behaviour of the church an extensive environmental monitoring campaign was conducted. For this purpose, a set of sensors for automatic and manual records were used. Measurements were taken from November 2011 to August 2013, with automatic records every 10 minutes and using three different types of sensors, as it can be seen in Table 2.4. All of the sensors respect the uncertainties defined in the European Standards EN 15758 [51] for the temperature and the EN 16242 [52] for the relative humidity.

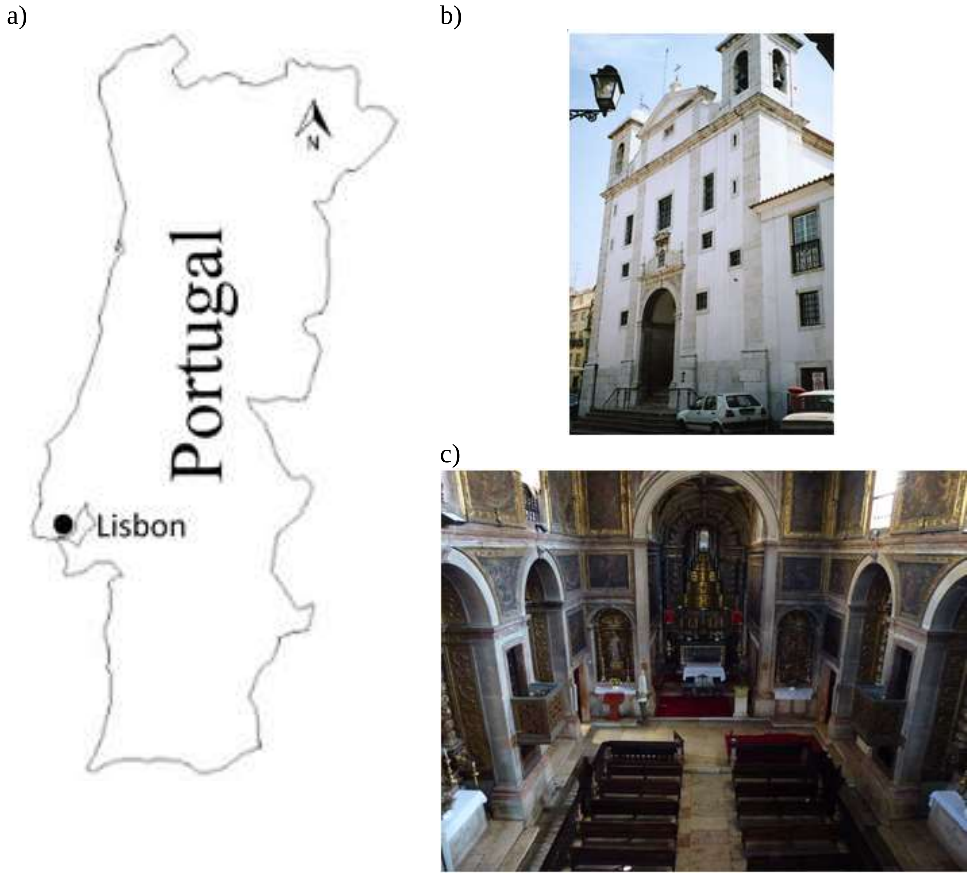


Figure 2.5. Location of the church (a); the main façade (b) and the interior (b)

Table 2.4. Sensors used in the monitoring system

Sensor	Accuracy
Hobo U12-13 (H)	T: ± 0.35ºC; RH: ± 2.5%
T&RH Delta T probe	T: ± 0.1ºC; RH: ± 2%
Thermocouples (T)	T: ± 0.5ºC

The monitoring system included 25 sensors in the nave (1 sensor type H, 1 T&RH probe and 23 thermocouples) and 1 sensor type H on the northern tower to monitor the external conditions, as it is possible to see in Table 2.5 and Figure 2.6. For the purpose of the current chapter, the sensors H on the northern tower (S.6) and pulpit (S.3) were selected to analyse the relationship between the indoor and outdoor conditions. A more detailed description can be found in the Refs [28,49].

Table 2.5. Location of the sensors

Sensors	Site (see Figure 2.6)	Height [m]
1 horizontal profile (T)	A	5.3
1 sensor – door of sacristy (T)	B	3.1
1 horizontal profiles (T)	C	3.9
1 horizontal profiles (T)	D	7.5 (S.4)
1 vertical profile	E	0.15 (S.1); 1.5; 3.9; 7.5; 10 (S.5)
1 sensor – northern pulpit (H)	E	3.9 (S.3)
2 wall surface sensors (T)	E	1.5 (S.2); 3.9
2-floor surface sensors (T)	E	-
1 horizontal profiles (T)	F	3.9
1 horizontal profiles (T)	g	7.5
1 sensor in the chorus (T)	h	5.3
1 sensor – northern tower (H)	-	(S.6)

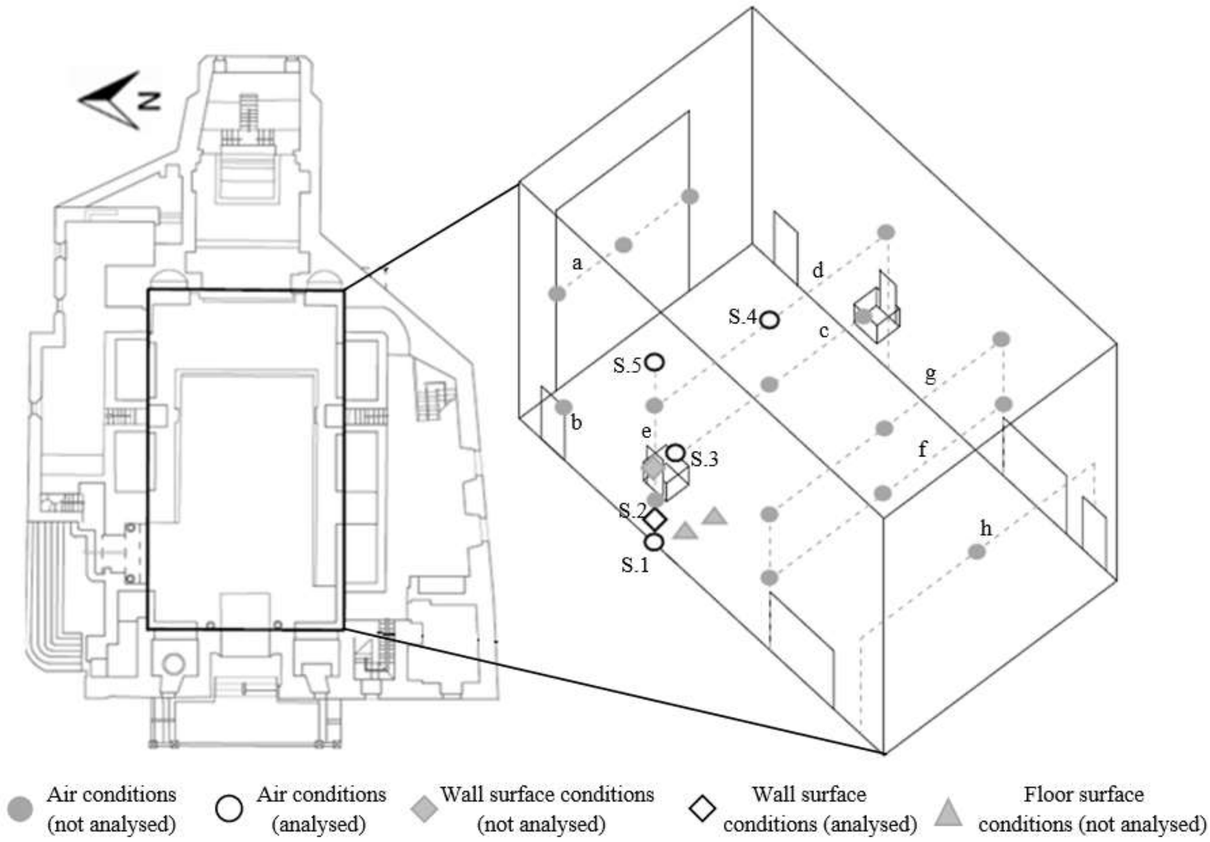


Figure 2.6. Horizontal plan of the church of São Cristóvão and location of the T and RH sensors in the nave

2.3. Results

2.3.1. Climate analysis

2.3.1.1. General analysis

The monitoring process is one of the most important steps of the hygrothermal rehabilitation, allowing a profound knowledge about the behaviour and limitations of the buildings. The analysis of the recorded data showed the relationship between the outdoor (S.6) and indoor (S.3) conditions (Figure 2.7 and Figure 2.8). As expected, the indoor temperature is much more stable than the outdoor, both in term of seasonal and instantaneous fluctuations (Figure 2.7.a). The influence of the thermal inertia in delaying and damping of the seasonal cycles was confirmed, with a delay of 7.1 days in the winter of 2011/2012 (Figure 2.7.b) and 7.5 days in the summer of 2012 (Figure 2.7.c). The thermal inertia compensates the high thermal conductivity of the existent materials, providing a damping of 2.6ºC in the winter 2011/2012 (Figure 2.7.b).

The summer situation is slightly different. As it is possible to see in Figure 2.7.c, the delay remains and is consistent with the one in winter, but the damping is more attenuated (0.6ºC). This fact can be justified by the high solar radiation in the summer and the low mass of the coverage, composed by a wood ceiling and a ventilated roof of ceramic tiles that quickly responds to the external fluctuations.

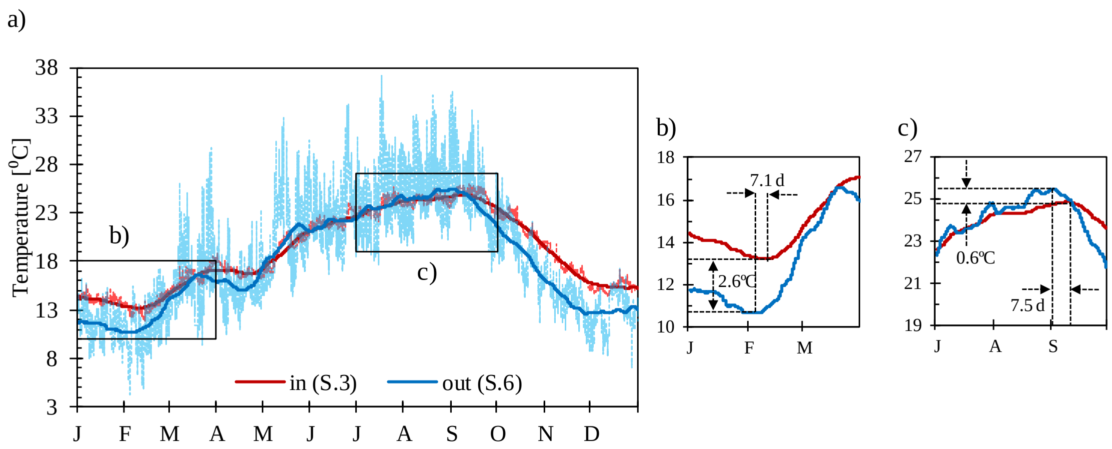


Figure 2.7. Indoor and outdoor temperatures and seasonal cycles: a) annual behaviour; b) effect of the thermal inertia in winter; c) effect of the thermal inertia in summer

The behaviour for relative humidity is similar (but inverse) to the one of temperature, with the maximum values occurring in the winter and the minimum in summer, as shown in Figure 2.8.

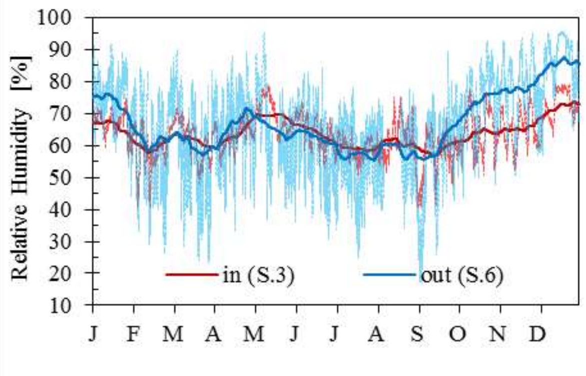


Figure 2.8. Indoor and outdoor recorded RH and seasonal cycles

Relative humidity is the parameter most frequently used to characterize the air hygrometric conditions. However, it depends on temperature and water vapour pressure. Its individual analysis makes it possible to characterize the climate and to assess the risk of degradation, but it is not possible to conclude if the fluctuations are due to an inadequate temperature or water vapour pressure. The analysis of Figure 2.9 allows to conclude that the internal water vapour pressure accompanies the external tendency very closely, although with smaller fluctuations. In seasonal terms, the internal pressure shows slightly higher values than the exterior ones throughout the year. In general terms, an average differential of 0.4 hPa (internal water vapor pressure excess) was obtained, which according to the international literature does not seem to be enough to cause mould germination. The monthly averages of Δe were plotted in a diagram similar to that presented in the EN ISO 13788 [13] in function of the monthly outdoor temperatures, as shown in Figure 2.10.

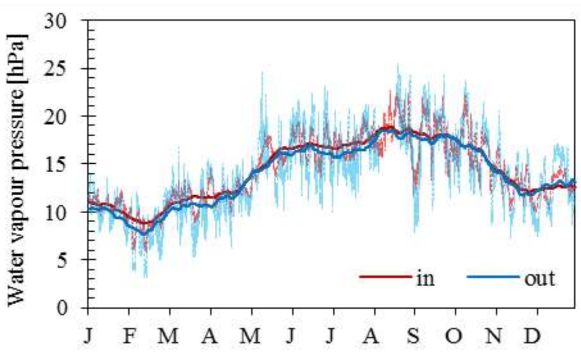


Figure 2.9. Indoor and outdoor water vapour pressure and seasonal cycles

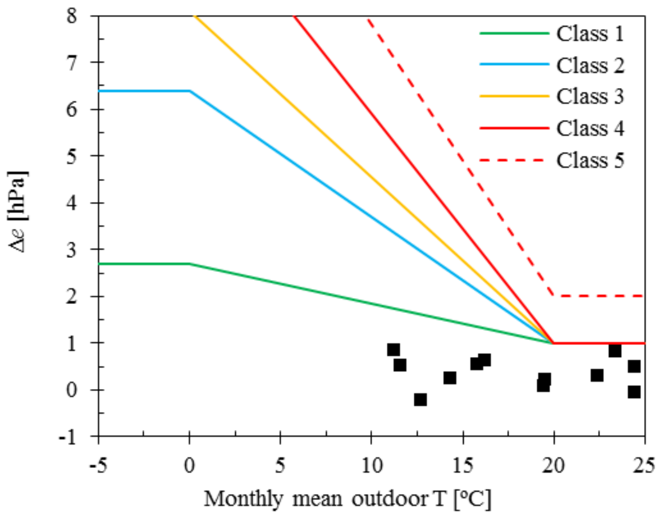


Figure 2.10. Variation of internal humidity classes with external temperature [13]

This diagram is based on data from buildings in western Europe and recommended for design purposes, being possible to use it as a reference for the evaluation of the hygrometric conditions. The standard presents 5 classes: class 1 for unoccupied buildings, storage dry goods; class 2 for offices, dwellings with normal occupancy and ventilation; class 3 for buildings with unknown occupancy; class 4 for sports halls, kitchens and canteens and class 5 for special buildings, e.g. laundry, brewery and swimming pool. According to Figure 2.10, it is possible to observe that the *Δe* is relatively constant and independent of the external temperature and remains below the limit of the class 1 throughout the year, which indicates a low internal water vapour pressure excess and allows to conclude the presence of an adequate relationship between the occupancy and ventilation.

2.3.1.2. <u>Statistical analysis</u>

The statistical analysis was performed in accordance with the methodology proposed in 2.2.2. The process to calculate the seasonal amplitudes and the typical short-term fluctuations is illustrated in Figure 2.11. These and the other statistical parameters can be found in Table 2.6.

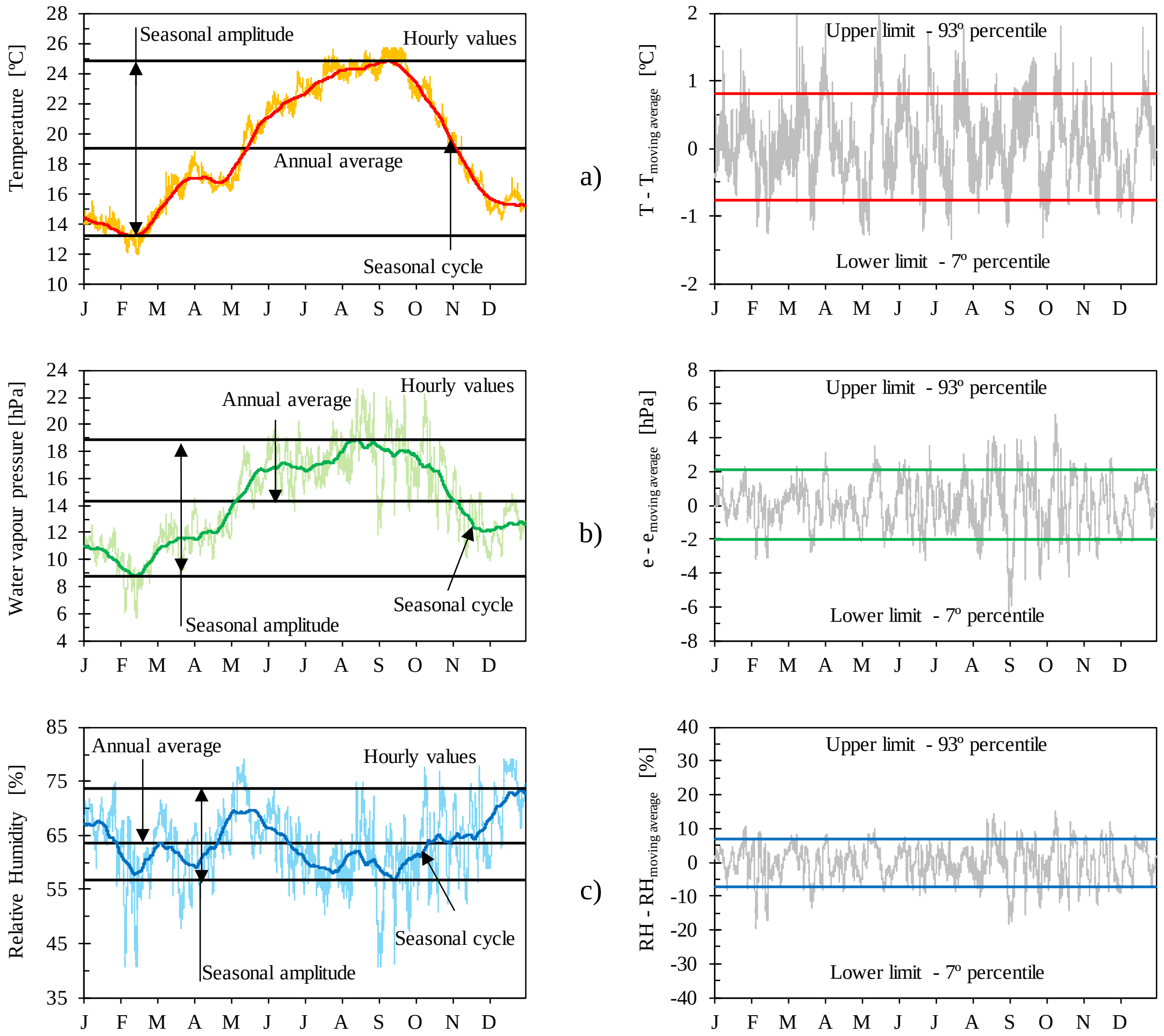


Figure 2.11. Calculating the seasonal amplitudes and typical short-term fluctuations for the temperature (a), water vapour pressure (b) and relative humidity (c)

As shown in Table 2.6, an average temperature of 19.1°C, an average relative humidity of 64% and an average water vapour pressure of 14.3 hPa were obtained. The temperature changed between the extreme values of 12 and 25.7 ºC, while the relative humidity varies between 41 and 79% and the water vapour pressure between 14.3 and 22.7 hPa. The analysis of the percentiles, which allows to exclude the extreme values, allows to conclude that during 96% of the year the temperature was between 12.8ºC and 25.3ºC, the relative humidity between 48% and 77% and the water vapour pressure between 8.1 and 20.9 hPa. Using the 10th and 90th percentiles it was concluded that during 80% of the year the temperature varied between 14 and 24.5 ºC, the relative humidity between 56 and 72% and the water vapour pressure between 10.2 and 18.8 hPa. As regard the seasonal cycles, amplitudes of 11.7ºC for the temperature, 17% for the relative humidity and 10.1 hPa for the water vapour pressure were found, while for short-term fluctuations a typical fluctuation of ± 0.8ºC was obtained around the seasonal cycle for temperature, ± 7% around the seasonal cycle for relative humidity and -2 to +2.1 hPa around the seasonal cycle for the water vapour pressure.

Table 2.6. Statistical parameters of T, RH and e

Variable	Mean	Max	Min	Percentiles							Seasonal amplitude	Typical short-term fluctuations
				2º	10º	25º	50º	75º	90º	98º		
T [ºC]	19.1	25.7	12.0	12.8	14.0	15.6	18.2	22.9	24.5	25.3	11.7	± 0.8
RH [%]	64	79	41	48	56	59	64	68	72	77	17	± 7
e [hPa]	14.3	22.7	5.7	8.1	10.2	11.5	14.0	17.1	18.8	20.9	10.1	-2/+2.1

Particularly regarding relative humidity, this analysis raises the possibility of a natural indoor climate reasonably stable for conservation and with a high potential for optimization without causing exaggerated energy consumptions.

2.3.2. Response of the building and collections

The use of standards and guidelines is a good tool, especially when it is not possible to make detailed studies for each location. However, it is necessary to note that the guidelines do not always fit all objects and climates [49,53]. Sometimes it becomes necessary to carry out a detailed risk-based analysis to allow strong conclusions. This research was designed in order to evaluate the building and collection response to the natural climate and according the targets defined by the EN 15757, PAS 198 and the pair 20ºC;50% RH, with the analysis divided in 5 points: performance index, mechanical, biological and chemical degradation and the visitors' thermal comfort.

2.3.2.1. Performance index

This point aims to compare the influence of four different set-points in the conservation, in the capacity of the building to respond to the targets and in the visitors' comfort. Firstly, the historic set-point of 20±2 ºC and 50±5% RH was used, followed by the targets defined by EN 15757 and PAS 198. Finally, an analysis according to the natural indoor climate was made.

The dynamic target defined by the EN 15757 is calculated in function of the seasonal cycle, calculated as a 30-day moving average and the short-term fluctuations, calculated by the exclusion of the 14% major differences between the recorded data and the seasonal cycle. Adding the 7th and 93th percentiles of the short-term fluctuations to the seasonal cycles it was obtained the target range that aims to limit the mechanical degradation of organic hygroscopic materials [10]. The seasonal cycle and short-term fluctuations can be seen in Figure 2.11. The final targets can be found in Figure 2.12.

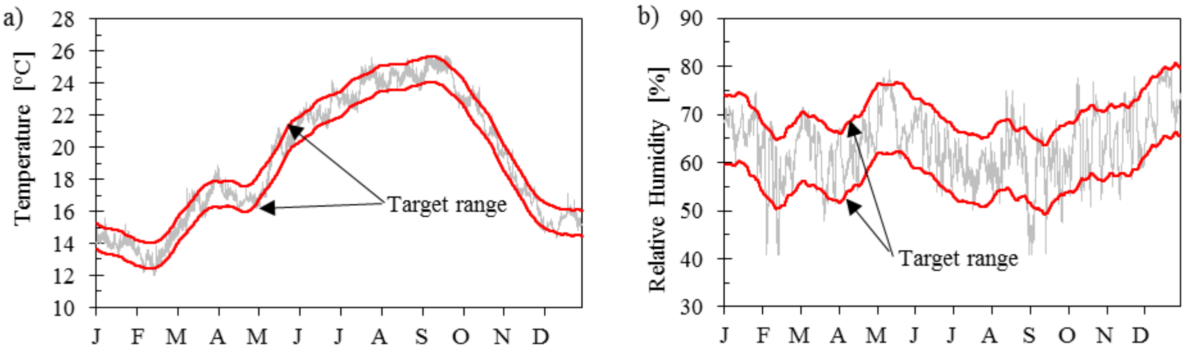


Figure 2.12 Climate control strategy defined in accordance with the EN 15757: a) temperature; b) relative humidity

The PAS 198 [11] determines some ranges of temperature and relative humidity considering various factors as the chemical, mechanical and biological degradation, energy efficiency and human comfort. For this purpose, it was defined a range of temperature from 7ºC to 23ºC, according the energy considerations. For the RH it was defined a range from 30% to 65% to consider the mechanical stability and the energy considerations. Finally, it was used the data records of the church without any limits.

To qualify the hygrothermal capacity of the building to meet the three different climate control strategies, the concept of *performance index* (fully described in 2.2.3) was adopted. Lower values of this ratio indicate the need for a greater amount of energy to ensure the defined range.

The 3 set-points and the *PI* for T, RH and the combination of T plus RH are presented in Figure 2.13. The analysis of the performance index allows to conclude that the building does not have the natural capacity to simultaneously meet the temperature and relative humidity limits imposed by the set-point 20ºC;50% RH and by the PAS 198 in percentages of time that may be considered reasonable, namely by comparison with congeners values present in the literature. The target defined by the PAS 198 according to mechanical damage and energy concerns, presents a better behaviour, but it is only satisfied in a short period – 38%. It was noted that the ranges defined as economics for a certain country may not be for other locations. The dynamic target of the EN 15757 allows the better behaviour among the three guidelines, with a PI of 75.3%. The PI values for the natural climate are obviously 100% (according to the definition of the index).

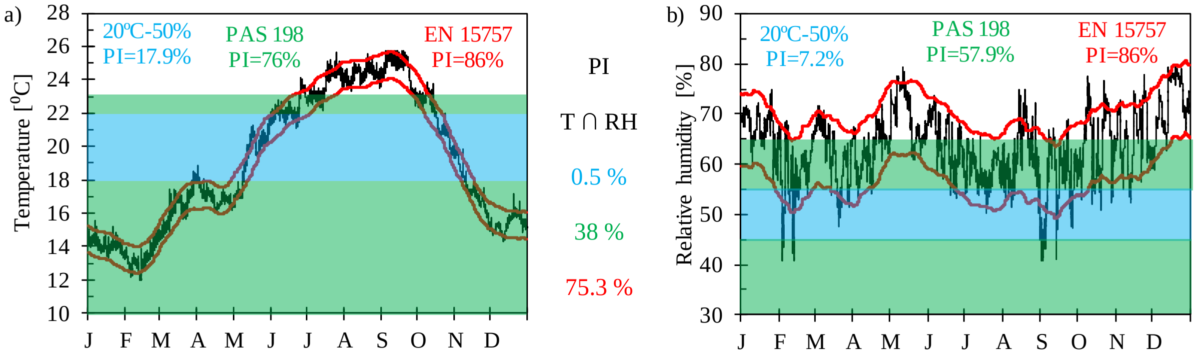


Figure 2.13. Building Response (PI) according with the 3 set-points in analysis: 20ºC-50%, EN 15757 and PAS 198. a) Temperature; b) Relative humidity

The data presented in Figure 2.14 allow a more careful analysis. The detailed analysis of the PI for the set-point 20ºC; 50% RH allows to conclude that the temperature range is fulfilled in 17.9% of the time, while the relative humidity is only fulfilled in 7.2% of the time. When analysing what occurs during the periods when the limits are not met, most of the time the relative humidity is above the maximum (91.7% of the time), the temperature is above the maximum in 33.2% of the time and below the minimum in 48.9%. The climate is classified as too humid and too cold at 45% of the year and as too humid and too hot in 29.3%. The use of this set-point makes clear the need to dehumidify and to control the temperature practically all year round.

Concerning the climate control strategy defined in accordance with the PAS 198, it can be seen that the temperature range is fulfilled during 76% of the year while the relative humidity is fulfilled in 57.9% of the time. When analysing what occurs during the periods when the limits are not met, most of the time the relative humidity is above the maximum (42.1% of the time). The temperature is above the maximum in 24% of the time. The use of this climate control strategy makes clear the need to dehumidify in 42.1 % of the year and to cool in 24 %.

The dynamic ranges obtained through the EN 15757 allow a significantly better behaviour. The temperature range is fulfilled at 86% of the year while the relative humidity range is also fulfilled at 86% of the time. The *PI* for this climate control strategy makes clear its potential do reduce the energy demand, but a careful analysis must be made to prove its effectiveness to limit the degradation phenomena. For these targets, only the classification of the PI is presented in Figure 2.14 due to the impossibility of presenting the dynamic targets.

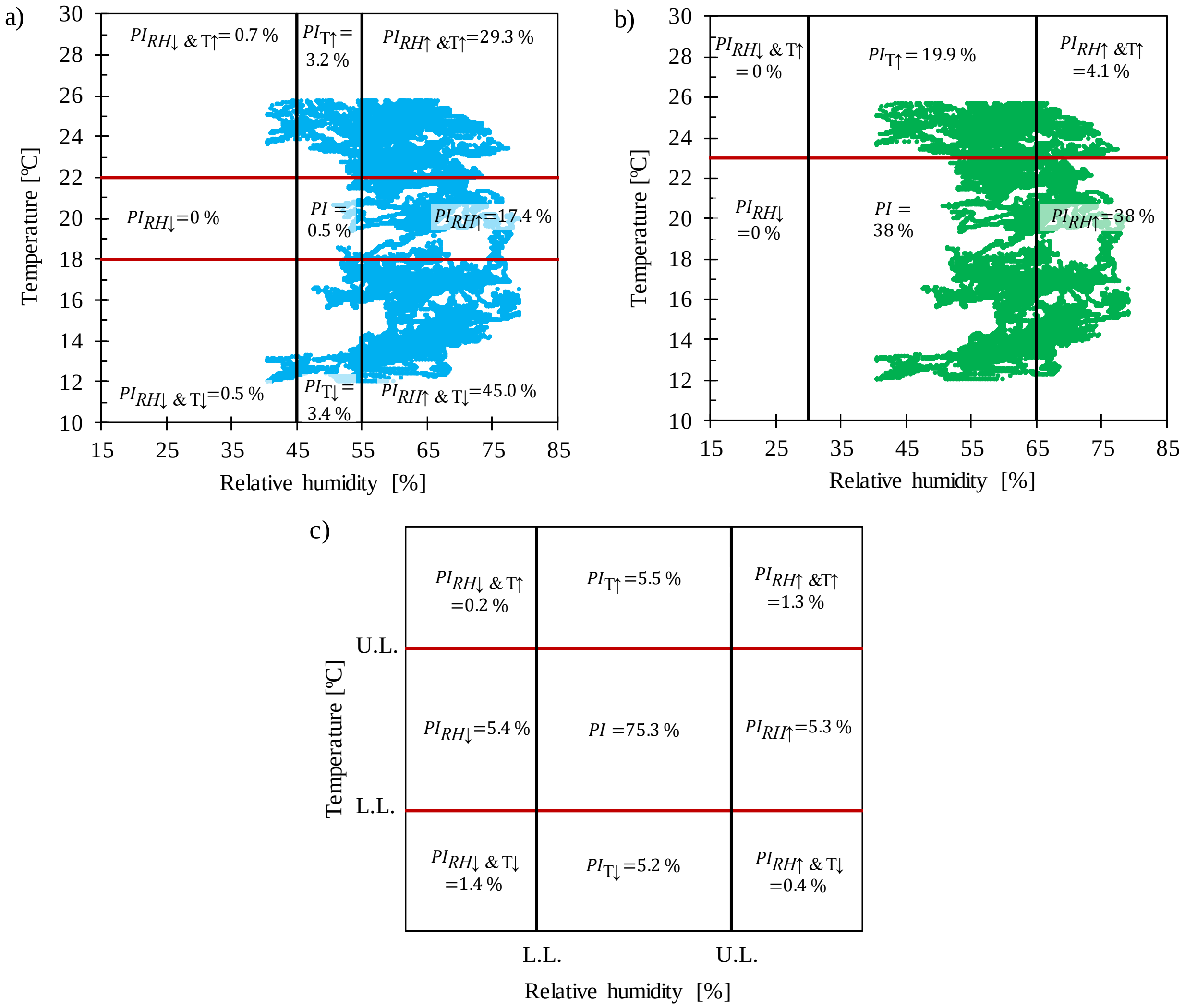


Figure 2.14. Performance index to evaluate the building capacity to meet the three climate control strategies: a) set-point 20ºC; 50% RH; b) PAS 198; c) EN 15757

2.3.3. Risk-assessment

2.3.3.1. Mechanical degradation

To evaluate the mechanical damage in painted panels, two methodologies were used: the first one defined by Mecklenburg *et al.* [19] to evaluate the wooden substrate, and the second defined by Bratasz *et al.* [20] to evaluate the response of the pictorial layer. To evaluate the risk along the time, it was considered that the water content in the inner of the objects varies in function of their response time, thereby changing the internal restrictions, instead of considering a global restriction. In parallel, a risk analysis was performed for the sculptures using the method defined by Jakieła *et al.* [21] for a step change in RH, considering the higher response time of the core in relation to the superficial layers. To analyse the damage-risk associated to the furniture, a method published by Bratasz et al. [22] that analyses the response of the wooden support and the lacquer was used. The description of the methods can be found in 2.2.4.1.

Applying these four methodologies to the four climate control strategies in analysis (natural climate, 20ºC;50% RH, PAS 198 and EN 15757) it was possible to verify the influence of each one on the mechanical degradation, as can be seen in Figure 2.15.

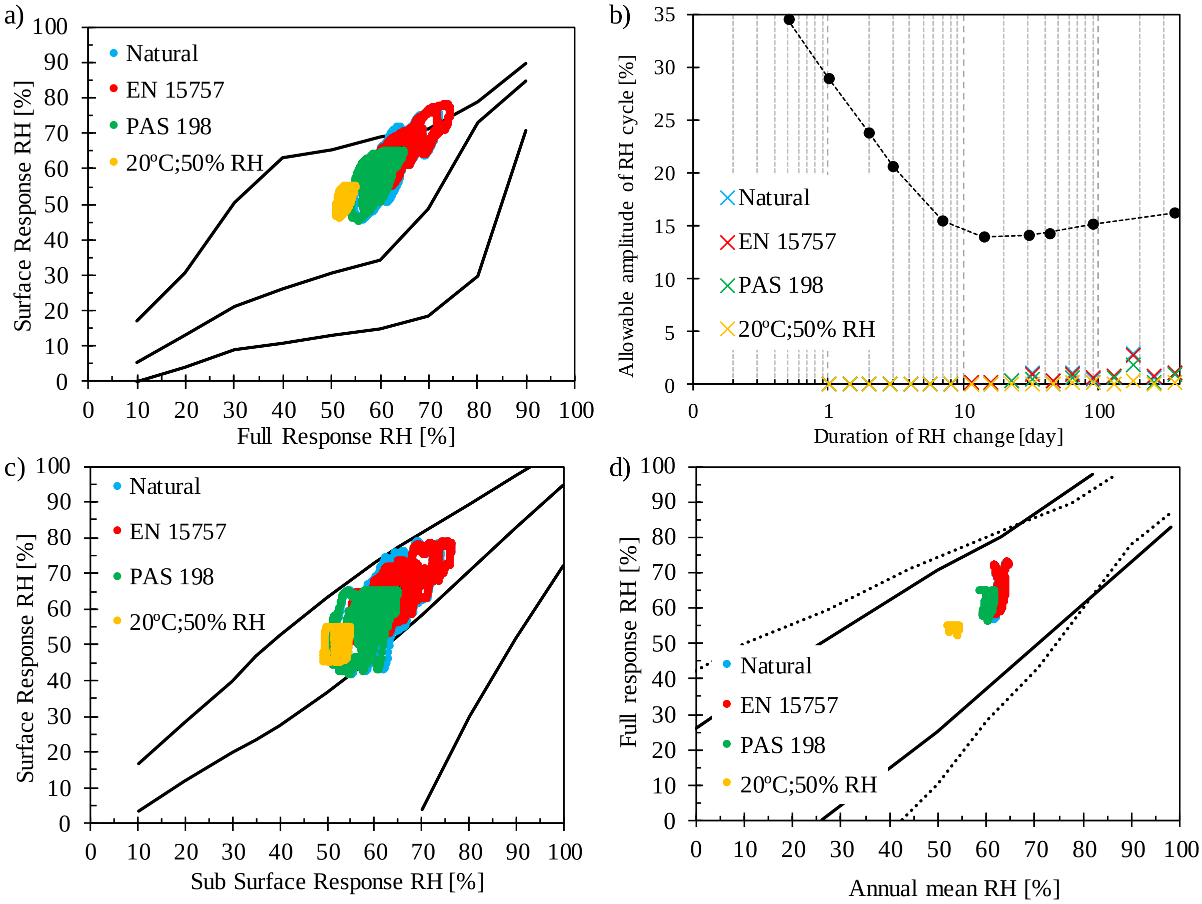


Figure 2.15. Mechanical risk-assessment: a) wooden substrate of painted panels; b) pictorial layer of painted panels; c) sculptures; d) furniture

The indoor climate limited by the set-point of 20ºC;50% RH allows a perfect mechanical response, as expected since the climate fluctuations are strongly limited. The indoor climate obtained by applying the limits of the PAS 198 allows to exclude all the risks for the painted panels: as regards the base layer an elastic response was obtained for the whole year while for the pictorial layer a maximum amplitude of 7.5% RH was obtained, which means no risk since it is below the first alarm defined for 14% RH. As regards the furniture, the absence of risk was concluded, since both the wooden layer and the varnish show an elastic response throughout the year. As regard the sculptures, the response was not perfect, and there was a possibility of damage, although very small, since the elastic limit was exceeded only in 0.5% of the time.

The dynamic target defined by the EN 15757 enabled a perfect response for the sculptures and furniture with a total response in the elastic region. As regard the painted panels, a perfect behaviour was obtained for the pictorial layer with a maximum amplitude of 11 % RH (below the first alarm defined for the

14 % RH). For the wooden substrate, the damage is possible, since the yield strain has been exceeded. The material presented a plastic response in compression during 7.4% of the year.

It was verified that these three targets do not lead to an extreme dangerous response but doubts about the response of the natural climate still remain. Applying the damage functions to the natural climate without any restrictions, it was possible to verify a general satisfactory response. For the painted wood, the damage is possible, since there was possible to find a plastic behaviour in compression during 8.6 % of the time. As regard the pictorial layer, a maximum amplitude of 11 % RH was obtained which evidences the absence of risk. For the sculptures the damage is also possible since the yield strain was exceeded in 0.8 % of the time with a tensile response. As regard the furniture, a perfect behaviour was found.

Despite the better performance of the tightest ranges, one can conclude that in any case the risk of mechanical damage is not too high, showing that the natural climate present in the unheated building do not lead to high risks of physical damage especially for permanent collections acclimatized to the historic climate.

2.3.3.2. Biological degradation

The isopleth system for the substrate type I was used. Applying the more conservative case would mean that if the climate is safe for this condition all the others should also be safe [29].

The representation of the four climate control strategies is plotted in the so-called isopleth diagram, as it can be seen in Figure 2.16.a. As expected, the climates limited by the 20ºC;50% RH and the PAS 198 do not lead to any risk with a mould risk factor (MRF) equal to zero. The results for the EN 15757 and the natural climate are less conclusive, being possible to see that in certain periods the conditions for the spore germination is reached, but without conclusions about the time of exposure. Trying to obtain a more conclusive result it was decided to use the concept of mould risk factor (MRF), as can be seen in Figure 2.16.b. Observing the MRF evolution a value of 0.08 was obtained for the environment limited by EN 15757 and 0.13 was obtained for the natural climate, both below the 0.5-value, considered as the boundary of the safe zone. Despite neither strategy considers the biological risk, limiting the maximum RH value and/or the fluctuations contribute to improve the mould germination risk.

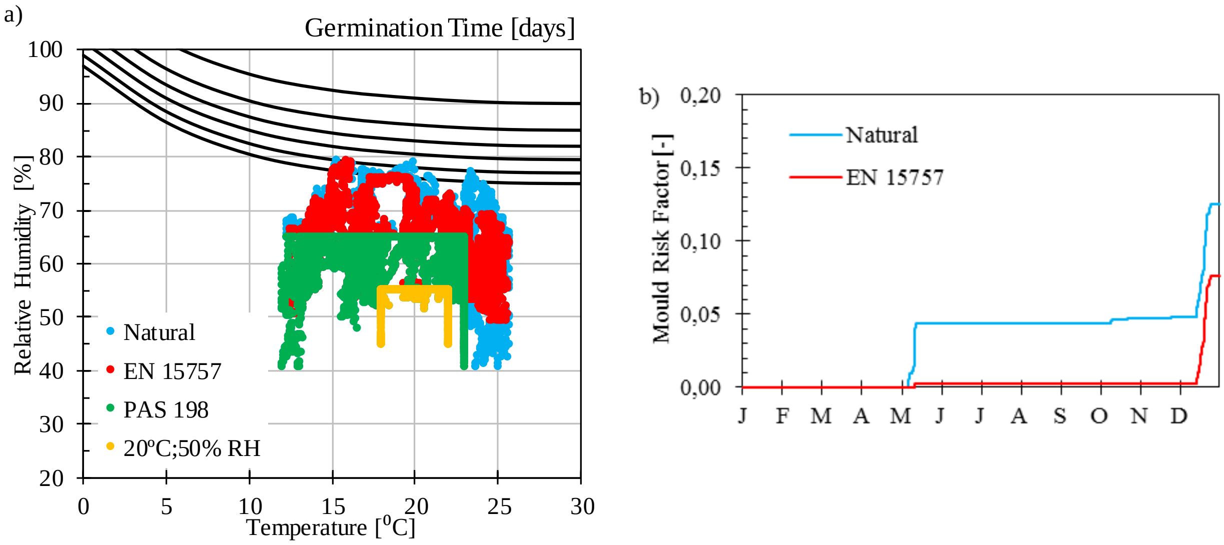


Figure 2.16. Biological risk-assessment: a) representation of the data records on the isopleth diagram for the substrate type I; b) mould risk factor

2.3.3.3. Chemical degradation

The concepts of lifetime multiplier (LM) and equivalent lifetime multiplier (eLM) were used to evaluate the chemical risk. The evolution of the lifetime multiplier for the cellulose and varnishes can be seen in Figure 2.17 according the impositions of the four climate control strategies. It is possible to note that the bad conditions from this point of view occur for the high temperatures of summer but not for the high relative humidities of winter. Considering the concept of equivalent lifetime multiplier, that enhances the influence for the worst cases, it was verified that the environment limited by the set-point 20ºC;50% RH presents the best results, as expected, since the multiplier relates the current records with the stationary condition of 20ºC and 50% RH. Despite this, some risks were found, since eLM of 0.90 and 0.89 were obtained for the varnish and cellulose respectively.

The climate limited by the PAS 198 assumes the second better response to the chemical degradation with eLM values of 0.82 and 0.81 for the varnish and cellulose respectively. Curiously, the environment defined by EN 15757 and the natural climate present an identical response with eLM values of 0.76 for the varnishes and 0.73 for the cellulose. This fact can be justified by the imposition of the lower and upper limits of temperatures. The positive impact of the upper limit is compensated by the lower limit.

This study shows that any of the used targets do not conduct to perfect conservation conditions, as far as chemical degradation is concerned. Despite the existing risks, it is necessary to consider that not all collections are equally sensitive to chemical degradation; a detailed analysis for each case is required, to understand if there is a real need to improve the internal environment.

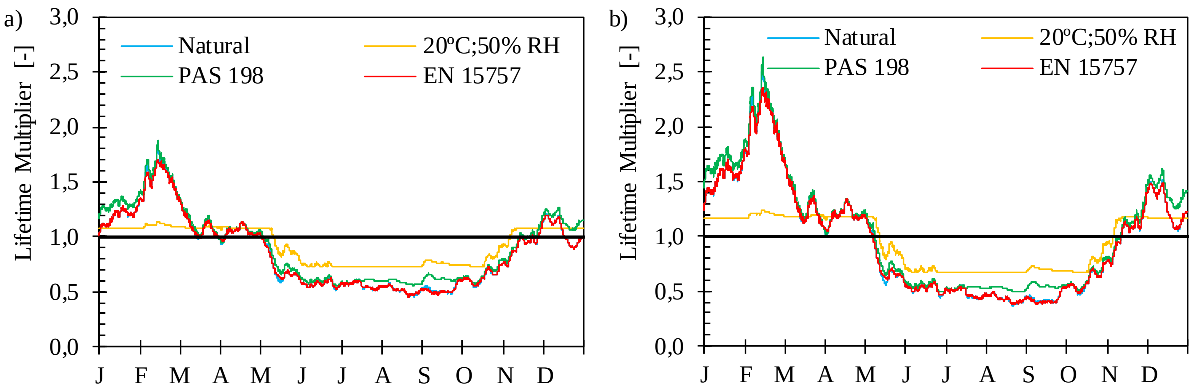


Figure 2.17. Chemical risk-assessment: lifetime multiplier for varnish (a) and cellulose (b)

2.3.4. Thermal comfort

Despite none of the climate control strategies presented concerns about thermal comfort, it was decided to verify whether they have any impact on their improvement. The adaptative model proposed by Matias for naturally ventilated buildings was adopted. An acceptance level of 80 % corresponding to a moderate expectancy level was assumed. In 2012 the church only opened during the religious celebrations, something that was changed in 2015. Thus, it was decided to evaluate the thermal comfort for nine hours a day between the 10:00 and 19:00 h.

The analysis of Figure 2.18 allows to conclude that during a high percentage of time the visitors do not feel a thermal sensation of comfort, which is only obtained during 46 % of the year for the natural climate. The use of the set-point 20ºC;50% RH allows a significant improvement of the comfort which is felt 66% of the time. This improvement is significant and results mainly from the increase of the temperature during the winter, but in summer the sensation of cold remains to be felt. PAS 198 has no impact on improving comfort, as it only limits the upper temperature, and as it is possible to confirm, in this case the problem is related with the low temperatures. The EN 15757 had no impact on comfort. The fact that even in the summer visitors feel cold inside the church is related to the high thermal inertia of the building.

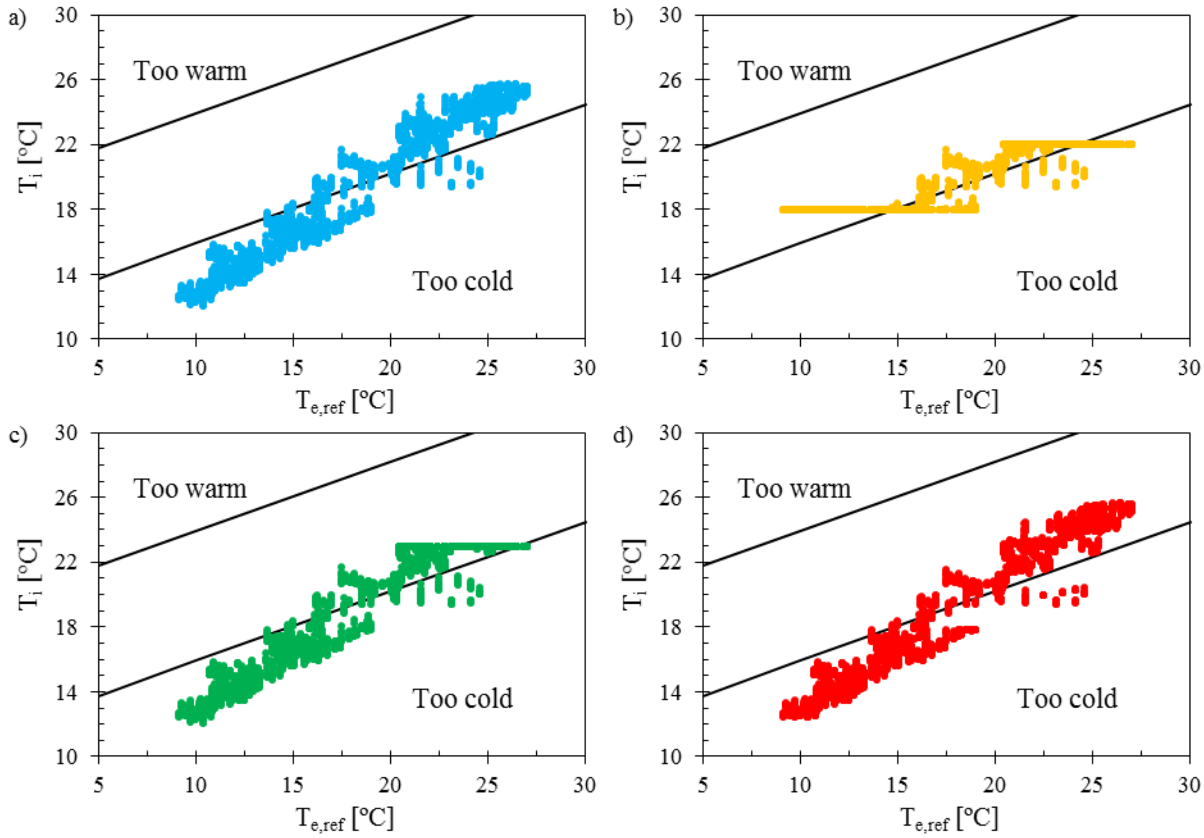


Figure 2.18. Impact of the climate control strategies on the thermal comfort: a) natural; b) 20ºC;50% RH; c) PAS 198; d) EN 15757

2.3.5. Global evaluation

In an attempt to quantify the effects of climate control strategies and to allow an objective comparison between them for any user, even for those less familiarized with the tools in use, it was decided to apply the classification proposed in 2.2.6 as shown in Table 2.7. Despite its application, it is always necessary to proceed to an individual analysis of each parameter to really understand the situation.

Applying this classification to the four targets it is possible to conclude that the set-point 20ºC;50% RH presents the best response to the mechanical, biological and chemical degradation, but the tight limits are too exigent for the building that can only comply the target ranges in 0.5% of the year, revealing high requirements of energy to achieve the limits.

The dynamic targets defined by EN 15757 allow a better response of the building, that can achieve the limits without any other measure, active or passive, during 75.3% of the time, conducting to a high energy economy. Despite the more permissive targets, the EN 15757 presents a satisfactory response of mechanical and biological degradation.

Table 2.7. Microclimatic classification of the recorded data

Set-point	PI [%]		Painted wood				Sculptures		Furniture		MRF		eLM		Thermal comfort [%]
			Base		Pictorial								Varnish		
20ºC; 50% RH	0.5	1	E	3	<14%	3	E	3	E	3	0	3	0.82	2	66
PAS 198	38	1	E	3	<14%	3	P: 0.5 %	2	E	3	0	3	0.82	2	46
EN 15757	75.3	2	P: 7.4 %	2	<14%	3	E	3	E	3	0.08	3	0.76	2	46
Natural	100	3	P: 8.6 %	2	<14%	3	P: 0.8 %	2	E	3	0.13	3	0.76	2	46

E: elastic response P: $_{x\,\%}$.: Plastic response in x % of time

Using the PAS 198 it is possible to observe an ideal mechanical behaviour for the painted woods and furniture and the absence of mould risk. For the sculptures there are some risks but not extremely dangerous. Despite the use of a temperature target considering energy reduction and a RH target to avoid mechanical degradation, the building responds positively to this target only in 38% of the year, demonstrating that guidelines should not be used widely without previous validation.

For the natural climate it was possible to note the absence of mould risk and a good mechanical response for the pictorial layer of painted panels and furniture, while for sculptures and the wooden substrate of painted panels some risks were found. It was also possible to note that the elastic limits are exceeded only in 0.8% of time in the case of the furniture and in 8.6 % of the time for the wooden substrate of painted panels.

As regard the thermal comfort, none the PAS 198 or the EN 15757 allow to obtain better results than those obtained for the natural climate. The setpoint 20ºC;50% RH allows to improve the comfortable percentage of time from 46 to 66 %.

Recalling that the methods described for the mechanical degradation analysis are based on yield strains obtained for new materials and considering the possibility of the acclimatization of the permanent collections, it is possible to conclude that the dynamic model described in EN 15757 can be a useful tool to control the indoor climate in cultural heritage buildings in Southern Europe, controlling the higher mechanical risks and simultaneously reducing the energy demand.

2.4. Conclusions

This chapter analysed the influence of four climate control strategies (20ºC;50% RH; PAS 198; EN 15757 and the natural climate) in an unheated historic building in temperate climate and made a comparison between those targets and the natural climate by using a risk-based analysis. It was evaluated the hygrothermal capacity of the building and the mechanical, biological and chemical response of the collections and the thermal comfort of the visitors. It was possible to achieve some relevant conclusions, namely:

- There was a perfect mechanical response of the collections when the set-point 20ºC;50% RH was applied. The dynamic target of EN 15757 lead to a perfect response for sculptures and furniture and a plastic response in 7.4% of the year for the painted wood. The target defined by PAS 198 allows perfect conditions for the painted wood and furniture, with plastic response in 0.5% of the year for sculptures. The natural climate without any constraints lead to a plastic response in 8.6% of the year for the painted wood and in 0.8% for sculptures;

- There were no biological risks for the four conditions;

- All targets allow chemical risks especially from May to October when the temperatures are higher. Since not all the collections are equally sensitive to chemical degradation, a detailed analysis may be required to understand if there is a real need to improve the internal environment;

- None of the climate control strategies have obtained satisfactory results as regard the thermal comfort. With the setpoint 20ºC;50% RH the comfort sensation was felt during 66 % of the year while for the other strategies this sensation occurred only in 46 % of the time;

- The target of 20ºC;50% RH is very demanding in terms of the hygrothermal response of the building, being reached only during 0.5% of the time, while the EN 15757 is reached in 75.3% and the PAS 198 in 38%;

It was possible to conclude that the more demanding set-points require the use of strong HVAC systems and high energy consumptions that often are not required by the collection. Some guidelines conceived for particular climates may not result if applied in other locations, hence the need for a previous validation for each climate before they are used.

Finally, it was concluded that a detailed knowledge about the hygrothermal response of each building and a risk-based analysis could lead to energy savings without compromising the conservation of the collections.

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3. The impact of mass tourism on the conservation and visitors' comfort in the Jeronimos Monastery, Lisbon (Portugal)

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3.1. Introduction

Cultural heritage plays a crucial role in modern societies as symbols of their past and a way to safe keep their identity in the future, and 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 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 for 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 recognized that cultural tourism accounts for around 40 % of European tourism, representing a key economic sector with high growth potential [4]. However, the influence of heritage on other sectors must also be considered, as presented by the 2017 WTTC report that showed that the travel and tourism sector in 2016 had a total contribution of 10.2% in the European Union (EU) gross domestic product (GDP) and was responsible for 11.6 % of all jobs [5].

The recently published Eurobarometer report [6] reinforce the importance of cultural heritage for the EU. In a study based on 27881 surveys, 84% of Europeans considered cultural heritage to be important to them personally and 90% believed 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 jeopardize 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, where references [2,7-10] are examples. Additionally, The UN’s Agenda 2030 and Sustainable Development Goals (SDGs), ratified by 193 countries in 2015 [11], 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 buildings 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, since they release heat, water vapour and carbon dioxide in addition to the transport of exterior pollutants. This set of factors have a high potential to affect the conservation and comfort and compromising the sustainability of buildings [12,13], since, by definition, comfort and mainly conservation both require narrow intervals of temperature and relative humidity [14-16].

In air-conditioned buildings, as museums or other important buildings, this can lead to an increasing energy demand and degradation risks in building elements, since old buildings are usually characterized by poor hygrothermal behaviour [17]. On the other hand, in naturally ventilated and unheated buildings, as it is the case of most of the churches and monasteries in southern Europe, the high number of visitors will contribute for 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.* [13] published one of the reference works in this field, where among other subjects, they studied the influence of mass tourism in four European museums (Correr Museum - Venice, Italy; - Antwerp, Belgium; Sainsbury Centre for Visual Arts - Norwich, United Kingdom). 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 climate control systems. It is possible to find other studies that relate the impact of visitors on conservation or on the indoor climate, as the work carried out at Royal Museum of Fine Arts (Antwerp, Belgium) [18], the papers about the Scrovegni Chapel (Padova, Italy) [19,20] or about the Casa di Diana [21]. Other works as [22,23] evaluated the conflicts between conservation and comfort, the influence of occupation profile [24] or the visitors' expectancy on museums [25].

Despite this evidence there are still no clear studies on the risks that tourism can bring to cultural heritage and in 2017 only 37% of Europeans believed that the increased tourism can be a threat to heritage conservation [6]. 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 [26] with greater understanding among people and awareness of the value of heritage, thus contributing to its preservation [27]; and in 2018 the European Year of Cultural Heritage [28] 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.

This seems to be the ideal time to evaluate the impact of tourism on the interior climate of built heritage and the risks for conservation, comfort and sustainability with the aim of enabling careful management of the heritage in the future. This chapter intends to evaluate the impact of tourism on one of the most emblematic Portuguese monuments - the Jeronimos Monastery, a UNESCO World Heritage building located in Lisbon - which is the most visited monument among the 23 managed by the Portuguese Directorate-General for Cultural Heritage, with a 154% increase in the number of visitors from 2005 to 2017. For this purpose, a climatic monitoring campaign was carried out during 15 months with records every 10 minutes and a simulation model of the monastery were developed in the software WUFI®Plus and validated against the real data. Then the impact of the number of visitors was evaluated according to the past occupancy taxes and a forecast for 2027, analysing the risks for conservation, air quality and visitors' comfort.

3.2. 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 GDP [29,30]. This evolution can be seen in Figure 3.1.

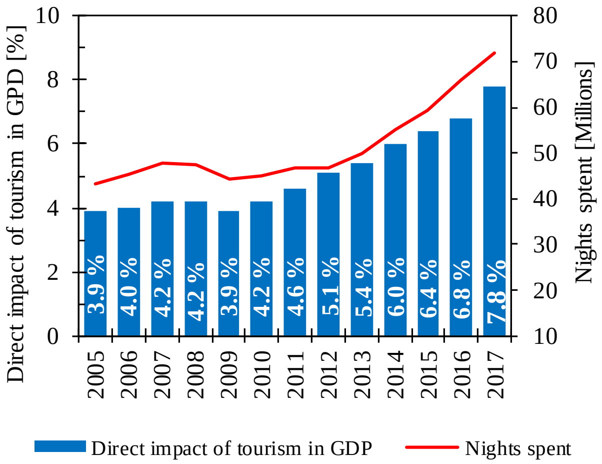

Figure 3.1. Evolution of the number of nights spent in Portugal and the direct impact of tourism on gross direct product (GDP) [29,30]

A report published in 2017 [31] by the Portuguese Government predicted three scenarios for the number of nights spent until 2027. As a more optimistic scenario, it forecasts an average growth of 6.1%/year; as the medium scenario and the more plausible one, a growth of 4.2%/year; while the less optimistic scenario predicts a growth of 3.1%/year.

The increase in general tourism has also contributed to the increase of interest in the Portuguese cultural heritage that incorporates 471 buildings classified as national monuments [32]. With regard to the cultural tourism, according to the Portuguese Directorate-General for Cultural Heritage, that currently manages 23 main monuments and museums in Portugal including five UNESCO World Heritage buildings and 15 national museums, the number of visitors increased by 55% from 2010 to 2016, where foreigners represented 70 % of the total visitors, a value that increases to 84 % if museums were excluded. In Figure 3.2 it is possible to find the geographical distribution of the national monuments and the five buildings classified as UNESCO heritage.

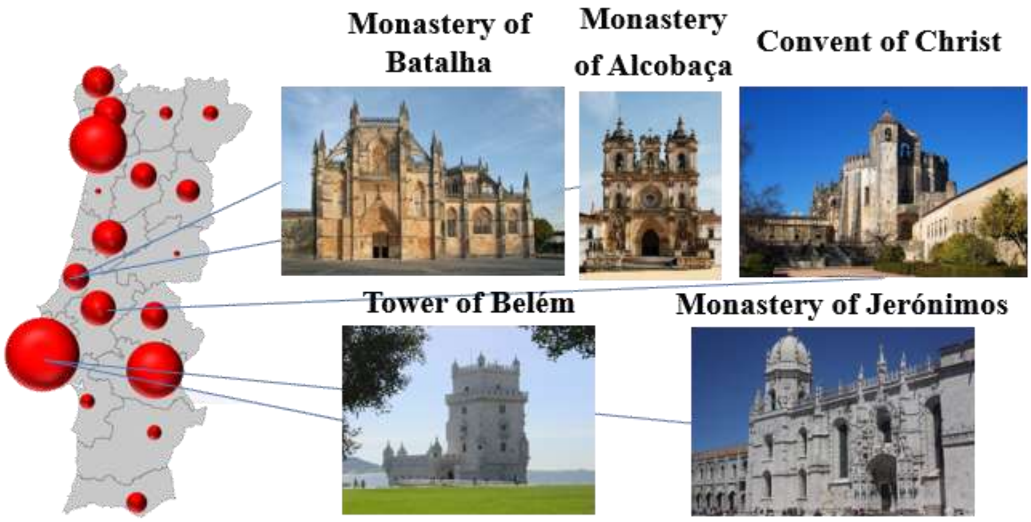

Figure 3.2. Geographical distribution of the 471 national monuments and the 5 world heritage buildings [32]

Jeronimos Monastery is one of the most evident cases of the increasing interest in the Portuguese heritage, with an increase in the number of visitors from about 460 000 in 2005 to over 1 million in 2017, which represented an increase of 154 % and an average annual growth of 11%/year over the last 5 years. These numbers refer to the cloister of the Monastery. However, the Monastery also has the church in which visitors' entrance is neither controlled nor paid and where the visitor's number was estimated as 3 times the visitors of the Cloister, performing a total of more than 3 million visitors in 2017. International tourism has a preponderant impact on the total number of visitors. Between 2005 and 2017 the foreign visitors made up 92% of the total of visitors. The evolution of the number of visitors in the church and the distribution between national and international visitors can be seen in Figure 3.3.

Relating the total number of nights spent in Portugal with the number of visits in the Jeronimos Monastery, the presence of a direct relationship between 2012 and 2017 was noted, as shown in Figure 3.4. During this period, one visit to the Jeronimos 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.

Figure 3.3. Increasing number of visitors at the church of the Jeronimos Monastery

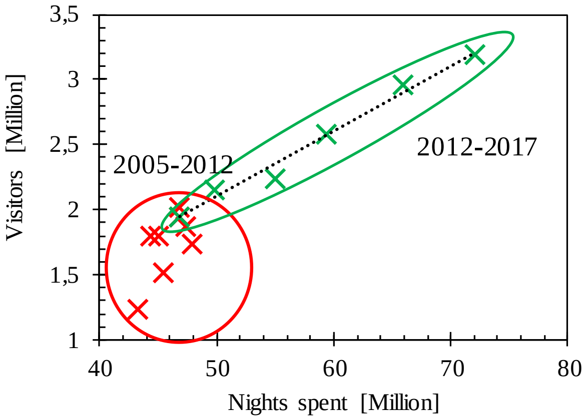

Figure 3.4. Relationship between the total nights spent in Portugal and the number of visits to the Jeronimos Monastery

Considering the 3 scenarios of tourism growth presented by the Portuguese government and the average growth rate of visitors at the Monastery of 11% per year during the last 5 years, the number of annual visitors for the next 10 years was estimated, as can be seen in Figure 3.5.

This increase in the number of visitors can have a negative impact on the conservation of the building and artefacts and on the health of visitors. Respiratory, cardiovascular and nausea problems are regularly reported in the days of higher affluence. In some cases, the risks of mass tourism can be justified to a certain extent by the increase in revenues, which is not true in this case, since the visit to the church is free. 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 internal climate to define a safe strategy that will safeguard the heritage for future generations.

In order to study the impact of the growing tourism in the monument, the monitoring of the climatic conditions of the Jeronimos Monastery was carried out between August 2017 and October 2018 to understand the interior climate, and afterwards a simulation model in WUFI®Plus was developed and validate against the measured data. The model was used to simulate different occupancy rates relating the visitors with the conservation, comfort and indoor air quality.

This chapter aims to contribute to the management of the Portuguese cultural heritage, highlighting the risks of an uncontrolled tourism, and to the definition of a sustainable ratio of visits that do not put the cultural heritage in risk.

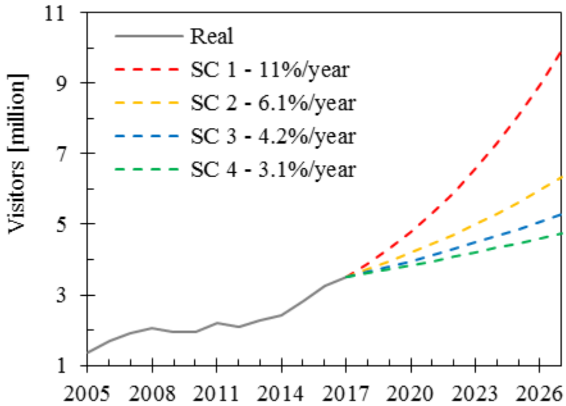

Figure 3.5. The increasing visitors' scenarios in the Jeronimos Monastery

3.3. The indoor microclimatic characterization

3.3.1. The case study – Jeronimos Monastery

The Jeronimos Monastery was built during the 16th century and is characterized by the late Gothic Manueline architectonic style. The building is one of the most important heritage buildings in Portugal. The construction costs were mostly borne by the named "pepper tax" equivalent to 5% of the revenues from trade with Africa and the Orient [33]. The Jeronimos Monastery was classified as a National Monument in 1907 and classified as a World Cultural Heritage by UNESCO in 1983.

The church presents a majestic volume, characterized by a horizontal plan in Latin cross with the nave, a crossing, two transepts and the choir. On the west side of the nave are the tombs of Vasco da Gama and Luis de Camões. According to the monastery's directorate, the largest influx of tourists occurs in this area. The church has a total length of 90 m between the west entrance and the choir to the east, a width of 23 m at the nave and 50 m at the transepts and an average height of 24 m (dimensions were taken from blueprints supplied by the Monastery Directorate and confirmed *in situ*). The stone vaulted ceilings connect the external walls with the support of two rows of columns with a height of 16 m. On the vaults are brick masonries built during the 1930s to support the roof of ceramic tiles [34]. The horizontal plan of the monastery can be seen in Figure 3.6 and a longitudinal cross-section of the church from west to east in Figure 3.7. The south façade and a longitudinal photo can be found in Figure 3.8.

The church is open to the public from Tuesday to Sunday varying the schedule. October to April: from 10:00 h to 17:30 h; May to September: from 10:00 h to 18:30 h. The church is closed on Mondays, 1st January, Easter Sunday, 1st May, 13th June and 25th December [35]. Religious celebrations run from Monday to Saturday at 9:30 h and 19:00 h. On Sunday and Holy Days, the mass occurs at 9:00 h, 10:30 h and 19:00 h.

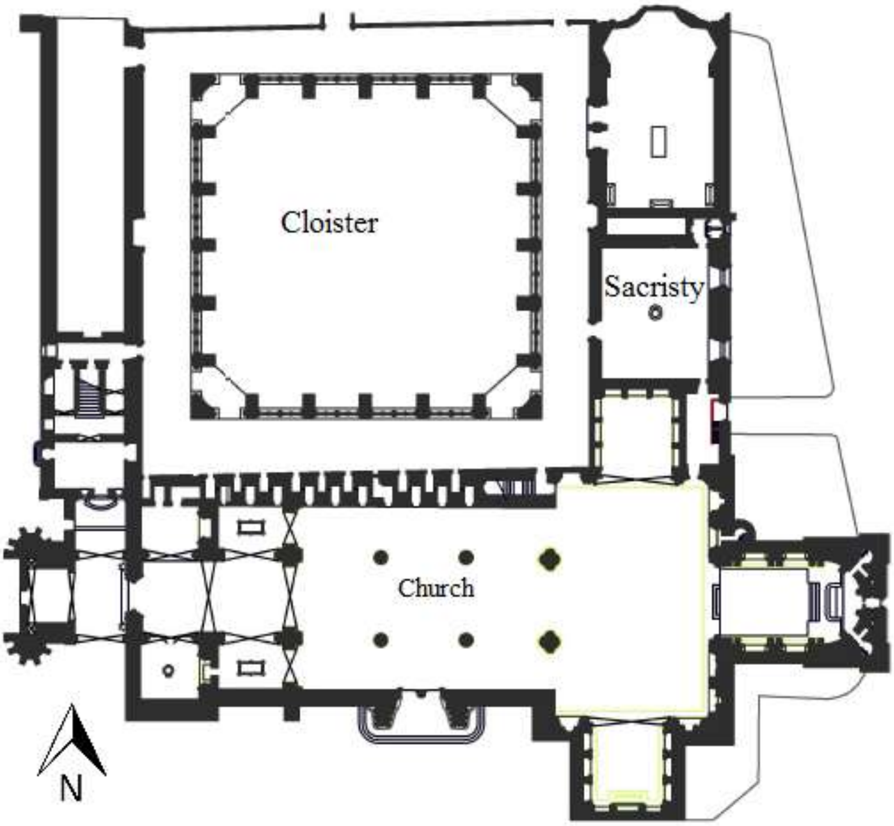

Figure 3.6. Horizontal plan of the Jeronimos Monastery (with no scale)

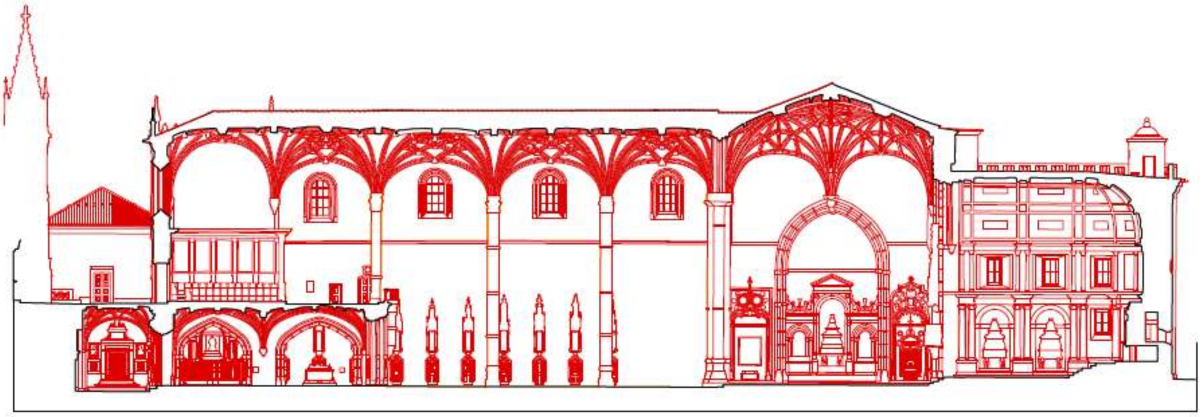

Figure 3.7. Longitudinal cross-section of the church from west to east

a) b)

Figure 3.8. Jeronimos Monastery: a) south façade of the church; b) longitudinal photo (west to east)

3.3.2. Monitoring campaign

3.3.2.1. General considerations

The monitoring of the climate in buildings plays an important role in its characterization, pathological study, risk analysis and climate optimization. The environmental monitoring of the Jeronimos Monastery was conducted to understand the microclimate of the church, its relationship with the outdoor and the visitors' impact.

3.3.2.2. Sensors description

In order to choose an appropriate sensor for each monitoring campaign, there are several factors that must be considered, such as the compatibility of the sensor with the ambient conditions, its measuring range, resolution, accuracy, response time, drift and compatibility with the recording instrument and, obviously, its cost [17]. The sensors' accuracy must comply certain limits – for temperature standard EN 15758 [36] recommends the use of sensors with a minimum accuracy of 0.5 ºC, but preferentially it should be lower than 0.2 ºC; for relative humidity standard EN 16242 [37] recommends the use of a minimum accuracy 3 %RH for electronic capacitive sensors.

Usually the monitoring depends on generic data loggers marketed by several manufacturers. The high costs typically associated to these devices and their lack of flexibility are obstacles to their use. For the current thesis, low-cost and open source data loggers based on the Arduino platform were developed to record the temperature, relative humidity and CO_2. Arduino technology includes a set of open-source electronic microcontrollers with flexible hardware that is easily programmable in C ++ through its proprietary IDE software [38]. For the construction of the prototypes used in this paper, the Arduino Pro

Mini 3.3 V with 8 MHz of clock speed and equipped with an Atmel ATmega328P microprocessor was chosen based on the recommendations of the Refs. [39- 41].

The tutorials [40] and [41] and the analysis made in [39] were used as a starting point for the data loggers development. To measure the temperature, a 10k PT103J2 thermistor with an accuracy of ±0.2 ºC from US Sensor/Littelfuse was used. For the relative humidity, an SHT31-DIS from the Sensirion [42] with a typical accuracy of ± 2% RH were used. For the CO2 measurements, the SenseAir CO2 Engine® K30 STA [43]. For further technical information, consult Refs. [39-41]. The generic assembly of the T & RH data logger with capacity for two SHT31-DIS sensors and five thermistors can be seen in Figure 3.9. It was possible to construct data loggers with an SHT31-D sensor and a thermistor for approximately 64 €. The comparison of this value against for example the cost of an ML4106 data logger (ca 300 € [44]) or an ATX-11 data logger (295 € [45]) shows the competitivity of this prototype. The use of two SHT31-D sensors and five thermistors makes the data logger even more versatile, resulting in a total cost of ca 87 euros. Data loggers were powered by four 1.2 V and 2700 mAh Camelion rechargeable batteries. As regard to the CO_2 data logger, its power was made through the electric current whenever possible, and in the remaining situations through a battery of 6 V and 12 000 mAh from Kaise. The code for the T and RH data logger can be seen in Appendix I – T and RH code.

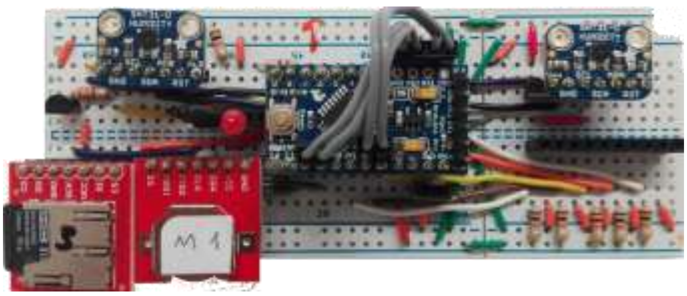

Figure 3.9 Scheme of the Temperature (T) and relative humidity (RH) data logger

3.3.2.3. Monitoring campaign description

In a monitoring campaign the sensors location must be carefully chosen to accurately register the indoor climate differences both in plan and in height without the influence of unwanted sources, such as the radiation from the sun or the lighting system, the air flow through open doors/windows and the heat loss through the envelope. For the outdoor sensors, it is further important to take into account the influence of the rain.

The monitoring campaign must be long enough to completely record the indoor climate variability, and the recording frequency has to allow the proper reconstruction of the indoor environment with the minimum number of values. *Camuffo* [17] states that monitoring campaigns should last at least one complete year and have a recording frequency of 10 minutes arguing that the climate monitoring should encompass four dimensions to describe the spatial variability (x, y, z) and the time variability.

EN 15757 [46] follows the same line arguing that to define the historical climate it is necessary to perform a long-term monitoring campaign of at least one year with a recording frequency of one hour or less.

In the monitoring campaign of the Jeronimos Monastery, six data loggers were installed in the interior and one on the outside (installed in the bell tower). In two of the interior data loggers, several sensors were attached to analyse the distribution of temperatures in height. Globally, 13 temperature sensors and 9 RH sensors were used. The monitoring campaign of the Jeronimos Monastery is summarized in Table 3.1 and the location of the sensors is presented in Figure 3.10.

Table 3.1. Location and type of sensor

#	Location	Type	Height
D. 1	Entrance	T & RH	3.30 m
D. 2	Nave – North	T & RH	3.30 m
D. 3	Nave - South	T & RH	3.30 m
D. 4	Crossing	T & RH	3.00 m
D. 5	Northern transept	T & RH T T & RH T T	4 m 7 m 10 m 13 m 16 m
D. 6	High choir	T & RH T & RH T	10 m 15 m 20 m
D. 7	Exterior – tower	T & RH	3.00 m

The distribution of the sensors was made in order to understand the variation of the interior climate in time and space. The monastery has an east-west orientation. Inside there is a well-defined tour circuit (identified with the blue arrows in Figure 3.10) where visitors enter through the west door and spend most of the time visiting the Vasco da Gama and Luis de Camões tombs near the entrance. Sensor 1 was placed aiming to verify the influence of the visitors and the opening of the doors. During the religious celebrations, the concentration of people is higher in the area of the crossing, which justified the placement of sensor 4. Sensors 2 and 3 were placed with the intention of studying the influence of sun exposure from south to north. Since the climate also varies in the vertical direction, two vertical profiles were used to evaluate the stratification of the air by temperatures – the data logger 5 with 5 reading points placed in the northern transept and the data logger 6 with 3 reading points placed in the high choir. In addition, a data logger was placed in the bell tower to evaluate the external conditions. Data was collected for 15 months – from August 2017 to October 2018 (the sensors still remain in use) – with a recording frequency of 10 minutes. Given the battery limitations, the CO_2 concentration was monitored for nine weeks on the interior and one week at the exterior with records every 30 seconds.

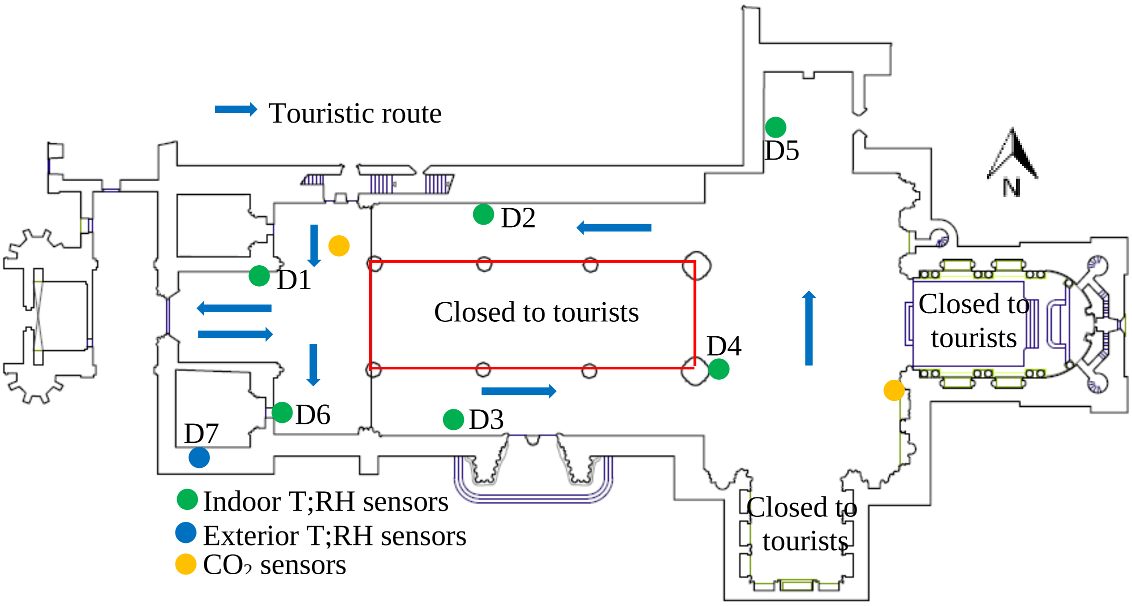

Figure 3.10. Location of temperature and relative humidity and CO_2 sensors

3.3.2.4. Sensors' calibration

It is indispensable to carry out the calibration of the sensors before starting a monitoring campaign to guarantee the quality of the results and the comparability among the sensors [47-49]. Obviously, this stage is even more important when the recordings are performed by prototypes for obvious reasons.

Temperature and relative humidity sensors, in addition to their margin of error, are susceptible to losses of accuracy over time, either through misuse, exposure to extreme weather conditions or harmful environments, or simply due to the ageing of the sensor. Sensor calibration is essential in multi-sensor monitoring campaigns, where accuracy and comparability are necessary.

The RH sensors were calibrated by comparison with a reference sensor previously calibrated in a controlled environment with saturated salt solutions that remain reasonably constant with the temperature, chosen from Ref. [50], as shown in Table 3.2.

The remaining sensors were calibrated in a climatic chamber (FITOCLIMA 300 EDTU from Aralab) by comparison with the reference sensor. The sensors were exposed for three hours to four climatic stationary conditions of temperature and relative humidity, recording the data every minute. These conditions can be seen in Figure 3.11. For temperature, the average temperature recorded by all the sensors was taken as reference.

To perform the calibration of the sensors, the data collected during the first 60 minutes were neglected.

Then, the mean value was calculated for each level and compared with the reference sensor. Figure 3.12a shows the calibration of temperature comparing the records of each sensor with the reference average. All the sensors have maximum differences between ± 0.1 % in relation to the reference value. These differences are lower than the uncertainty declared by the manufacturer (± 0.2 %), which guarantees reliability and comparability between the sensors.

Table 3.2. Saturated salt solutions used to calibrate the reference sensor [50]

Relative humidity (%)								
Salt solution		**Temperature (°C)**						
		5	10	15	20	25	30	35
Magnesium chloride hexahydrate	$MgCl_2.6H_2O$	33	33	33	33	33	32	32
Magnesium nitrate hexahydrate	$Mg(NO_3)_2.6H_2O$	53	57	56	54	53	51	50
Sodium Chloride	NaCl	75	76	76	75	75	75	75
Potassium chloride	KCl	84	87	86	85	84	84	83
Potassium nitrate	KNO_3	94	96	95	95	94	92	91

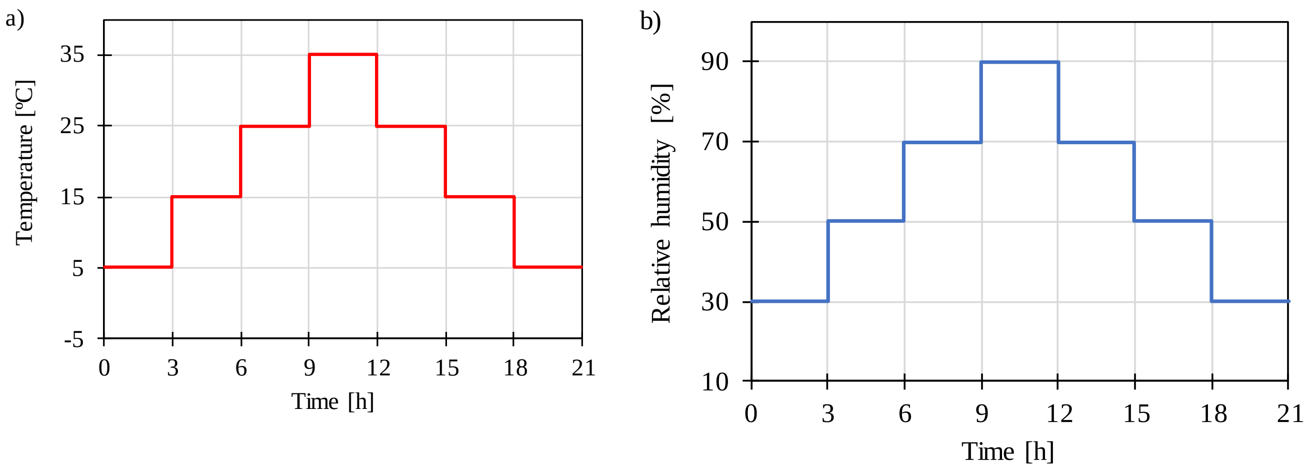

Figure 3.11. Calibration campaign: a) temperature; b) relative humidity

The comparison of the RH recorded by each sensor with the reference sensor, guaranteeing a validation of the absolute values, can be seen in Figure 3.12b. To ensure the comparability among all the sensors, the comparison of each one with the average of all of them can be seen in Figure 3.12c. As far as absolute calibration is concerned, all the sensors return a greater uncertainty for the lower relative humidities, exceeding the uncertainty declared by the manufacturer. However, it is noted that the maximum deviation from the reference value is 3.1 % RH, close to the maximum tolerance of 3 % RH defined by EN 16242 [37], and therefore it was not considered necessary to design a calibration curve to insert into the code and generating a more disruptor factor to the campaign. As regards to the comparability of the sensors, it was noted that the maximum difference verified between each of the sensors and the average of the group is 1.1 % RH, which clearly guarantees their comparability.

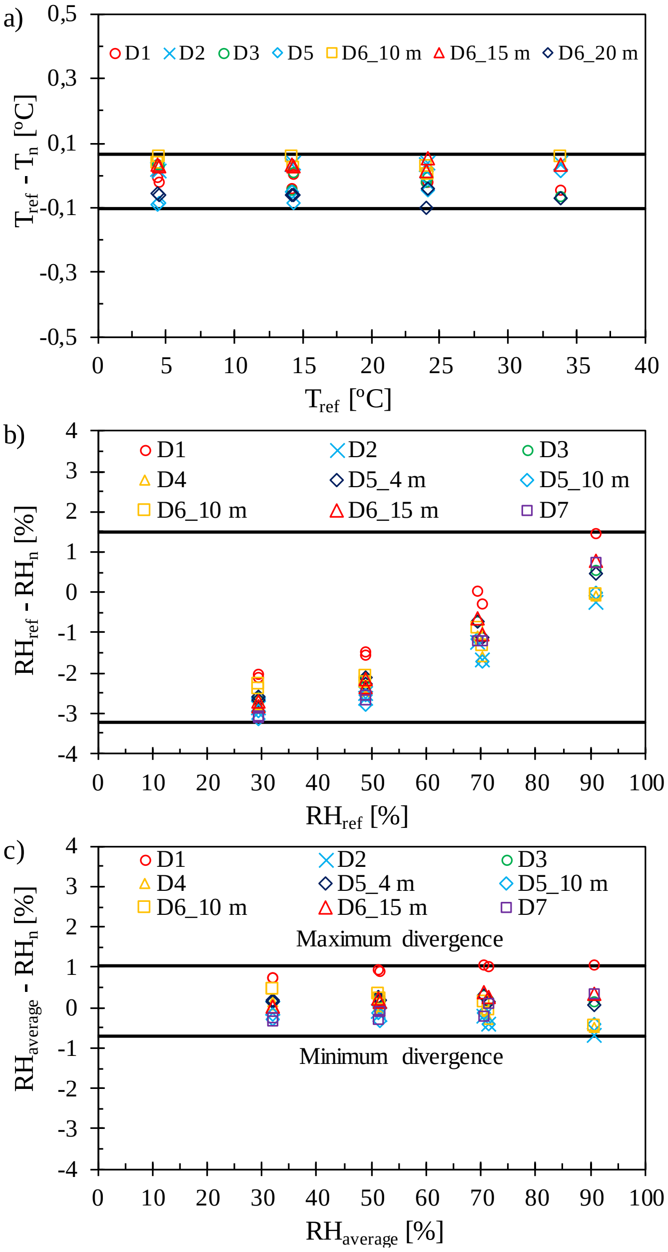

Figure 3.12. Sensors' calibration: a) comparison between the temperature recorded by each sensor and the reference value; b) comparison between the RH recorded by each sensor and the reference sensor; c) comparison between the RH recorded by each sensor and the average of all of them

To validate the CO_2 records, the prototype with the K-30 sensor was compared with the records of a Telaire 7001 CO_2 Sensor [51] with an accuracy of ±50 ppm or 5 % of reading, whichever is greater. This comparison can be seen in Figure 3.13. The results agree with those obtained in Refs. [39,41] and show that the K-30 sensor generally returns lower values. Since only one CO_2 sensor was used in the monitoring campaign, no further calibration was considered necessary.

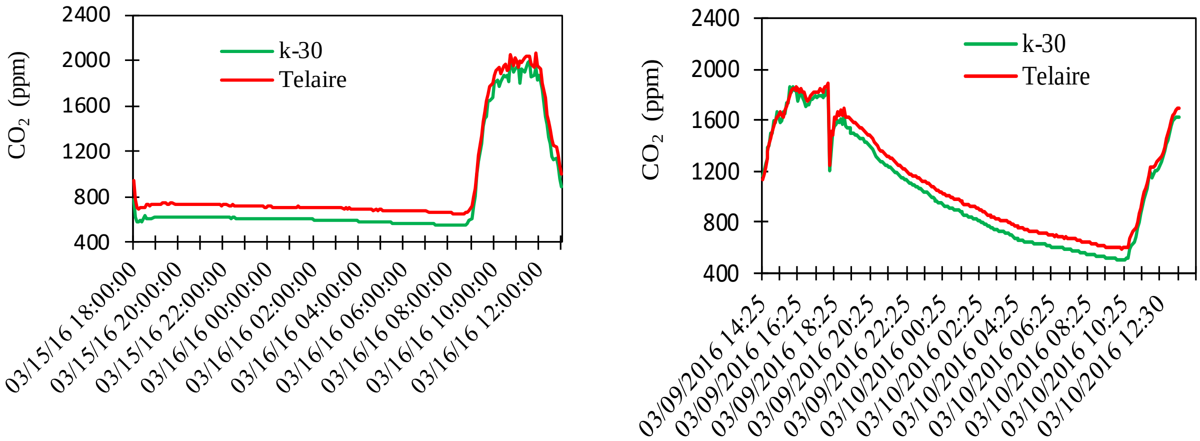

Figure 3.13. CO_2 recordings by the developed prototype and by Telaire 7001

3.3.3. Results

3.3.3.1. Monitoring limitations

Before starting the analysis of the results, it is considered relevant to discuss the limitations of the monitoring campaign. Periodic visits were made to the Monastery to collect data and replace batteries with a maximum period of 3 months. Since the campaign is composed by devices manufactured by the author himself, it was decided to evaluate the battery lifetime in four data loggers – D1, D2, D3 and D4. In these devices, the batteries were replaced only when the records stopped. The batteries of these data loggers were replaced for the first time on 31 January 2018. The D1 data logger after 191 days was still operating at a voltage of 3.55 V (the data logger requires a minimum power supply of 3.30 V). The D1, D2 and D3 data loggers had a shorter lifetime. The D2 data logger ceased registrations on 29/12/2017 with a total lifetime of 158 days, while the D3 and D4 data logger refuted registrations until 6/01/2018 with a total lifetime of 165 days. The D6 sensor had a problem at the beginning of the campaign with the data storage system, it was solved on 11/09/2017. The data logger D5 ceased its activity on 30/07/2018 due to an error of the technicians in the replacement of the batteries. The external data logger ran out of battery between 13/12 to 18/12 of 2017 and between 6/03 to 19/03 of 2018.

3.3.3.2. Temperature, water vapour pressure and relative humidity - general analysis

To analyse the indoor climate of the building the average values obtained from the data loggers located at the same level (D1, D2, D3, D4 and the sensors located at 4 m of the D5) were used. Following the recommendations of standard EN 15757, monitoring periods should be used of at least one year, or multiple periods. Thus, it was decided to carry out the analysis between September 2017 and August 2018.

The comparison between the indoor and outdoor conditions is presented in Figure 3.14. As regard to temperature (Figure 3.14a), the indoor climate is much more stable than the outdoor, which is justified by the thermal inertia and high volume of the building. Regarding the seasonal cycles obtained by a

30-day moving average, it is possible to conclude that the indoor temperature is higher than the outdoor throughout the year with a relatively constant difference of about 2.8 ºC. This behaviour is justified by the high thermal inertia that characterizes the building, the high internal gains due to the flow of visitors and a presumably low ventilation rate due to the low relationship between the openings area and the building volume.

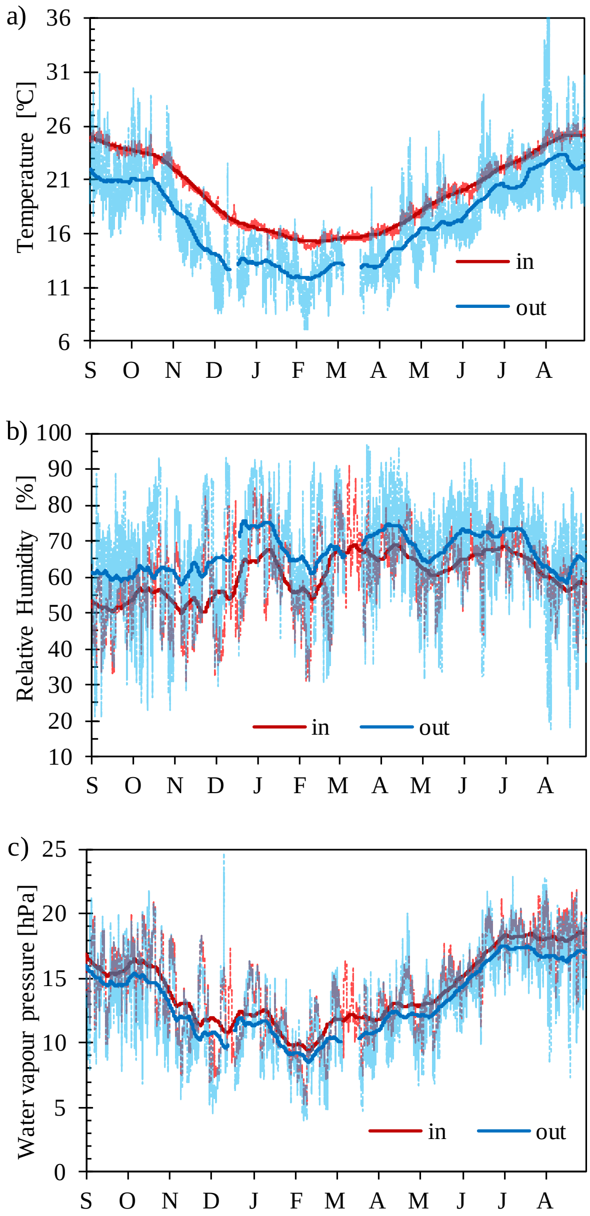

Figure 3.14. Indoor and outdoor climate: a) temperature; b) relative humidity; c) water vapour pressure

Regarding the relative humidity (Figure 3.14b), the interior climate has smaller fluctuations along the year and the seasonal cycle is always lower than the one of the exterior. Despite the relative humidity being the parameter most frequently used to characterize the hygrometric conditions of the air, it depends on temperature and water vapour pressure. Its individual analysis makes it possible to characterize the climate and to assess the risk of degradation, but it does not allow to conclude if the fluctuations are due to an inadequate temperature or water vapour pressure. The analysis of Figure 3.14c allows concluding that the internal vapour pressure accompanies the external tendency very closely, but with smaller fluctuations. In seasonal terms, the internal pressure shows slightly higher values than the exterior ones throughout the year. In general terms, an average differential of 0.4 hPa was obtained, which according to the international literature classifies the building as having a low hygrometry denoting a reasonable relationship between the air change rate and the internal water vapour production [52].

3.3.3.3. Correlation between the indoor and outdoor conditions

In Figure 3.15 it is possible to find the correlation between the daily, weekly and monthly averages of the values registered in the exterior and in the interior. The correlation between the inner and outer temperatures can be found in Figure 3.15a. As expected, the dispersion observed for daily averages is much higher than that observed at the weekly or monthly level. It is noted that for the 3 types of correlations the interior temperature is higher than the exterior in the great majority of the time, which is curious mainly because the building does not have heating.

As previously justified, the internal gains, ventilation and thermal inertia together with the temperate climate that characterizes Lisbon contribute to this fact. Despite the influence of these factors, which make the average indoor temperature higher than the outside for much of the year, the strong linearity observed with correlation factors of 0.81 for the daily averages, 0.88 for the weekly averages and 0.96 for the monthly averages allows to concluded that the interior climate follows external tendencies closely. It is usually considered that there is a strong correlation for R^2 values greater than 0.75 [53].

As regard to the water vapour pressure, the analysis of Figure 3.15b shows a stronger correlation between the indoor and outdoor with R^2 values of 0.93 for the daily averages, 0.96 for the weekly averages and 0.99 for the monthly averages. As described during the analysis of Figure 3.14, there is a slight supremacy of the internal pressures to the exterior due to the indoor water vapour generation from human occupancy, for example.

Regarding the relative humidity dispersion, it is necessary to consider that this variable depends on the water vapour pressure and the temperature. The production of indoor water vapour could indicate higher mean relative humidity values in the interior, however the analysis of Figure 3.15c shows the opposite, concluding its higher temperature dependence.

Figure 3.15c also allows to see the greater dispersion of the relative humidity when compared to the other two variables, which is justified by the propagation of the fluctuations evidenced by the other two variables. The lowest coefficient of determination was obtained for the weekly correlation with a value of 0.64, followed by the daily correlation with a value of 0.66 and finally the monthly correlation with a value of 0.76.

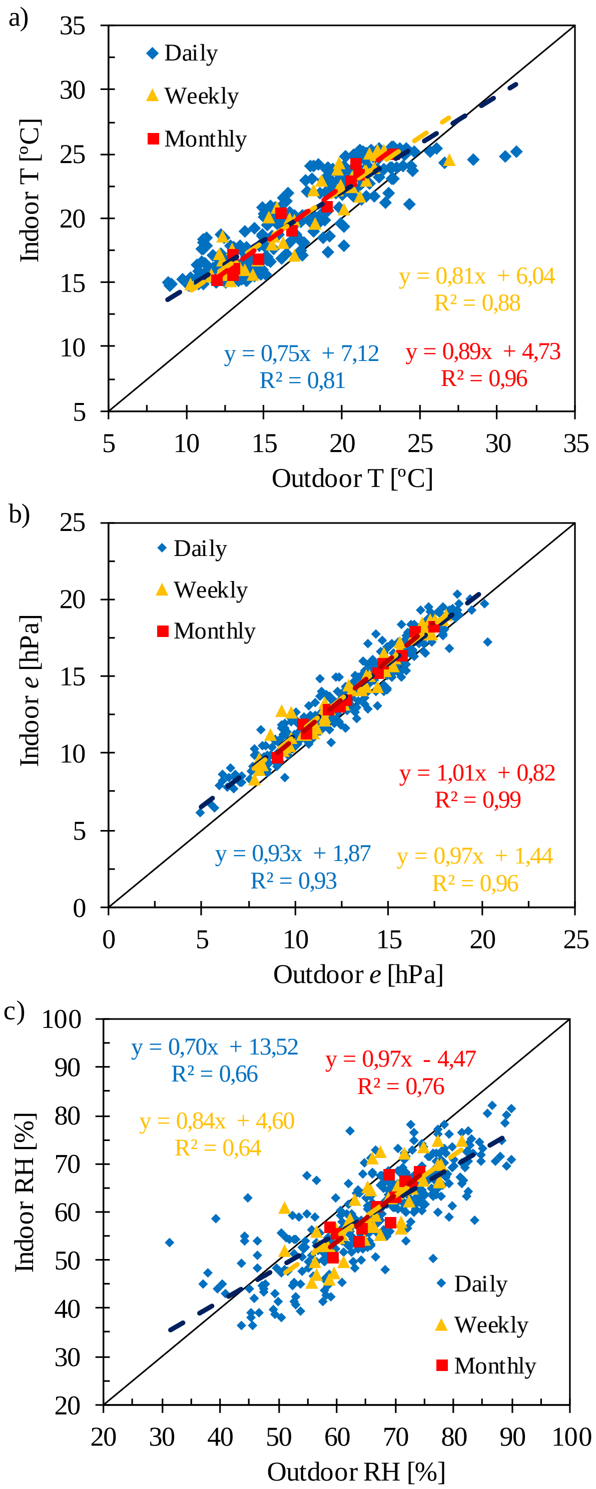

Figure 3.15. Comparison between the indoor and outdoor daily, weekly and monthly averages: a) temperature, T; b) water vapour pressure, *e* ; c) relative humidity, RH

The linearity obtained for partial water vapour pressure and temperature may be particularly useful for the use of approximate methods of risk prevention or hygrothermal rehabilitation, such as those recommended in EN ISO 13788 [54], since they allow the estimation of the monthly average indoor depending on the exterior with a reasonable level of precision. The expansion of the monitoring campaigns may lead to linear regressions that allow explaining the behaviour of buildings with no climate control according to the outdoor conditions and constitute a useful tool to support the design of heritage conservation.

3.3.3.4. <u>Statistical analysis</u>

In this thesis, in addition to a common statistical analysis, the seasonal cycles and the typical short-term fluctuations were determined based on the methodology defined in EN 15757 [46]. The process to calculate the seasonal amplitudes and the typical short-term fluctuations is illustrated in Figure 3.16. These and the other statistical parameter can be found in Table 3.3.

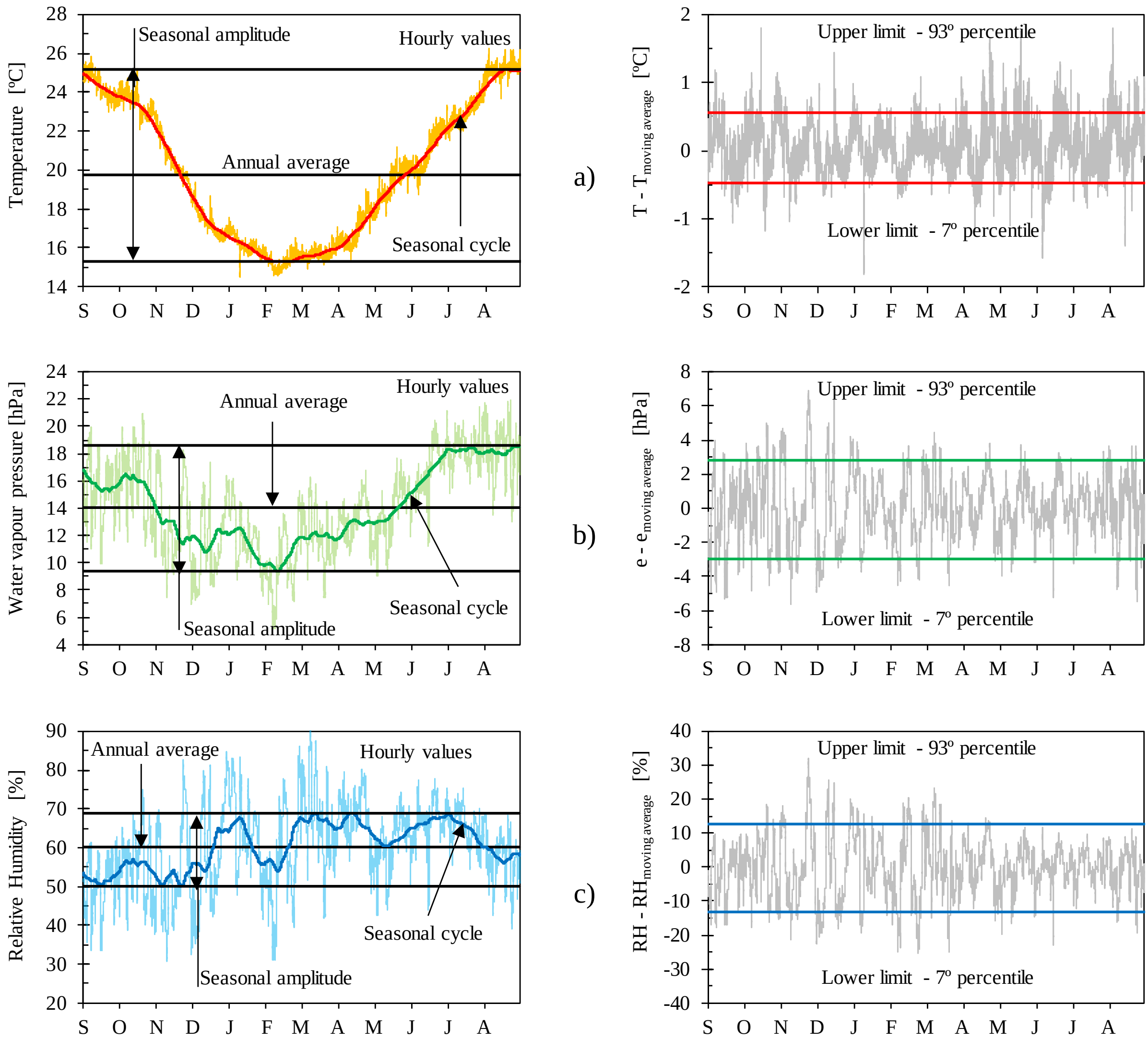

Figure 3.16. Calculating the seasonal amplitudes and typical short-term fluctuations for the temperature (a), water vapour pressure (b) and relative humidity (c)

As shown in Table 3.3, averages values of 19.8 °C, 60 % RH and14 hPa were obtained. The temperature varies between the extreme values of 14.5 and 26.2 ºC, while the relative humidity varies between 31 and 91 % RH and the water vapour pressure between 5.2 and 21.9 hPa. The analysis of the percentiles, which permits to exclude the extreme values, allow to conclude that during 96 % of the year the temperature was between 15 and 25.3 ºC, the relative humidity between 39 and 80 % RH and the water vapour pressure between 7.8 and 19.8 hPa. Using the 10th and 90th percentiles, it was concluded that during 80 % of the year the temperature varied between 15.5 and 24.6 ºC, relative humidity between 46 and 73 % RH and the water vapour pressure between 9.7 and 18.5 hPa. As regard to the seasonal cycles, amplitudes of 9.9 ºC for the temperature, 19 % for the relative humidity and 9.2 hPa for the water vapour pressure were found, while as regard to the short-term fluctuations around the seasonal cycles, typical fluctuations of -0.5/+0.6 ºC for temperature, ± 13 % for relative humidity and -3/+2.8 hPa for water vapour pressure were obtained.

Table 3.3. Statistical parameters of T, RH and e

Variable	Mean	Max	Min	Percentiles							Seasonal amplitude	Typical short-term fluctuations
				2º	10º	25º	50º	75º	90º	98º		
T [ºC]	19.8	26.2	14.5	15	15.5	16.3	19.7	23.1	24.7	25.4	9.9	-0.5/+0.6
RH [%]	60	91	31	39	46	53	61	67	73	80	19	± 13
e [hPa]	14.0	21.9	5.2	7.8	9.7	11.5	14.1	16.8	18.5	19.8	9.2	-3/+2.8

3.3.3.5. Air stratification and spatial variation

Previously a graphical analysis was carried out based on the average indoor climate, but it is of common sense that both the temperature and the water vapour pressure vary according to several factors, such as the wind direction and intensity, the proximity to the walls, exposure to radiation from the sun or the lighting system or due to human presence.

Historic buildings with a high thermal inertia tend to have a stable indoor climate, in which due to the great capacity to store heat of their thick walls it is possible to maintain the equilibrium with the previous season. These elements are very efficient in reducing mainly the temperature daily cycles and the seasonal cycles, but to a less extent, making the indoor climate less susceptible to the outdoor higher fluctuations.

The interior temperature is determined by the heat exchanges with the building envelope and other factors such as the presence of air conditioning systems, lighting or human presence. When the temperature rises, the air loses density and tends to rise. In ideal conditions where the floor, walls and the ceiling have similar thermal inertias and there are no disturbance factors, the air tends to stratify by temperature, where the warm and less dense air is in the upper zone and the cooler and denser air in the lower zone. However, in real cases it is difficult to find an ideal stratification, since boundary conditions are not constant in space and time, leading to a seasonal stability change.

In historic religious buildings, the floor often exhibits a high thermal inertia, followed by the walls with high thicknesses and finally by the ceiling which usually is characterized by the lowest thermal transmittances and thermal inertia which make it more susceptible to outer cycles mainly due to gains throughout the day from to solar radiation and the losses during the night by infrared radiation. In summer, it is normal for the floor to exhibit lower temperatures due to the lag provided by its high thermal inertia, while the ceiling has higher temperatures, which contributes to a well-defined air stratification.

During the winter the reverse occurs. In other words, the floor remains under the influence of the high temperatures of the previous season and the ceiling that accompanies the outer conditions with more proximity presents a lower temperature. The air when contacting the hottest floor will lose density and climb until finding the coldest surface of the ceiling, where it will gain density and descend again, forming a convective current.

In order to understand the variations of the indoor conditions throughout the year, a 4-day representative period of each season was selected. Each of these four periods corresponds to a Saturday, a Sunday, a Monday and a Tuesday (in this order). As was previously mentioned, the church is only closed to the public on Mondays but opens for religious celebrations at 9:30 and 19:00.

The analysis of allows to confirm the behaviour previously described. During summer (Figure 3.17 d) a clear air stratification by temperature was found, with the highest temperatures near the ceiling. A maximum gradient of 0.2 ºC/m was recorded. In the winter the situation is the opposite and the lower temperatures in the lower zone evidence the presence of convective currents (Figure 3.17 b). In spite of this, it is concluded that the interior variation is less susceptible to the exterior in winter than in summer, with the presence of a gradient of -0.04 ºC/m. During certain periods of spring and autumn (Figure 3.17 a and c) no significant differences are found, evidencing the gradual transition between summer and winter behaviours.

As regard the water vapour pressure, there are no significant differences in height throughout all year. The values for both measured heights almost perfectly overlay each other during the winter period (Figure 3.18 b, in which the average difference is 0.1 hPa) and the spring period (Figure 3.18 c, in which the average difference is almost non-existence). During the summer and the autumn periods more significant differences are detected (Figure 3.18 d and a, in which the average difference is 0.4 and 0.2 hPa, respectively). Considering that the greater flow of visitors occurs in the summer and that the air loses density with the increase of the water vapour concentration, this fact seems perfectly justifiable. It is visible that for the selected four 4-day periods the highest values of water vapour pressure are attained also for the weekend.

In addition to the differences in height, it is likely that the indoor climate also varies in the horizontal plane, with more stable conditions in the interior zones and greater fluctuations near the openings and the envelope. In order to study the spatial variability of the indoor conditions, the temperature and relative humidity were measured at the west, north, south and east areas of the church.

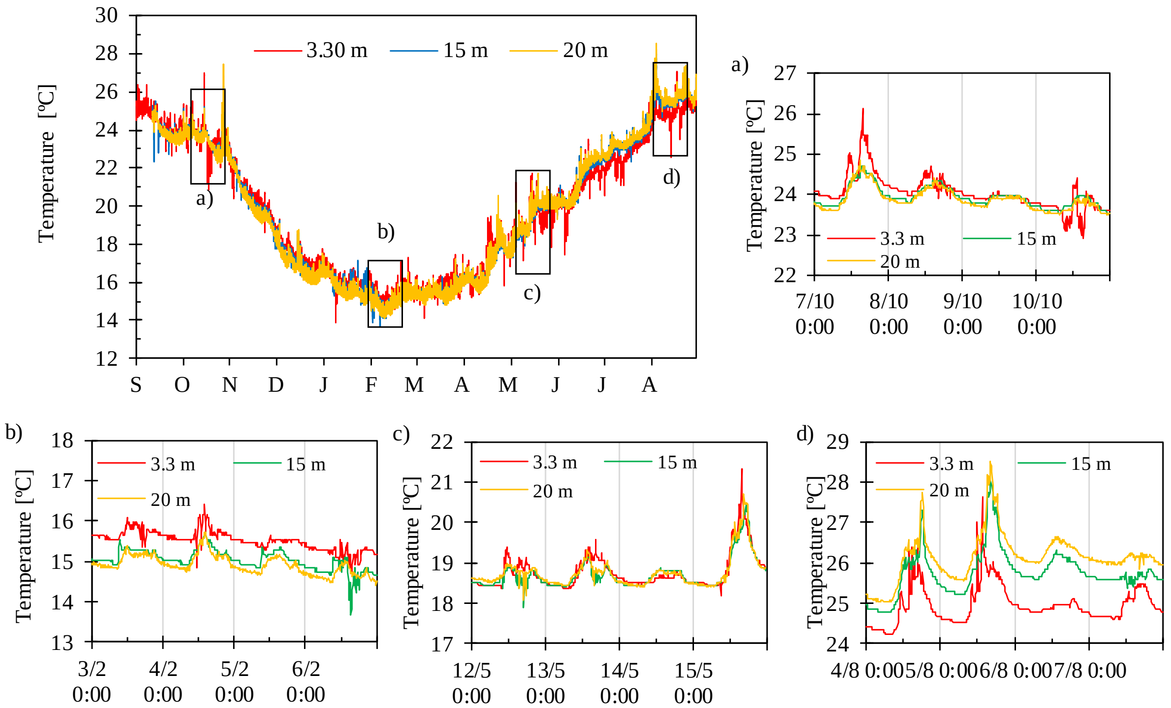

Figure 3.17. Indoor temperature measured at 3.30, 15 and 20 m. Four 4-days periods representative of the four seasons are presented: a) autumn – 7/10 to 10/10, b) winter – 3/2 to 6/2, c) spring – 12/5 to 15/5, and d) summer – 4/8 to 7/8

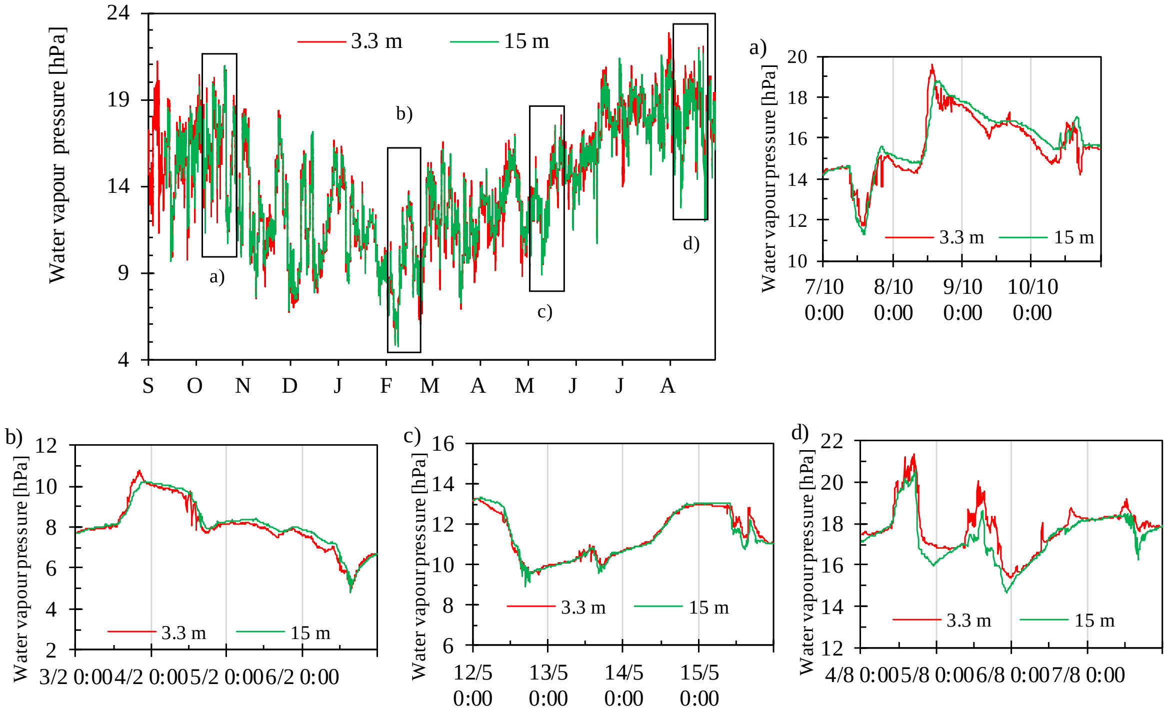

Figure 3.18. Indoor water vapour pressure measured at 3.30 and 15 m. Four 4-days periods representative of the four seasons are presented: a) autumn – 7/10 to 10/10, b) winter – 3/2 to 6/2, c) spring – 12/5 to 15/5, and d) summer – 4/8 to 7/8

The analysis of Figure 3.19 shows a greater dispersion in the western zone, near the entrance and the tombs where more visitors accumulate. It follows the zone near the south wall in the nave. The sensors placed in the crossing and in the north zone of the nave are more stable. These differences are especially noteworthy in the relationship between the west sensor and the others. The differences are more noticeable with regard to temperature, although they are also noticed in the water vapour pressure. Figure 3.19a shows the comparison between the four sensors, while Figure 3.19b shows the comparison between the two sensors placed in the main nave to the south and the north and Figure 3.19c shows the comparison between the sensors placed next to the entrance and on the cruise.

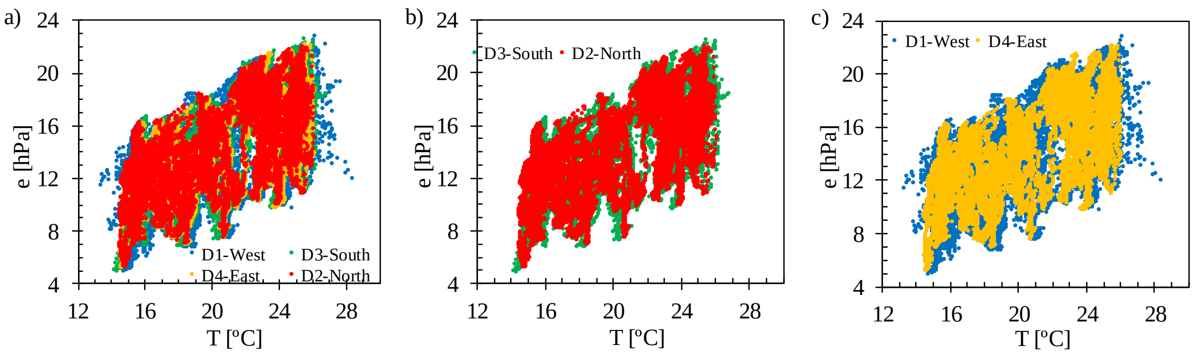

Figure 3.19. Spatial dispersion of temperature and partial water vapour pressure: a) comparison between the sensors placed near the entrance, in the nave at south and north walls and in the cruise; b) comparison between the two sensors located in the nave; c) comparison between the sensors located at the entrance to the west and the cruise at the east

3.3.3.6. CO_2 analysis

A constant CO_2 concentration of 400 ppm was adopted for the exterior according to the mean value obtained from the records made between the 23rd and 30th of July 2018 as shown in the Figure 3.20. This value is in accordance with the recommendation of the standard EN 13779 [55] for polluted city centres.

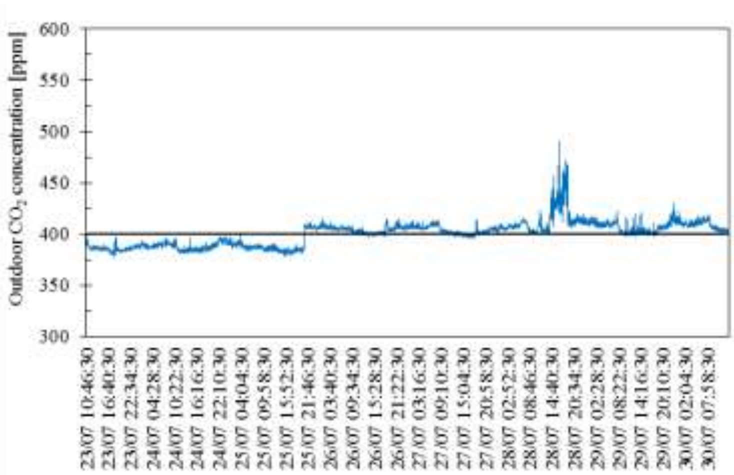

Figure 3.20. Outdoor CO_2 concentration between the 23rd and 30th of July 2018

As regard to the indoor CO_2, the concentrations recorded near the Vasco da Gama tomb can be seen in

Figure 3.21.a, b and c and the data recorded near the high altar in Figure 3.21.d. A general analysis allows to verify that during the nocturnal period the inner concentration approaches the external levels, increasing later during the visiting hours. The influence of the visitors is clear when comparing the behaviour verified on Mondays with the other days. Note that on Monday the church only opens for the typical religious celebrations at 9:30 and 19:00. It is also confirmed the higher concentration of CO_2 and consequently of visitors near the tomb of Vasco da Gama.

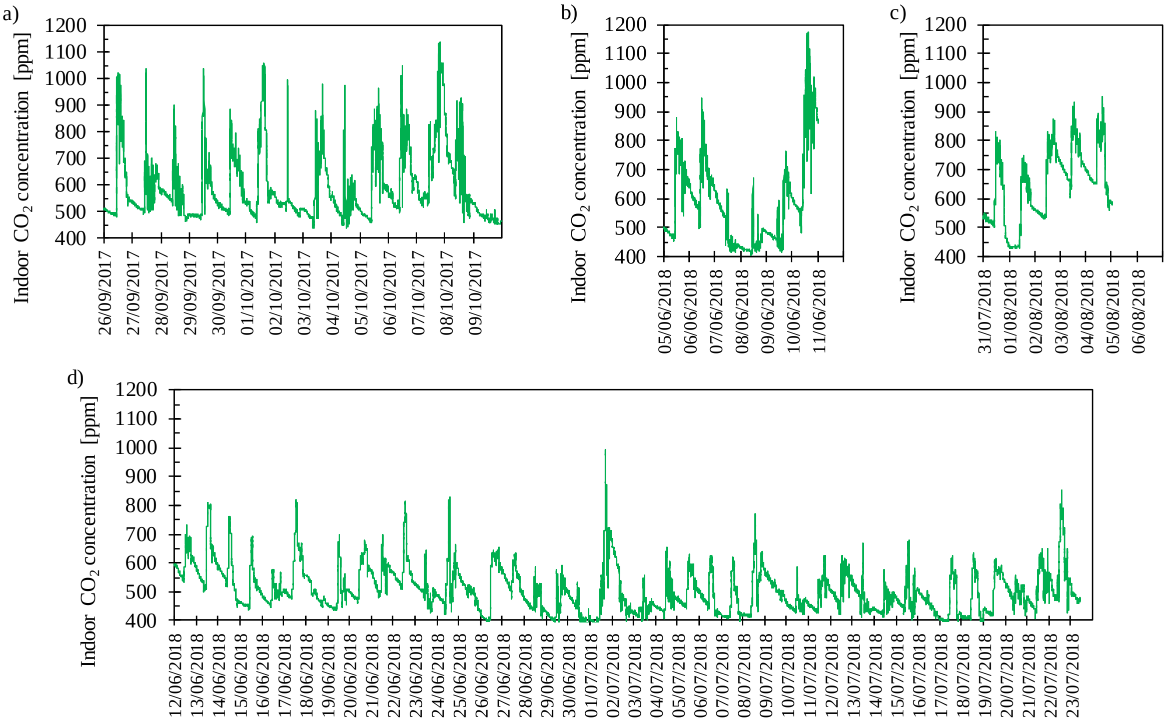

Figure 3.21. Indoor CO_2 concentration near the Vasco da Gama tomb (a,b,c) and in the crossing (d)

To understand in a more clearly way the flow of visitors throughout the day and the week, the internal CO_2 concentration over the exterior was organized by week-days. This process was performed for both the tomb and the crossing. Figure 3.22 shows the average concentration of CO_2 above the exterior during the day for each of the week days. It is confirmed once again that the highest concentrations occurred near the tomb. The comparison of the profiles of Monday with the remaining days allows to conclude the influence of the occupants in the indoor concentration of CO_2. Note that on Monday the monastery does not receive visitors. Numerically integrating the average curve of each of the days it is verified that the greatest influx of visitors takes place on Sundays, followed by Tuesdays, Wednesdays, Saturdays, Fridays and finally Thursdays.

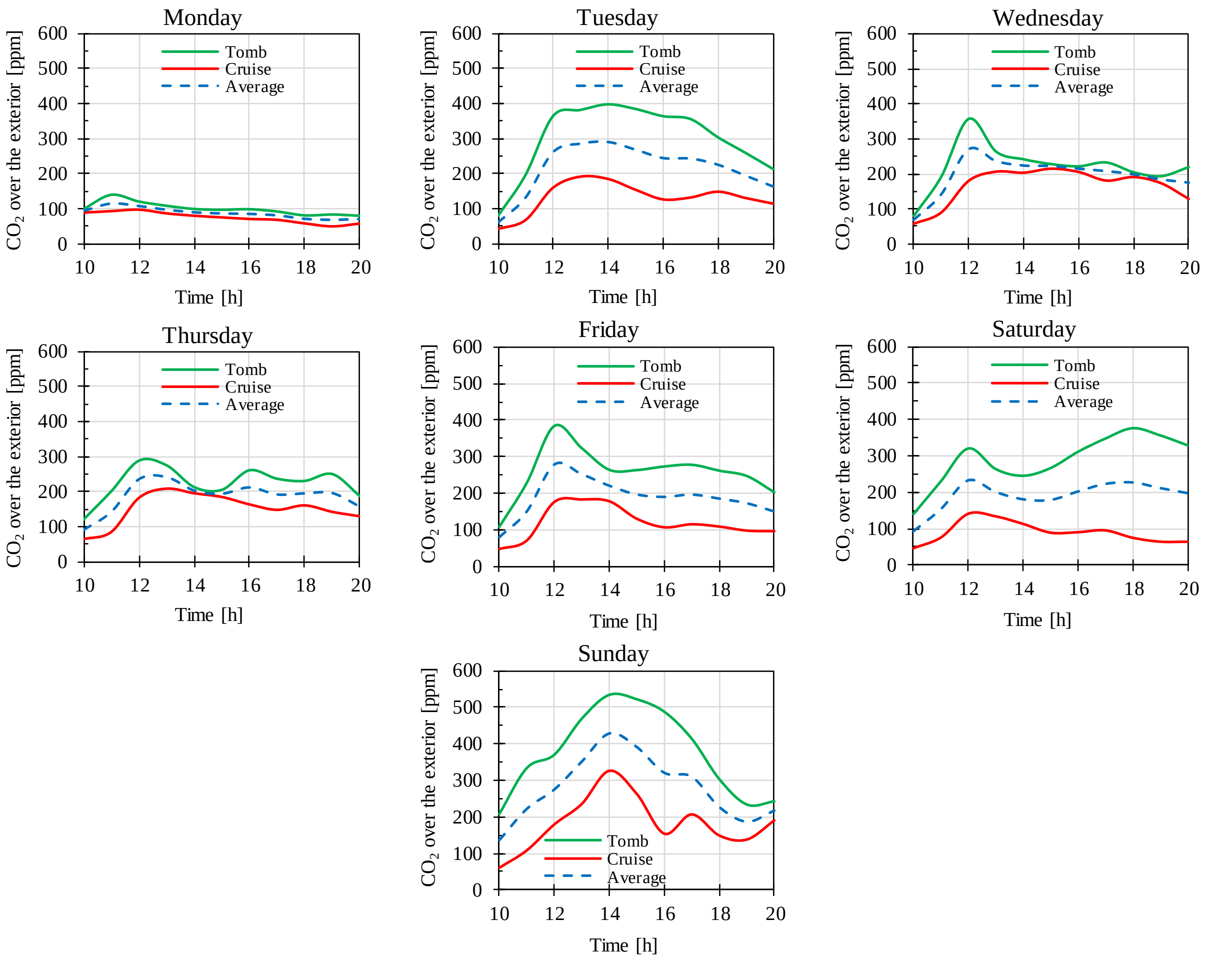

Figure 3.22. Daily occupational profile

3.4. The impact of tourism on conservation and comfort

3.4.1. General considerations

Despite the effectiveness of the monitoring campaigns for microclimatic analysis, the resulting data do not allow to test other scenarios, either in terms of improvements in the envelope, 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 order to study the influence of visitors on the indoor climate and the risks they can cause to conservation, air quality and comfort conditions, a hygrothermal model of the monastery was developed in the hygrothermal simulation software WUFI®Plus v3.1.1.0 [56]. The software has been extensively tested and validated as can be confirmed in the refs. [57,58] and has being used to simulate other cultural heritage buildings [59-62].

A weather file generated by the EnergyPlus Weather Converter [63] and based on the outdoor air temperature and water-vapour pressure recorded on the northern 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) recorded in the Geofisico weather station (located at 1.4 km from the church) were used.

The computational model will allow to evaluate the effect of the increasing number of visitors over the last decade and to predict the future behaviour based on projections from the Tourism of Portugal and the growth rate verified in the last five years in the monastery.

Four different increasing visitors' scenarios were considered: 11 % a year; 6.1 % a year, 4.2 % a year and 3.1 % a year, as described in 3.2 and shown in Figure 3.5. The different scenarios to simulate can be found in Table 3.4.

Table 3.4. 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	2022		5.9	4.7	4.3	4.1
7	2027		9.9	6.3	5.3	4.8

3.4.2. Building simulation model

3.4.2.1. Building geometry and construction elements

The model geometry shown in Figure 3.23 was defined in accordance with the blueprints provided by the monastery directorate and confirmed by on-site measurements. The building was constructed with limestone extracted from the region of Lisbon and usually denominated as "lioz". The church is composed by thick walls varying 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 one.

The slab has of about 0.2 m of limestone directly discharging the structural loads into the soil. The walls are made with two masonry layers of limestone with 0.2 m each one and that the remaining space is filled by clay soil. This technique was widely used at the time [64]. The windows represent 1% of the total floor area. Since it was not possible to verify the windows properties due to their inaccessibility (located at high heights), the use of an average U_w of 5.1 W/m^2.K and an average SHGC of 0.85 usually adopted for single glazed windows were assumed. The ceiling has limestone vaults and masonry over the top to support the roof. To ensure the structural stability of the vaults there should be some filler material to provide the necessary mass in the areas near the columns and the walls. Thus, in order to consider the vaults, the filling and the upper masonry, a simplified solution composed of limestone and lime mortar was admitted. The thermal characteristics are based on the data present in the refs. [64,65]. The hygric properties were chosen from the Wufi database to fit the materials in use. The attic is heavily ventilated. The summary of the constructive features can be seen in the Table 3.5.

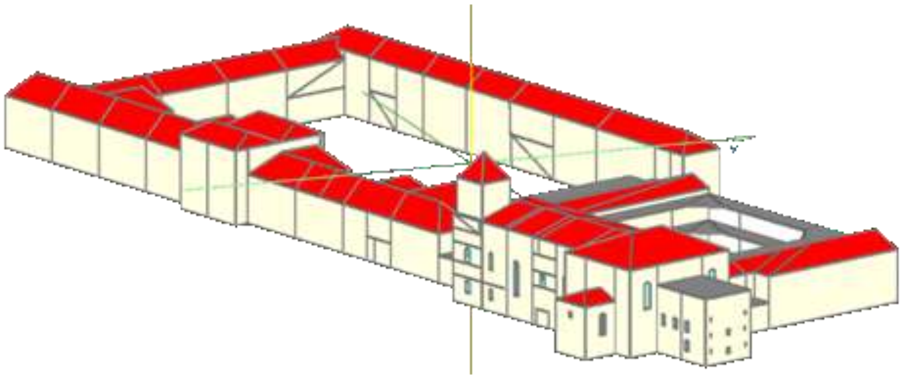

Figure 3.23. Geometry of the model

Table 3.5. Thermal properties of the building elements [64,65]

Building component	Materials	d [m]	λ [W/m.K]	ρ [kg/m^3]	C [J/kg.K]
Walls Outside → Inside	Limestone	0.20	2.3	2400	850
	Clay soil	0.60 – 1.90	1.5	1500	880
	Limestone	0.20	2.3	2400	850
Ceiling Outside → Inside	Lime mortar	0.15	0.7	1785	850
	Limestone	0.20	2.3	2400	850
Floor	Limestone	0.20	2.3	2400	850
Windows	Wooden single-glazed window frames			U_w =5.1 W/m^2.K	SHGC=0.85

3.4.2.2. Internal gains

From September 2017 to August 2018 it is estimated that 3.25 M people visited the church, with main attendance in the summer months. In Figure 3.24 it is possible to find the monthly distribution of visitors. On average a typical duration of 10 minutes was observed for the visits.

Despite the monthly occupancy profile being known, the weekly and daily profiles are not. These profiles can be estimated from the CO_2 concentration as made by Kramer et al. [66]. To obtain the weekly occupational profile the average line of the CO_2 concentration presented in Figure 3.22 was used. Each day is represented by the integral of the internal CO_2 concentration over the exterior during the opening hours. The sum of the values obtained for all Tuesdays, Wednesdays and subsequent days allowed to obtain the weekly profile. For the daily profile the internal CO_2 concentration was organized by each hour. The relation of the sum obtained for each hour with the total sum allows to obtain the daily profile. These results can be found in Figure 3.25.

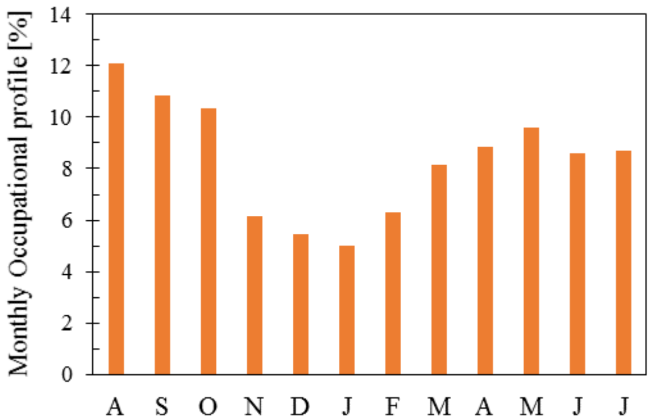

Figure 3.24. Monthly occupational profile of the Jeronimos Monastery from August 2017 to July 2018

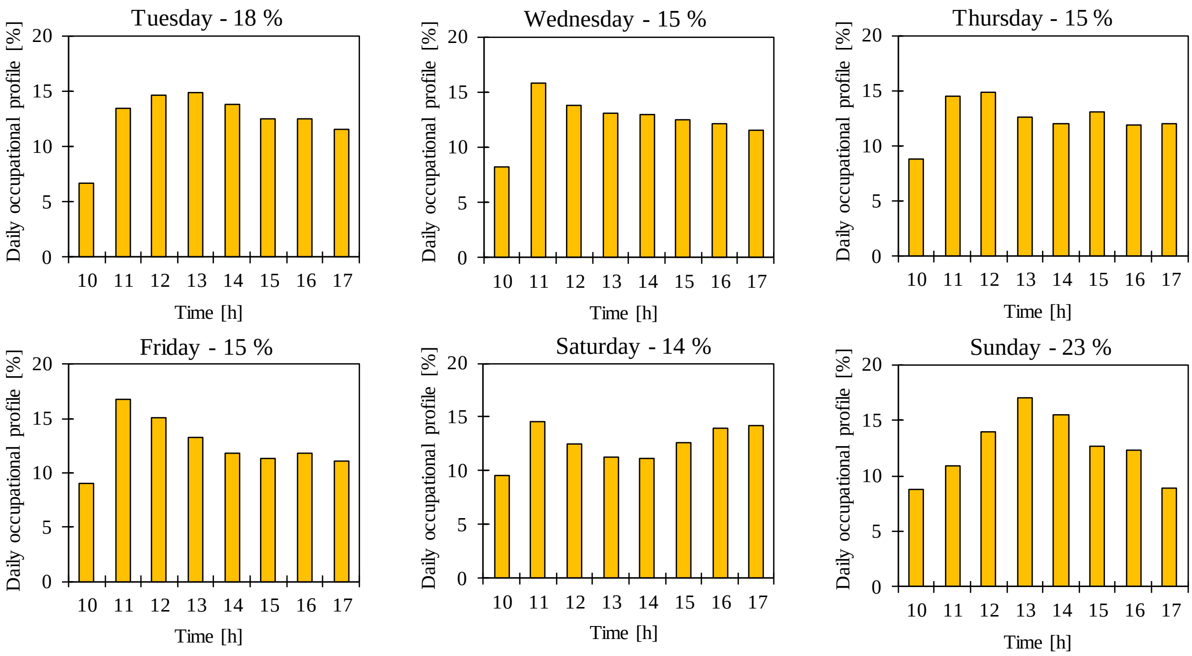

Figure 3.25. Daily occupational profile

For human occupancy, an average metabolic rate of 1.4 met was estimated assuming that visitors spend 40% of the time walking calmly (1.7 met - walking about [67]) and 60% of the time stopped to observe the building and the artefacts (1.2 met - standing, relaxed [67]). 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 [67] it is possible to obtain the released heat per occupant. Since the released heat varies according to gender and age, a group divided equally among men, women and children were considered. Considering that the amount of heat released by women is 85% of men and by children is 75 % according to the ref. [68], an average value of 127 W/visitor was obtained.

The total heat was divided into sensible and latent heat based on the polynomial equation used by the EnergyPlus software [69] as a function of total heat and ambient temperature numerically calculated from the eq. (3.1) to fit the data published in the ref. [70] and graphically represented in Figure 3.26. A mean indoor temperature of 19.8ºC was considered in accordance with the mean value obtained in the building along the monitoring campaign, resulting in 89 W of sensible heat (60% emitted by radiation and 40% by convection according to the recommendation of [68] for typical office conditions) and 38 W of latent heat. The water vapour production rate of 61 g/h per occupant was obtained through the quotient between the latent heat quantity (W) and the value corresponding to the water evaporation enthalpy (2257 J/g [66]).

$$S = 6.461927 + 0.946892 \cdot M + 0.0000255737 \cdot M^2 + 7.139322 \cdot T - 0.0627909 \cdot T \cdot M + 0.0000589172 \cdot T \cdot M^2 - 0.198550 \cdot T^2 + 0.000940018 \cdot T^2 \cdot M - 0.0000014953\,2 \cdot T^2 \cdot M^2 \quad (3.1)$$

where S is the amount of sensible heat [W]; M is the metabolic rate [W] and T is the air temperature [ºC].

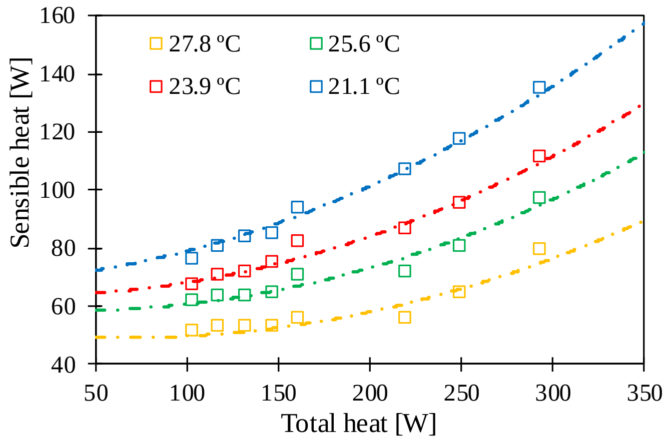

Figure 3.26. Sensible component of the total heat released by humans according the indoor air temperature [69]

The CO_2 generation rate per person was obtained from the equation (3.2) in accordance with the ref. [71]:

$$V_{CO2} = \frac{0.00276 \cdot A_D \cdot met \cdot 3.6}{(0.23 \cdot RQ + 0.77)} \cdot RQ \quad (3.2)$$

where V_{CO2} is the CO_2 generation rate per person (m^3/h), met is the metabolic rate, here assumed as 1.4 (met), A_D is the surface corporal 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 21ºC and 1 atm, this value can be converted to 34 g/h [72].

It was considered that the church lighting is guaranteed by halogen and tungsten. In a simplified way, a constant illuminance of 100 lux was admitted for all the main room as made in the ref. [62] 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 [17]. The lighting power density was obtained by dividing the illuminance by the luminous efficacy, which results in a value of 5.8 W/m^2. In accordance with the refs. [73,74], the emitted heat by tungsten and halogen lamps can be divided in 30 % of radiant heat and 70 % of convective heat.

3.4.2.3. Ventilation

The air change rate (ACH) is a key factor in any monitoring campaign due to its great influence on the variability of the indoor conditions. However, the ACH is usually left out of many of these studies [75] due to the difficulty to obtain a value that characterizes the interior environment, mainly in buildings with high volume. CO_2 monitoring can be used as a prompt way of estimating the indoor ventilation with a reasonable level of accuracy and to study the flow of visitors. The *concentration decay method* was used to estimate the ACH in the Jeronimos Monastery [76].

The method consists on the release and subsequent monitoring of the concentration values of a certain trace gas in the room. The gas must be non-toxic, chemically stable, not absorbable or adsorbable by the building materials, with a density identical to the air and a low concentration in the atmosphere, and allowing a proper mix with the ambience [76]. In this monitoring campaign the chosen trace gas was the carbon dioxide (CO_2) produced by the monastery visitors. Since the occupancy rate is unknown, the ACH was estimated from the moment in which people leave the monastery. The ACH was obtained based on the regression method using the following mass balance equation for those cases where the pollutant generation stopped [71,77]:

$$ln\left(CO_{2i,t} - CO_{2e}\right) = -ACH \cdot t + ln\left(CO_{2i,0} - CO_{2e}\right) \tag{3.3}$$

where ACH is the air change per hour (h^{-1}), $CO_{2\_i,t}$ the is the internal CO_2 concentration at the end of the slope (ppm), $CO_{2\_i,0}$ is the indoor CO_2 concentration at the beginning of the slope (ppm), CO_{2_e} is the external CO_2 concentration (ppm) and t is the time (h).

To estimate the *Air Changes per Hour* (ACH), a set of conditions were considered to guarantee the process reliability: the use of at least 100 points to obtain the regression, a minimum difference of 80 ppm between the initial and final concentrations and a R^2 of 0.90. Usually higher concentration differences are used for this process, however the specificities of the building and the need to estimate the ACH led to this decision. Therefore, it becomes necessary to compare the obtained ACH with the literature values to confirm their robustness.

As mentioned previously, CO_2 concentrations were recorded for two distinct locations: the first one near the entrance to the west, under the tomb of Vasco da Gama where the largest number of visitors is concentrated; and the second in the vicinity of the crossing and the main chapel, where people gather mainly during the religious celebrations. The linear regressions resulting from the application of the equation (3.3) can be seen in Figure 3.27 and Figure 3.28 for the results obtained near the tomb and the crossing, respectively.

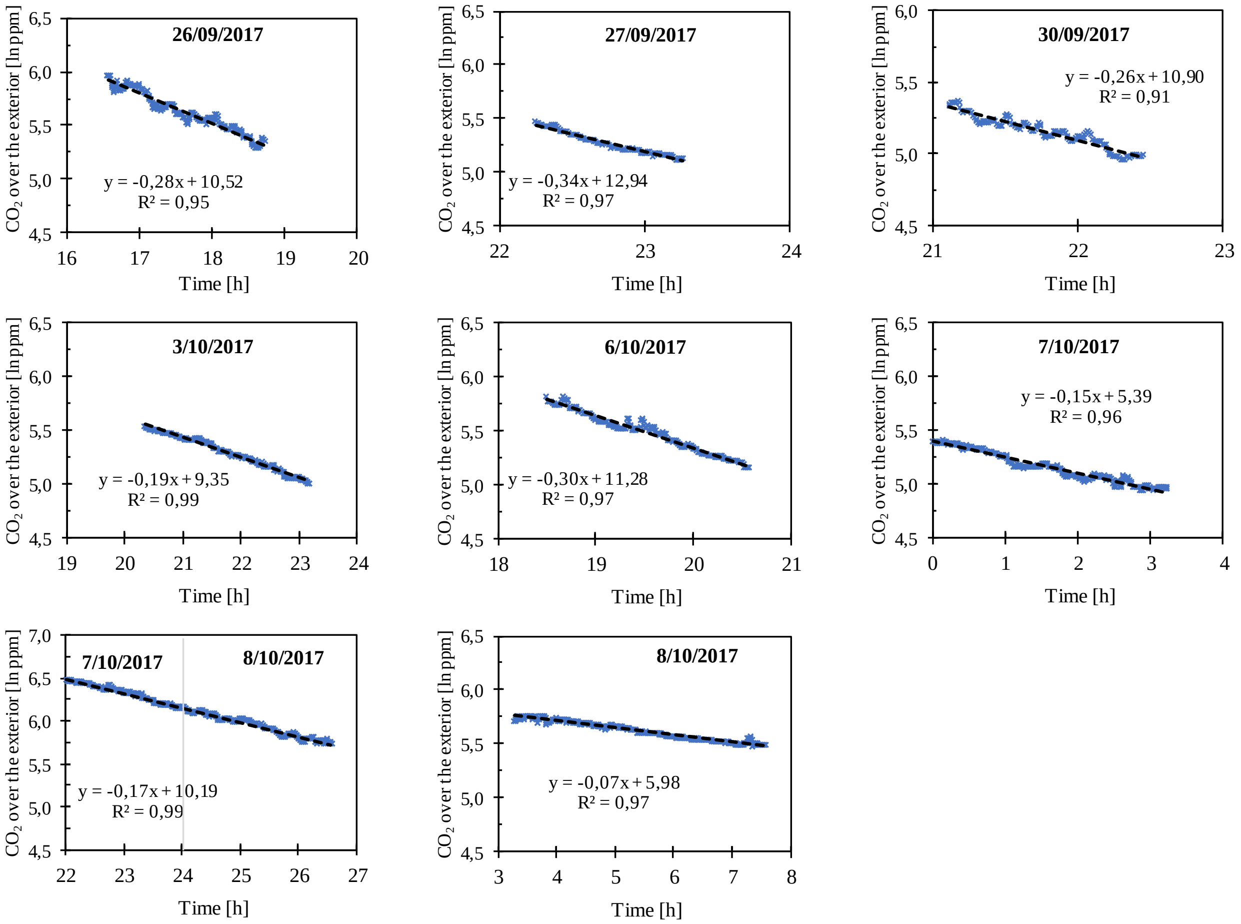

Figure 3.27. Regressions to obtain the ACH at the tomb of Vasco da Gama

The following results were obtained: an average ACH of 0.22 h^{-1} with a standard deviation of ± 0.08 for the zone near the Vasco da Gama's tomb and an average ACH of 0.05 h^{-1} with a standard deviation of ± 0.007 for the zone of the crossing and the main chapel. To estimate the average ACH inside the church, the average among the two obtained values was considered, resulting in a mean value of 0.13 h^{-1}.

These ACH values are corroborated by other authors that have obtained similar values for churches using the decay method. Mleczkowska *et al.* [78,79] obtained an ACH of 0.13 for a masonry Basilica in Tarnow (Poland); Schellen [80] obtained ACH values between 0.08 and 0.12 for churches with stone vaults in the Netherlands; Samek *et al.* [81] obtained an ACH of 0.17 for a brick structure church in Krakow and Bencs *et al.* [82] obtained an ACH of 0.13 for a church with no heating system in Italy.

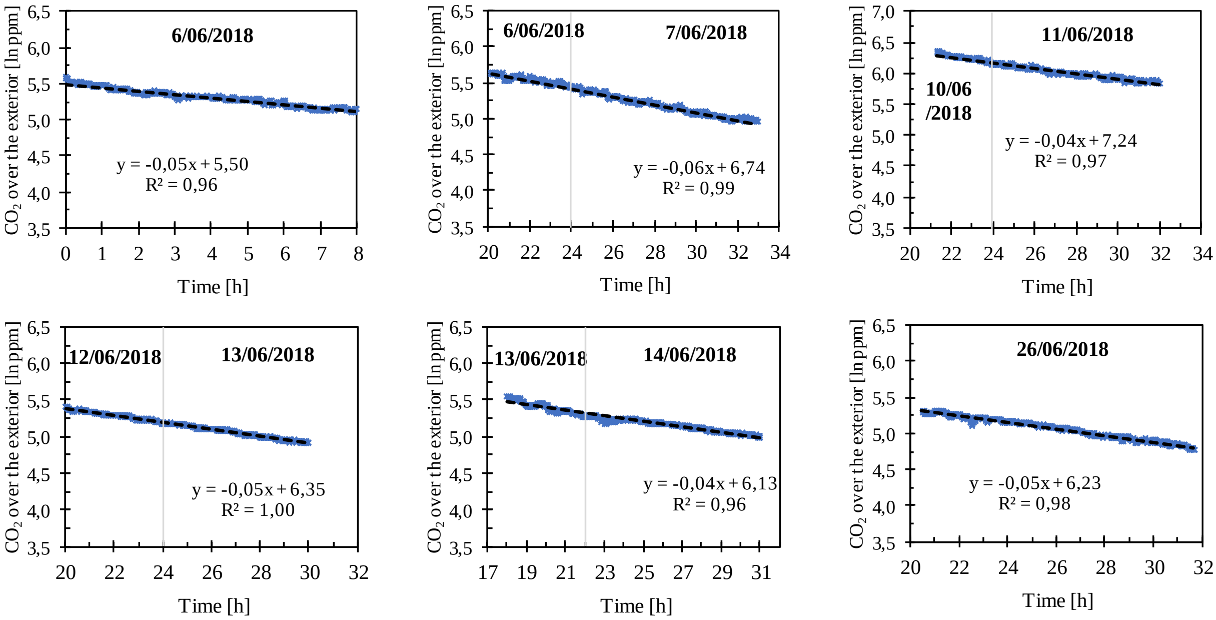

Figure 3.28. Regressions to obtain the ACH near the main Chapel

3.4.2.4. Model validation

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 will induce errors in decision-making. The use of statistical indices published in the international literature and used in several cases (such as those present in [59,83-87]) can contribute for the model validation and to ensure the robustness of the results.

In order to validate the Jeronimos Monastery model, a graphical comparison of the simulated and measured results was carried out in addition to a statistical analysis comparing the annual average, maximum, minimum, 2º, 10º, 25º, 50º, 75º, 90º and 98º percentiles and the internal water vapour pressure excess.

In addition, three other statistical indices were used, namely the coefficient of determination (R^2), the normalized 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 [53], the NMBE and CVRME are lower than 5 % and 20 %, respectively [53]. The model is more robust when the R^2 is higher and *CVRMSE* and *NMBE* are lower.

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

$$R^2 = \left(\frac{\sum_{i=1}^{N} \left(X_{i,meas} - \overline{X_{meas}} \right) \cdot \left(X_{i,sim} - \overline{X_{sim}} \right)}{\sqrt{\sum_{i=1}^{N} \left(X_{i,meas} - \overline{X_{meas}} \right)^2 \cdot \sum_{i=1}^{N} \left(X_{i,sim} - \overline{X_{sim}} \right)^2}} \right)^2 \tag{3.4}$$

The normalized mean bias error (NMBE) expresses the general normalized mean error and shows the influence of smaller errors [83] and can be calculated from the equation:

$$NMBE = 100 \cdot \frac{\sum_{i=1}^{N}\left(X_{i,meas} - X_{i,sim}\right)}{\overline{X_{meas}} \cdot (n-1)} \tag{3.5}$$

The coefficient of variation of the root mean square error (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 [83]:

$$CVRMSE = 100 \cdot \frac{\sqrt{\frac{\sum_{i=1}^{N}\left(X_{i,meas} - X_{i,sim}\right)^2}{(n-1)}}}{\overline{X_{meas}}} \tag{3.6}$$

For the validation process three parameters were used: the temperature, the relative humidity and the water vapor pressure.

3.4.3. Climate characterization

3.4.3.1. <u>Risk-assessment</u>

The methodology proposed in the chapter 2 to evaluate the indoor climate was applied. A general analysis was performed on the average indoor climate and a risk-based analysis were then evaluated. The chemical risk analysis was considered irrelevant for this case. The building and artefacts damage-risks are made according to the methodology and rating scale presented in 2.2.4.

3.4.3.2. <u>Thermal comfort</u>

As regards the thermal comfort, it was considered that the expectancy of cultural heritage visitors is lower than that evidenced by office occupants for example, due several reasons such as the fact that the visits takes less than 15 minutes and because the thermal comfort is not considered a pronounced factor in the visitors' satisfaction [25]. Furthermore, it is expected that visitors dress according to the outdoor conditions [88] and walk throughout the building. So, the adaptive model defined by Matias [89] for naturally ventilated buildings with an 80 % acceptance level was adopted. A more detailed description of the model can be seen in 2.2.5.

3.4.3.3. <u>Indoor air quality</u>

The definition of the IAQ in terms of comfort is based on the occupants of a certain space perception; however, the human sensitivity to pollutants and discomfort vary according to several factors [90,91]. 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 [92]. 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 expectation level or cultural adaptation.

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 [93]. 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 [94,95], USA [96] and Japan [97] 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. These levels of acceptance were obtained for people not adapted to the environment. For adapted people, the rate of ventilation per occupant to achieve the same level of acceptance can be estimated as one-third of the value for non-adapted people [71].

The European results [94,95] form the basis of several international documents, namely EN 15251 [92] and ASHRAE 62.1 [98]. IAQ can be evaluated as a percentage of dissatisfied occupants in function of their mean vote and approximated with a high level of confidence by equations (3.7) and (3.8) [99]:

$$PD = 395 \cdot e^{(-1.83(q/3.6)^{0.25})} \quad \text{for } q \geq 1.15 \text{ m}^3\text{/h.olf} \quad (3.7)$$

$$PD = 100 \quad \text{for } q \leq 1.15 \text{ m}^3\text{/h.olf} \quad (3.8)$$

where PD is the percentage of dissatisfied people (%), q is the airflow (m^3/h.olf) and one olf corresponds to the bio effluents emitted by a standard person.

From these results, a relationship between the percentage of dissatisfied people and the concentration of indoor CO_2 was stablished, which proved to be a good indicator to evaluate the IAQ, since while people are releasing CO_2 are also releasing odours. The work that gave rise to these results allowed to conclude that an airflow of 27 m^3/h per person corresponds to 80% of satisfied people, which corresponds to a CO_2 concentration of about 650 ppm above the external value [71]. The difference between indoor and outdoor CO_2 concentrations can be used as an expeditious indicator of the IAQ, since the CO_2 concentration is usually more easily obtained than the ventilation rate.

The concentration of 650 ppm over the outdoor concentration can be used to evaluate the indoor air quality according the odours. However, as mentioned by the standard ASTM D-6245 [71] the limit was obtained for non-adapted people.

In order to assess the indoor air quality in the Jeronimos Monastery, the internal concentration of CO_2 minus the outdoor conditions were compared the limit of 650 ppm. This analysis is presented by the percentage of time in which the internal concentration of CO_2 during the open hours is not within the imposed limit.

3.4.4. Results

3.4.4.1. Model validation

The global comparison of the recorded values and those simulated can be seen in Figure 3.29. The visible gaps in the figures 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. Despite this agreement, it is possible to find some situations with notable differences, namely with regards to temperature in winter. The difficulty in obtaining accurate data of the constructive elements and their properties partly justifies the differences. However, it is believed that the major cause is related with the real flow of visitors that is not known and the ventilation of the building. Although ACH values have been estimated, it is known that ventilation is not constant throughout the day and the year. Nevertheless, the results seem to fulfil the objective of reproducing the monastery's annual inner behaviour.

The annual averages, the maximum and minimum extremes and the 2^{nd}, 25^{th}, 50^{th}, 75^{th} and 98^{th} percentiles and the internal water vapour excess for the measured and simulated data can be seen in Table 3.6. Concerning temperature, a difference of 0.3 ºC was obtained between the measured and the simulated annual average, a difference of 0.3ºC for the maximum value and a difference of 0.7ºC for the minimum value. The percentile analysis reinforces the greater proximity between the measured and simulated values during the summer. Regarding the relative humidity, a difference of -1% RH for the annual average and 2% RH for the maximum and for the minimum values were obtained. The analysis of the percentiles allows to confirm that in general the results converge.

The model was simulated for the external data recorded during this thesis and validated against the internal data. The sensors used have an uncertainty of ± 0.2 °C for the temperature and a typical uncertainty of ± 2% RH for the relative humidity. 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, so it seems plausible to use the model with a high degree of reliability.

As regards water vapour pressure, the differences are less pronounced and denote a good relationship between the model and the reality. Since the main purpose of this chapter is to study the impact of visitors on conservation, air quality and thermal comfort, it was considered essential to compare the internal water vapor pressure excess that relates the rate of water vapor production in the interior with the ventilation. Through the analysis of Table 3.6 it is possible to see a perfect correspondence for the average annual value that guarantees reliability for the research.

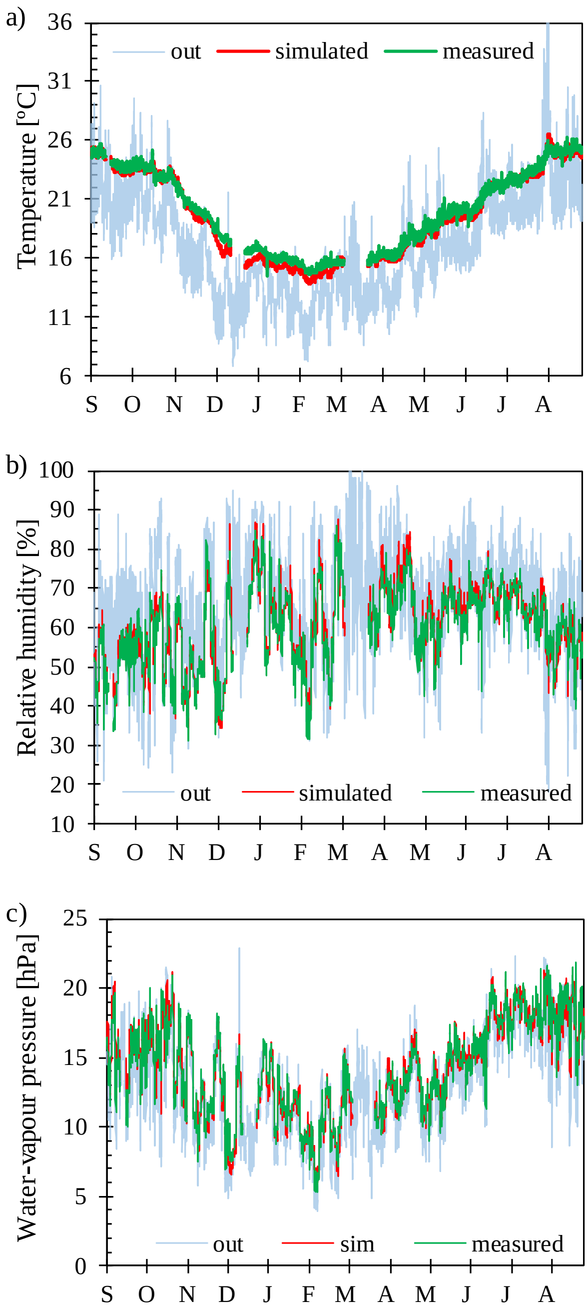

Figure 3.29. Comparison between the simulated and the measured climate data: a) temperature; b) relative humidity; c) water vapour pressure

Table 3.6. Annual average, seasonal amplitude and typical short-term fluctuations of T and RH

Variable	Situation	Mean	Max	Min	Percentiles					Δe
					2º	25º	50º	75º	98º	-
T [ºC]	Meas	20	26.2	14.5	15.0	16.5	19.9	23.3	25.4	-
	Sim	19.7	26.5	13.8	14.4	15.9	19.5	23.1	25.4	
RH [%]	Meas	60	86	31	38	53	61	67	79	-
	Sim	61	88	33	39	54	62	68	81	-
e [hPa]	Meas	14.2	21.8	5.3	7.8	11.7	14.3	17.0	19.9	0.9
	Sim	14.1	21.5	6.0	7.3	11.5	14.3	16.8	19.8	0.9

Even if the previous analysis suggests the validity of the model, it was considered essential to reinforce this conclusion with the use of three statistical parameters frequently used to validate models. The values of the statistical coefficients used to validate the model can be seen in Table 3.7. Focusing the attention on the parameters R^2, NMBE and CV(RMSE) and comparing them with the limits frequently presented in the bibliography it is possible to conclude that the model does represent the reality. Coefficients of determination of 0.99, 0.88 and 0.93 were obtained for the temperature, relative humidity and water vapor pressure, respectively, all of them higher than the lowest admissible limit of 0.75. As regard the normalized mean bias errors (NMBE), coefficients of 2.1 % for temperature and 4.4 % for the relative humidity and 4.5 % for the water vapour pressure were obtained, which accomplishes with the maximum admissible limit of 5 %.

Finally, coefficients of variation of the root mean square error (CVRMSE) of 2.5 % for temperature and 6.0 % for relative humidity and 6.2 % for the water vapour pressure were obtained complying with the maximum admissible limit of 20 %.

Table 3.7. Accuracy parameters for the sensitivity study to optimize the simulation model

R^2			NMBE [%]			CV(RMSE) [%]		
T	*RH*	*e*	*T*	*RH*	*e*	*T*	*RH*	*e*
0.99	0.88	0.93	2.1	4.4	4.5	2.5	6.0	6.2

3.4.4.2. The impact of visitors on the indoor climate

The increase of the number of visitors inside buildings has a clear impact on the indoor climate, as they release heat, water vapour, CO_2, odours and acts as an open door for pollutants. In naturally ventilated and large-volume buildings, such as the Jeronimos Monastery, it is expected that ventilation will remain reasonably constant and will not accompany the increase in internal gains contributing for the disruption of the indoor climate.

In Figure 3.30 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, considering the most optimistic growth scenario of 11%/year up to 2027. Despite the high volume and thermal inertia of the building, the impact of visitors on temperature is notorious, especially during summer when the largest flows occur. The simulation for 2017 allowed an average increase of 0.2 ºC through the year in relation to the reference year. The simulation of the future scenario SC 1 for 2027 allowed to obtain an average increase of 0.5 ºC through the year. As regards relative humidity, this difference is also felt. Average differences of 3% RH over the year for 2017 compared to the reference case and of 8% RH for the 2027 in the SC 1 scenario were obtained.

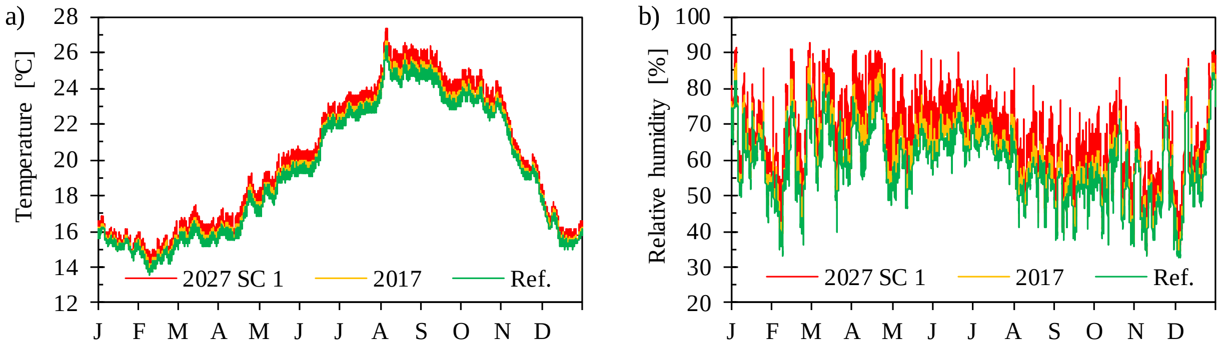

Figure 3.30. Visitors impact on the indoor climate: a) temperature; b) relative humidity

The statistical analysis of the impact of visitors on temperature and relative humidity can be seen in Table 3.8 and Table 3.9, respectively. The analysis of the maximum, minimum and the percentiles allows to conclude that the increase in the number of visitors has a more significant impact during summer, with a maximum increase of 0.9 ºC in the maximum value and 1 ºC excluding 2% of the highest values. Despite these differences, seasonal amplitude and short-term fluctuations are fairly constant. Regarding the seasonal amplitude, this fact results from the balance between the rise of the minimum and maximum, resulting in a balanced translation of the cycle that maintains the amplitude. For short-term fluctuations, excluding 14% of the largest fluctuations makes the impact of changes less meaningful.

Table 3.8. Statistical analysis of the impact of visitors at the indoor temperature

Visitors (Million)	Year/ scenario	Temperature [ºC]								
		Mean	Max	Min	Percentiles				Seasonal amplitude	Short-term fluctuations
					2º	10º	90º	98º		
0	Reference	19.3	26.4	13.6	14.2	15.2	24.4	25.1	10.4	0.6
1.4	2005	19.4	26.5	13.8	14.2	15.2	24.5	25.1	10.4	0.6
2.0	2008	19.4	26.5	13.8	14.4	15.2	24.5	25.3	10.5	0.7
2.8	2015	19.5	26.5	13.8	14.4	15.2	24.6	25.3	10.5	0.7
3.5	2017	19.5	26.6	13.8	14.4	15.2	24.7	25.4	10.5	0.7
4.1	2022 (SC 4)	19.5	26.7	13.8	14.4	15.2	24.7	25.4	10.5	0.7
4.3	2022 (SC 3)	19.5	26.7	13.8	14.4	15.2	24.7	25.4	10.6	0.7
4.7	2022 (SC 2)	19.6	26.7	13.8	14.4	15.3	24.7	25.4	10.6	0.7
4.8	2027 (SC 4)	19.6	26.7	13.8	14.4	15.3	24.7	25.4	10.6	0.7
5.3	2027 (SC 3)	19.6	26.8	13.8	14.4	15.3	24.7	25.6	10.6	0.7
5.9	2022 (SC 1)	19.6	26.8	13.9	14.4	15.3	24.8	25.6	10.6	0.7
6.3	2027 (SC 2)	19.6	26.9	13.9	14.5	15.3	24.8	25.6	10.6	0.7
9.9	2027 (SC 1)	19.8	27.3	13.9	14.6	15.5	25.0	26.1	10.7	0.7

The differences referring to the relative humidity 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 7 %RH for the most burdensome case.

The analysis of the percentiles allows to conclude that for the reference case the relative humidity ranged between 37 and 79% RH during 96% of the year and between 44 and 71% RH during 80% of the year. For the data of 2017 the relative humidity ranged between 40 and 82% RH during 96% of the year and between 47 and 74% RH during 80% of the year. 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 44 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. Regarding the seasonal amplitude and short-term fluctuations, the values remain reasonably constant, for reasons already referred for the temperature.

Table 3.9. Statistical analysis of the impact of visitors at the indoor relative humidity

Visitors (Million)	Year/ scenario	Relative Humidity [%]								
		Mean	Max	Min	Percentiles				Seasonal amplitude	Short-term fluctuations
					2º	10º	90º	98º		
0	Reference	58	86	33	37	44	71	79	20	12
1.4	2005	59	86	33	38	46	72	80	20	12
2.0	2008	60	86	33	39	46	73	81	21	12
2.8	2015	61	86	33	39	46	73	81	21	12
3.5	2017	61	88	33	40	47	74	82	21	12
4.1	2022 (SC 4)	62	89	34	40	48	74	83	21	12
4.3	2022 (SC 3)	62	89	34	41	48	74	83	22	12
4.7	2022 (SC 2)	62	90	34	41	48	75	83	22	12
4.8	2027 (SC 4)	62	90	34	41	48	75	83	22	12
5.3	2027 (SC 3)	63	90	34	41	49	76	84	22	12
5.9	2022 (SC 1)	62	90	34	41	48	75	83	22	12
6.3	2027 (SC 2)	63	91	34	41	49	77	85	22	13
9.9	2027 (SC 1)	66	93	34	44	52	81	89	24	13

3.4.4.3. The impact of visitors on conservation

Previously it was possible to observe that the increase of the number of visitors changes the internal microclimatic balance, especially in relation to relative humidity. As far as temperature is concerned, the thermal inertia of the building and its large volume contribute to the stability, therefore changes are not dramatic. It was concluded that seasonal cycles and short-term fluctuations remain reasonably stable for both temperature and relative humidity, however, it should be noted that the calculation of typical fluctuations excludes 14% of the largest fluctuations. Thus, it is imperative to carry out a risk-based analysis of mechanical degradation and to study what happens in fluctuations beyond this typical value. On the other hand, the increase of RH throughout the year shows a possible increase in the risk of mould germination.

In order to study the impact of visitors on mechanical degradation, the use of the damage functions for the base layer and the pictorial layer of painted panels, for the sculptures and for the furniture were adopted. The risk associated with several levels of occupation can be found in Figure 3.31: a) reference building without occupation; b) 1.4 M visitors per year (2005); c) 3.5 M visitors per year (2017); d) 5.3 M visitors (growth scenario 3 to 2027); and e) 9.9 M visitors (growth scenario 1 to 2027).

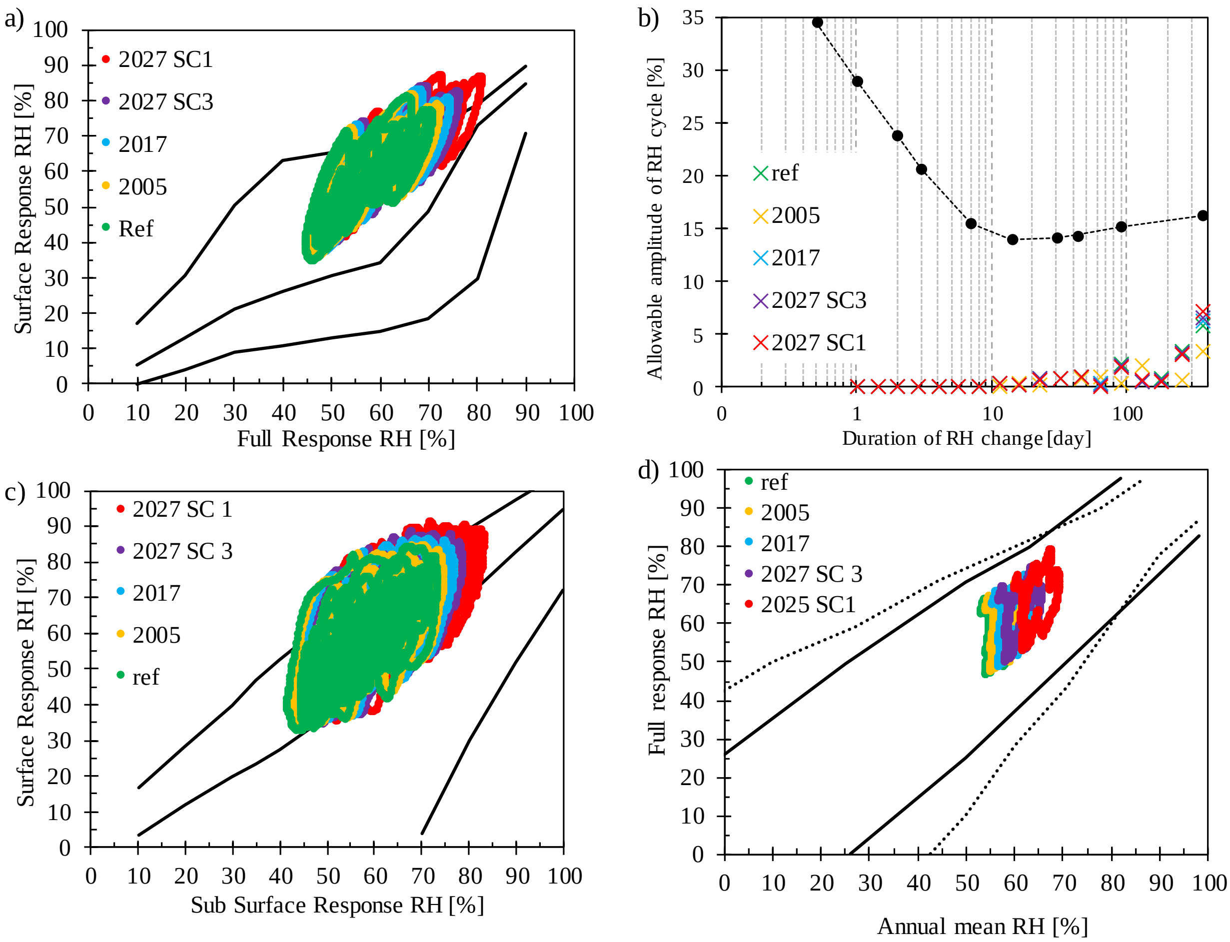

Figure 3.31. Mechanical risk-assessment: a) wooden substrate of painted panels; b) pictorial layer of painted panels; c) sculptures; d) furniture

The analysis of the figure allows to conclude in a clear way the negative impact of the increase of the number of visitors in all cases. However, in some cases these changes are not sufficient to cause risks. Take the case of furniture, in which the impact of the visitors is visible, but nevertheless none of the cases causes irreversible deformations. The same is true for the pictorial layer of painted panels, where the risk never reaches a high level, even though the first level of alert (amplitude between the complete response of the layer and the annual average > 14% RH) is exceeded for the occupations of 5.3 M and 9.9 M.

As regards the base layer of the painted panels and the sculptures the scenario is different. The elastic limit is exceeded in all cases, showing that the materials have already undergone irreversible deformations and an adaptation to the climate, that is, the artefacts are now acclimatized. However, the negative impact of the increase of visitors is still perceived. In the case of the reference building the elastic limit is exceeded in 9.3% of the time; for an occupancy of 1.4 M (2005) the limit is exceeded by 11.1% of the time; for an occupancy of 3.5 M (2017) the limit is exceeded in 13.9% of the time and in

2027 the occupancy predicted for the scenarios 3 and 1 obtain 16.2% and 25.5%, respectively. In the case of sculptures, the same happens, but with lower differences: there is a maximum increase from 7.6% in the reference case to 11.2% in 2027 for the evolution scenario 1. Despite the risk of deformation, according to this method the risk of failure or cracking is not real.

As regards mechanical conservation, it is concluded that the materials have already undergone a process of acclimatization, 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 relative humidity control can limit the risk 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 the relative humidity may also contribute to increase the risk of mould germination. In this particular case, it was chosen to evaluate the germination risk for the interior surface conditions of the northern wall because it presents the lowest thermal resistance and is not exposed to solar radiation. Since the wall is made up of limestone elements that recently underwent a conservation intervention, the isopleths defined by Sedlbauer for class II were adopted.

The representation of the same five scenarios also considered for the mechanical risk is plotted in the so-called isopleth diagram for substrate II, as can be seen in Figure 3.32.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. According to 2.2.4.2 a low risk was considered for MRF values between 0 and 0.5, a potential risk up to 1 and a high risk above 1. The analysis of Figure 3.32.b allows a clear conclusion about the increased 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 on the surfaces. If the presence of pictures or furniture was considered to obscure the wall, the risk increases. This analysis allows to conclude that whatever the future scenario of visitor’s growth, the safe limit for the mould germination will be exceeded.

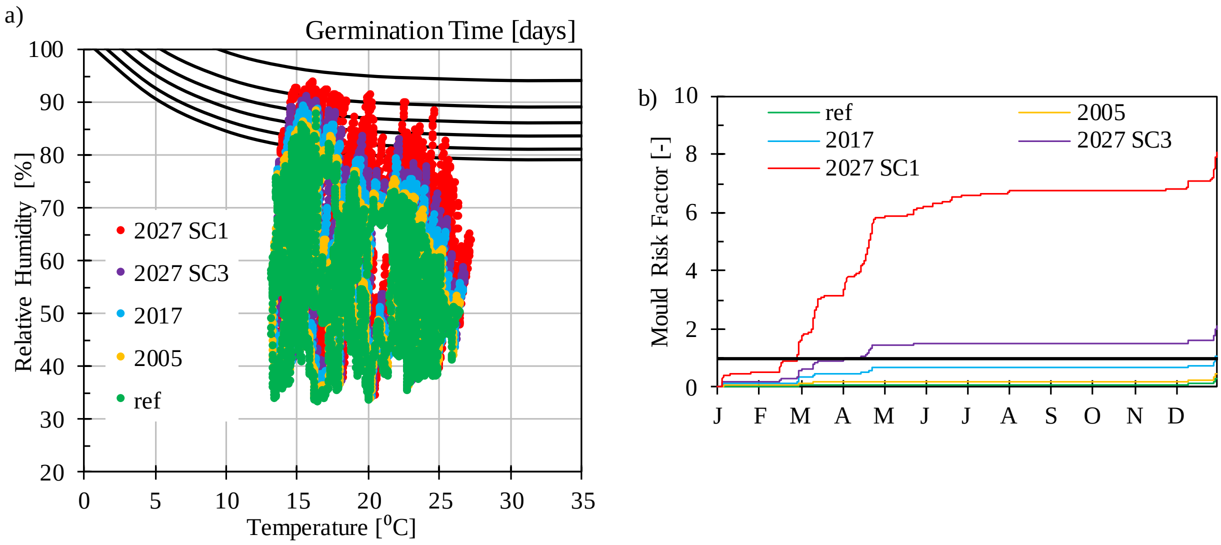

Figure 3.32. Biological risk-assessment: a) representation of the data records on the northern surface on the isopleth diagram for the substrate type II; b) mould risk factor

The evolution of the mould risk factor (MRF) and the mycelium growth according to the number of visitors can be seen in Figure 5.28. For the occupancy of 2017 an MRF greater than 1 (MRF = 1.08) was obtained. In addition to the germination conditions, it was concluded that growth was also possible.

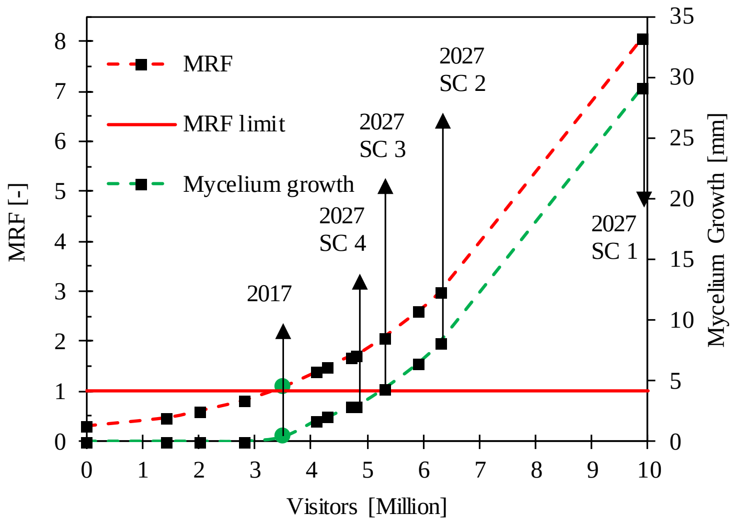

Figure 3.33. Mould risk factor (MRF) and mycelium growth according the number of visitors

It is known that indoor climate heavily depends 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.

The classification of mechanical degradation risk and mould germination can be seen in Table 3.10 for all the simulated scenarios.

Table 3.10. Degradation risk evaluation for all the simulated scenarios: mechanical risk (painted panels, sculpture and furniture) and the mould risk at the northern wall surface

Visitors [Million]	Year/ scenario	Painted wood				Sculptures		Furniture		MRF	
		Base		Pictorial							
0	Reference	P: 9.3 %	2	<14%	3	P: 7.6 %	2	E	3	0.30	3
1.4	2005	P: 11.1 %	2	<14%	3	P: 7.7 %	2	E	3	0.46	3
2.0	2008	P: 12 %	2	<14%	3	P: 7.8 %	2	E	3	0.60	2
2.8	2015	P: 13.2 %	2	<14%	3	P: 7.8 %	2	E	3	0.81	2
3.5	2017	P: 13.9 %	2	<14%	3	P: 8.1 %	2	E	3	1.08	1
4.1	2022 (SC 4)	P: 14.3 %	2	>14%	2	P: 8.3 %	2	E	3	1.38	1
4.3	2022 (SC 3)	P: 14.5 %	2	>14%	2	P: 8.3 %	2	E	3	1.50	1
4.7	2022 (SC 2)	P: 15.2 %	2	>14%	2	P: 8.4 %	2	E	3	1.69	1
4.8	2027 (SC 4)	P: 15.2 %	2	>14%	2	P: 8.4 %	2	E	3	1.71	1
5.3	2027 (SC 3)	P: 16.2 %	2	>14%	2	P: 8.6 %	2	E	3	2.08	1
5.9	2022 (SC 1)	P: 17.7 %	2	>14%	2	P: 8.9 %	2	E	3	2.59	1
6.3	2027 (SC 2)	P: 18.4 %	2	>14%	2	P: 9.1 %	2	E	3	2.99	1
9.9	2027 (SC 1)	P: 25.5 %	2	>14%	2	P: 11.2 %	2	E	3	8.08	1

3.4.4.4. Indoor air quality and thermal comfort

Visitors have a direct impact on the interior microclimate of the cultural heritage and its conservation and an inappropriate occupancy can compromise the indoor air quality and consequently the comfort and health of the visitors. In naturally ventilated buildings, the problem of the relationship between ventilation and occupancy is of greater importance, since it is not possible to control ventilation accurately.

Thermal comfort

Thermal comfort is not usually considered as a preponderant factor in buildings of this type, since the short duration of visits and the cultural and heritage interest of the building reduce the level of expectancy regarding temperature.

Nevertheless, it was decided to evaluate the impact of the increasing number of visitors in the thermal comfort through the use of the adaptive model defined by Matias [89] for an acceptance level of 80%. The result of this analysis can be seen in Figure 3.34. Contrary to what happened in the risk-based analysis, it can be seen that the higher number of visitors leads to better comfort conditions. It should be noted that the discomfort is solely due to the cold sensation. The increase in the number of visitors contributes to the increase of the temperature and consequently to the increase of percentage of time in which comfort conditions exist.

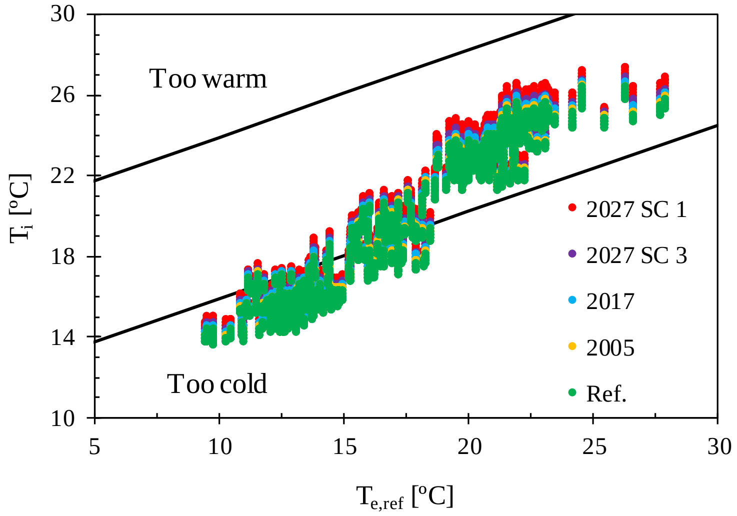

Figure 3.34. Impact of visitors in the thermal comfort according the adaptative model developed by Matias [89]

<u>Indoor air quality</u>

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 buildings with mechanical ventilation the increase in CO_2 can be counterbalanced by increasing air exchanges with the exterior. However, 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.

Despite CO_2 alone does not contribute to the sensory discomfort of occupants, it is seen as a good indicator of odours, since as people release odours they also release CO_2. It is common to consider a concentration of 650 ppm above the exterior, representing an acceptance level of 80 %, to evaluate the indoor air quality. Concentrations above 5000 ppm may cause harmful health effects. The adoption of the 650-ppm limit fulfils both the requirements of comfort and health.

The CO_2 concentration above the exterior throughout the year according to occupancy can be seen in Figure 3.35. For the reference case, where the monastery only receives people during the religious celebrations, the interior levels are practically identical to the exterior ones. The occupancy recorded in 2005 (1.4 M) also does not compromise the indoor air quality, since the limit of 650 ppm above the environment is never exceeded. The occupancy of 2017 (3.5 M) induces a considerable increase in CO_2 concentration, where the comfort limit is exceeded during 3.2% of the time the monastery is open to the public. These data are corroborated by the analysis made in section 3.3.3, where the records at the tomb only exceed the 650-ppm limit for short periods.

The analysis of the figure makes it clear that tourism growth can bring indoor air quality to unwanted levels. The growing scenario 3 applied to 2027 will cause inadequate air quality levels to be achieved during 23.3% of the year, while the application of the scenario 1 returns inadequate indoor quality levels for most of the year (72.3% of the year).

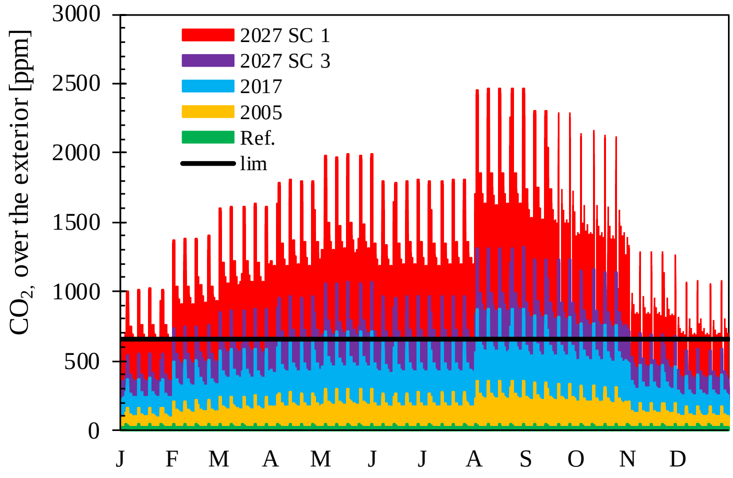

Figure 3.35. CO_2 over the exterior according the number of visitors

The percentage of time in which the indoor air quality is inadequate for each of the simulated scenarios is presented in Figure 3.36. The evolution of the air quality deterioration is evident and even the scenario with more conservative growth gives rise to worrying values.

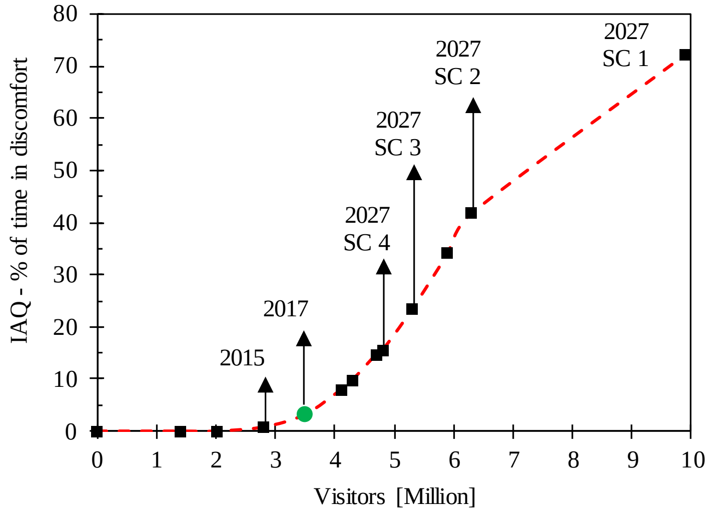

Figure 3.36. Indoor air quality: percentage of time with the difference between the indoor and exterior CO_2 higher than 650 ppm

Since it is not possible to increase significantly the ventilation of the building and it is not foreseeable the installation of a mechanical ventilation system, the only way to guarantee the indoor air quality is to limit the number of visitors to the monument.

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 guarantee the desirable indoor air quality level. Analysis in steady-state conditions does not consider the volume of the space, which affects the necessary time 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 continuously occupancy during the opening hours the use of a steady-state analysis was considered satisfactory [73]:

$$q_{tot} = \frac{n \cdot G_{CO2} \cdot 10^6}{\varepsilon_v \cdot (C_{CO2,i} - C_{CO2,e})} \tag{3.9}$$

where q_{tot} is the total airflow (m^3/h), n the number of visitors (-), G_{CO2} the emission rate of CO_2 (m^3/h), $C_{CO2,i}$ the allowed indoor concentration of CO_2 (ppm), $C_{CO2,e}$ the concentration of CO_2 in the exterior (ppm) and ε_v 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: 49039 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 3.4.2.2. Through the application of eq. (3.9), the maximum number of occupants can be estimated:

$$0.13 \cdot 49039 = \frac{n \cdot 0.01872 \cdot 10^6}{650} \Leftrightarrow n \approx 221 \text{ visitors} \tag{3.10}$$

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 referred this value is conservative since it was obtained under steady state conditions. At the 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 Jeronimos Monastery is one of the main points of tourist interest of the city, it can easily be seen that this limit can be largely exceeded.

The distribution of visitors throughout the year can be seen in Figure 3.37. It is concluded that there is a need to control the number of entrances to guarantee the sustainability of the building. This number should be controlled on the basis of the CO_2, limiting the access to the monument when the concentration exceeds the limit imposed and restoring the flow only after acceptable concentrations have been achieved, which in addition to the sustainability of the space should also contribute to the experience and comfort of the visitors.

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 it is not expected a constant occupancy profile. The only way to control the indoor air quality is based on the CO_2 demand. This method allows to consider the fluctuation on the ACH and control effectively the IAQ at each moment.

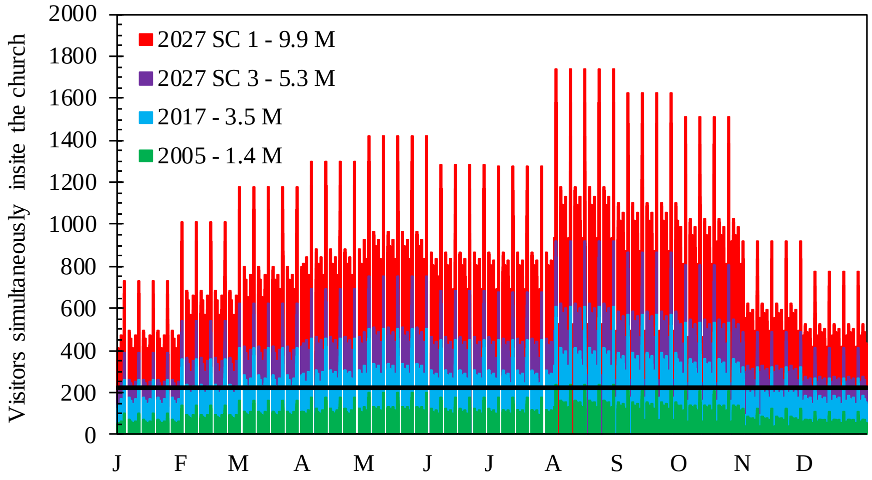

Figure 3.37. Occupancy distribution through the year for the visits obtained in 2005, 2017 and the future scenarios 1 and 2 for 2025. The horizontal line represents the maximum number of visitors simultaneously inside the church

The global results of thermal comfort and indoor air quality for all the simulated cases can be seen in Table 3.11.

Table 3.11. Percentage of time the visitors felt discomfort with the thermal conditions and the indoor air quality for all the simulated cases

Visitors [Million]	Year/ scenario	Thermal comfort [% of time in discomfort]	IAQ [% of time in discomfort]
0	Reference	45.5	0
1.4	2005	44.8	0
2.0	2008	44.2	0
2.8	2015	43.4	0.8
3.5	2017	42.8	3.2
4.1	2022 (SC 4)	42.4	7.9
4.3	2022 (SC 3)	42.0	9.8
4.7	2022 (SC 2)	41.7	14.7
4.8	2027 (SC 4)	41.7	15.4
5.3	2027 (SC 3)	41.5	23.3
5.9	2022 (SC 1)	41.3	34.0
6.3	2027 (SC 2)	41.1	41.7
9.9	2027 (SC 1)	38.8	72.3

3.5. 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 Jeronimos Monastery, the increase in the number of visitors may rise 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 affluence 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 to 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 increases with the visitors' increasing. No risks were found for the pictorial layer until 2017. For the furniture, no risks were found for any of the analysed scenarios. 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 a reality. In terms of thermal comfort, it was found that the increase in the number of visitors has a positive impact, albeit slight, as the indoor temperature increases. 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 (0.8% 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. Regarding thermal comfort, the situation remains practically constant, while indoor air quality can be severely deteriorated. For the slower growth scenario, visitors will experience discomfort in 15.4% of the time the church is open for visitors. In the fastest growing scenario, it was estimated that air quality will be unacceptable in 72.3% 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.

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Appendix I – T and RH code

```
//******************************************************************

// HES - DECFCT T/RH datalogger - v.3.0
// Last edited on May 26. 2017

// Based on OSBSS T/RH datalogger code - v0.03


//******************************************************************

#include <EEPROM.h>
#include <DS3234lib4.h>
#include <PowerSaver.h>
#include <SdFat.h>
#include <Wire.h>
#include "Adafruit_SHT31.h"
#include "Wire.h"

// Launch Variables   ******************************
long interval = 600;  // set logging interval in SECONDS. eg: set 300 seconds for an interval of 5 mins
char filename[15] = "m_6.txt";    // Set filename Format: "12345678.123". Cannot be more than 8 characters in length. contain spaces or begin with a number

// Global objects and variables   ******************************
#define POWA 6    // pin 6 supplies power to microSD card breakout and SHT15 sensor
#define LED 7  // pin 7 controls LED
int SDcsPin = 9; // pin 9 is CS pin for MicroSD breakout

PowerSaver chip;    // declare object for PowerSaver class
DS3234 RTC;    // declare object for DS3234 class
Adafruit_SHT31 s_1 = Adafruit_SHT31();  // declare object for SHT31 (i2d adress equal to 0x44) class: Hardware Connections (Breakoutboard to Arduino):VCC = 3.3V; GND = GND; SDA = A4; SCL = A5
Adafruit_SHT31 s_2 = Adafruit_SHT31();  // declare object for SHT31 (i2d adress equal to 0x45) class: Hardware Connections (Breakoutboard to Arduino):VCC = 3.3V; GND = GND; SDA = A4; SCL = A5; tie the ADR pin to Vin
SdFat sd;     // declare object for SdFat class
SdFile file;    // declare object for SdFile class

// ISR ****************************************************************
ISR(PCINT0_vect)  // Interrupt Vector Routine to be executed when pin 8 receives an interrupt.
{
  //PORTB ^= (1<<PORTB1);
  asm("nop");
}

// setup ****************************************************************
void setup()
{
  Serial.begin(19200); // open serial at 19200 bps

  pinMode(POWA. OUTPUT);  // set output pins
  pinMode(LED. OUTPUT);

  digitalWrite(POWA. HIGH);    // turn on SD card
  delay(1);    // give some delay to ensure RTC and SD are initialized properly

  s_1.begin(0x44); // Initialize the I2C using the 0x44 adress
  s_2.begin(0x45); // // Initialize the I2C using the 0x45 adress

  if(!sd.init(SPI_FULL_SPEED. SDcsPin))  // initialize SD card on the SPI bus - very important
  {
    delay(10);
    SDcardError();
  }
  else
```

```
  {
    delay(10);
    file.open(filename. O_CREAT | O_APPEND | O_WRITE);  // open file in write mode and append data to the end of file
    delay(1);
    String time = RTC.timeStamp();    // get date and time from RTC
    file.println();
    file.print("Date/Time.T_0(C).T_1(C). T_2(C). T_3(C). T_7(C).RH_s1(%)".RH_s2(%)");    // Print header to file - Therm1
= thermistor linked to A0; T_s1 & RH_s1 = sht31 (0x44); Therm2 = thermistor linked to A1; T_s2 & RH_s2 = sht31 (0x45);
Therm3 = thermistor linked to A2;
    file.println();
    PrintFileTimeStamp();
    file.close();    // close file - very important
                 // give some delay by blinking status LED to wait for the file to properly close
    digitalWrite(LED. HIGH);
    delay(10);
    digitalWrite(LED. LOW);
  }

  int actual_time=RTC.minute*60+RTC.second; // actual time in seconds
  int minStart;
  int time_start;
  {time_start=(interval - (actual_time%interval)); //defining the minStart according the interval
  time_start=ceil(((RTC.minute*60+time_start+RTC.second)/60));
  }
   if (time_start < 59)
   {
   minStart=time_start;

   }

   else     {
   (minStart=time_start-60);
   }

  Serial.println(minStart);

  RTC.checkInterval(minStart. interval); // Check if the logging interval is in secs. mins or hours
  RTC.alarm2set(minStart);  // Configure begin time
  RTC.alarmFlagClear();  // clear alarm flag

  chip.sleepInterruptSetup();    // setup sleep function & pin change interrupts on the ATmega328p. Power-down mode is used
here
}

// loop ****************************************************************
void loop()
{

  digitalWrite(POWA. LOW);  // turn off microSD card to save power
  delay(1);  // give some delay for SD card and RTC to be low before processor sleeps to avoid it being stuck

  chip.turnOffADC();    // turn off ADC to save power
  chip.turnOffSPI();  // turn off SPI bus to save power
  //chip.turnOffWDT();  // turn off WatchDog Timer to save power (does not work for Pro Mini - only works for Uno)
  chip.turnOffBOD();    // turn off Brown-out detection to save power

  chip.goodNight();    // put processor in extreme power down mode - GOODNIGHT!
                  // this function saves previous states of analog pins and sets them to LOW INPUTS
                  // average current draw on Mini Pro should now be around 0.195 mA (with both onboard LEDs taken out)
                  // Processor will only wake up with an interrupt generated from the RTC. which occurs every logging interval

  // code will resume from here once the processor wakes up ============== //
  chip.turnOnADC();    // enable ADC after processor wakes up
  chip.turnOnSPI();   // turn on SPI bus once the processor wakes up
  delay(1);    // important delay to ensure SPI bus is properly activated

  RTC.alarmFlagClear();    // clear alarm flag
```

```
  pinMode(POWA. OUTPUT);
  digitalWrite(POWA. HIGH);  // turn on SD card power
  delay(1);    // give delay to let the SD card and SHT15 get full powa

  RTC.checkDST(); // check and account for Daylight Savings Time in US

  for(int i=0; i<5; i++)
   analogRead(A0);  // first few readings from ADC may not be accurate. so they're cleared out here
   analogRead(A1);
   analogRead(A2);
   analogRead(A3);
   analogRead(A7);
  delay(1);

  // get sensor values
  float adc_0 = averageADC(A0);
  float R_0 = resistance(adc_0. 10000); // Replace 10.000 ohm with the actual resistance of the resistor measured using a multimeter (e.g. 9880 ohm)
  float T_0 = steinhart(R_0);  // get temperature from thermistor using the custom Steinhart-hart equation by US sensors
  float adc_1 = averageADC(A1);
  float R_1 = resistance(adc_1. 10000); // Replace 10.000 ohm with the actual resistance of the resistor measured using a multimeter (e.g. 9880 ohm)
  float T_1 = steinhart(R_1);  // get temperature from thermistor using the custom Steinhart-hart equation by US sensors
  float adc_2 = averageADC(A2);
  float R_2 = resistance(adc_2. 10000); // Replace 10.000 ohm with the actual resistance of the resistor measured using a multimeter (e.g. 9880 ohm)
  float T_2 = steinhart(R_2);  // get temperature from thermistor using the custom Steinhart-hart equation by US sensors
  float adc_3 = averageADC(A3);
  float R_3 = resistance(adc_3. 10000); // Replace 10.000 ohm with the actual resistance of the resistor measured using a multimeter (e.g. 9880 ohm)
  float T_3 = steinhart(R_3);  // get temperature from thermistor using the custom Steinhart-hart equation by US sensors
  float adc_7 = averageADC(A7);
  float R_7 = resistance(adc_7. 10000); // Replace 10.000 ohm with the actual resistance of the resistor measured using a multimeter (e.g. 9880 ohm)
  float T_7 = steinhart(R_7);  // get temperature from thermistor using the custom Steinhart-hart equation by US sensors
  float RH_s1 = s_1.readHumidity();
  float RH_s2 = s_2.readHumidity();

  pinMode(SDcsPin. OUTPUT);
  if(!sd.init(SPI_FULL_SPEED. SDcsPin))    // very important - reinitialize SD card on the SPI bus
  {
    delay(10);
    SDcardError();
  }
  else
  {
    delay(10);
    file.open(filename. O_WRITE | O_AT_END);  // open file in write mode
    delay(1);

    String time = RTC.timeStamp();    // get date and time from RTC
    SPCR = 0;  // reset SPI control register

    Serial.print(time);
    Serial.print(".");
    Serial.print(T_0. 2);  // print temperature upto 2 decimal places
    Serial.print(".");
    Serial.print(T_1. 2);  // print temperature upto 2 decimal places
    Serial.print(".");
    Serial.print(T_2. 2);  // print temperature upto 2 decimal places
    Serial.print(".");
    Serial.print(T_3. 2);  // print temperature upto 2 decimal places
    Serial.print(".");
    Serial.print(T_7. 2);  // print temperature upto 2 decimal places
    Serial.print(".");
    Serial.println(RH_s1. 2);  // print temperature upto 2 decimal places
    Serial.print(".");
```

```
    Serial.println(RH_s2. 2);  // print temperature upto 2 decimal places

    file.print(time);
    file.print(".");
    file.print(T_0. 2);  // print temperature upto 2 decimal places
    file.print(".");
    file.print(T_1. 2);  // print temperature upto 2 decimal places
    file.print(".");
    file.print(T_2. 2);  // print temperature upto 2 decimal places
    file.print(".");
    file.print(T_3. 2);  // print temperature upto 2 decimal places
    file.print(".");
    file.print(T_7. 2);  // print temperature upto 2 decimal places
    file.print(".");
    file.print(RH_s1. 2);  // print temperature upto 2 decimal places
    file.print(".");
    file.print(RH_s2. 2);  // print temperature upto 2 decimal places
    file.println();
    PrintFileTimeStamp();
    file.close();    // close file - very important
                    // give some delay by blinking status LED to wait for the file to properly close
    digitalWrite(LED. HIGH);
    delay(10);
    digitalWrite(LED. LOW);
   }
  RTC.setNextAlarm();      //set next alarm before sleeping
  delay(1);
}

// Averaging ADC values to counter noise in readings  ********************************************
 float averageADC(int pin)
 {
 float sum=0.0;
 for(int i=0;i<5;i++)
 {
    sum = sum + analogRead(pin);
  }
  float average = sum/5.0;
  return average;
}

// Get resistance ***************************************************************
 float resistance(float adc. int true_R)
 {
 float R = true_R/(1023.0/adc-1.0);
 return R;
 }

// Get temperature from Steinhart equation (US sensors thermistor PT103J2. 10K. B = 3892)
*****************************************
 float steinhart(float R)
{
   float A = 0.00113929600457259;
   float B = 0.000231949467390149;
   float C = 0.0000001059924762189 67;
   float D = -0.00000000000667898975192618;
   float E = log(R);

   float T = ((1/(A + (B*E) + (C*(E*E*E)) + (D*(E*E*E*E*E))))-273.15);
   delay(50);
   return T;
 }

// file timestamps ****************************************************************
void PrintFileTimeStamp() // Print timestamps to data file. Format: year. month. day. hour. min. sec
{
  file.timestamp(T_WRITE. RTC.year. RTC.month. RTC.day. RTC.hour. RTC.minute. RTC.second);    // edit date modified
```

```
  file.timestamp(T_ACCESS. RTC.year. RTC.month. RTC.day. RTC.hour. RTC.minute. RTC.second);    // edit date accessed
}

// Read file name ***************************************************************
void readFileName()  // get the file name stored in EEPROM (set by GUI)
{
  for(int i = 0; i < 12; i++)
  {
    filename[i] = EEPROM.read(0x06 + i);
  }
}

// SD card Error response ***************************************************************
void SDcardError()
{
    for(int i=0;i<3;i++)   // blink LED 3 times to indicate SD card write error
    {
      digitalWrite(LED. HIGH);
      delay(50);
      digitalWrite(LED. LOW);
      delay(150);
    }
}

//***************************************************************
```

4. A statistical methodology to define a sustainable climate control strategy for cultural heritage buildings in temperate climates

The chapter was partially published in:

H.E. Silva, F.M.A. Henriques, Microclimatic analysis of historic buildings: A new methodology for temperate climates, Building and Environment. 82 (2014) 381–387. doi:10.1016/j.buildenv.2014.09.005.

H.E. Silva, F.M.A. Henriques, Hygrothermal analysis of historic buildings: Statistical methodologies and their applicability in temperate climates, Structural Survey. 34 (2016) 12–23. doi:10.1108/SS-07-2015-0030.

4.1. Introduction

Places of worship are an important part of the world's cultural heritage. Some of them have endured climate changes over the centuries, with their materials undergoing adjustments in order to adapt to the local climate. It is important to study the microclimate inside these buildings and set the values for which the materials themselves have been adapting, aiming to raise awareness and to contribute to a proper conservation. However, there is often a conflict between the needs for thermal comfort of the occupants and the requirements for a proper conservation of cultural property, which requires a reasonable compromise to be achieved [1,2].

Even when the studies are focused on the needs of materials and artefacts, a general analysis based on ideal values for each material is often taken. These values, although theoretically correct, may not express the microclimate conditions in which the artefacts were conserved and can increase the risk of degradation of the storage conditions.

For a long period, the definition of ideal temperatures was related to the comfort of visitors [3], while for RH the values were defined based on studies performed on museums and historic buildings, assuming that the combination of both would create adequate environments for conservation, no matter the type or location of the building [4,5].

Later the concerns turned towards the needs of various materials and laboratory studies were performed to provide optimal values of temperature and relative humidity for the proper conservation of each material [2,6] or artefacts composed for various materials [7]. During the last decade, the trend of change was higher, the dynamic approach replaced the earlier methods and the search for ideal values was partially abandoned [8]. It was assumed that if a particular material or artefact is exposed for a long period (over 1 year) to the influence of certain conditions, it can experience cracks and irreversible deformations resulting from the new achieved equilibrium. This process is known as acclimatization [9-12]. Changes in historic microclimate for which the objects were acclimatized can cause a catastrophic response, because the materials may have exceeded its capacity of deformation, which can ultimately lead to total losses [3]. Also based in the past conditions, but with slight differences, Michalski [13] defined the concept of "proofed fluctuations" as the fluctuations experienced by the object in the past as a target, assuming that if the largest past fluctuations are not exceeded in the future the risk of new mechanical damage will be extremely low.

The implementation of tight limits has another worrisome consequence: the high-energy consumption needed to keep the building at the desired levels. Nowadays, one of the biggest challenges in historic buildings, such as museums, is to reach an equilibrium between the conservation requirements and the energy economy [14,15], as it is evidenced in the British specification PAS 198 [16], where the targets are defined according the collection needs, searching also achieve the energy economy without jeopardizing a proper conservation.

Quite often the authors of the existing studies adopt different analysis methodologies, making it difficult to compare results and decide on their applicability. The emergence of new standards – such as EN 15757 [9] in Europe (examples of application: [17-20]) and ASHRAE specification [21] (Museums, galleries, archives and libraries) in North America (examples of application: [22,23]) – led to a greater standardization of methodologies.

The European standard is based, among other references, on laboratory tests [7] and on the behaviour of several objects located in the church of Santa Maria Maddalena [24]. It is also possible to find some case-studies based on similar methodologies performed by the same authors [18].

The impact of the climate recorded in the church of São Cristóvão in Lisbon and the application of several climate control strategies were evaluated in chapter 2. It was possible to conclude that the use of some of those strategies requires the use of powerful climate control systems during practically the whole year. It was possible to conclude that the use of the dynamic method based on the historical climate described in the EN 15757 can be a useful tool for temperate climates, allowing to safeguard the conservation of buildings and collections in a sustainable way.

However, the European standard is still recent and there is not an exhaustive study on its application in all types of climates. It is necessary to evaluate this methodology in temperate climates and eventually propose changes, if required. To achieve this objective, data obtained from the climate monitoring carried out in the church of São Cristóvão in Lisbon (Portugal) was used, with records from November 2011 to August 2013.

4.2. Microclimate analysis according to the standard EN 15757

To fully understand the hygrothermal behaviour of a building it is important to understand the internal microclimate but also its relationships with the outside. For this purpose, it was decided to use an analysis based on the standard EN 15757 [9], described later, analysing the internal and external environment in terms of seasonal cycles.

It is impossible to define optimal values covering all materials and all locations; there are, however, several reference values in the literature. The definition of the ideal microclimate is an ambiguous issue, although the importance of limiting the cycles of temperature and relative humidity is consensual, with its main focus on short-term fluctuations and the study of the historic climate [8,9]. This is paramount to keep the conditions stable and consistent with the past and to define a target microclimate which should be respected and considered for the future in order to ensure the preventive conservation of the objects [25].

The historic microclimate can be defined based on the most frequent temperature and relative humidity values and their variations. These values are defined according to the EN 15757 [9] in order to specify the levels that limit the physical damage caused by the microclimatic fluctuations in organic and hygroscopic materials conserved for more than a year in a specific environment.

The annual average, seasonal cycle (calculated based on a 30-day moving average) and short-term fluctuations (calculated by the difference between the instantaneous measures and a moving average) were used as reference variables. The sustainable limits based on the historical climate are imposed by the 7th and 93rd percentiles of short-term fluctuations. In this way, 14% of the most dangerous fluctuations are excluded [9,17]. Despite this, the standard allows fluctuations of 10%RH around the seasonal cycle if the limits defined by the 7º and 93º percentiles are below that value. Only the short-term fluctuations are limited. The EN 15757 does not impose seasonal limits and gives little relevance to temperature.

This approach can be used both for temperature and relative humidity, assuming that if future variations do not exceed the higher past values, the mechanical damage risks are low [8,13]. The method is summarized in Table 4.1.

Table 4.1. Description of the EN 15757 methodology [9]

Source	Setpoint	Seasonal cycle	Short-term fluctuation	Notes
EN 15757 (2010)	T: No specification; RH: Historic yearly average	Historic seasonal cycle*	T: No specification; RH: ±10% or target range calculated from the historical data** (the higher range)	* This cycle is obtained by calculating a moving average of 30 days, centred on the current value.
				** The short-term fluctuations are calculated as a difference between a current RH reading and a moving average. The target range is obtained by adding the 7th and 93rd percentiles of the short-term fluctuations in the seasonal cycle.

The climate data recorded in the church of São Cristóvão was used to exemplify the application of the standard. The instantaneous values of temperature, the annual average and the seasonal cycles for the church's interior are presented in Figure 4.1. It is possible to observe the seasonal temperature varying between 13.2 ºC (in February) and 24.9 ºC (in September). The indoor climate has an annual average of 19.1ºC. According to the relative humidity, an indoor annual average of 63.6% is observed, with seasonal values varying between 56.6% (in September) and 73.7% (in December).

The short-term fluctuations (Figure 4.2), calculated by the difference between the instantaneous values and the seasonal cycle (30-day moving average) and limited by 7º and 93º percentiles, define the sustainable band around the seasonal cycle [9,17,18]. It was, then, possible to define sustainable intervals for short-term fluctuations of ±0.8ºC for temperature and ±7 % for relative humidity. The sustainable range of temperature (a) and relative humidity (b) obtained from the addition of the positive and negative short-term fluctuation to the moving average can be seen in Figure 4.3.

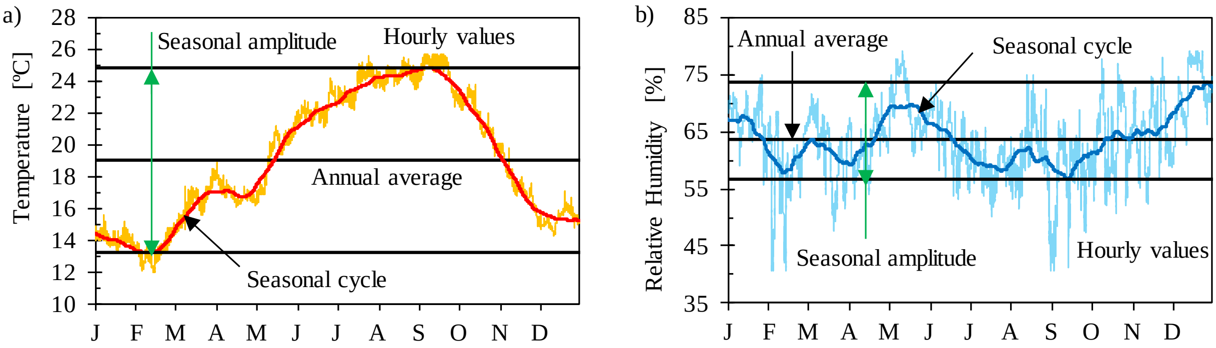

Figure 4.1. Indoor air conditions, seasonal cycle and annual average: a) temperature; b) relative humidity

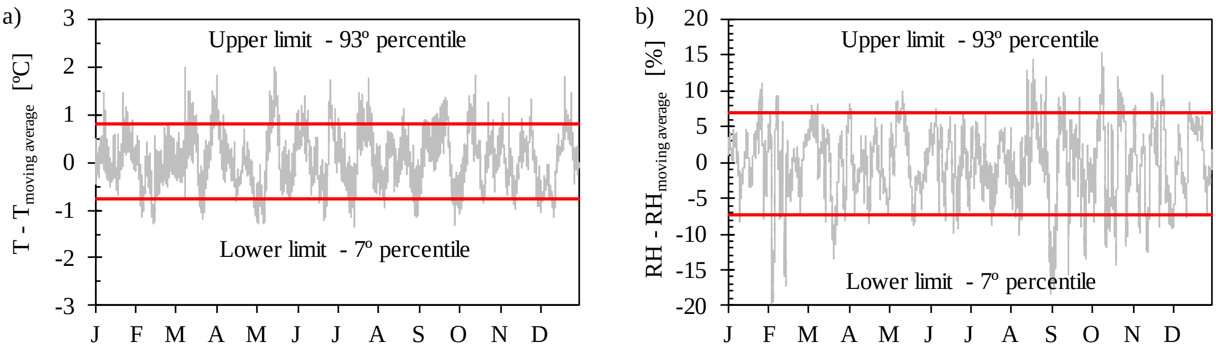

Figure 4.2. Short-term fluctuation – a) T; b) RH

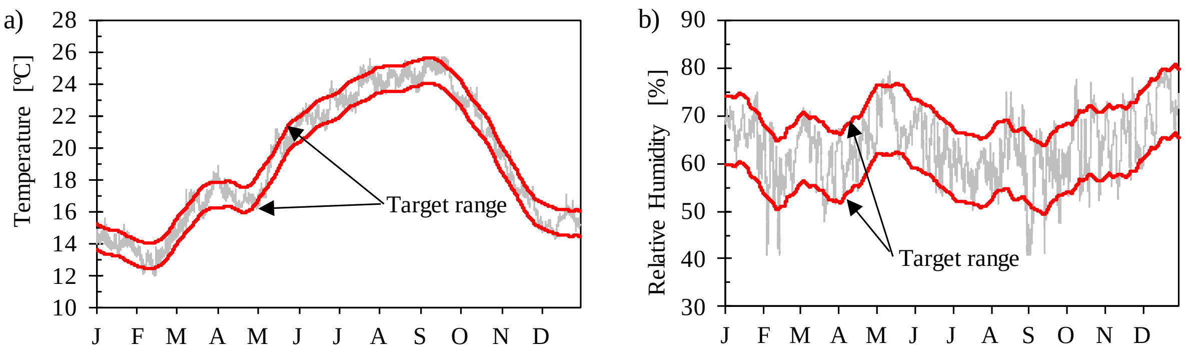

Figure 4.3. Target band of tolerable fluctuations (market by the two red lines) compared to the real variations (the grey lines) – a) T; b) RH

According to this approach, it is possible to define a safe target for the temperature and relative humidity, which should be followed in the future as a preventive measure, especially in the case of the installation of an air conditioning system. These targets should be respected to avoid serious and irreversible damage to materials inside the church. In this case, it was possible to verify the extreme values of relative humidity between 49.2% and 80.6% and between 12.4 and 25.7 °C for temperature. Despite this, the extremes of the safe target must not be used like reference, since according to this approach the safe target is composed by dynamic values, changing along the time and based on the historic climate.

The use of the target band based on historical climate implies its suitability to the conservation of the objects and their preservation evolution in each environment. The change of the target band to the optimal values defined in the literature can trigger an important phenomenon of deterioration and lead to the loss of the object [26].

Despite being an important part of Portuguese history and a national monument, the church has not had the necessary attention that a building of this type requires. According to an inventory and diagnosis report performed in 2011 [27], in addition to the accumulated dirt, it is possible to find signs of deterioration in the screens in gilt, in the painted wood and in the woods supporting the roof. However, it is stated in that report that the wood and stone are not in immediate danger. The causes of these deteriorations are attributed to water infiltrations through the roof. The author confirmed this and concluded there was no risk of surface condensation in the building in question as can be confirmed in 2.3.1.1.

To confirm the suitability of the referred sustainable band, the author analysed other results from laboratory studies and analysis of similar cases. It was found, for example, that the pinewood (much used in Portugal) can withstand the relative humidity of approximately 45% to 78% without affecting plastic deformations from the relative humidity in equilibrium at RH of 63.6% (annual average for the current case) [7].

In analogy, a study conducted in Rocca Pietore (Italy) [24], with seasonal variations between 1 º C and 24 º C for temperature and 35% to 72% relative humidity, concluded that natural fluctuations did not cause plastic deformations in objects and it was predicted that massive timber elements can withstand variations of up to 25% RH when run by an initial relative humidity of 70% RH.

4.3. European microclimatic panorama

The rising number of microclimatic studies in the recent years has contributed to the development of knowledge of their effect on historic buildings, clarifying the influence of the climate on heritage conservation.

The recent approach described in the standard EN 15757 made it easier to analyse the data and contributed to the standardization of studies, increasing the credibility of the results and ensuring the comparability between different works.

However, there are still problems that need to be solved. The standard EN 15757 is not yet fully disseminated and almost in all cases, it is applied in cold climates [17-20], such as the studies that supported its definition [24]. Countries with temperate climates, such as Portugal, have a limited number of microclimatic studies in historic buildings and the results of the application of EN 15757 are almost unknown.

The wider applicability of this standard in cold climates justify the preponderance of the short-term fluctuations over seasonal cycles, since it is expected that the buildings in cold climates are equipped with heating systems which contributes to more stable seasonal cycles, less dependent on the external conditions. However, often the heating systems do not run continuously, and although they contribute to an increased seasonal stability, quite often short-term fluctuations are increased. The standard EN 15757 contemplates this behaviour and defines the sustainable limits as a range obtained by the exclusion of 14% of the largest short-term fluctuations around the moving average.

This approach may not be completely suitable for temperate climates, because it is undemanding in the case of seasonal cycles since it does not impose any limit. The European standard EN 15757 does not specify methods of analysis or categories for temperatures. Although it is consensual that heating systems are frequently not required for churches in temperate climates [28], it is important to study the evolution of temperatures in such cases, especially because they have a direct influence on RH. Regarding short-term fluctuations, the opposite occurs and a demanding limit is defined by the elimination of the 14% (7º and 93º percentiles) greater variations, with the suggestion that the safe target should not be stricter than ±10% RH around the moving average.

In addition to the issues surrounding the fluctuations already discussed in the previous paragraph, it is intended to compare the current case with other European churches, unheated or intermittently warmed. The results are expressed in Table 4.2 and Figure 4.4.

Table 4.2 – Location, climate and constructive characterization of four European churches [17,18,29,30]

Building	**Location**	**Köppen Classification**	**Construction type**	**Heating**	**RH seasonal amplitude (%)**	**Short-term fluctuations (%)**
Church of Cristóvão	Lisbon (Portugal)	Csa	Stone	No	18	±7
Church of Saint Michael Archangel [18]	Debno (Poland)	Cfb	Wood	No	25	-9/+14
Basilica S. Maria Maggiore [18]	Rome (Italy)	Csa	Brick	No	10	-11/+8
Church of Santa Maria Maddalena [17]	Rocca Pietore (Italy)	Dfb	Stone	Intermittent	24	-9/+8

Csa - temperate with dry or hot summer
Cfb - temperate with a dry season and temperate summer
Dfb - cold without dry season and temperate summer

It can be seen that buildings located in colder climates, and where the internal variations are strongly dependent on external factors such as heating, lighting and human presence, the short-term fluctuations are substantially higher than in the Portuguese case, as can be confirmed by the analysis of Figure 4.4.

As regards to seasonal cycles, the highest amplitudes were observed in the church of Saint Michael Archangel and in the church of Santa Maria Maddalena, mainly because they were situated in more severe climates than the other 2 cases. The intermittent heating system installed in the church of Santa Maria Maddalena does not improve the seasonal stability and contributes significantly to the increase of the short-term fluctuations.

The Basilica of S. Maria Maggiore, located in Rome, where the external climate has higher variations than in Lisbon, is an unheated brick building, but has a lot of visitors and a powerful lighting system, unlike the Church of São Cristóvão, what explains the decrease of the seasonal amplitude, since this heating obtained indirectly leads to a decrease in the relative humidity, maintaining the seasonal values more stable. The short-term fluctuations show a new reality, where the church of St. Cristóvão has the smallest amplitude and confirms the proposed theory. Other examples of the application of EN 15757 can be found in the references [19,20].

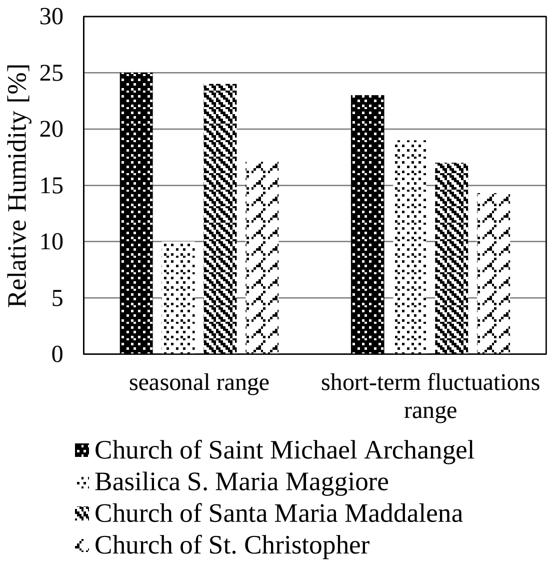

Figure 4.4 – Seasonal and short-term fluctuations range of relative humidity for four European case-studies

It is common to consider the relative humidity as the main factor to be analysed, but in this case, as the building is not equipped with climate control systems, it is also required a careful analysis of the temperature because it can directly influence the relative humidity and contribute to its stability.

It is concluded that the buildings in temperate climates and in the absence of climate control systems depend largely on the seasonal outdoor variations since short cycles are lower and more stable which justifies a careful analysis and definition of a new methodology of analysis.

Some may say that the standard EN 15757 provides an alternative to the problem described in the previous paragraph. While this is true, the issue is not completely solved. When short-term fluctuations are shorter than 10%, EN 15757 allows the adoption of this value instead of the design values defined by the statistical methodology. This approach minimizes the problems relating to changes in short-term but does not contribute to limiting the seasonal cycles and does not specify limits for temperature.

4.4. A new approach to temperate climates

4.4.1. Climate control strategy to avoid new mechanical damages

In an effort to define a methodology to analyse the historic microclimate in temperate climates, an approach based on the EN 15757 and ASHRAE specification was used (rather than a totally innovative method that could increase entropy to its applicability), in order to improve its applicability and to facilitate comparison between several studies.

In general, the computation of the historic climate and sustainable limits remain, but new items are added with the purpose of limiting the seasonal cycles and lighten the short-term fluctuations. In the case of temperature, there was no concern of limiting the target according to human comfort, since this factor is not considered dominant in the satisfaction of visitors to a particular place or exposure [31]; a statistical analysis based on historical data was adopted both for the temperature and the relative humidity.

For this purpose, it was considered that in addition to the seasonal values also the annual average plays an important role. From the results obtained it was decided that the highest seasonal cycles of temperature and relative humidity should be limited in the relation to the annual average. This limit is defined by the 10^{th} and 90^{th} percentiles of the values obtained by subtracting the annual average to the moving average, in an attempt to limit seasonal variations and make the most stable indoor climate.

For short-term fluctuations, it was adopted a less demanding approach than the one described in EN 15757, with the exclusion of 10% of the largest differences between the instantaneous values and the computed seasonal cycle. This means that it is possible to get a sustainable range by adding the 5^{th} and 95^{th} percentiles to the seasonal cycle.

This approach was intended to replicate the statistical analysis of the EN 15757 and the limits of the ASHRAE specification, but without absolute targets, always using the historical values. This method can be easily applied in various regions, since it is based on the climate of the building itself and not based on empirical or specific values defined for certain climates.

Two classes were defined in terms of conservation. The first and more demanding class considers the risk of biologic attack, aiming to reach a better seasonal balance that may decrease the mechanical risks.

For that purpose, it was defined a maximum variation of ±15% RH to the annual average, with a maximum acceptable value of RH defined in accordance with the methodology presented in 4.4.2. As regards temperature a maximum variation of +10ºC to the annual average with a threshold of 30ºC is accepted (in accordance with class B of the ASHRAE specification [21]). A minimum limit of about 13ºC and 35% RH was defined to avoid the embrittlement of the materials [32].

The second class is similar to the first in relation to seasonal cycles and short-term fluctuations, but less demanding because it does not consider the risk of biological attack and the control of the amplitudes is more permissible, being only limited by the seasonal cycles and short-term fluctuations and without the definition of *extra limits*. The first class must be applied to the buildings with higher requirements, such as museums, while the second class that ensures greater freedom for microclimates can be applied to churches for example. Table 4.3 is a summary of the entire method. The application of the class 2 of the proposed method and the comparison with the application of the method presented in EN 15757 can be seen in Figure 4.5.

Table 4.3 – Temperature and relative humidity specifications according the FCT-UNL methodology

Reference value	Seasonal cycles(1)	Short-term fluctuations(2)	Extra limits	Notes
T & RH: historic yearly average	T and RH: -10º/+90º percentiles	T and RH: -5º/+95º percentiles	$\lvert \mathrm{RH} - \overline{RH} \rvert \leq 15\%$; $RH_{max} \leq (3)$; $RH_{min} \geq 35\%$ $\lvert \mathrm{T} - \overline{\mathrm{T}} \rvert$ up 10℃, but not above 30℃ but not above 30ºC nor below 13ºC	Class 1 - Low risk of mechanical damage and biological attack. Applicable in special buildings where the materials require tight control of climatic levels. Example of museums or other buildings with important and permanent exhibitions.
	T and RH: -10º/+90º percentiles	T and RH: -5º/+95º percentiles	-	Class 2 - Moderate risk of mechanical damage. The risk of biological attack is not a major factor and there is no need for a climate as constant as in class 1. Example of churches.

(1) This cycle is obtained by calculating a moving average of 30 days, centred on the desired value. Its variation is observed around the annual average;
(2) The target range is calculated from the historical climate. The lower and upper limits of the target range are determined as the 5th and 95th percentiles of the short-term fluctuations recorded in the monitoring period. The short-term fluctuations are calculated as the difference between the current value reading and a 30-day moving average calculated for that reading;
(3) Extra method

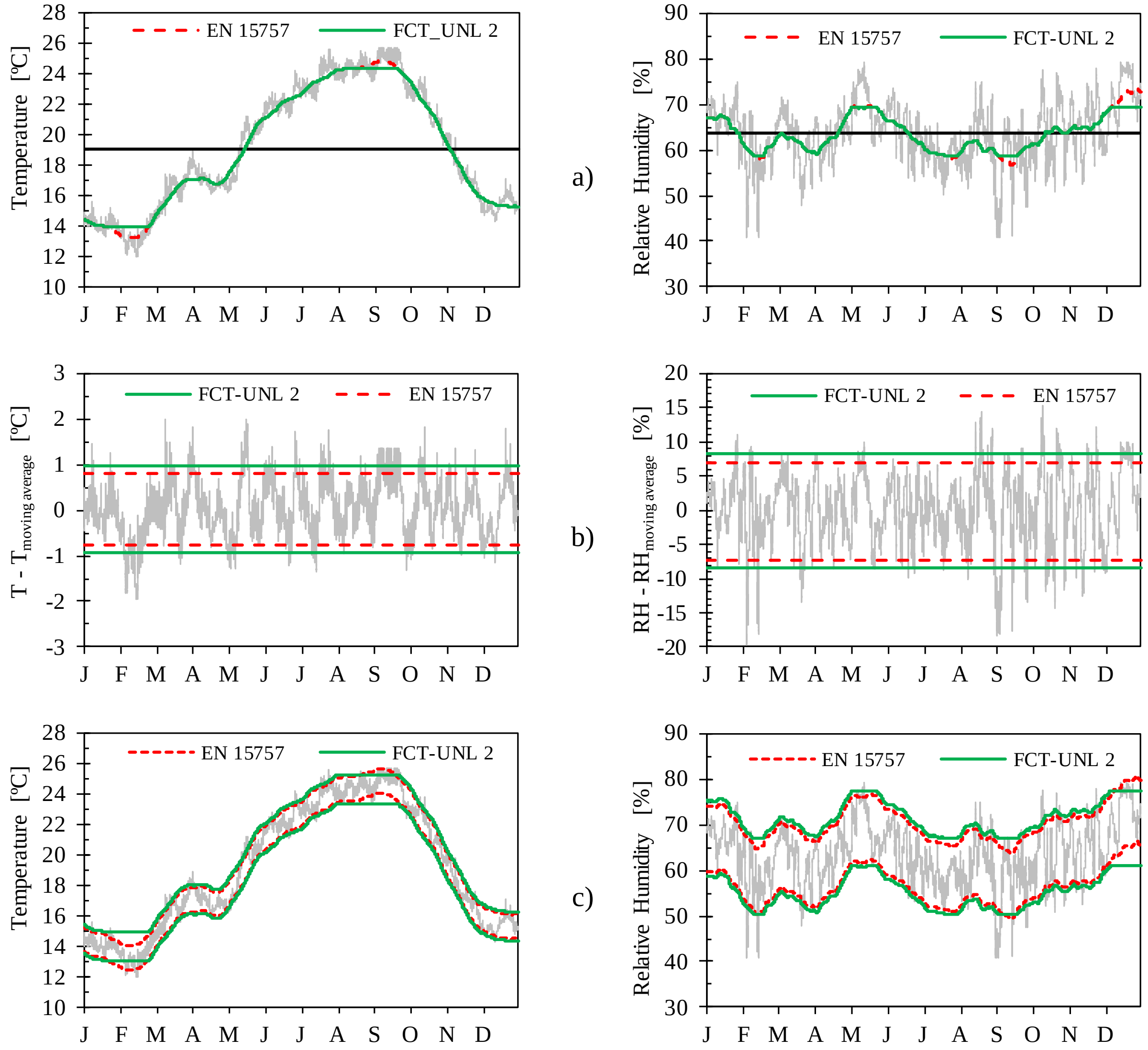

Figure 4.5. Comparison of the application of the FCT-UNL class 2 methodology and the EN 15757 for the church of São Cristóvão: a) seasonal cycles; b) short-term fluctuations; c) final sustainable targets

4.4.2. Climate control strategy to avoid the mould germination

It is generally assumed that values of RH lower than 60% prevent mould germination, while values above 75% represent a real risk [22,33-35]. These values consider the difference between the temperature of the air and the surfaces, which in late winter and spring (for high thermal inertia elements) present lower temperatures than the indoor air leading to an increase of RH. Some international standards recommend the use of a maximum RH of 75 % to avoid biological risks [36,37], however this value may not be sufficient since the temperature differences between surface and air depend on several factors, as the characteristics of the envelope, indoor and outdoor climate conditions and the occupancy habits. So, the use of an absolute RH limit should not be generalized.

The analysis of moisture transfer mechanisms, prevention of surface condensations and mould germination is complex, however there are some simplified methods that may assist in thermal design of building elements to avoid surface condensations and to minimize the mould risk, as the methodology of standard EN ISO 13788 [38].

This method is intended to reduce the mould risk and/or surface condensation by choosing the appropriate thermal resistance of the elements. It is a generic and simplified method that may not adapt to all climates and situations, which considers average monthly climatic data and assumes the moisture transport only in the vapour phase, neglecting the surface resistance to water vapour. If other sources of moisture, such as liquid water penetration, are insignificant, the results will be on the safe side [38].

The use of the original method may be a useful tool on the design of new buildings or in the hygrothermal refurbishment of existing ones, but it is useless in situations where the envelope improvement is not possible. The proposed approach adapts its use to transform the original method into a management tool for cultural heritage buildings to define the maximum RH values to avoid mould germination.

The application of the method presupposes the knowledge of the external climate, that can be easily obtained by measurement or in climatic reports, the interior conditions, which are sometimes not known, the assumption of the same water vapour pressure in air and surfaces and mould germination for RH higher than 80% [38]. The use of monthly averages considers the fact that mould germination is not instantaneous, requiring prolonged exposures until occurrence. A 30-day period at 80 % RH is considered a valid approximation [38,39].

Currently there are other models with greater acceptance for the evaluation of the mould risk, from which it is possible to emphasize the isopleth method of Sedlbauer [40], broadly described in 2.2.4.2. This method uses an isopleth that changes the RH required for the mould germination according the temperature, the substrate and the germination time instead of considering a constant value as presented by EN ISO 13788. Since the intended objective is to propose a design tool, it was decided to maintain its easy application with a month-by-month analysis. Thus, a 30-day isopleth was interpolated both for the substrate category I and II, as shown in Figure 4.6

As mentioned, this method is intended for existing buildings where hygrothermal improvements are not possible. Thus, the existent thermal resistance must be used to estimate the maximum indoor RH to avoid the mould risk according to the outdoor climate and the thermal quality of the envelope. The symbology and formulation refer to EN 16242 [41].

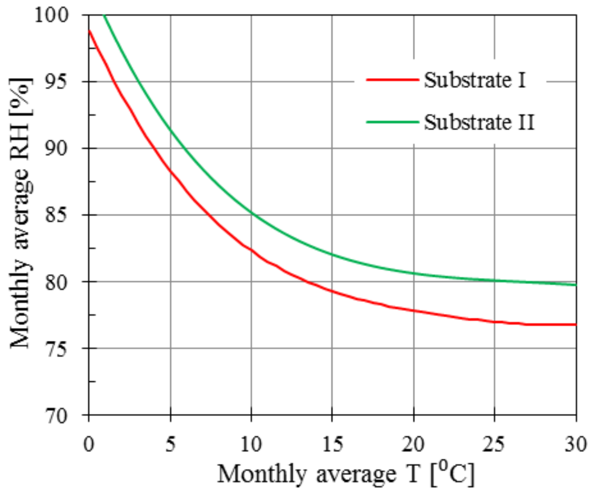

Figure 4.6. Isopleth method of Sedlbauer for the substrate category I and II for a germination time of 30 days

Thus, the following step-by-step method is proposed to calculate the maximum indoor air RH:

a) Obtain the monthly averages of outdoor *T*, the indoor *T* and *RH* and calculate the indoor water vapour pressure by applying equation (4.1):

$$e_n = 6.112 \times 10^{\frac{7.65 \cdot T_n}{243.12 + T_n}} \times RH_n \tag{4.1}$$

where *n* corresponds to outdoor, indoor or surface conditions, *T* is the temperature (ºC), *RH* is the relative humidity (%) and *e* is the water vapour pressure (Pa).

b) Calculate the effective interior surface temperature ($T_{si,eff}$):

Since in some periods the surface temperature can be higher than the air temperature, in a conservative way the minimum of these two values must be used (hear named as effective interior surface temperature ($T_{si,eff}$). It is important to take this into account since the mould germination at the building surfaces is not the only risk. The mould can also germinate in objects located in the room, so the use of the effective interior surface temperature takes all these situations into account. The effective interior surface temperature may be obtained from:

$$T_{si,eff} = \min\,(T_{si}; T_i) \tag{4.2}$$

T_{si} may be obtained from eq. (4.3) [38]:

$$T_{si} = T_i - R_{si} \cdot \mathrm{U} \cdot (T_i - T_e) \tag{4.3}$$

where T_{si} is the monthly mean temperature at the internal surface (ºC), T_e is the monthly mean outdoor air temperature (ºC); T_i is the monthly mean indoor air temperature (ºC); R_{si} is the thermal resistance of the interior surface (m^2.ºC/W) – a value of 0.25 m^2.ºC/W shall be used for the analysis of condensations and mould risk to consider the effect of corners, furniture or curtains [38] and *U* is the thermal transmittance (W/m^2.ºC).

For plane elements the thermal transmittance is obtained from the eq. (4.4):

$$U = \frac{1}{R_{si} + R + R_{se}} \tag{4.4}$$

where R is the thermal resistance of the element (m^2.ºC/W) and R_{se} is the thermal resistance of the exterior surface (m^2.ºC/W) – a value of 0.04 m^2.ºC/W shall be used [38].

c) Calculate the *e* at the surface by applying equation (4.1) and adopting the adequate isopleth of the Figure 4.6 and considering the surface T obtained in b). This *e* will be considered constant both at the surface and in the air;
d) Calculate the saturated *e* of the air from the equation (4.1) for an RH equal to 100 % and using the indoor air T;
e) Calculate the maximum RH of the air by dividing the *e* obtained in c) by the saturated *e* obtained in d).

Figure 4.7 shows the graphical application of the method according to the outdoor temperature for cases where the interior temperature is known. Whenever the measured monthly averages of RH exceed the maximum RH there is a risk of mould germination.

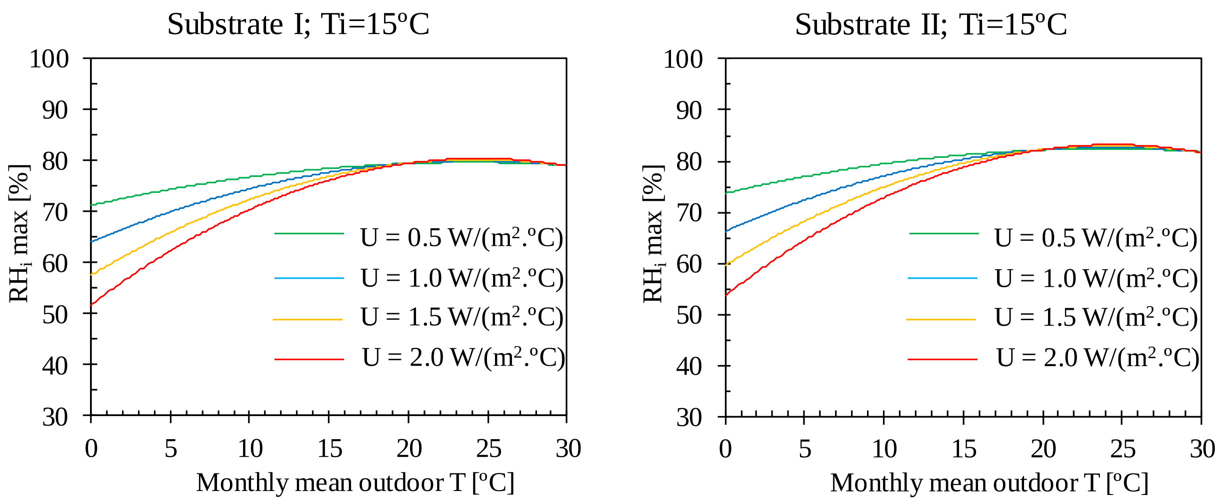

Figure 4.7. Maximum indoor RH to avoid the mould germination for different indoor temperatures and envelope thermal quality in function of the outdoor temperature

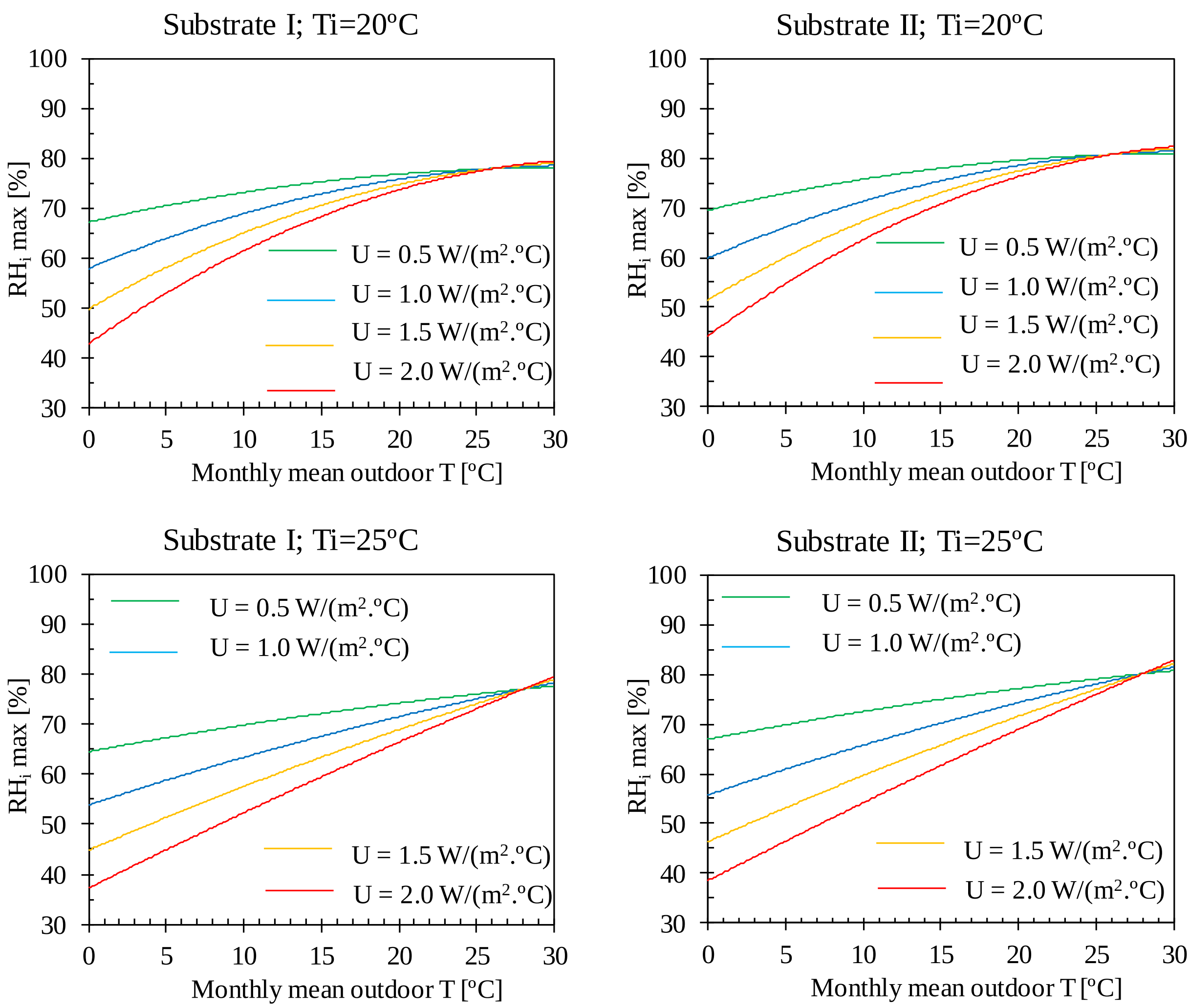

Figure 4.7 (continuation). Maximum indoor RH to avoid the mould germination for different indoor temperatures and envelope thermal quality in function of the outdoor temperature

4.5. Validating the Methodology

4.5.1. General considerations

In order to validate the application of the FCT-UNL methodology, the simulation model of the Jeronimos Monastery defined and validated in chapter 3 was used. As concluded in 3, there are several conservation risks associated with the climate that can be enhanced by the increasing number of visitors. It was concluded that for the outdoor climate measured during the monitoring campaign and even if the building is closed to the public there are risks of mechanical damage to the objects, which makes plausible the scenario that the materials had to find a new equilibrium and underwent a process of acclimatization with possible irreversible deformations. As regards mould germination, it was concluded that the increase in the number of visitors significantly increases the germination risk. While monitoring the number of visitors may limit the risk, an effective strategy can hardly be defined, since other factors such as the exterior climate play a major role in the internal climate.

It is not intended nor reasonable to tightly control the indoor climate with powerful climate control systems, but the insertion of certain limits can control the risks of biological and mechanical degradation. Any intervention at heritage level should be primarily concerned with the conservation of the monuments and their preservation for the future generations, but the current concerns about environmental and economic sustainability dictate that interventions must also balance all these concerns.

The possibility of using a dynamic climate control methodology described in the European Standard EN 15757 [9] was analysed in chapter 2. This methodology aims to limit the mechanical degradation of acclimatized hygroscopic organic materials. Despite the novelty and quality of the document, some limitations have been observed that may hinder its application in temperate climates, namely by giving greater emphasis to short-term fluctuations, disregarding the need to control the seasonal cycles. It should be remembered that in naturally ventilated buildings in temperate climates with low internal gains, as is the case of most functioning churches, indoor climate tends to follow the external seasonal trends. Thermal inertia, high volume and reduced internal gains contribute to short-term internal stability. The complete ineffectiveness of the method to control the biological risk was also noted.

In order to overcome these limitations, a new methodology called FCT-UNL was proposed that, in addition to short-term fluctuations, also focus on the seasonal cycles. The methodology is composed by two classes: a) a more demanding that limits the seasonal cycles, the short-term fluctuations and also limits the maximum fluctuations around the annual average and subscribes an additional methodology to limit the biological risk; b) the second one only limits the seasonal cycles and short-term fluctuations and is more similar to the method of EN 15757.

4.5.2. Applying the dynamic methodologies

Before starting the direct application of the FCT-UNL methodology it is necessary to estimate the maximum RH at the air that avoids the mould germination on a certain surface. The methodology described and exemplified in 4.4.2 was adopted. The analysis is made for the northern wall, since it presents the lowest thermal resistance and does not receive solar radiation. The northern wall has a thermal resistance of 0.57 $m^2.^oC/W$ and outer and inner surface thermal resistances of 0.13 $m^2.^oC/W$ since the wall is protected by another external wall. The monthly averages of temperature and relative humidity obtained for an annual occupancy of 3.5 M visitors can be seen in Figure 4.8.

Despite the use of this method, some doubts exist about its validity. The model assumes in a simplified way the calculation of the average monthly surface conditions in steady state conditions. This assumption may be too simplistic if applied to walls with high mass and great capacity to store heat. In order to verify the validity of this simplification, the simulation model of the monastery was used to obtain the superficial T and RH and then compare them with the values estimated in steady state.

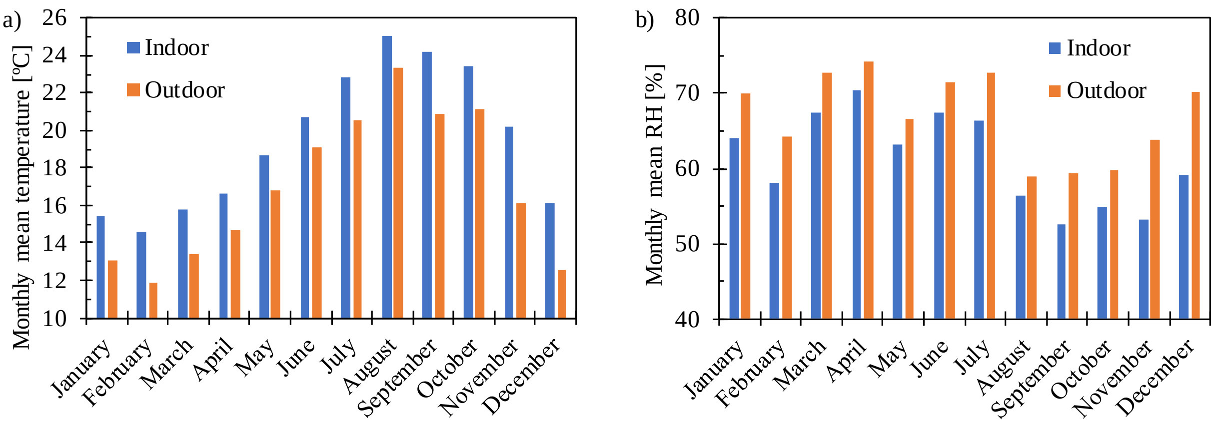

Figure 4.8. Monthly mean temperature (a) and relative humidity (b) for the indoor and outdoor obtained from the simulation model of the Jeronimos Monastery for an annual occupancy of 3.5 M visitors

In stationary conditions the internal surface temperature can be calculated according the equation (4.3) and the thermal transmittance for plane elements can be obtained from the equation (4.4). Since the element is not directly exposed to wind and solar radiation, the same thermal resistance of 0.13 m^2.ºC/W should be used both for the inner and outer surface.

The method also assumes that the water vapour pressure at the surface is the same as that observed in the air, decreasing the adsorption capacity of the materials and other moisture sources. The water vapour pressure of the air was obtained by applying the equation (4.1).

Based on the estimated surface temperature with equation (4.3), it was possible to calculate the saturation water vapour pressure from the equation (4.5):

$$e_{sat} = 6.112 \times 10^{\frac{7.65 \cdot T_{air}}{243.12 + T_{air}}} \times 100 \tag{4.5}$$

Finally, by dividing the water vapor pressure by the saturation pressure at the surface it is possible to obtain the RH at the surface. All the results can be found in Table 4.4.

To assess the accuracy of the method, the estimated monthly averages were compared with the monthly averages calculated from the exported surface conditions of the model. This analysis is presented in Figure 4.9 from which it can be concluded that the adopted simplifications does not present a significant loss of rigor in the calculations since there is only a mean difference of 0.1 ° C and 1.7% RH for the ranges under analysis. The use of the monthly averages attenuates the differences.

After ensuring the validity of the simplifications, the FCT-UNL methodology was applied. The isopleth for substrate class II to obtain the maximum admissible RH at the surface was used since the walls are composed by limestone blocks. An internal surface thermal resistance of 0.25 m^2.ºC/W was adopted to consider the thermal bridges. The summary results of the step-by-step method can be seen in Table 4.5. For more details about the application of the method please see 4.4.2.

Table 4.4. Application of the step-by-step methodology proposed in 4.4.2 to avoid the mould germination

Month	T_e [ºC]	T_i [ºC]	U [W/m².ºC]	T_{si} [ºC]	RH_{air} [%]	e_{air} [Pa]	$e_{sat,si}$ [Pa]	RH_{si} [%]
January	13.0	15.4	1.2	15.0	64	1119	1706	66
February	11.9	14.6		14.2	58	965	1614	60
March	13.4	15.8		15.4	67	1207	1744	69
April	14.7	16.6		16.3	70	1326	1850	72
May	16.8	18.7		18.4	63	1360	2110	64
June	19.1	20.7		20.5	68	1646	2399	69
July	20.5	22.8		22.4	66	1835	2707	68
August	23.3	25.0		24.8	56	1785	3115	57
September	20.9	24.2		23.7	52	1578	2916	54
October	21.1	23.4		23.1	55	1580	2811	56
November	16.1	20.2		19.5	53	1257	2267	55
December	12.5	16.1		15.5	59	1081	1762	61

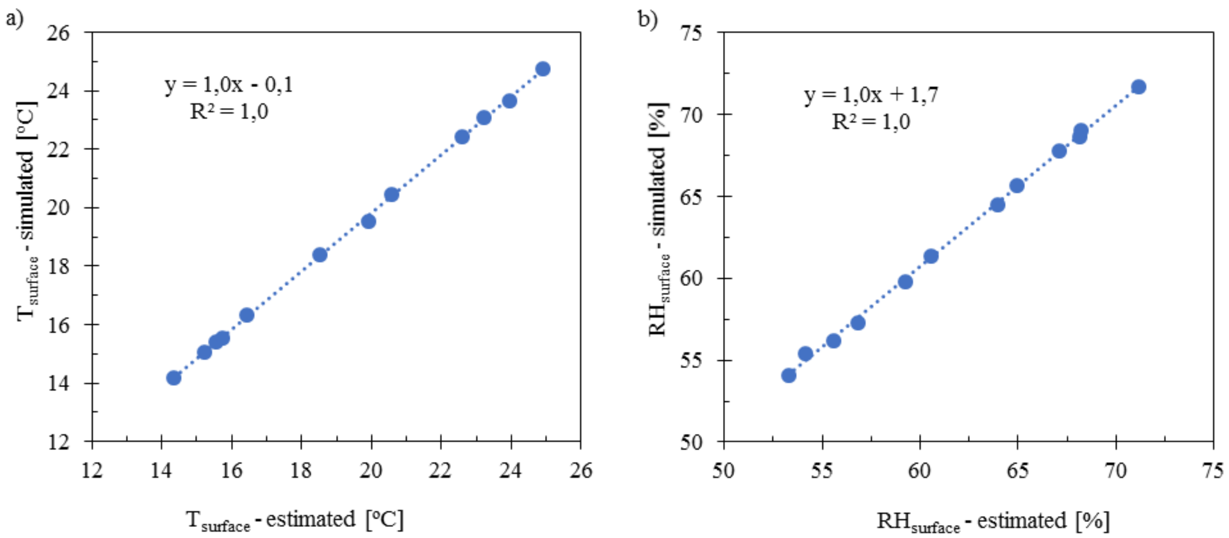

Figure 4.9. Comparison between the surface conditions under steady state conditions and those obtained with the simulation model: a) temperature; b) relative humidity

Conservatively, the lowest RH should be used. In this case a RH of 76% obtained for November appears as the most conditioning, and it should be used as the maximum limit for the application of class 1 of the FCT-UNL methodology.

In order to reach a compromise between conservation and sustainability, the methodologies described in the EN 15757 and that proposed in this thesis were tested. The dynamical limits obtained through each of the methodologies can be seen in Figure 4.10.

In order to assess the natural capacity of the building to comply with each of the intervals, the *Performance Index* (PI) concept described in 2.2.3 was used. The results obtained for each of the three methodologies are shown in Figure 4.11. Since the temperature mainly affects the comfort and relative humidity the conservation, the application of the T and RH targets and only the RH target were evaluated.

Table 4.5. Application of the step-by-step methodology proposed in 4.4.2 to avoid the mould germination

Month	T_e [ºC]	T_i [ºC]	U [W/m^2.ºC]	$T_{si,eff,min}$ [ºC]	Substrate type II				
					$e_{sat\cdot si}$ [Pa]	*RH si,max*	e_{si} [Pa]	$e_{sat\cdot i}$ [Pa]	RH_i [%]
January	13.0	15.4	1.0	14.8	1678	82	1378	1747	79
February	11.9	14.6	1.0	13.9	1584	83	1307	1659	79
March	13.4	15.8	1.0	15.1	1716	82	1406	1787	79
April	14.7	16.6	1.0	16.1	1825	82	1489	1886	79
May	16.8	18.7	1.0	18.2	2084	81	1687	2149	79
June	19.1	20.7	1.0	20.3	2373	81	1912	2438	78
July	20.5	22.8	1.0	22.2	2668	80	2142	2766	77
August	23.3	25.0	1.0	24.6	3082	80	2468	3164	78
September	20.9	24.2	1.0	23.3	2856	80	2290	3007	76
October	21.1	23.4	1.0	22.8	2770	80	2223	2873	77
November	16.1	20.2	1.0	19.1	2207	81	1783	2358	76
December	12.5	16.1	1.0	15.2	1720	82	1409	1826	77

The analysis of the impact of the use of temperature and relative humidity limits allows to conclude that any of the classes of the FCT-UNL methodology provides better results than EN 15757. Class 2 of the FCT-UNL methodology is fulfilled during 82% and class 1 during 79% of the time while the limits defined by EN 15757 are fulfilled in 74% of the time.

The individual analysis of the impact of temperature and relative humidity targets allows to increase the robustness of the analysis. Regarding to temperature, any of the classes of the FCT-UNL methodology is fulfilled in 91% of the time, while EN 15757 is fulfilled in 86% of the time. Regarding the relative humidity, class 1 of the FCT-UNL methodology and EN 15757 are met in 86% of the time while the class 2 of the FCT-UNL methodology is fulfilled in 90% of the time. Despite the FCT-UNL methodology imposing new limits on the internal climate, namely at the level of the seasonal cycles and the maximum limit of RH for the class 1 to avoid the mould germination, it is concluded that it accompanies the indoor climate more closely, making it possible to obtain global better results.

Despite the Performance Index analysis, it is necessary to evaluate what happens when the limits are not met and to evaluate the impact of each of the methodologies for conservation and energy consumption. Since the time of each visit is low, which leads to low levels of expectation with regards to thermal comfort, the main concerns are related to conservation. Thus, each of the three methodologies was applied for temperature and relative humidity and then only for relative humidity.

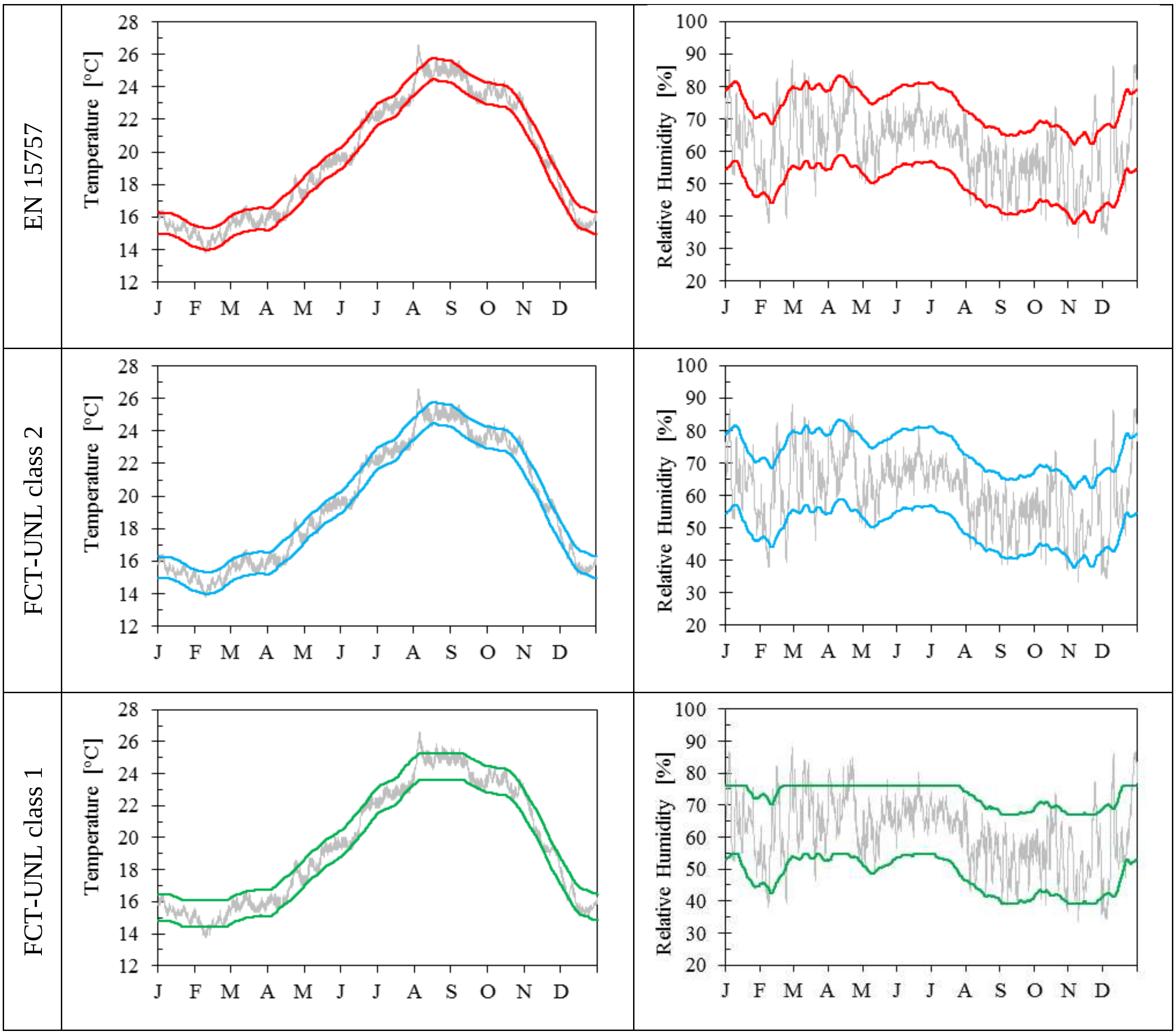

Figure 4.10. Results of the application of the dynamic climate control strategies EN 15757, FCT-UNL class 2 and FCT-UNL class 1

In Table 4.6 it is possible to find the results obtained by the application of the damage functions for the painted panels - base layer and pictorial layer, sculptures, furniture and for the risk of mould germination on the interior surface of the north wall. In addition to the impact of climate control strategies on conservation, their impact on energy consumption was also assessed.

The application of any of the strategies tested in terms of mechanical conservation is considered valid since they all reduce the current risk, reducing the percentage of time in the plastic region. Even if this reduction may not be strongly noticed, it contributes to the fact that the risk levels do not increase, since the collections have already had adaptation phenomena to the past climate.

Concerning the mould germination, it is concluded that all strategies contributed to the reduction of the risk. In spite of this conclusion, it is necessary to consider that only class 1 of the FCT-UNL methodology has concerns about mould, so the improvement of the conditions for the remaining methodologies is only due to the reduction of the short-term fluctuations that have indirectly contributed to the reduction of biological risk. If it is desired to effectively control the mould germination, the choice should always be the class 1 of the FCT-UNL methodology. Note that this class returns an MRF of 0. As expected, it was concluded that controlling the temperature has an almost negligible impact on conservation.

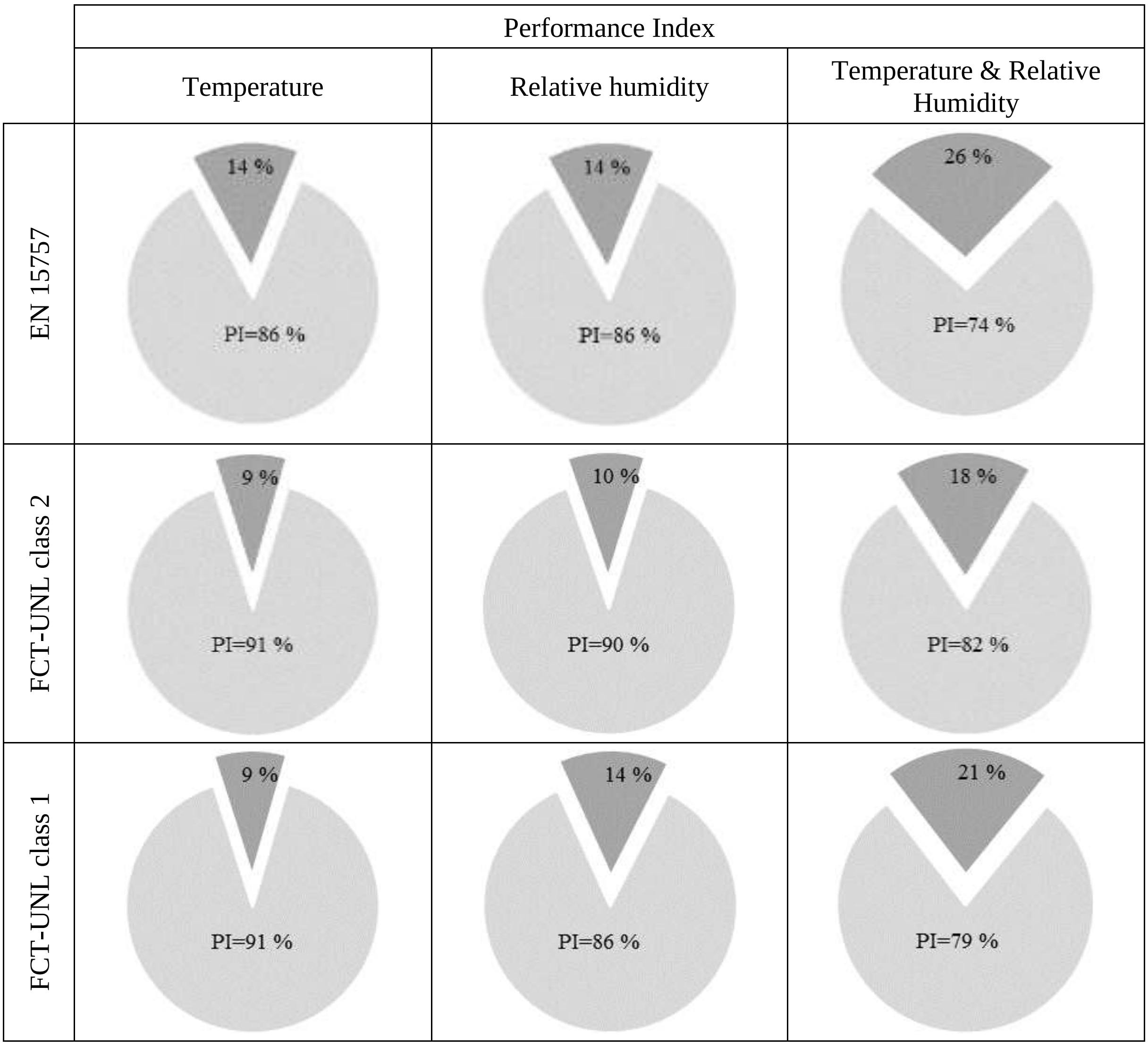

Figure 4.11. *Performance Index* (PI) according with the 3 climate control strategies: EN 15757, FCT-UNL class 2 and FCT-UNL class 1

In addition to the analysis of the impact of climatic control strategies on conservation, their impact on energy consumption was also analysed. Analysing the application of the three strategies for both temperature and relative humidity, the best results are obtained by FCT-UNL methodology: 12.0 MWh for class 2 and 13.7 MWh for class 1; the application of EN 15757 gives an annual consumption of 17.7 MWh. This result is of particular importance if it is considered that only the FCT-UNL methodology imposes limits on seasonal cycles and a minimum temperature to avoid material breakage and still obtain a better result, which proves its greater suitability for temperate climates.

If it is desired to only control relative humidity, it is concluded that class 2 of the FCT-UNL methodology presents the best result with an annual consumption of 3.0 MWh, followed by EN 15757 and the class 1 of the FCT-UNL methodology with 4.8 MWh.

This allows to conclude the feasibility of applying the FCT-UNL methodology in the cultural heritage, namely the class 2 for those cases where it is only intended to limit the mechanical damage, or class 1 in cases where a more controlled climate is required and where the biological risk is real.

Table 4.6. Degradation risk evaluation and energy demand for all the simulated scenarios

Climate control strategy	Painted wood				Sculptures		Furniture		MRF		Energy demand [MWh]
	Base		Pictorial								
Reference case	P: 13.9 %	2	<14%	3	P: 8.1 %	2	E	3	1.08	1	-
EN 15757 – T & RH	P: 12.3 %	2	<14%	3	P: 3.5 %	2	E	3	0.15	3	17.7
FCT-UNL class 2 - T & RH	P: 12.6 %	2	<14%	3	P: 5.4 %	2	E	3	0.43	3	12.0
FCT-UNL class 1 - T & RH	P: 11.0 %	2	<14%	3	P: 3.1 %	2	E	3	0	3	13.7
EN 15757 – RH	P: 12.1 %	2	<14%	3	P: 3.5 %	2	E	3	0.17	3	4.8
FCT-UNL class 2 – RH	P: 12.6 %	2	<14%	3	P: 5.3 %	2	E	3	0.43	3	3.0
FCT-UNL class 1 – RH	P: 11.0 %	2	<14%	3	P: 3.1 %	2	E	3	0	3	4.8

4.6. Conclusions

The microclimatic study of the Church of São Cristóvão in Lisbon has allowed to apply the standard EN 15757 to a historic building in a temperate climate. This process has enabled to test and validate the applicability of this standard to a climate different from those that are present in most of the literature.

The results obtained and the comparison with other case-studies show that EN 15757 can present an overly rigid approach when applied in temperate climates because it was developed based on buildings present in cold climates, which have other requirements.

In the southern Europe, most of the cultural heritage buildings do not usually have HVAC systems and interiors climates largely depend on the variations of the outdoor climate. This justifies that short-term fluctuations are very controlled, although the seasonal cycle follows the outdoor cycle and shows more significant variations.

The method described in EN 15757 assumes that the short-term fluctuations cause a higher risk, and limits their range significantly; however, it has no limitations for seasonal cycles. When applying this methodology in temperate climates it is clear that seasonal cycles are still large, but short-term fluctuations are limited too rigidly. It was therefore considered that it was necessary to adapt this methodology to ensure a reliable application in temperate climates. A new analysis method was therefore prepared based on EN 15757 and influenced by the ASHRAE specification.

As the short-term fluctuations are low it is possible to lighten their limit, while the seasonal variations were limited. It was also considered the risk of biological attack and the fact that some materials require greater stability conditions than others. So, two classes of analysis were defined, one for less demanding buildings such as churches and other more demanding for museums. This methodology can be a useful tool to manage the indoor climate in cultural heritage buildings and reducing the energy demand without jeopardizing the conservation.

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5. A sequential process to assess and optimize the indoor climate of the Nacional Museum of Ancient Art of Lisbon

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5.1. Introduction

Nowadays one of the largest challenges for museums is to achieve sustainability by reducing costs and energy demands without jeopardizing the conservation and thermal comfort [1–3]. Frequently it is hard to manage the conflicts and to reach a compromise between conservation thermal comfort and energy efficiency since conservation requires by definition a very stable climate with short fluctuations which imposes high demands to the air conditioning systems in order to meet those requirements.

In addition to those requirements it is important to note that frequently museums are located in historical buildings with a poor hygrothermal response. If hygrothermal rehabilitation with the use of passive techniques is a common solution in many cases for classified buildings is not always the case due to the impossibility to transform their façades. The use of less stringent climate targets seems to be a possible solution but after more than one century of research in the museum environment field there is still not a consensus on this theme [4].

Quite often very demanding limits are used, around 20 °C for temperature and 50% for RH. This trend goes back to the beginning of the concerns about the climate in museums, and was strengthened during some periods afterwards, namely with the positive result of the transfer of the collections from the National Gallery of London to the controlled environment of the Manod slate quarries, Wales, during the second world war [5]. The large increase of the concerns about buildings housing museums during the 70's with the use of air conditioning systems, also contributed to the definition of tight targets for design purposes, often without scientific basis, beginning a new approach named as "designing to the numbers" [5]. Over time, it became evident that the use of stringent targets may not be scientifically justifiable since new researches showed higher resistances of some materials to ampler ranges than those considered so far [6–9].

The increasing concerns on sustainability and energy reduction also affected museums and in the last decade several studies testing different climate control strategies to achieve energy reduction have been considered by the scientific community [10–14] with interesting results as those of Ascione *et al.* [14] or Kramer *et al.* [11] with energy savings of around 40 % on the first case and 77 % on the second, thus confirming the validity of this approach.

Despite the proven influence of the use of different climate control strategies, most studies focus primarily on energetic issues, not optimizing the targets in accordance with the local climate, collections or comfort needs. The climate optimization should be a consequence of a previous analysis, and not carried out only by energy saving concerns.

In this chapter the data recorded along one year in a national museum of Portugal was used to test the application of a sequential process to classify the indoor microclimate in terms of HVAC efficiency, the risk of damage for collections and thermal comfort in an attempt to reach a balance between conservation needs, thermal comfort and energy reduction by the climate optimization.

5.2. Methodology

5.2.1. Site description

For the current chapter, the data recorded in a Portuguese museum were used. The museum is located in a palace of the late 17th century near the waterfront of Lisbon, under the influence of a Mediterranean climate, influenced by the proximity of the Atlantic Ocean.

Over the years after the conversion of the palace into a museum, several renovations and enlargements were made, including the incorporation of an ancient convent dated from the 16th century and the construction of a new annexe in the late 1930s. A new east wing was built from 1942 to 1974. During the 1990s a central HVAC system was installed, remaining in use until now [15].

The museum architecture is characterized by an irregular rectangular plan divided into three articulated buildings, evidencing the presence of distinct types of architecture: residential (Palace), composed by two exhibition floors; religious (Convent) and cultural (Annex), composed by three exhibition floors and an underground floor for the areas forbidden to visitors. The external walls are made with a stone and brick masonry with lime renderings on both sides, with a total thickness around 0.90 m. A thermal resistance of 0.56 m^2.°C/W was estimated from the database present in the ref. [16] for the Portuguese ancient buildings. The façades are painted in beige/yellow and topped by a frieze, cornice and eaves. The corners, the floors, the basement, the pilasters, gables and the staircases are in limestone [17].

All the rooms of the Museum, with the exception of the Chapel, are conditioned by a central HVAC system with the imposition of lower and upper limits for both temperature (20-22 °C) and relative humidity (50- 60 %). The Museum is open to visitors from Tuesday to Sunday from 10 to 18 hours and received 221000 visits in 2014 [17].

5.2.2. Microclimatic measurements

To understand the general response of the building, three air-conditioned and one uncontrolled room were analysed by taking measurements of T and RH with an hourly frequency from December 2013 to January 2015. Four data loggers ML 400 by Hanwell (uncertainty of ± 0.2 °C and ± 2 % for relative humidity) were used - one in each room – placed at a height of 1.5-2.5 m close to internal walls to prevent the influence of external factors, as shown in Figure 5.1. With regard to air-conditioned rooms, the first one is located on the first floor and presents a collection of Portuguese furniture (room 41), the second is located on the second floor and presents a collection of Portuguese faience and furniture (room 25) and the last is located on the third floor exposing a European painting collection (room 12). The Room 25 is exposed to south radiation and has an area of about 170 m^2 with double-glazed windows and aluminium frames with interior shading and a ratio between the window and the floor area of 0.15. The room 41 has about a half of the room 25 area and there are no windows open to the outside. Room 12, although it does not have windows open to the outside, is on the top floor of the building, which makes it more vulnerable to the outdoor climate. To complement the analysis data from the chapel was also used. This chapel is non-conditioned and remained closed to visitors during 2014; it features lower ventilation and exposure to disturbing factors, as the pollutants, heat and moisture generated by human presence. The location of the rooms and sensors in the horizontal cross-section of the museum can be seen in Figure 5.1.a), and in the Figure 5.1 b), c), d) and e) the analysed rooms.

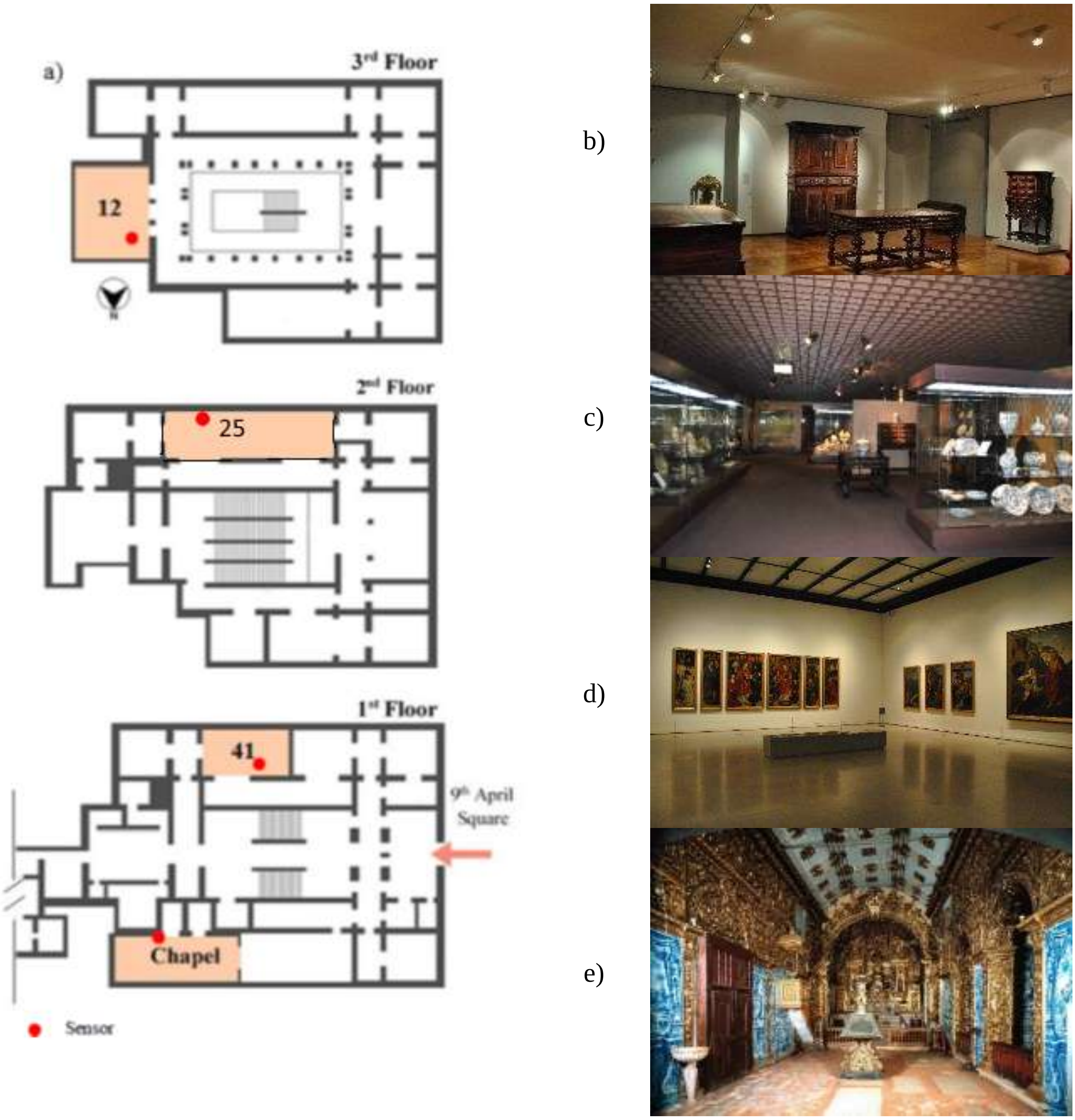

Figure 5.1. Horizontal cross-sections of the museum (a), and the interior of the rooms 41 (b), 25 (c), 12 (d) and the chapel (e) [17]

5.2.3. Performance index and climate characterization

Museums are usually equipped with air conditioning systems to control temperature and relative humidity and to limit the risks of loss of the collections, often using stringent targets that lead to large energy consumptions. Despite this, sometimes the targets are not kept due to the ineffectiveness of the HVAC system or by possible limitations of the building envelope.

To assess the compliance of the imposed targets a method defined and tested by Corgnati et al. [18,19] named "Performance Index" and described in 2.2.3 was used. This index expresses the percentage of time in which the measured parameters are within the reference target. This approach can easily be used to evaluate the performance of HVAC systems and their ability to keep the hygrothermal parameters within the imposed limits. It is important to consider that this index does not evaluate the damage risks, but only the effectiveness of the control system.

For the current case, the performance index to qualify the HVAC system was calculated in accordance with the limits imposed by the museum: 20 – 22 ºC for temperature and 50 – 60 % for RH. To classify the performance of the HVAC system a 3-points scale proposed in 2.2.6 was used.

To complete the indoor characterization in terms of T and RH, the annual average, the seasonal fluctuations (maximum and minimum differences of a 30-day moving average) and the typical short-term fluctuations around the seasonal cycle were also calculated.

5.2.4. Risk-assessment and thermal comfort

The risk assessment was based on the evaluation method defined in 2.2.4.1. 2.2.4.2 and 2.2.4.3 and classified according to a 3-points scale presented in 2.2.6. For the evaluation of thermal comfort, the adaptive model defined by Matias [20] for buildings with climate control was adopted. Since it is a large national museum, the model was applied for the highest level of acceptance: 90%. The method is duly described in 2.3.4.

5.3. Results

5.3.1. Performance index and climate characterization

Although not directly linked to the conservation needs the performance index is a good management tool, since sometimes the targets of T and RH imposed by museums are not complied by the HVAC systems. Despite the uncontrolled environment in the chapel, it was decided to check its behaviour according to the values taken as comfortable for the museum.

By analysing Figure 5.2, Figure 5.3 and Table 5.1 it is possible to see that the registered indoor climate did not simultaneously comply with the predefined limits in significant percentages, particularly when compared with similar values existing in the literature [18,19]. A value of 26.3 % was obtained for room

12, 13.4 % for the room 24, 17.4 % for the room 41 and 12.1 % for the chapel.

The Figure 5.3 allows a complete analysis of all scenarios. A separate analysis in terms of temperature and relative humidity confirmed that the temperature is the main reason for the global low index in the controlled rooms. The range imposed for the temperature is exceeded in 57.5 % of the year in the room 12, in 66.7 % of the year for the room 25 and in 59.3 % for room 41. The analysis of the periods for which the target is not met allows concluding that the high values of temperature are the main reason, especially for the rooms 25 and 41 where the temperature is always higher than 20 ºC. In the chapel, a different response was obtained with index values of 44.9 % for the temperature and 27.4 % for the relative humidity. In this case, the low temperatures are the main reason for the infringement of the limits.

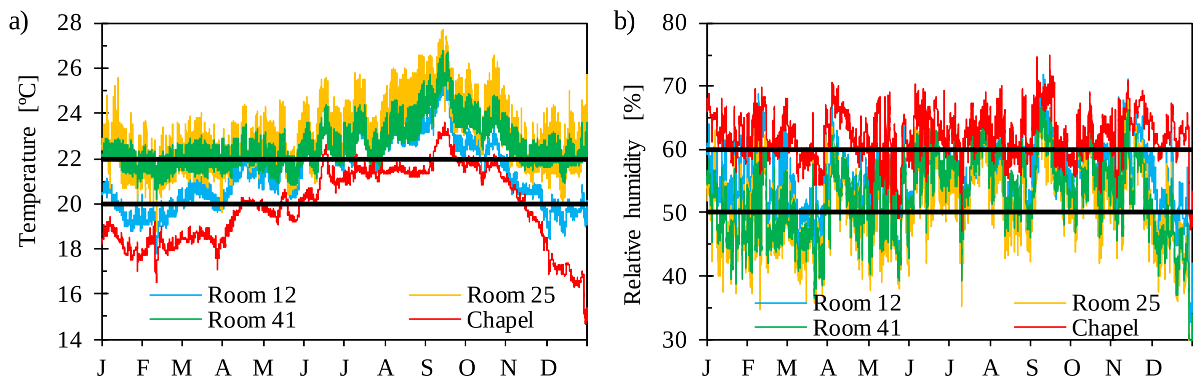

Figure 5.2. Hourly values of T and RH and the limits imposed to the HVAC system by the museum

The limits imposed to the temperature can always be considered too tight (the bibliography typically accepts greater variations [18,21]), whereby the performance index analysis could be confined mainly to relative humidity variations which are usually more significant for conservation. But even looking only at the relative humidity the index remains too low with 68.3 % in room 12, 49.3 % in the room 25, 53.5 % in the room 41 and 27.4 % in the chapel. It is obvious from the analysis of Figure 5.3 that the main reason for the low index of the chapel is the relative humidities higher than 60 %, while the opposite is verified for the rooms 25 and 41. In the room 12, the dispersion is uniform.

The statistical analysis was performed according to 2.2.2. Figure 5.4 illustrates the process of calculating the seasonal amplitudes and the typical short-term fluctuations for the room 25. Analysing the climate evolution along the year and the statistical parameters in Table 5.1 is possible to verify that the chapel (unheated room) shows the lowest annual average of T and the highest seasonal fluctuations and annual RH average. Despite this and the low-performance index, the chapel presents the lowest short-term fluctuations for T and RH and the lowest seasonal fluctuations of RH, showing that the high thermal inertia of the building and the absence of disrupting factors as human presence and HVAC system contribute to a more stable climate.

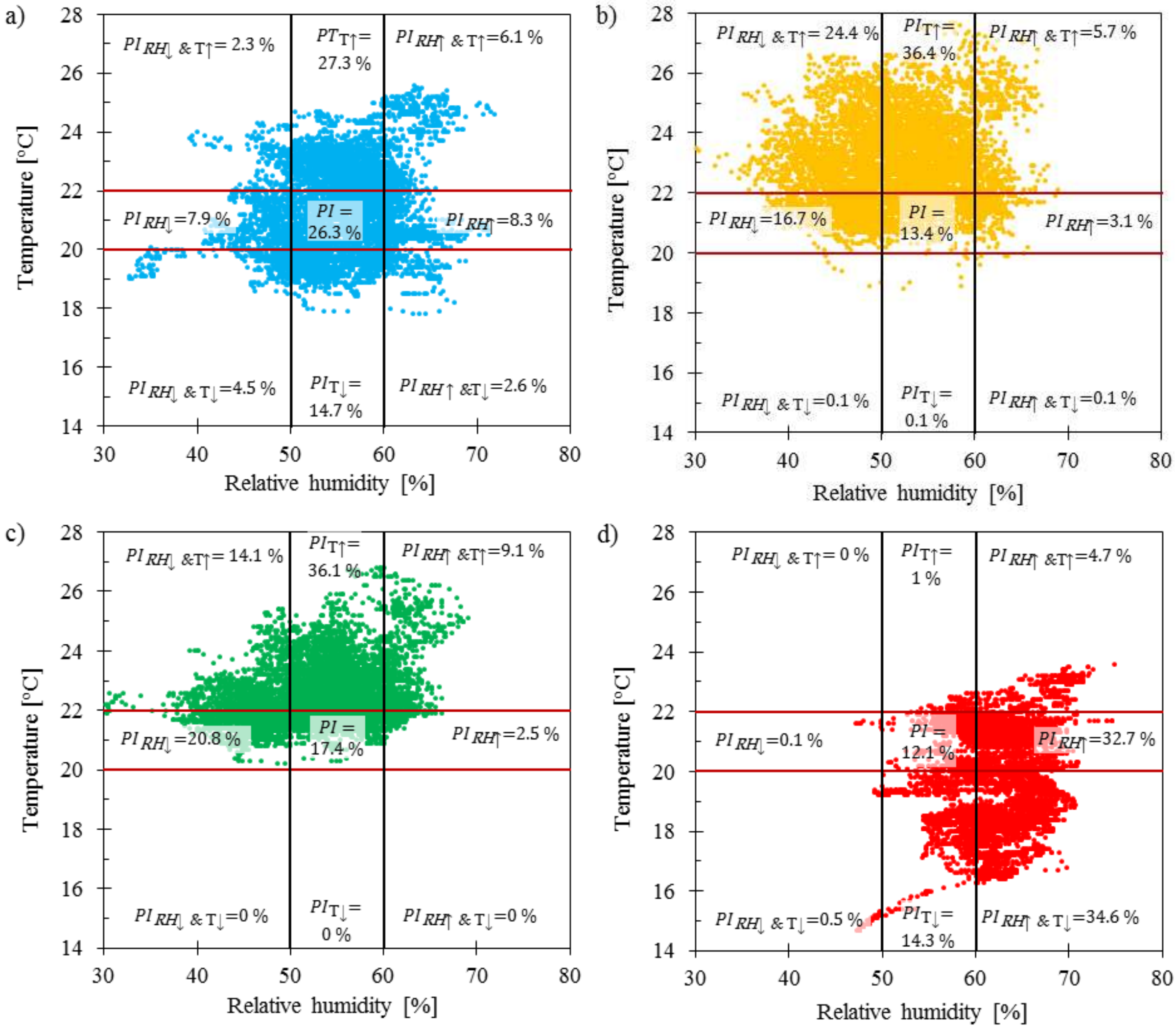

Figure 5.3. Performance index: a) room 12; b) room 25; c) room 41; e) chapel of Albertas

As regards the controlled rooms, it is possible to conclude that room 41 shows the more stable temperatures in terms of seasonal fluctuations, but the second worst results with regard to the short-term fluctuations of T and RH and in terms of RH seasonal fluctuations. Considering an equivalent influence of visitors, this fact can be only justified by the HVAC system since the room is located in an intermediate floor in which only one wall is exposed to outdoor and without windows open to outdoors. The room 12 presents the highest seasonal amplitude of T justifiable with its presence near the roof and with three exterior walls. As regard the other parameters, room 12 shows a reasonable stable condition. The worst case in terms of short-term fluctuations and seasonal amplitude of RH can be found in the room 25. This fact can be justifiable by the large number of windows that characterize the room.

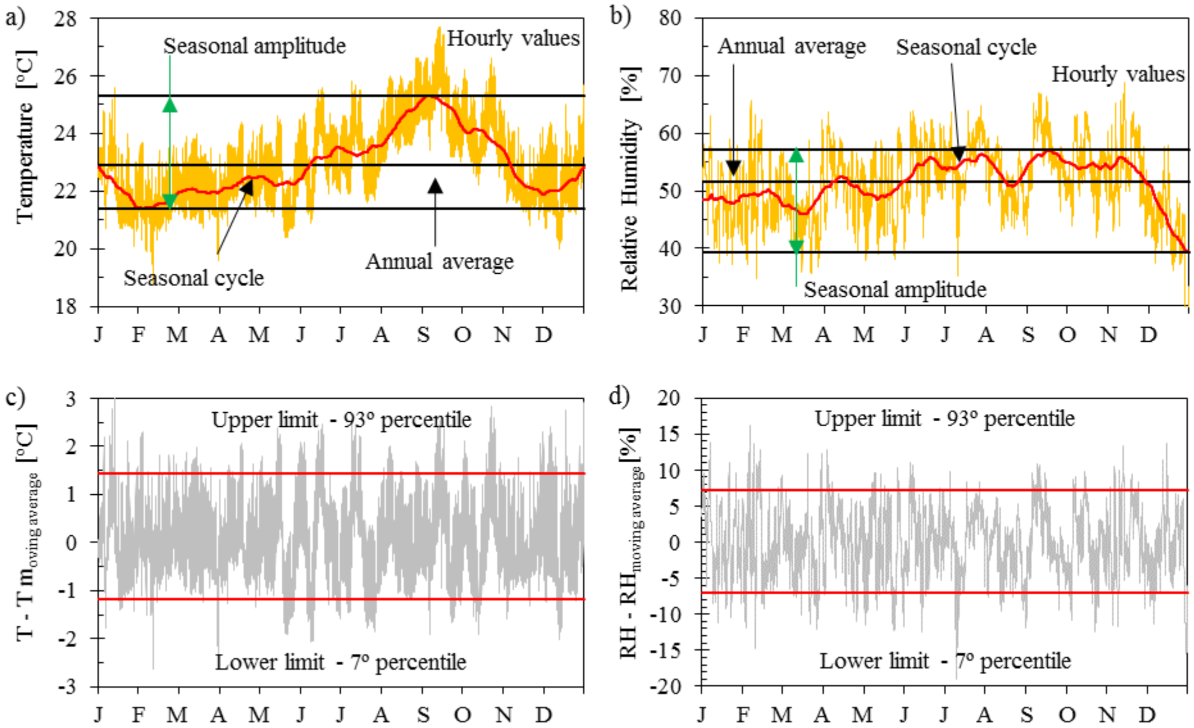

Figure 5.4. Calculating the seasonal amplitudes and typical short-term fluctuations for the room 25: a) hourly data, seasonal cycle, annual average and seasonal amplitude of T; b) hourly data, seasonal cycle, annual average and seasonal amplitude of RH; c) typical short-term fluctuations of T; d) typical short-term fluctuations of RH

Table 5.1. Annual average, seasonal fluctuations, daily cycles and performance index of T and RH

Room	Temperature				Relative Humidity				PI_{T+RH} [%]
	Mean [ºC]	Seasonal amplitude [ºC]	Short-term fluctuations [%]	PI [%]	Mean [%]	Seasonal amplitude [%]	Short-term fluctuations [%]	PI [%]	
Room 12	21.4	4.7	-0.8/+0.8	42.5	55.2	12.2	-6.4/+6.5	68.3	26.3
Room 25	22.9	3.9	-1.2/+1.4	33.3	51.5	17.5	-7.0/+7.2	49.9	13.4
Room 41	22.5	3.2	-0.7/+0.9	40.7	52.5	12.7	-6.4/+6.3	53.5	17.4
Chapel	19.9	6.3	-0.5/+0.5	44.9	62.1	5.6	-4.9/+5.1	27.4	12.1

5.3.2. Risk-assessment

The analysis of Figure 5.5 shows a general good behaviour in terms of mechanical response for all rooms. For the painted panels no risks were found, both for the wooden substrate (a) where the RH fluctuations remain in elastic response during all the year and for the pictorial layer (b) where the maximum difference between the full-response and the annual average of the panels never exceeds the safe-limit of 14 %.

Concerning the sculptures (c) it is possible to see a perfect behaviour in the chapel and for 99.7% of the time in the room 12, in 99.2 % in the room 25 and in the 99.4 % in the room 41. The RH fluctuations are not large enough to put the collections at risk. Finally, with regard to furniture (d), it was obtained a perfect response, where the climate does not lead to irreversible deformations both for the wood as for lacquer, with an elastic response during the whole year for the four rooms under analysis.

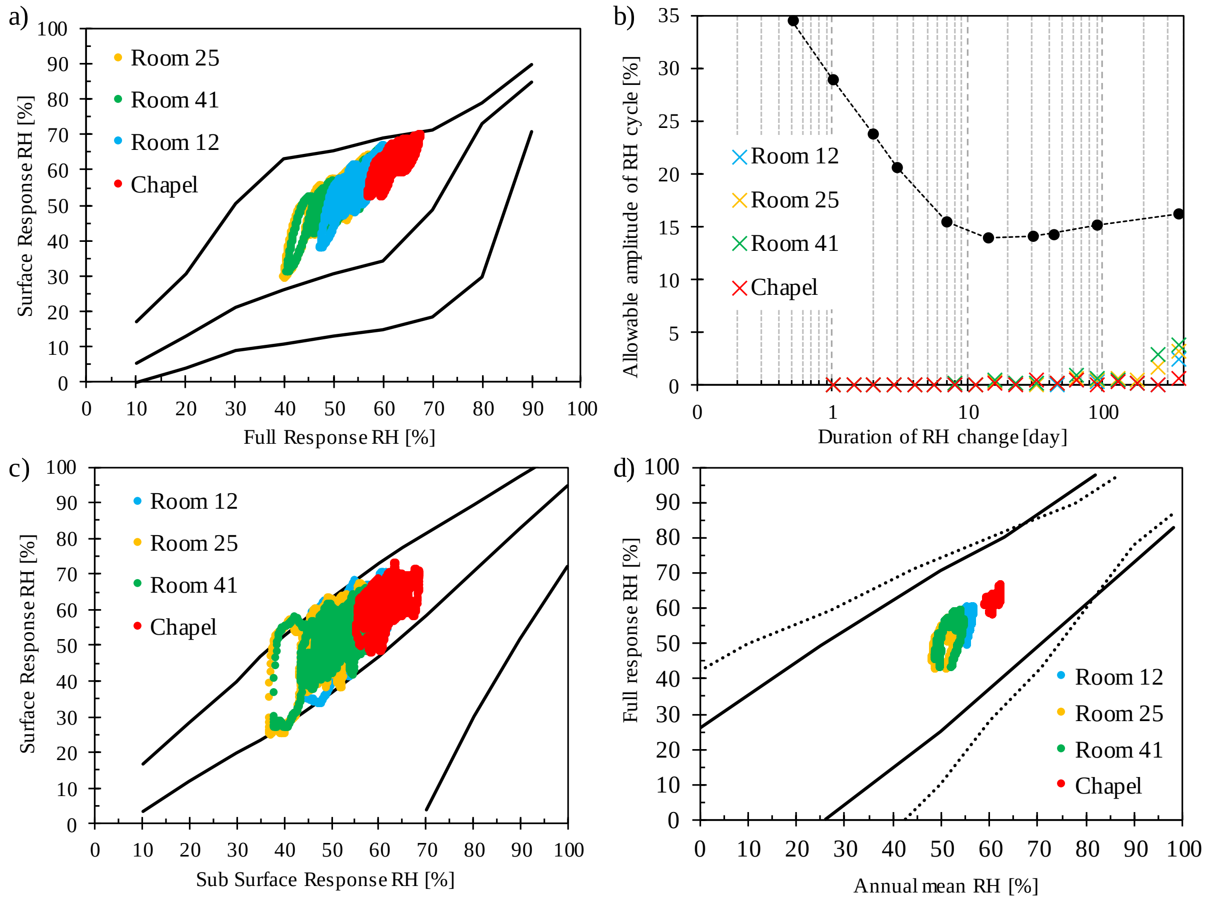

Figure 5.5. Mechanical risk-assessment: a) wooden substrate of painted panels; b) pictorial layer of painted panels; c) sculptures; d) furniture

The analysis of biological risk with the isopleth method for the substrate category I (Figure 5.6) allowed to conclude the absence of risk, since the pair T-RH never reaches or exceeds the limit isopleth, resulting in an MRF equal to zero. Considering the conservative approach used with the worst scenario (subtract type I) it is possible to verify the absence of any risk of spore germination.

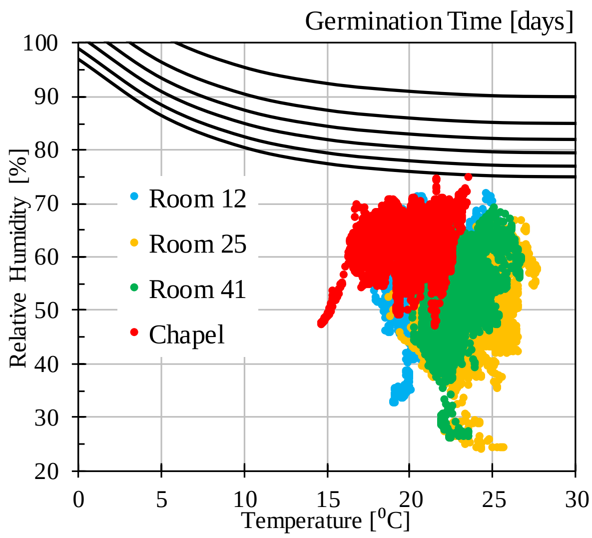

Figure 5.6. Biological risk-assessment: representation of the data records on the isopleth diagram

Although in this case the chemical degradation is not considered a major factor (given the nature of the exhibition), it was also evaluated for the four rooms to test the full method of risk-assessment verifying the risk for varnishes.

Analysing the LM for the four environments (Figure 5.7), it is possible to note that the worst results were obtained for the high temperatures of summer. The chapel, that usually presents lower temperatures, presents a slightly better response. Values of 0.76, 0.72, 0.73 and 0.75 were obtained for rooms 12, 25, 41 and Chapel, respectively, with regard to varnish degradation.

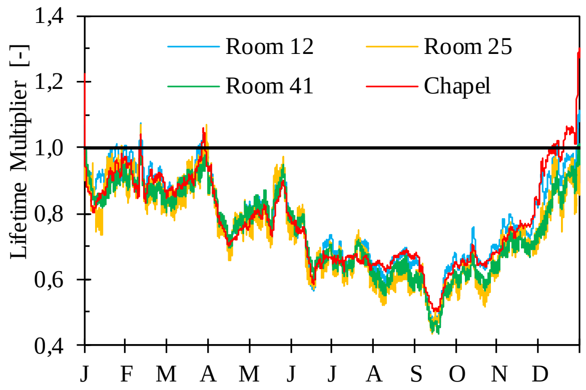

Figure 5.7. Chemical risk-assessment: lifetime multiplier for varnish

5.3.3. Thermal comfort

As regards the analysis of thermal comfort Figure 5.8 shows the different responses obtained in the four rooms. All the three climatized rooms met the comfort range at least in 98 % of the year denoting a good experience for the visitors. In general terms this analysis shows that the tight ranges of temperature fairly constant throughout the year met the comfort requirements in a high percentage of time.

Room 41 shows the more stable behaviour where the comfort target is met in 100 % of the open hours through the year. Room 25, which has the highest indoor temperatures, shows a less stable behaviour with the comfort being achieved in 98.2 % of the time. The high indoor temperatures are the main reason for no compliance of this target with 2 % of the measurements above the higher limit. Curiously the warm sensation was obtained both during winter and the summer. The climate of the room 12 met the comfort targets during 99.2 % of the year. During the remaining period, the interior temperature is below the comfort temperature.

The non-heated chapel shows a different behaviour with lower temperatures. For this room, the acceptance level is accomplished in 60.5 % of the time. The cold sensation is the reason for the discomfort felt in the chapel throughout the year.

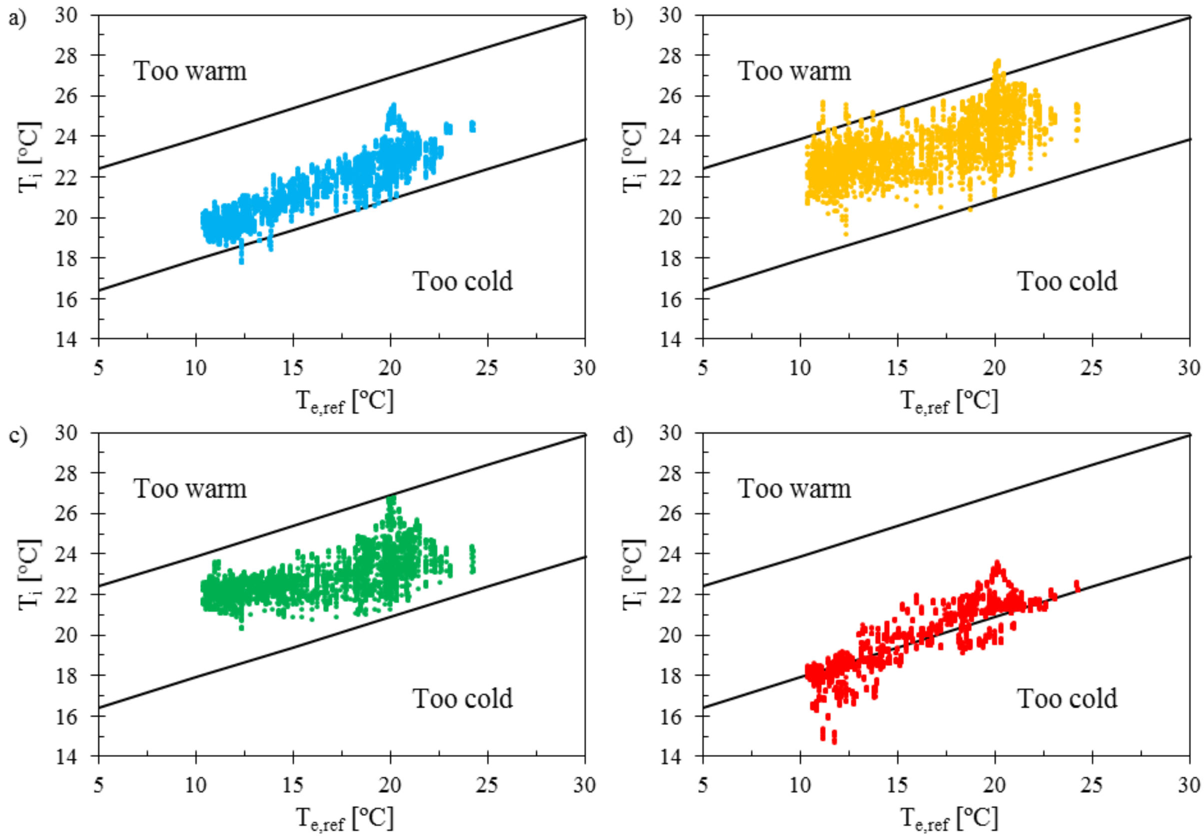

Figure 5.8. Thermal comfort evaluation: a) room 12; b) room 25; c) room 41; d) chapel

5.3.4. Global evaluation

To facilitate the perception of the results for any user, even for those less familiarized with the tools in use, it was decided to apply the classification proposed in 2.2.6 as shown in Table 5.2. Despite its application, it is always necessary to proceed to an individual analysis of each parameter to really understand the situation.

Table 5.2. Microclimatic classification of the recorded data

Room	PI [%]		Painted wood				Sculptures		Furniture		MRF		eLM		Thermal comfort
			Base		Pictorial								Varnish		
12	26.3	1	E	3	<14%	3	P: 0.3 %	2	E	3	0	3	0.76	2	99.2 %
25	13.4	1	E	3	<14%	3	P: 0.8 %	2	E	3	0	3	0.72	1	98.2 %
41	17.4	1	E	3	<14%	3	P: 0.6 %	2	E	3	0	3	0.73	1	100 %
Chapel	12.1	1	E	3	<14%	3	E	3	E	3	0	3	0.75	2	60.5 %

E: elastic response P: $_{x\%}$.: Plastic response in x % of time

The joint analysis of all surveys shows that although the limits are not met in a reasonable percentage of time, the results as far as conservation is concerned are very positive, except for chemical behaviour which is not a predominant issue in the analysed rooms. Besides that, the results of the chapel are quite significant. Despite the low-performance index, the high relative humidities and the dispersion of temperatures, a perfect classification for mechanical and biological risks was obtained. This result showed that the existence of tight limits is not always needed for a proper conservation. A comprehensive analysis of the performance index and the risk-assessment values show that the optimization of the climate may reduce the targets without jeopardizing the conservation. The visitors' comfort was not compromised in none of the analysed rooms.

5.4. Climate optimization

Whenever it is concluded that pre-defined limits are too stringent and/or not being met, it may be useful to proceed to climate optimization. However, this decision cannot be taken lightly and it must be sustained on environmental monitoring, risk-assessments and observation of the current state of the artefacts. After this evaluation is made, the direct application of limits and/or methodologies defined in studies sometimes carried out for different climates is not recommended unless previously validated [21].

In this case, it was found that despite the limits imposed by the museum are not met in a significant percentage of time the response of the collections was positive. With regard to thermal comfort, it was found that although the limits imposed by the museum not being fulfilled in a percentage of satisfactory time, the comfort of the visitors is not affected.

The biological and mechanical risks are mainly influenced by RH, being only necessary to avoid low temperatures to prevent the embrittlement of materials. A minimum value of 12.8 ºC (temperature of the glass transition for the acrylic paints) should be sufficient to guarantee the safety of collections [22]. On the other hand, the thermal comfort is strongly influenced by temperature.

Despite the use of damage functions to evaluate the risk by considering the response time of the collections (only valid for undamaged objects) and the yield strain criterion, it was decided to optimize the RH set-point to minimize the mechanical and biological risks by using a statistical method based on the historical climate, considering the effect of possible past damages. This method, called FCT-UNL [23], is supported by the concept of acclimatization that considers the adaptation of the artefacts if exposed for long periods (usually a period of at least one year) to the new conditions, reaching a new equilibrium [24] and by the concept of proofed fluctuations, which assumes that the risk of new mechanical damage in the future is negligible if the past fluctuations were not exceeded [25].

In the concept of proofed fluctuations, fatigue or relaxation of the materials may reduce the limits for the safe fluctuations and the concept is no longer applicable for the cases in which the materials were submitted to conservation treatments that "erase" the effects of the past fluctuations [25].

The FCT-UNL methodology allows to reduce the past fluctuations in terms of seasonal and short-term fluctuations by not considering the extreme registered values, overcoming the issues related to fatigue and relaxation. To deal with past conservation treatments the method should be used in parallel with other risk assessment methods, such as the damage functions used in this work, extending its scope and satisfying the needs of both old and new objects.

This methodology that was designed for temperate climates is composed by two classes and allows to define new targets based on historic climates; the application is summarized in Table 5.3. For the current case, it was decided to apply class 1 that also considers the biological issues and tries to reduce the mechanical risks allowing a maximum fluctuation of RH around the annual average of ± 15 % and imposing a minimum limit of 35% RH to avoid the materials embrittlement. Despite the method can also be applicable to temperature, it was decided to only use the RH specifications.

Table 5.3. Application of the step-by-step methodology proposed in 4.4.2 to the four room of the NMAA to prevent the mould germination

Month	T_e [ºC]	T_i [ºC]				$RH_{i.max}$ [%] – Substrate type II			
		Room 12	Room 25	Room 41	Chapel	Room 12	Room 25	Room 41	Chapel
January	12.2	19.8	22.1	22.0	18.3	71	67	68	73
February	11.5	19.4	21.5	21.5	18.1	70	67	67	72
March	12.9	20.4	22.0	21.9	18.4	71	68	69	73
April	15.3	21.2	22.3	22.1	19.5	72	71	71	75
May	17.8	21.2	22.2	21.7	19.7	76	74	75	78
June	19.1	22.6	23.2	22.5	20.9	76	75	76	78
July	20.4	22.5	23.3	22.6	21.4	77	76	77	79
August	20.5	23.0	24.5	23.4	21.4	77	75	76	79
September	19.6	23.7	25.1	24.7	22.3	75	73	73	77
October	19.1	22.4	24.1	23.6	21.6	76	73	74	77
November	13.9	20.6	22.3	22.3	19.8	71	69	69	73
December	11.5	19.6	22.2	22.1	16.9	70	67	67	74
					Minimum	70	67	67	72

To apply the 1st class of the FCT-UNL methodology, the first step is to define the maximum RH that does not cause the mould germination. The methodology described and exemplified in 4.4.2 was adopted. The monthly averages of the recorded indoor climate were calculated to apply the method, while the exterior conditions were obtained from the Portuguese Institute for Sea and Atmosphere (IPMA) for the Geofísico weather station. A thermal resistance of 0.56 m^2.ºC/W for the external walls and the outer and inner surface thermal resistances of 0.04 m^2.ºC/W and 0.25 m^2.ºC/W, respectively, were considered. The isopleth for substrate II to obtain the maximum admissible RH at the surface was used since the walls are plastered with mineral materials (see Figure 4.6). The summary results of the step-by-step method can be seen in Table 5.3 for the four rooms under analysis. From a conservative point of view, the minimum RH should be used for each of the rooms: 70% RH for the room 12; 67% RH for the rooms 25 and 41 and 72% RH for the chapel. For more details about the application of the method see 4.4.2.

From this point it is possible to apply the statistical analysis referring to class 1 for the rooms under analysis: Room 12 - Figure 5.9; Room 25 - Figure 5.10; room 41 - Figure 5.11; the chapel - Figure 5.12.

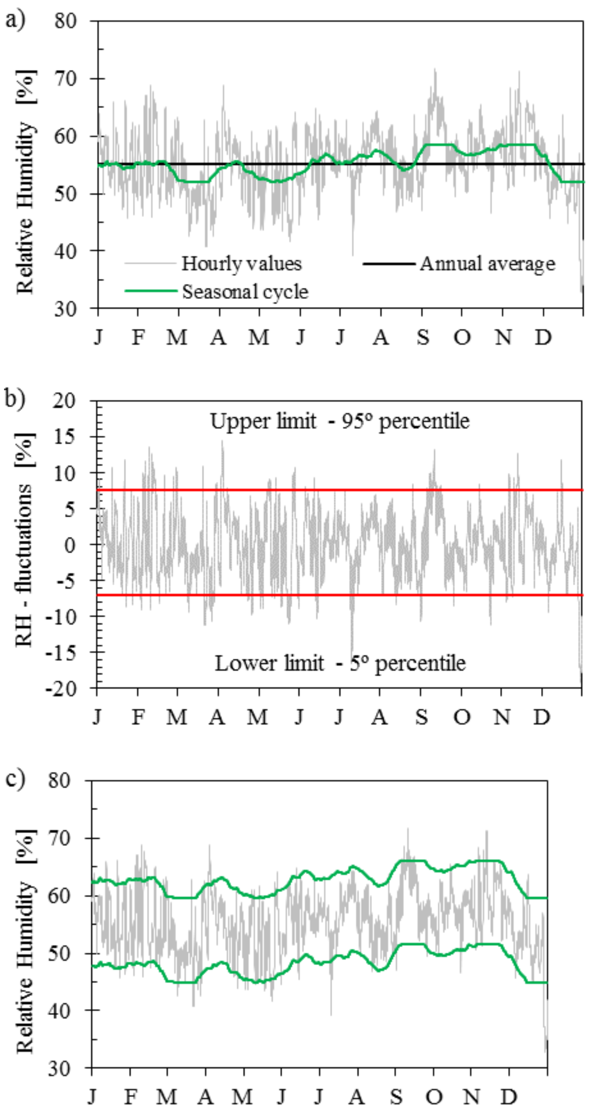

Figure 5.9. Application of the FCT-UNL class 1 methodology to the room 12: a) seasonal cycles; b) short-term fluctuations; c) final sustainable targets

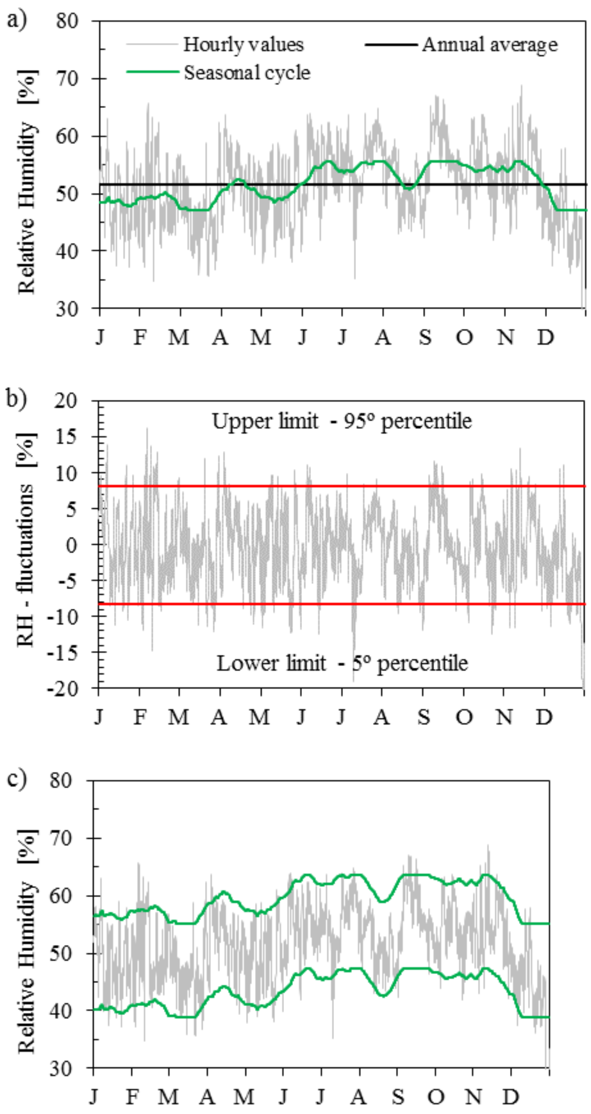

Figure 5.10. Application of the FCT-UNL class 1 methodology to the room 25: a) seasonal cycles; b) short-term fluctuations; c) final sustainable targets

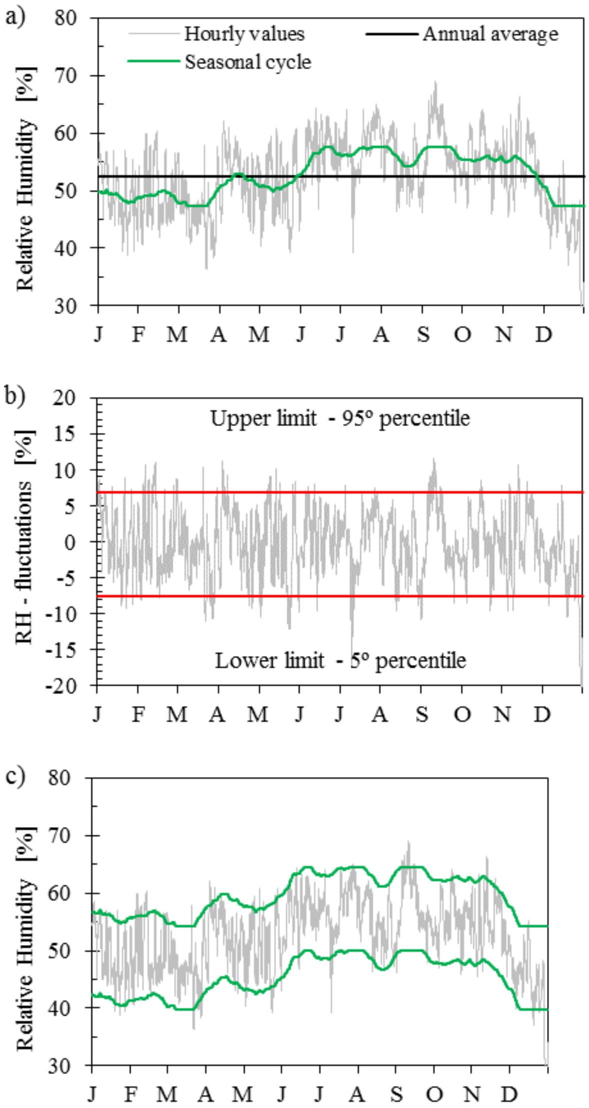

Figure 5.11. Application of the FCT-UNL class 1 methodology to the room 41: a) seasonal cycles; b) short-term fluctuations; c) final sustainable targets

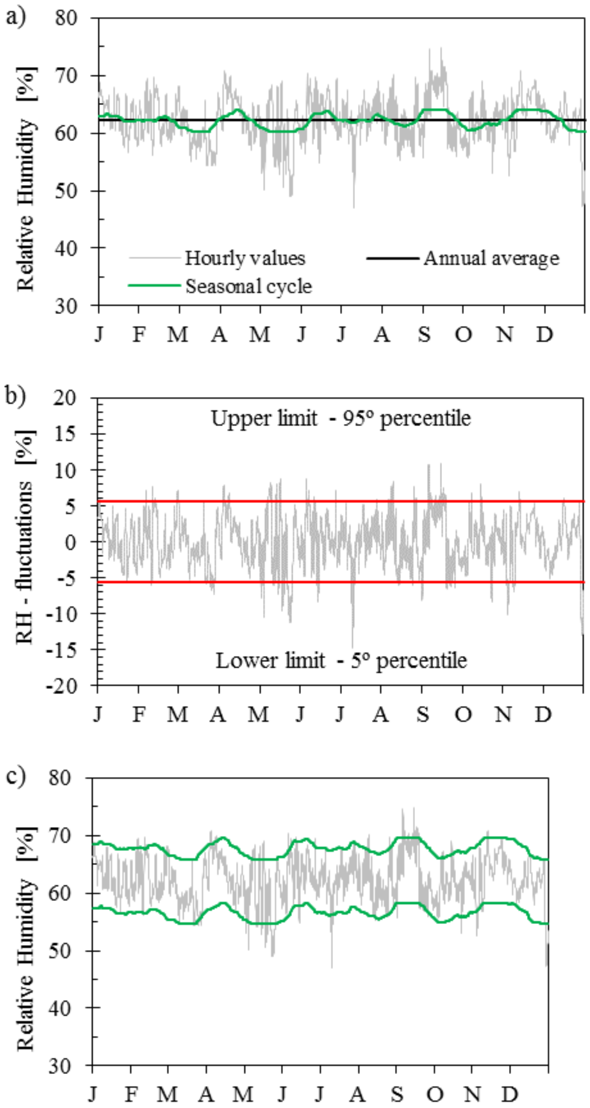

Figure 5.12. Application of the FCT-UNL class 1 methodology to the chapel: a) seasonal cycles; b) short-term fluctuations; c) final sustainable targets

The temperature was optimized according to the thermal comfort of visitors, adopting the adaptative model defined by Matias [20] for buildings with HVAC systems. Since it is a large national museum, it was decided to apply the model for the highest acceptance level: 90%. The graphical application of the model can be seen in Figure 5.13. The model can be applied from the equations (5.1) and (5.2). For more detailed information please see 2.3.4.

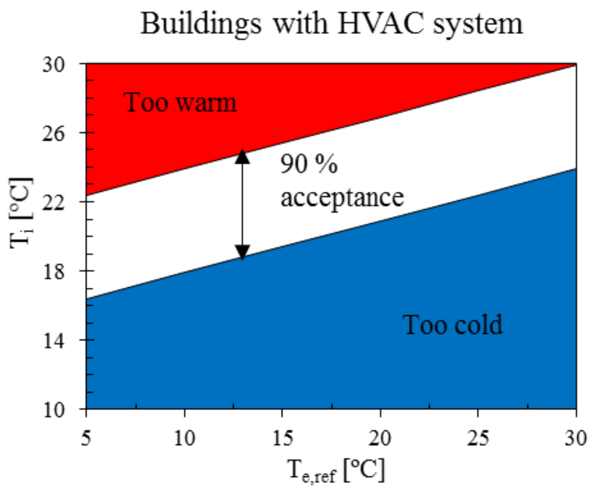

Figure 5.13. Adaptive model of thermal comfort assessment according to Matias for climatized buildings for an acceptance level of 90 % [20]

$$\text{Upper limit: } 0.30 \cdot T_{e.ref} + 20.9 \quad (5.1)$$

$$\text{Lower limit: } 0.30 \cdot T_{e.ref} + 14.9 \quad (5.2)$$

The $T_{e.ref}$ is the reference outdoor temperature and it can be determined by:

$$T_{e,ref} = \frac{T_{e,i-1} + 0.8 \cdot T_{e,i-2} + 0.6 \cdot T_{e,i-3} + 0.5 \cdot T_{e,i-4} + 0.4 \cdot T_{e,i-5} + 0.3 \cdot T_{e,i-6} + 0.2 \cdot T_{e,i-7}}{3.8} \quad (5.3)$$

where $T_{e.i-1}$ is the arithmetic mean temperature of the day before that under analysis (24 h) and so on.

Since the adopted adaptative model of thermal comfort is only dependent on of the outdoor temperature, the targets are the same for all the rooms. The final result can be seen in Figure 5.14.

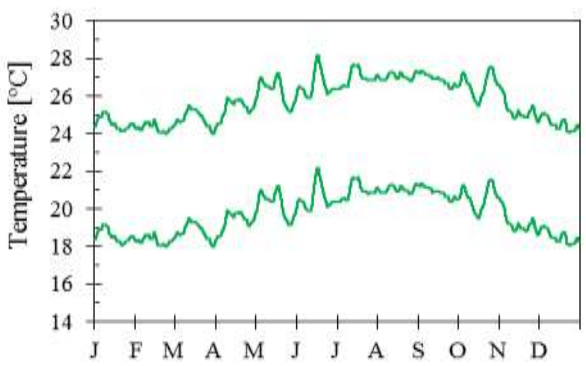

Figure 5.14. Temperature optimization for a 90 % acceptance level

The new targets are summarized in Table 5.4 in a more intuitively form distributed for each season. Making a final analysis with the annual registers it was possible to find limits for the temperature of 18-28 ºC for the three controlled rooms. As regards the relative humidity the limits were 45-66 % for the room 12, 39-64 % for the room 25 and 40-64 % for room 41. For the chapel, only RH limits were defined since the room is naturally ventilated and closed to visitors: a RH target of 55-70 % was obtained.

These fewer demanding targets evidence a high potential of energy reduction and control the biological risk while keeping the actual level of mechanical risk (with some improvements by the exclusion of the extreme values) and guaranteeing the thermal comfort at a level of 90 % of acceptance.

To increase the reliability of results of similar processes it is recommended to use records of a reasonably long period to ensure that the decisions are not based on unusual years (a period of 5 years is recommended). Before changing the set-points it is absolutely necessary to verify the capacity of the HVAC system to meet the new targets to obtain the expected results in terms of energy reduction, conservation and comfort. The temperature setpoint is only intended to guarantee the human comfort, so if any room is closed to the public these limits can be ignored. The intermittent heating, switching on only during the visiting periods can also be considered. However, it should be noted that this greater degree of freedom can lead to a less stable climate and influence the relative humidity. Any changes in order to reduce costs should be studied and implemented only if it is found that it does not introduce risks to the collections.

Table 5.4. The result of the optimization process

		Temperature [°C]						Relative Humidity [%]							
Room	Seasons	18	20	22	24	26	28	40	45	50	55	60	65	70	75
12	Winter														
	Spring														
	Summer														
	Autumn														
25	Winter														
	Spring														
	Summer														
	Autumn														
41	Winter														
	Spring														
	Summer														
	Autumn														
Chapel	Winter														
	Spring														
	Summer														
	Autumn														

5.5. Conclusions

This work brought together several tools useful for climate management in museums. It was noted the importance of a detailed study of the situation with data collection over a sufficiently long period in order to allow strong conclusions. The importance of the evaluation of HVAC effectiveness to meet the predefined values, risk assessment of the collections, comfort level and a reasoned optimization based on the indoor climatic conditions was also emphasized.

The scientific development of the preventive conservation field has shown that the application of stringent targets cannot be sustained by conservation needs and can be unsustainable for the management of museums. However, they are still frequently used as confirmed by the case discussed.

In the current work the ineffectiveness of the HVAC system to keep the limits was noted, but even so, the results from the risk assessment were quite low. Thus, it was possible to test and validate the application of a dynamic optimization method to improve better conditions for the conservation and thermal comfort, which results in less demanding targets, evidencing the influence of a detailed process to obtain energy reduction without jeopardizing the conservation and thermal comfort.

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6. Sustainable rehabilitation of museums

6.1. Introduction

The use of museums housed in historical buildings allows the combination of the intrinsic value of the collections with the historical and architectural values of the building itself, thus contributing to the increase of the cultural and touristic interest of the space. However, this combination of interests may be a threat for the conservation of buildings and collections, to visitors' comfort and for environmental and economic sustainability, since historical buildings often have a poor hygrothermal response.

These buildings, although usually made with thick elements with high thermal inertia, very effective in damping and delaying the heat flow, are characterized by elements with low thermal resistance, poor quality windows, low hygroscopic inertia and low area/volume ratio in the noblest buildings, which renders them ineffective in maintaining a stable indoor climate adequate for the conservation, comfort and energy efficiency issues [1].

Traditionally comfort and conservation impose the use of tight ranges of temperature and relative humidity [2-6], sometimes with no scientific justification. Take the case of the National Museum of Ancient Art of Lisbon, which imposes a tight climate control of 20-22 °C and 50-60% RH even though the building is unable to comply with it in percentage of time that can be considered satisfactory [2]. These constraints coupled with the poor response of ancient buildings lead to high energy consumptions.

Rising environmental concerns and the publication of directives in the pursuit of greater sustainability and reduction of global warming that emerged over the last two decades have led to the hygrothermal rehabilitation of buildings which significantly contribute to the total energy consumption in Europe [7]. The European energy policy has become more demanding and the European Union (EU) has taken energy efficiency as an urgent need developing some ambitious directives aiming to achieve the energy reduction in the building sector, where it is possible to highlight the 2010/31/CE [8] which is very demanding and binding on new buildings or great rehabilitations while leaving cultural heritage buildings out given their needs and specificities, namely the risk of loss of identity and historical quality induced by invasive interventions [6,9].

Despite these directives, the evolution of energy consumption in the services sector, including museums, has not followed the global trend and an increase of 23.3% of the final energy consumption from 2000 to 2016 in the EU28 was found; in Portugal, for example, the increase was even more significant, reaching a value of 38.8% [10].

The ineffectiveness of European policies to reduce energy consumption in the services sector in general, and in particular on cultural heritage, cannot be solved by the publication of new directives focusing solely on energy, since the patrimonial character associated with these buildings does not allows it, thus enhancing the need to find a balance between conservation, comfort and energy [11] rather than an incessant search for the numbers. Despite all the evolution in the use of passive techniques in the design of new buildings and in rehabilitation, the intervention in classified buildings is not obvious and impossible to standardize [9,12,13]. Due to the impossibility of changing the original architecture [14,15], quite often the change in the climate control strategy, the windows refurbishment or in some cases the use of thermal insulation by the interior are some of the most obvious solutions to implement.

The impact of the thermal rehabilitation and the climate control strategies on cultural heritage has been studied by several authors [16-22]. Interesting results were obtained by Kramer *et al.* [16] for example, achieving energy savings of around 77 % for a Dutch museum by changing the original constant set-point of 21ºC and 48 %RH by a less demanding RH target – 40-50 % RH; and a dynamic temperature set-point based on an adaptative thermal comfort model and in free floating at the nigh time. This new scenario allows to obtain a high energy reduction wile significantly improving the conservation and thermal comfort. At the level of thermal rehabilitation, the studies developed by Wang et al. [21] at the National Gallery of Edinburgh or by Sciurpi et. al [17] at the "La Specola" museum in Florence can be highlighted. Wang *et al.* [21] achieved energy savings of around 15 % in the heating needs, 28% in the cooling needs, 4% in the humidifying needs and 34% of the dehumidifying needs by replacing the original skylight of a model of the National Gallery of Edinburg with a U_W of 5.67 W/m^2.ºC by a new solution with 2.25 W/m^2.ºC. For a museum located in Florence, Sciurpi *et al.* [17] achieved energy savings of around 51 % in a certain room by replacing the original windows with U_w=4.96 W/m^2.°C and SHGC = 0.87 for windows with U_w = 2.36 W/m^2.°C and SHGC = 0.21.

In this chapter, a generic room of the National Museum of Ancient Art of Lisbon is simulated for 15 different European cities. It is intended to highlight the differences in energy consumption and consequently the need to use different rehabilitation strategies adapted to each climate.

In a second phase, the impact of the windows and opaque envelope refurbishment in parallel with the use of two different climate control strategies were evaluated for the Portuguese case through a sensitivity study composed by 128 different combinations. In addition to the statistical analysis of the impact of each scenario, the result of a purely mathematical optimization is compared with the results of an economic feasibility study based on the concept of optimal cost. The result of this chapter is to break down various taboos in energy rehabilitation, showing that interventions should be designed according to the local needs of each building rather than using standard solutions.

6.2. Energy requirements according the museum’s location

6.2.1. General overview

The energy and environmental concerns highlighted over the last decades, the easier access to information and its dissemination have contributed to an internationalization of the architecture and rehabilitation techniques that often do not meet the specific needs of the buildings given their use and location.

The European energy policy has become more demanding, requiring the thermal improvement of new buildings and major rehabilitations, while leaving cultural heritage buildings out. One of the main measures is related with the reduction of the thermal transmittance of the external envelope to values that may prove to be too demanding for the countries of southern Europe - for example in Lisbon (Portugal) a maximum U-value of 0.70 $W/m^2.ºC$ is imposed for walls in new service buildings and 0.50 $W/m^2.ºC$ is imposed for new dwellings [23].

Trying to prove that the rehabilitation solutions cannot be generalized to all climates and situations, a simulation model of a generic room of the National Museum of Ancient Art of Lisbon was developed with the software WUFI®Plus and simulated for 15 European cities. The WUFI®Plus v3.1.1.0 [24] is an hygrothermal simulation software based on the calculation model presented in the Ref. [25]. The software has been extensively tested and validated [26-28] and has several applications for cultural heritage [28-31], in particular within the European project "Climate for Culture" [32].

The model was simulated for the climate control strategy used by the National Museum of Ancient Art which is in accordance with the more conservative values used in museums: 20-22 ºC and 50-60% RH.

The 15 cities chosen for this analysis, their geographical location and the Köppen classification can be seen in Figure 6.1. Köppen's classification was defined about 100 years ago and remains one of the most used classifications in climatological studies around the world. This classification defines several types of climates based on the average monthly values of precipitation and temperature [33]. In this chapter the climates Csa, Csb, Cfb and Dfb are approached. The temperate climates are classified as type C and characterized by an average temperature of the coldest month between 0 and 18ºC. Cold climates are classified as type D and present an average temperature of the coldest month below 0°C. The subtype "s" shows the presence of a markedly dry periods during the summer and the subtype "f" shows the absence of a dry season. The last letter of the classification depends on summer: the subtype "a" characterizes hot summers with the average temperature of the hottest month exceeding 22°C and the subtype "b" characterizes mild summers with the average temperature of the hottest month equal or lower than 22°C. Thus, the Csa classification applies to temperate climates with dry and hot summers; the Csb classification applies to dry temperate climates with mild summers; the Cfb classification applies to temperate climates without dry season and with mild summers; and the Dfb classification applies to cold climates without dry season and mild summer.

For Lisbon a test reference year (TRY) was developed in accordance with the international standard ISO 15927-4 [34] for the hourly climatic data provided by the Portuguese Institute for Sea and Atmosphere (IPMA) for the Geofisico weather station from 2005 to 2015. The files include the atmospheric pressure, temperature, relative humidity, global radiation, wind direction, wind speed and rain.

	City	Köppen class
1	Lisbon, Portugal	Csa
2	Oporto, Portugal	Csb
3	Seville, Spain	Csa
4	Madrid, Spain	Csa
5	Paris, France	Cfb
6	Florence, Italy	Csa
7	Rome, Italy	Csa
8	Athens, Greece	Csa
9	Amsterdam, The Netherlands	Cfb
10	Copenhagen, Denmark	Cfb
11	London, United Kingdon	Cfb
12	Berlin, Germany	Cfb
13	Kraków, Poland	Dfb
14	Vienna, Austria	Cfb
15	Oslo, Norway	Dfb

Csa – temperate with dry or hot summer	Csb – temperate with dry or temperate summer
Cfb – temperate with a dry season and temperate summer	Dfb –cold without dry season and temperate summer

Figure 6.1. Geographical location of the 15 European cities studied

The development of a TRY file intends to obtain a representative year for a long-term climatic series. The standard defines by default that TRY must consider the temperature, relative humidity and global radiation (TRY_2) as the main variables because it is intended to provide a tool to aid in energy calculation. Since this thesis also intends to address issues related to hygrothermal analysis, the TRY file included temperature, relative humidity, global radiation, wind direction and rainfall (TRY_1). The comparison between the 11 years of the data provided by the IPMA and the two developed TRY files can be seen in Table 6.1. Ultimately, the TRY_1 was adopted to perform the purposed study.

The Oporto weather file was provided by the Laboratório de Física das Construções (LFC) of the Faculty of Engineering of the Oporto University. The weather files of the remaining 13 cities under analysis were taken from the EnergyPlus weather database [35]. These files represent typical climatic years for energy calculations mostly of type IWEC (as a result of the ASHRAE Research Project 1015 by Numerical Logics and Bodycote Materials Testing Canada for ASHRAE Technical Committee 4.2 Weather Information) - Vienna, Berlin, Copenhagen, Paris, London, Athens, Amsterdam and Oslo, and by files created by agencies of each country such as the SWEC (Grupo de Termotecnia of the Escuela Superior de Ingenieros in Seville) - Madrid and Seville; IGDG (Italian Climatic data collection "Gianni

De Giorgio") - Rome and Florence; and IMGW (Polish Ministerstwo Infrastruktury) – Krakow.

Table 6.1. TRY development for Lisbon

Year	Temperature [Cº]			Relative Humidity [%]			Sum Global radiation (MWh/m²)	Mean Wind direction (ºC)	Mean Wind speed (m/s)	Sum Rain (mm)
	Mean	Max	Min	Mean	Max	Min				
2005	16.9	38.2	0.3	66	100	11	1.76	179	3.46	455
2006	17.4	36.8	1.9	73	100	18	1.81	207	3.23	994
2007	16.8	37.2	3.7	72	100	18	1.91	209	3.50	455
2008	16.7	34.4	5.6	71	100	21	1.84	210	3.50	658
2009	17.5	34.9	1.4	68	98	13	1.88	226	3.22	717
2010	17.1	38.7	3.1	72	100	17	1.83	220	3.34	968
2011	17.6	35.5	4.1	71	100	23	1.96	213	3.40	660
2012	16.9	36.2	2.9	70	100	16	1.96	223	3.24	637
2013	16.9	38.6	2.1	71	100	19	1.86	229	3.20	743
2014	16.2	33.7	3.6	75	100	18	1.67	227	3.04	1165
2015	17.4	35.2	2.4	70	99	18	1.76	218	3.69	405
TRY_1	16.9	36.2	5.2	72	100	21	1.86	221	3.36	754
TRY_2	16.9	36.2	4	70	100	13	1.85	228	3.36	702

The climatic classification according to Köppen, the annual averages of temperature and relative humidity, the annual global solar radiation and the typical range between the 5th and 95th percentile for temperature and relative humidity for the 15 cities can be seen in Table 6.2. It was decided to characterize the climatic extremes according to the percentiles instead of using the absolute maximum and minimum values because it is considered of greater utility for the typical understanding of the climate of each city.

It is easy to understand the differences between the cities. These differences are mainly evidenced for the temperature and solar radiation; see the case of Lisbon with typical temperatures between 8.7 and 26.4°C, an annual average temperature of 16.9°C and an annual global solar radiation of 1863 kW/m^2 while, for example, Amsterdam presents typical temperatures between 0.2 and 20°C, an annual average temperature of 10°C and an annual global solar radiation of 982 kW/m^2. These differences make it clear that energy and architectural needs cannot be defined in the same way.

Table 6.2. Climatic characterization of the fifteen cities under analysis

#	City	Köppen class	Temperature [ºC]			Relative Humidity [%]			Global radiation [kW/m²]
			Mean	Percentile		Mean	Percentile		
				5º	95º		5º	95º	
1	Lisbon	Csa	16.9	8.7	26.4	70	38	96	1863
2	Oporto	Csb	15.4	7.3	24.9	72	36	100	1229
3	Seville	Csa	18.3	7.5	32.2	63	28	95	1786
4	Madrid	Csa	14.3	3.9	28	56	25	86	1559
5	Paris	Cfb	11.1	0.6	23	77	46	99	1068
6	Florence	Csa	14.2	1.2	27.8	73	38	97	1142
7	Rome	Csa	15.3	3.8	28.0	75	43	97	1279
8	Athens	Csa	17.9	7.3	29.9	62	35	86	1670
9	Amsterdam	Cfb	10.0	0.2	20.0	84	57	99	982
10	Copenhagen	Cfb	8.3	-1.6	18.8	77	49	96	980
11	London	Cfb	10.2	0.4	20.8	79	49	97	1010
12	Berlim	Cfb	9.8	-1.4	22.8	74	41	95	985
13	Kraków	Dfb	8.3	-5.7	22.3	79	48	96	1045
14	Vienna	Cfb	10	-3.2	24	72	43	95	1122
15	Oslo	Dfb	6.9	-6.6	19.7	74	36	98	879

6.2.2. Simulation model

6.2.2.1. Geometry and envelope

A computational model of a generic room of the National Museum of Ancient Art of Lisbon (NMAA) south-oriented with ca. 590 m^3 (22.5 x 7.5 x 3.5 m^3) was used (see Figure 6.2). All surfaces were considered adiabatic except for the south façade.

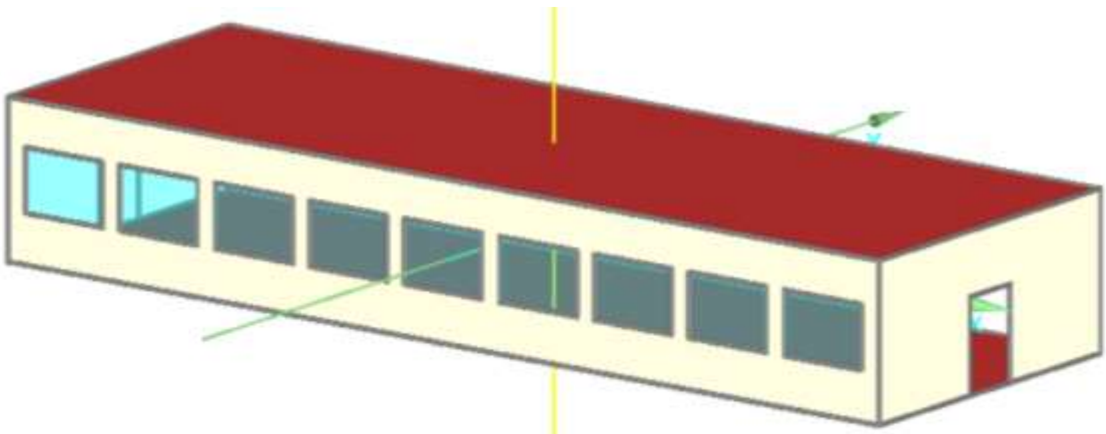


Figure 6.2. Model geometry

The building is characterized by mortared limestone walls with lime renderings on both sides with a total thickness of 0.90 m. The reinforced concrete floor has a wood flooring layer on top. The room is composed by nine aluminium frames double glazed windows resulting in a ratio of 0.15 between the window and the floor area and in a ratio of 0.31 for the relation between the windows area and the total area of the southern façade. The windows include interior clear and transparent shading elements, returning a total solar heat gain coefficient (SHGC) of 0.38 [36]. Usually, the SHGC is presented for the set of windows and shading elements. Dividing the global SHGC by the SHGC of the glazed (here named as $SHGC_g$), a valid approximation can be obtained for the theoretical SHGC of the shading elements (here named as $SHGC_s$). For the reference case, the windows present a $SHGC_g$ of 0.75. Consequently, dividing the global SHGC of 0.38 by the $SHGC_g$, a theoretical value of 0.51 is obtained ($SHGC_s$). This operation is particularly interesting for the cases in which it is desired to evaluate different scenarios. Multiplying the $SHGC_v$ by the $SHGC_s$ of each shading element allows to obtain the global SHGC.

The assemblies of all considered building elements (i.e. exterior and interior walls, the interior ceiling and floor and windows) as well as the respective properties of the materials can be seen in Table 6.3. The materials properties were collected from the refs. [37,38].

Table 6.3. Assemblies and respective material properties used in the model [37,38]

Building component	Materials	d [m]	λ [W/m.K]	ρ [kg/m³]	C [J/kg.K]
Walls Outside → Inside	Lime mortar	0.03	0.70	1785	850
	Mortared limestone	0.84	1.76	2122	850
	Lime mortar	0.03	0.70	1785	850
Ceiling Outside → Inside	Wooden layer	0.02	0.15	740	1400
	Concrete	0.25	1.70	2322	850
	Lime mortar	0.03	0.70	1785	850
Floor Outside → Inside	Lime mortar	0.03	0.70	1785	850
	Concrete	0.25	1.70	2322	850
	Wooden layer	0.02	0.15	740	1400
Windows	Double gazed aluminium frames		U_w=3.63 W/m².ºC		SHGC=0.38

6.2.2.2. Internal gains

The information published on the NMAA website made it possible to estimate that each visit takes an average of nine minutes per room. Considering that the museum is open to the public for 8 hours a day and 308 days a year and adopting the annual average number of visitors from the last 5 years, an average occupancy of 10 visitors per hour was obtained.

For human occupancy, an average metabolic rate of 1.4 met was estimated assuming 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 European average male adult [39] it is possible to obtain the heat released per occupant. Since the heat released varies according to gender and age, a group divided equally among men, women and children were considered. Considering that the amount of heat released by women is 85% of men and by children is 75 % according to [40], an average value of 127 W/visitor was obtained. The total heat was divided into sensible and latent heat based on the polynomial equation used by the EnergyPlus software [41] as a function of total heat and ambient temperature (a value 20ºC was considered), obtaining 88 W of sensible heat (60% emitted by radiation and 40% by convection according to the recommendation of [40] for typical office conditions) and 39 W of latent heat. A water vapour production rate of 61 g/h per occupant was obtained through the quotient between the latent heat (W) and the value corresponding to the water evaporation enthalpy (2257 J/g [42]). A CO_2 generation rate of 0.01872 m^3/h per person was adopted in accordance with the ref. [43]. At 21ºC and 1 atm, this value can be converted to 34 g/h [44].

According to the Portuguese transcription of the European directive 2010/31/CE [8], a maximum lighting power density (LPD) of 2.4 (W/m^2)/100 lux [23] was applied. For an illuminance of 200 lux adequate for collections insensitive to light degradation [45,46], an LPD of 4.8 W/m^2 is obtained.

6.2.2.3. Ventilation

The choice of a suitable ventilation is crucial for heritage sustainability. However, this management should be based on sound fundamentals, since ventilation has a major impact on climate stability and energy consumption and depends directly on the number of visitors. The indoor air quality (IAQ) theory can be a useful management tool to estimate the required ventilation according to the occupancy.

The standard ASHRAE 62.1 standard [47] which specifies the minimum airflow and other measures to ensure indoor air quality to an acceptable level for humans and to minimize health risks was adopted to define the ventilation to be used. This standard considers the IAQ as acceptable when the air contains no known contaminants at harmful concentrations and where a substantial majority of exposed people classify the air as comfortable (80% or more). According to the *Ventilation Rate* Procedure, ASHRAE 62.2 recommends that the total ventilation for museums should be determined from the use of the equation (6.1) considering an airflow of 13.68 m^3/h per person and 1.08 m^3/h per square meter of floor area.

$$q_{tot=n\cdot q_p+A\cdot q_b} \tag{6.1}$$

where n is the number of people in the analysed room (-) and A is the floor area (m^2).

The ventilation was designed to overcome occupancy peaks of 20 visitors/h, resulting in an airflow of 456 m^3 of fresh air per hour for the open hours. According to the standard EN 13779 [48], an airflow of 61 m^3/h was used for the night periods.

6.2.3. Results

The results of the energy simulation for the 15 cities under study can be seen in Figure 6.3. This analysis allowed to conclude that the cities of Oporto and Lisbon (in Portugal) present the lowest energy requirements with 44.9 kWh/m^2.year and 64.5 kWh/m^2.year respectively, while Oslo and Krakow are at the opposite extreme with consumptions of 134.7 kWh/m^2.year and 117 kWh/m^2.year respectively. Dividing the analysed cities into three groups ordered by the total energy consumption it is possible to place Oporto, Lisbon, Seville, Rome and Madrid in the first group; London, Athens, Amsterdam, Paris and Florence in the second group; and Berlin, Copenhagen, Vienna, Krakow and Oslo in the third group. It is easy to conclude that the cities of the first group are all located in the southern Europe.

However, this analysis can be reductive since it only focuses on absolute consumptions. Consider for example the case of Athens which, although classified in the second group with 81.2 kWh/m^2.year, behaves differently from London, also in the second group with a consumption of 77.8 kWh/m^2.year. In Athens, the cooling demand assumes 71% of the global energy consumption, while heating needs in London account for 80% of the global consumption.

This analysis allowed to conclude that the greatest energy needs in all the analysed cities are related with the need to maintain the temperature between the imposed set-point. In the most adverse case, the energy requirements to maintain relative humidity do not exceed 20% of the total energy consumption. It is clear that the use of less demanding climate control strategies can contribute to considerable energy reductions.

By analysing the energy consumed to maintain the temperature set-point, it can be observed that the cooling needs are clearly higher than the heating needs in three cities, accounting for more than 70% of the total consumption in Athens with 71 %, Lisbon with 74 % and Seville with 89 %. Oporto, Madrid, Rome and Florence show a more balanced behaviour, while for the remaining cities, the heating needs are clearly responsible for most of the energy consumptions. This analysis makes it clear the impossibility of defining a global policy for conservation and energy reduction in Europe, since the necessities of the different locations are quite different.

In order to define efficient and adjusted rehabilitation strategies to each case, the analysis of heat gains and losses between the building and the surrounding environment was carried out. The results are presented in Table 6.4. Heat losses to cooling the room (C), by ventilation (V), by the opaque envelope (O.E.) and by the windows (W) were analysed. Heat gains to heat the room (H), by ventilation (V), by the opaque envelope (E.O.), by the windows (W), due to internal gains (I.g.) and solar gains were also analysed.

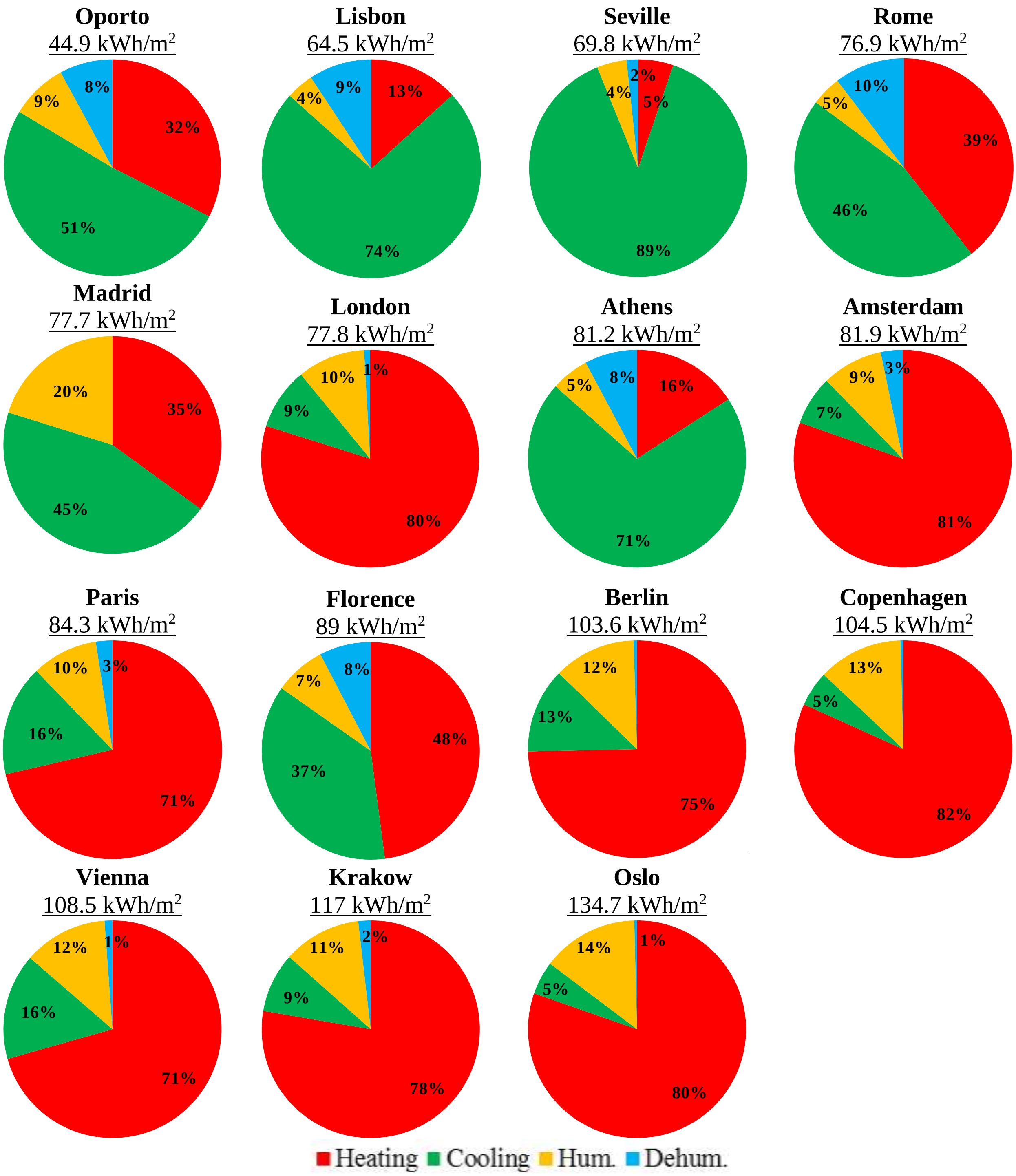


Figure 6.3. Energy consumption in the 15 cities under analysis

As far as losses are concerned, it is possible to observe a different behaviour for the 15 cities. For Lisbon, Seville and Athens the loss of heat through the HVAC system to cool the room plays a prominent role and is responsible for ca. 56%, 64% and 61% of the total losses, respectively. Following, the losses through the windows and ventilation can be found. The cities of Oporto, Madrid, Rome and Florence present losses relatively well distributed by the HVAC system, the windows and by the air exchanges with the exterior. It is interesting to note that for all the cities of the southern Europe the losses through the opaque envelope are practically negligible. For the remaining cities, located in central and northern

Europe, the panorama changes considerably. Losses through the HVAC system lose their preponderance and the losses through windows and ventilation assume a prominent position. The losses through the opaque envelope take values that can justify their improvement with losses ranging from ca. 12% in Paris and London to ca. 18% in Oslo.

Table 6.4. Heat gains and losses

#	City	Heat losses				Heat gains					
		C [%]	V [%]	O.E [%]	W [%]	H [%]	V [%]	O.E. [%]	W [%]	I.g. [%]	Solar gains [%]
1	Lisbon	55.7	16.6	0.7	27.0	5.7	2.4	35.5	2.1	16.8	37.6
2	Oporto	33.0	24.2	2.4	40.3	12.0	2.0	28.9	1.8	20.8	34.5
3	Seville	63.7	12.6	0.4	23.3	2.2	6.0	35.9	5.2	15.5	35.2
4	Madrid	38.0	21.4	3.2	37.4	18.1	2.8	26.8	2.6	16.7	33.0
5	Paris	13.7	29.3	12.2	44.8	41.0	0.8	16.5	0.7	17.1	24.0
6	Florence	33.7	21.5	8.9	35.9	29.9	3.4	21.8	2.8	17.6	24.6
7	Rome	39.9	19.5	6.4	34.2	22.3	3.5	25.2	3.0	18.5	27.5
8	Athens	60.8	14.7	1.1	23.4	8.4	4.8	33.3	4.9	16.4	32.3
9	Amsterdam	5.9	33.1	12.6	48.4	44.8	0.4	13.9	0.3	17.1	23.5
10	Copenhagen	4.6	33.0	14.9	47.6	51.8	0.1	11.7	0.1	15.2	21.1
11	London	7.3	31.8	12.0	49.0	43.1	0.4	14.4	0.3	17.4	24.4
12	Berlin	11.2	29.9	14.5	44.3	48.2	0.9	13.8	0.7	15.6	20.8
13	Kraków	8.2	29.9	16.0	46.0	53.0	0.6	11.7	0.5	14.6	19.6
14	Vienna	14.2	28.8	13.9	43.0	45.8	1.0	15.3	0.9	15.0	22.1
15	Oslo	4.7	31.6	17.8	46.0	58.4	0.1	10.0	0.1	13.6	17.8

C – cooling; H – heating; V – ventilation O.E.– opaque envelope W – windows
I.g. – internal gains

Regarding heat gains, it is possible to conclude the high influence of solar gains for all the 15 cities, ranging from ca. 18 % in Oslo to ca. 38 % in Lisbon. In fact, the solar gains take the main place of heat gains in Lisbon, Oporto, Madrid and Rome. The gains through the HVAC system to heat the room vary widely according to the cities: in Lisbon, Seville and Athens less than 10% of the gains are obtained by this source, while for example in Amsterdam, Copenhagen, London, Berlin, Krakow, Vienna and Oslo, heating gains accrue more than 40% of total gains.

The gains from the opaque envelop take also a prominent place. This can be justified by the high thermal inertia of the elements and the tightness of the indoor climate control which makes the surface temperature of the opaque elements often higher than the air temperature, triggering heat flows over extended periods. Data referring to Lisbon are presented in Figure 6.4: the comparison between the indoor air temperature and the internal surface temperatures of the southern wall, the three internal walls, the floor and the ceiling in (a) and the density of the heat flow rates in the surfaces in (b). The density of the heat flow rate in the surfaces was obtained from eq. (6.2)[49]:

$$q_x = \frac{(T_{amb} - T_{surface,x})}{R_s} \tag{6.2}$$

where q is the density of heat flow rate (W/m^2) of the element x; R_s means the internal surface resistance (m^2.ºC/W); T_{amb} means the indoor air temperature (ºC) and $T_{surface,x}$ means the internal surface temperature of the element x (ºC). In accordance with the standard EN 6946 [50], for the walls an internal surface resistance of 0.13 m^2.ºC/W was adopted. For the floor and the ceiling, surface resistances of 0.1 and 0.17 m^2.ºC/W were considered respectively.

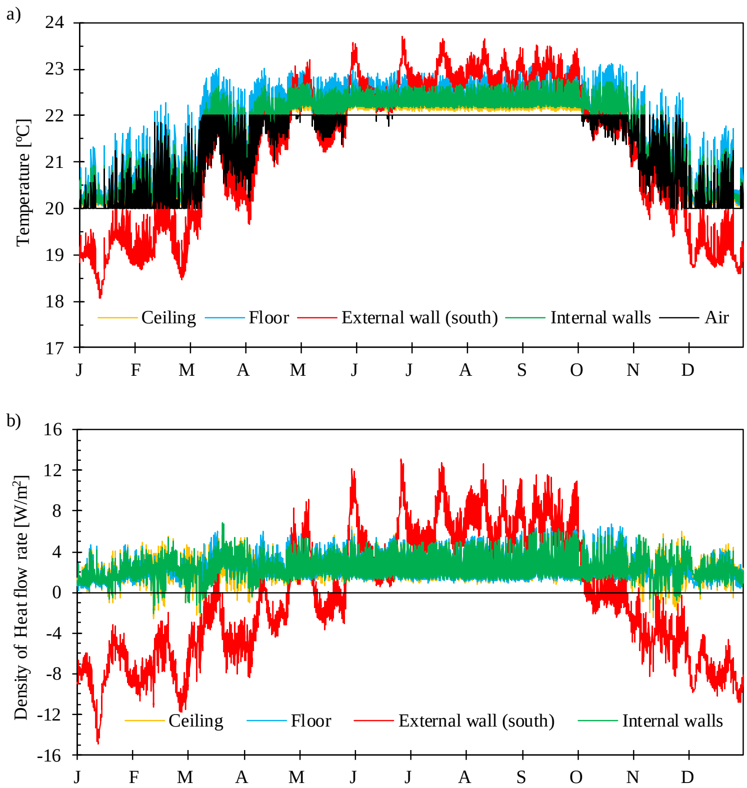


Figure 6.4. Comparison between the indoor air and the surface conditions: a) indoor air temperature and internal surface temperatures; b) density heat flow rate of the between the surfaces and the interior environment

The influence of internal gains varies between 14% in Oslo and 21% in Oporto. The gains from ventilation and windows are practically negligible for all the cities.

This analysis allows to conclude that energy reduction can be obtained firstly by changing the climate control strategy since the conservation and comfort are not compromised. In the warmer cities, considerable reductions may be achieved by reducing the solar heat gain coefficients of the windows or to include openings in the interior walls to reduce the heat storage. In these cases, where the cooling needs are higher than the heating needs and where the contribution of the opaque envelope in the losses is reduced, the implementation of thermal insulation can be hardly seen as an efficient way to reduce the energy demand. In cases where heating needs are the main contribution for the global energy consumption, the solution may be the windows refurbishment, increasing the SHGC and the implementation of thermal insulation in the opaque envelope.

6.3. Energetic rehabilitation

6.3.1. General overview

The difficulty of rehabilitating classified buildings makes the improvement of windows and the use of thermal insulation by the interior interesting measures to improve the indoor climate and to achieve energy savings.

In the previous section, the impossibility of defining similar energy saving strategies for the whole Europe was concluded since the regional climate has a determinant influence on how the buildings react to a certain strategy. For example, in the southern European countries with greater cooling needs, the rehabilitation may involve the reduction of the SHGC; for these cases, the opaque envelope plays a minor role. On the other hand, in the colder cities of central and northern Europe, the highest heating needs impose different solutions that may warrant the implementation of thermal insulation and the windows refurbishment.

Despite these conclusions, the European energy policy is becoming more and more demanding, requiring the thermal improvement of new buildings and major rehabilitations, while leaving cultural heritage buildings out. The transposition of the European directive 2010/31/EC [8] for the Portuguese law [51] has resulted in the imposition of a set of stringent measures, from which it is possible to emphasize the binding nature of the maximum thermal transmittance to be adopted for the opaque envelope. For Lisbon and Oporto, for example, a maximum thermal transmittance of 0.50 W/m^2.°C is imposed for new dwellings or great rehabilitations [52-54], while for service buildings, a maximum value of 0.70 W/m^2.°C is imposed [23]. For windows, maximum values of 2.80 and 4.30 W/m^2.°C are imposed for residential and service buildings, respectively. As regard the solar heat gain coefficient, a maximum solar heat gain coefficient of 0.56 were defined for high thermal inertia buildings.

6.3.2. Methodology

6.3.2.1. Sensitivity study

In this section a sensitivity study was designed to attest the impact of the windows and the opaque envelope on the energy demand in museums for two different climate control strategies for the case of Lisbon. Four solutions of window’s thermal transmittance, four solar heat gain coefficients and four solutions of the thermal transmittance of the opaque envelope were analysed through the use of a sensitivity study to correlate all the hypothesis, performing a total of 128 simulations.

As regard the opaque envelope, four different scenarios of thermal transmittance were evaluated: the first one considering the original wall with no thermal insulation (U=1.36 $W/m^2.ºC$); the second case considering the use of 2 cm of thermal insulation (mineral wool) and a plasterboard of 1.5 cm (U=0.77 $W/m^2.ºC$); the third scenario considering a thermal insulation layer with 6 cm (U=0.43 $W/m^2.ºC$); and the fourth and last scenario considering a thermal insulation layer with 10 cm (U=0.30 $W/m^2.ºC$).

For the windows, the U_w values were estimated according to CIBSE Guide A [55]: 6.01 $W/m^2.°C$ for single glazed and aluminium frames without thermal cut; 3.63 $W/m^2.°C$ for double-glazed with an air layer of 6 mm and aluminium frames with 4 mm of thermal shear; 2.55 $W/m^2.°C$ for double coated glazes (ε = 0.2) with an air layer of 12 mm and aluminium frame with 12 mm of thermal shear and 1.53 $W/m^2.°C$ for double coated glazes (ε = 0.05) with an argon layer of 16 mm and PVC frames with three hollow chambers. It was considered the use of windows with 1.4 x 2.0 m^2 and a ratio of 0.185 between the frame area and the total area.

As regard the solar heat gain coefficient (SHGC), a minimum value of 0 was used to simulate a window totally covered by a plasterboard and a maximum SHGC of 0.75 to simulate a double-glazed window with no shading elements [36]. SHGC can be obtained through various combinations of glazed and shading elements - more details can be found in [40,55].

The impact of the U, U_w and SHGC at the energy consumption was simulated for two different climate control strategies: a) the first one in accordance with that described in the section 6.2 (20-22ºC e 50-60 %RH); b) and the second using a fewer demanding target of 16-25 ºC during the closing hours and 18-25ºC during the opening hours to guarantee the visitors' thermal comfort. For the relative humidity, a set-point of 40-60 % RH was implemented. This less demanding strategy is in accordance with the targets argued by the Group of Organizers of Large-scale Exhibitions (Bizot Group, that comprises the directors of the world's leading museums and galleries), the Australian Institute for the Conservation of Cultural Materials (AICCM) and the Association of Art Museum Directors (AIC) for loan collections [56-59]. An ideal HVAC system (i.e. 100 % efficiency) was adopted, since the aim of this thesis is to compare the energy consumption of a set of conditions and not to analyse the absolute consumes. The simulation diagram can be seen in Figure 6.5.

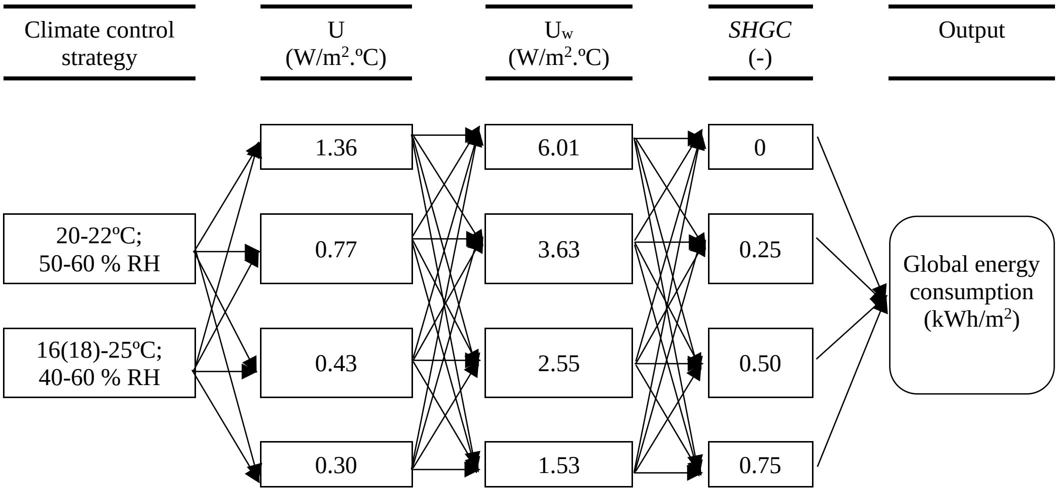


Figure 6.5. Sensitivity study to assess the impact the climate control strategy and windows refurbishment in the energy consumption

6.3.2.2. Cost-optimal analysis

To evaluate the economic suitability of the energetic rehabilitation strategies in museums, the cost-optimal approach was adopted. The net present value based on the energy demand for a 30-year period was calculated. This approach is in accordance with the cost-optimal analysis proposed in the Directive 2010/31/EU [8] and described in detail in the Delegated Regulation No 244/212 [60].

Since the analysis focuses on museums and cultural buildings, a macroeconomic approach has been adopted excluding fees and considering the greenhouse gas emissions (GHG). To consider the economic evolution, that should change throughout such a long period, equation (6.3) may be used to offset all the costs for the starting year:

$$C_g(t) = C_I + \sum_j \left[\sum_{i=1}^{t} \left(C_{a,i}(j) \cdot R_d(i) + C_{c,i}(j) \right) - V_{f,t}(i) \right] \tag{6.3}$$

where t is the calculation period (years), $C_g(t)$ means the net present value over the calculation period on the starting year (€/m^2), C_I means the initial cost of the measure or the set of measures j to rehabilitate the building (€/m^2), $C_{a,i}(j)$ means the annual energy costs during the year i (€/m^2) for the measure or set of measures j, $R_d(i)$ means the discount factor for the year i to obtain the real value for the starting year, $C_{c,i}(j)$ means the carbon cost associated to the energy consumption returned by each measure or set of measures j during the year i and the $V_{f,t}(i)$ means the residual value of the measure or set of measures j at the end of the calculation (in relation to the starting year t_0).

The discount factor for cases where the energy inflation is considered can be obtained from the equation (6.4) [61]:

$$R_d(p) = \left(\frac{1 + f/100}{1 + r/100}\right)^p \tag{6.4}$$

where *p* is the number of years from the starting period, *r* is the real discount rate (%) and *f* is the energy inflation rate (%).

The real discount rate (r) depends on the inflation rate (R) and on the marked interest rate (R_i) which both depend on the year. Here, a constant real discount rate for the whole period was considered:

$$r = \frac{R - R_i}{1 + R_i/100} \tag{6.5}$$

At the moment, the real discount rate is very low, however, it is not expected that these conditions will be maintained during all the considered period. Through the Delegate Regulation (EU) No 244 of 2012 [60], the European Union argued that all the member states shall perform a sensitivity analysis considering at least two discount rates each expressed in real terms and in which one of them should be 3 %. According to the Guidelines accompanying the Commission Delegate Regulation (EU) No 244/2012 [62]: "This rate is used in the Commission's Impact Assessment Guidelines of 2009 and broadly corresponds to the average real yield on longer-term government debit in the EU over a period since the early 1980s." According to the same document: "a discount rate higher than 4 % reflect a purely commercial and short-term approach to the valuation of the investments; and a discount rate ranging from 2 % to 4 % excluding inflation will more closely reflect the benefits that energy efficiency investments bring to building occupants over the entire investment's lifetime". In this thesis, a sensitivity analysis for the real discount rates of 3 % and 5 % was performed.

Regarding the *greenhouse gas emissions GHG*, according to the Portuguese law [63,64], a standard emission factor of 0.144 was used to convert the kWh of primary energy in equivalent kilograms of CO_2 due to the fuel combustion. For the electricity source, the final energy can be converted in primary energy by using the factor 2.5. According to the Ref. [60], a cost of EUR 20 per tonne of CO_2 by 2025, EUR 35 by 2030 and EUR 50 by 2030 was considered.

Electricity costs for the start year (2019 in this study) were taken from the recommendations of the Energy Services Regulatory Authority of Portugal (ERSE) for 2019 [65], resulting in a value of 0.1559 €/kWh in low tension for a single rate (this value do not include any taxes). As the price of energy varies, average rates of increasing prices provided by the European Commission's projections for electricity prices by 2050 [66] were used: 3 %/year until 2020; 0.6 %/year until 2030 and -0.2 %/year until 2050.

Finally, a set of interventions was considered. For the opaque envelope, the use of four different thicknesses of thermal insulation were evaluated, resulting in U-values of 0.64 W/m^2.°C, 0.49 W/m^2.°C, 0.37 W/m^2.°C and 0.30 W/m^2.°C. As regard the windows, two types of aluminium frames with thermal shear and three glazed solutions with different solar treatments were tested, resulting in six different scenarios. Regarding the solar heat gain coefficients, two sunscreen solutions were evaluated. To obtain low SHGC values, the hypothesis of using simultaneously two sunscreens was considered. According the standard EN 15459 [67], a lifespan of 30 year was considered for the walls and windows. For the sunscreens, a lifespan of 15 years was assumed, resulting in the necessity of replacing the elements one time in the 30-year period. The maintenance and repair necessities were considered the same for all the solutions, including the reference case, so their respective costs were not considered for this calculation. In addition to the rehabilitation measures, the change of the climate control strategy was also tested.

All the interventions and the respective costs are summarized in Table 6.5. The costs are presented as function of the square meter of walls, windows and sunscreens and after converted in costs per floor square meter. The costs were obtained from a national data base using price sampling [68].

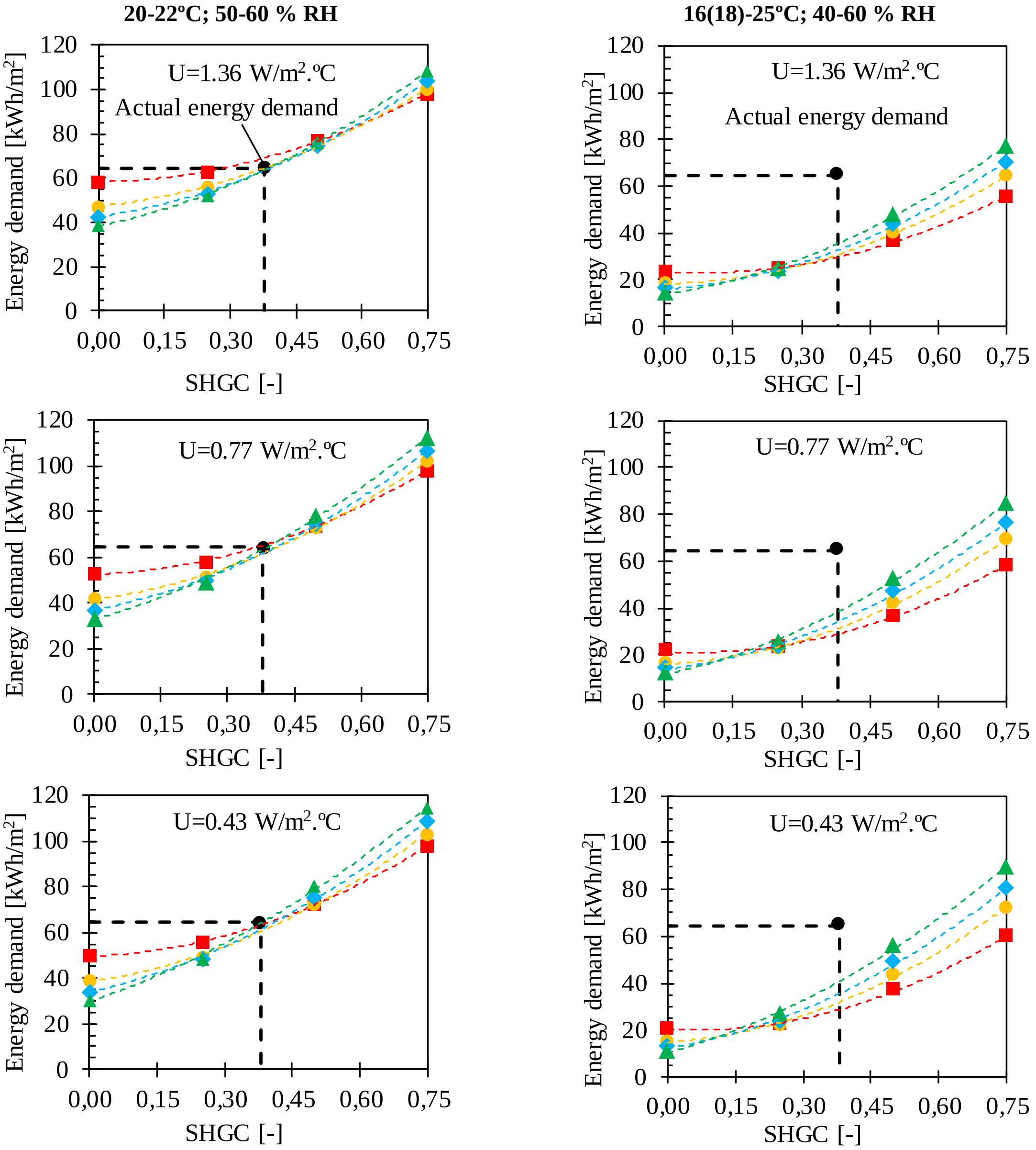
Table 6.5. Summary of all the rehabilitation interventions and the respective costs

		Intervention	Lifecycle (years)	Costs (€/m^2) [68]	C_I (€/m^2)
Opaque envelope	#1	Thermal insulation on inner face (3 cm): U=0.64 W/m^2.°C	30	35.35	11.22
	#2	Thermal insulation on inner face (5 cm): U=0.49 W/m^2.°C	30	38.80	12.31
	#3	Thermal insulation on inner face (7.5 cm): U=0.37 W/m^2.°C	30	44.25	14.04
	#4	Thermal insulation on inner face (10 cm): U=0.30 W/m^2.°C	30	48	15.23
Windows	#5	Double-glazed windows with aluminium frames with thermal shear: $SHGC_g$=0.60; U_w=2.55 W/m^2.°C	30	300.70	44.90
	#6	Double-glazed windows with aluminium frames with thermal shear: $SHGC_g$ =0.40; U_w=2.55 W/m^2.°C	30	315.70	47.14
	#7	Double-glazed windows with aluminium frames with thermal shear: $SHGC_g$ =0.20; U_w=2.55 W/m^2.°C	30	330.70	49.38
	#8	Double-glazed windows with aluminium frames with thermal shear: $SHGC_g$ =0.60; U_w=1.53 W/m^2.°C	30	409.65	61.17
	#9	Double-glazed windows with aluminium frames with thermal shear: $SHGC_g$ =0.40; U_w=1.53 W/m^2.°C	30	424.65	63.41
	#10	Double-glazed windows with aluminium frames with thermal shear: $SHGC_g$ =0.20; U_w=1.53 W/m^2.°C	30	439.65	65.65
Solar shadings	#11	Interior sunscreen: (42 % polyester + 58 % PVC) with and openness factor of 4 %. $SHGC_{sc}$ =0.43	15	74.20	11.08
	#12	2 Interior sunscreens (30 % polyester + 70 % PVC) with and openness factor of 3 %: $SHGC_{sc}$ =0.30	15	85.70	12.80
	#13	Interior sunscreen: (42 % polyester + 58 % PVC) with and openness factor of 4 %. $SHGC_{sc}$ =0.19	15	148.40	22.01
Climate control strategy	#14	16(18)-25ºC; 40-60 % RH	-	-	-

6.3.3. Results

6.3.3.1. Energetic analysis

The results of the sensitivity study relating the impact of the climate control strategies, U, U_w and the SHGC on the global annual energy consumption for the case of Lisbon can be seen in Figure 6.6. The reference energy consumption is also presented allowing to analyse in an effective way the impact of each one of the rehabilitation scenarios in the final result.



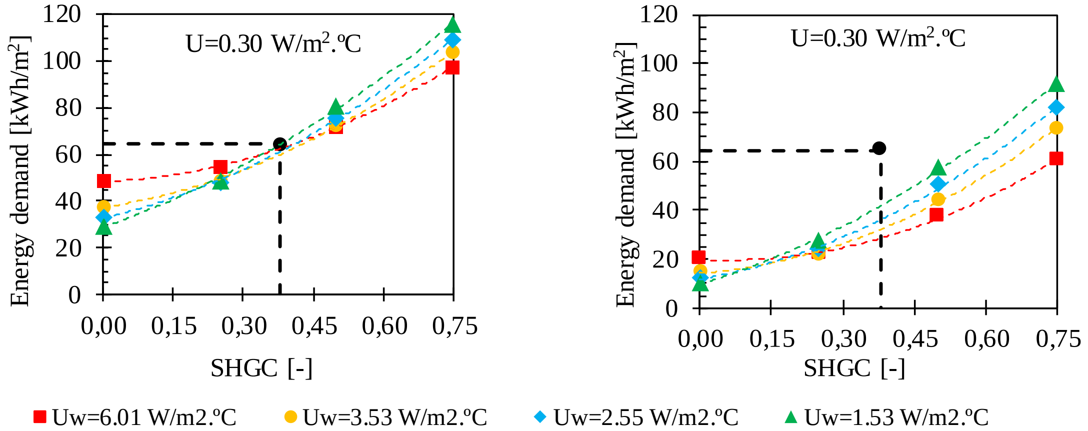


Figure 6.6. Impact of the climate control strategy, the rehabilitation of windows and opaque envelope on the energy consumption of a museum room - the case of Lisbon

The improvement of the thermal transmittance of the opaque envelope and windows provide better results as lower as the SHGC values. With the increase of the SHGC, the improvement of the U and U_w coefficients provide an opposite result in relation to that expected with the increase of the energy demand. This phenomenon is most evident for the less demanding climate control strategy in which the heating needs are less evident.

To quantify the impact of the rehabilitation and climate control strategies on the energy consumption, a mathematical model was designed to physically approach the simulated results: eq. (6.6) for the original climate control strategy and eq. (6.7) for the less demanding climate control strategy.

Equations	R^2	
<u>20-22 ºC; 50-60 % RH</u>		
$E = \left[(-7.65 \cdot U^3 + 16.61 \cdot U^2 - 9.07 \cdot U + 1.44) \cdot {U_w}^3 + (83.59 \cdot U^3 \pm 182.15 \cdot U^2 + 102.66 \cdot U - 19.09) \cdot {U_w}^2 + (-269.29 \cdot U^3 + 592.01 \cdot U^2 - 354.38 \cdot U + 82.03) \cdot U_w + (257.54 \cdot U^3 - 581.89 \cdot U^2 + 383.18 \cdot U - 35.37)\right] \cdot SHGC^2 + [(18.51 \cdot U - 51.47) \cdot \ln(U_w) + (-35.37 \cdot U + 99.20)] \cdot SHGC + [(0.03 \cdot ln(U) + 4.46) \cdot U_w + (9.20 \cdot U + 18.77)]$	0.98	(6.6)
<u>16(18)-25 ºC; 40-60 % RH</u>		
$E = [(0.31 \cdot U^2 - 0.33 \cdot U + 0.08) \cdot U_w^3 + (-4.39 \cdot U^2 + 6.79 \cdot U - 4.04) \cdot U_w^2 + (21.02 \cdot U^2 - 43.85 \cdot U + 33.11) \cdot U_w + (-34.46 \cdot U^2 + 78.39 \cdot U + 19.90)] \cdot SHGC^2 \cdot [(19.50 \cdot U - 55.58) \cdot ln(U_w) + (-35.76 \cdot U + 88.68)] \cdot SHGC + [(-0.11 \cdot U + 2.31) \cdot U_w + (4.18 \cdot U + 4.88)]$	0.97	(6.7)

These equations were used to optimize each parameter individually and all the possible combinations to obtain the lowest energy consumption. The model optimization was made with the aim of minimizing the total energy consumption. For this, several criteria were defined so that the feasibility of the model was not extrapolated. Regarding the SHGC, given the importance of daylight and visual contact with the outside for the quality of museum visits, total window occlusion was not considered - the use of a minimum SHGC of 0.10 was adopted. The optimization equation and the various criteria can be seen in eq. (6.8).

$$\min(E_{20-22℃;50-60\%RH}); E_{16(18)-25℃;40-60\%RH}) \tag{6.8}$$
$$1.36\ W/m^2 \cdot ℃\ \geq U \geq 0.30\ W/m^2 \cdot ℃$$
$$6.01\ W/m^2 \cdot ℃\ \geq U_w \geq 1.53\ W/m^2 \cdot ℃$$
$$0.75 \geq SHGC \geq 0.10$$

Focusing the attention on the improvement of the thermal transmittance of the opaque envelope, it was concluded that this refurbishment scenario has a reduced impact on the total energy consumption. Using the optimization model, an ideal U-value of 0.30 W/m^2°C was obtained, but only resulting in a reduction of 5.40% in the annual energy consumption (3.45 kWh/m^2 per year).

The replacement of the current windows with thermal transmittances of 3.53 W/m^2.°C has even a lower impact on the energy reduction, resulting in a maximum energy saving of 1.25 % (0.80 kWh/m^2.year) for the optimum thermal transmittances of 2.35 W/m^2.°C. As regard the SHGC, the panorama is slightly different, achieving savings of 22 % (14 kWh/m^2.year) by replacing the original windows with a global SHGC of 0.38 by one with an SHGC of 0.1.

It is interesting to note that for the higher values of SHGC, the windows refurbishment results in higher energy consumptions comparing with the reference case: above an SHGC of 0.52 for a U-value equal to 1.36 W/m^2.ºC or above 0.35 for a U-value equal to 0.30 W/m^2.ºC. These values were obtained by the interception between the curves for an U_w equal to 3.63 W/m^2.ºC and that for an U_w equal to 1.53 W/m^2.ºC. This fact is justified by the reduction of losses which contributes for the increase of the internal temperature and consequently the increase of the cooling needs. For the less demanding set-point, this inversion occurs for a lower SHGC: 0.24 for a U-value of 1.36 W/m^2.ºC and 0.16 for a U-value of 0.30 W/m^2.ºC.

The analysis of the impact of the climate control strategy was purposely left to the end as it could lead to significant savings without any initial investment. Savings of 52 % in the energy consumption (33.30 kWh/m^2.year) were achieved by replacing the original set-point of 20-22ºC for the temperature and 50-60% for the RH by the set-point of 18-25ºC during the opening hours and 16-25ºC in the night time with respect to temperature and 40-60% for the relative humidity without any further intervention. This change led to savings ca. 10 times higher than those obtained for the opaque envelope refurbishment, ca. 42 times higher than those achieved by the windows refurbishment and ca. 2.4 times higher than the one obtained for an SHGC equal to 0.1.

Optimizing the other three parameters for this less demanding climate control strategy, the following results were obtained: as regard the opaque envelope, the best result was obtained for the reference thermal transmittance, i.e. the improvement of the opaque envelope is not expected to improve the energy consumption of the model; as regard the windows' thermal transmittance, an interesting result is achieved - an optimum U_w of 5.85 W/m^2.ºC was obtained showing that even in buildings with windows with poor thermal response, their replacement from an exclusively energetic point of view can be not justified. Regarding the SHGC optimization, an optimal value of 0.1 was obtained for the two set-points.

Despite the analysis performed for each of the parameters, the analysis of the Figure 6.6 makes it obvious that optimizing simultaneously more than one parameter, the results can be considerably different. The savings for all the possible combinations comparatively to the reference case, such as the optimal values for each parameter, can be seen in Table 6.6.

This analysis led to the conclusion that only the scenarios involving the SHGC and/or the change of the climate control strategy provide considerable energy savings. Combining all the 4 parameters under analysis, a maximum saving of around 75% was obtained referring to the reference case which corresponds in absolute terms to a saving of around 48 kWh/m^2.year. This result was obtained for the following combination: set-point 16(18)-25ºC and 40-60% RH; U-value equal to 0.30 W/m^2.ºC; U_w-value equal to 2.08 W/m^2.ºC and an SHGC equal to 0.10. This result shows that the analysis performed individually for each parameter does not reflect the way they interact together. However, it should be noted that the change in the climate control strategy plays a leading role in optimizing the energy consumption in museums. If the rehabilitation of the opaque envelope and windows were excluded, a reduction of 70% was obtained representing an absolute saving of around 44.50 kWh/m^2.year. From an economic point of view this second option can lead to a best result, since the initial investment would be much smaller.

Table 6.6. Optimal solutions and energy savings

Optimizing parameters	Optimal values/ Energy savings	
	20-22ºC; 50-60 %RH	16(18)-25ºC; 40-60 %RH
Climate control strategy	-	52 %
U	(U=0.30 W/m^2.ºC) 5.4 %	(U=1.36 W/m^2.ºC) 52 %
U_w	(U_w=2.34 W/m^2.ºC) 1.2 %	(U_w=5.85 W/m^2.ºC) 53.8 %
SHGC	(SHGC=0.1) 21.9 %	(SHGC=0.1) 69.6 %
U+ U_w	(U=0.3 W/m^2.ºC; U_w=3.32 W/m^2.ºC) 5.5 %	(U=0.3 W/m^2.ºC; U_w=6.01 W/m^2.ºC) 56.3 %
U + SHGC	(U=0.3 W/m^2.ºC; SHGC=0.10) 35.3 %	(U=0.3 W/m^2.ºC; SHGC=0.10) 74 %
U_w + SHGC	(U_w=1.53 W/m^2.ºC; SHGC=0.10) 33 %	(U_w=1.53 W/m^2.ºC; SHGC=0.10) 72.8 %
U+ U_w + SHGC	(U=0.3 W/m^2.ºC ; U_w=1.53 W/m^2.ºC; SHGC=0.10) 44 %	(U=0.3 W/m^2.ºC ; U_w=2.08 W/m^2.ºC; SHGC=0.10) 75.3 %

6.3.3.2. Cost-optimal analysis

From an energy and environmental sustainability points of view the use of the previous analysis is valid to support the decision-makers. However, unless an economic analysis is done, it is impossible to choose the best solution in a rigorous way since the implementation of a certain rehabilitation measure may lead to insufficient savings to support its cost.

At this point it was intended to relate the energy consumption obtained by each one of the rehabilitation scenarios with the global costs obtained for a 30-year period. These costs include costs related to the energy consumption and those related to the initial and maintenance costs associated with the implementation of the rehabilitation scenarios.

In addition to evaluating the individual impact of each rehabilitation strategy, all possible combinations were analysed for two real discount rates, resulting in a total of 560 combinations.

All the results can be seen in Figure 6.7. It was decided to present the results in separate charts for the two climate control strategies with the intention of highlighting their importance for the energetic and economic sustainability of museums.

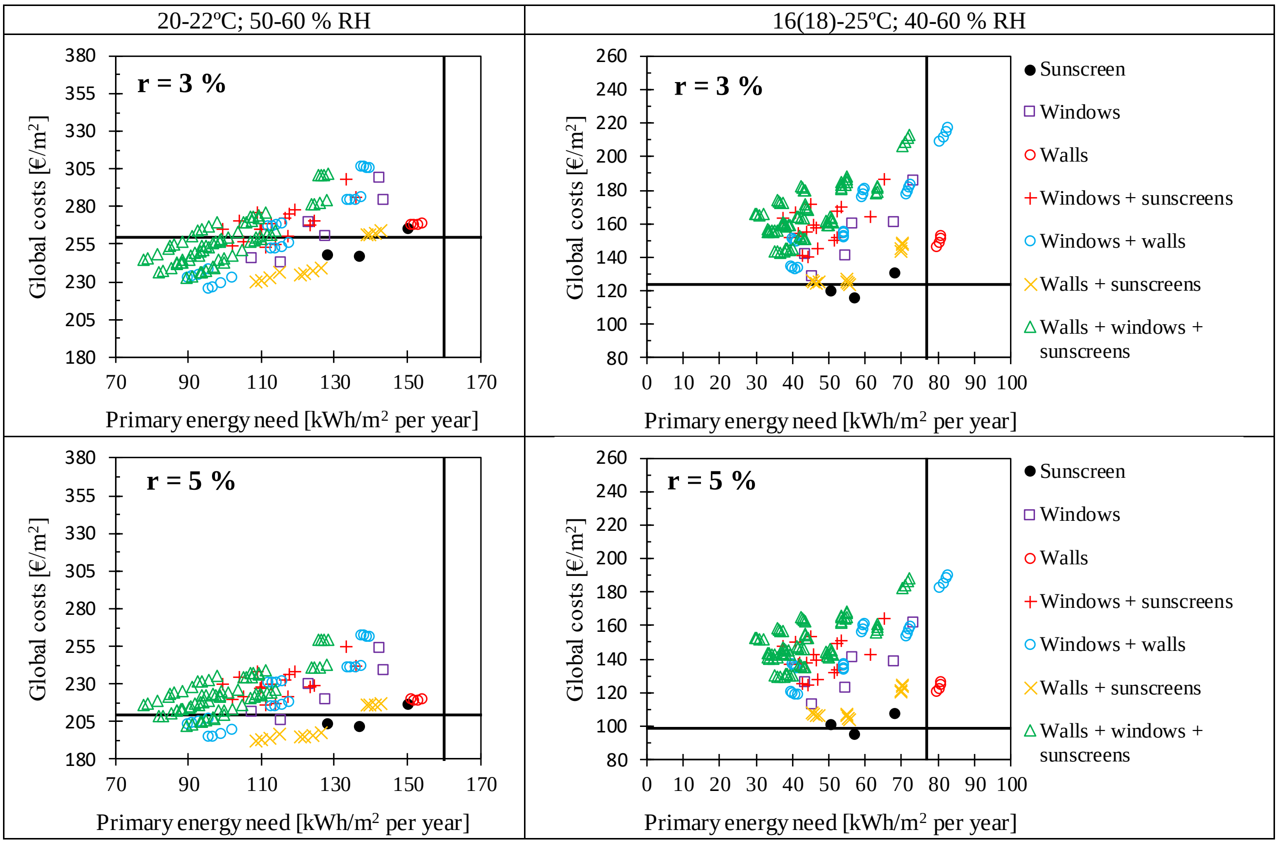


Figure 6.7. Cost-optimality comparison for all the simulated criteria for two real discount rates: 3% and 5 %

Given the unpredictability of the economy for such a long time, the analysis was performed simulating different scenarios with real discount rates of 3% and 5%. A discount rate lower than 2 % means an optimistic scenario associated with low inflation. This discount rate may be appropriate for cases where energy reduction is the main concern – if the economy growth slows down, the investment may not generate a profit. On the other hand, a discount rate of 5% represents a more sceptical and appropriate scenario in cases where the main concern is related to profit.

With regard to cultural heritage, a balance between the energy and economy is sought. The use of an average real discount rate of 3% may support this balance. This value is often used in optimal cost analysis applied to energy rehabilitation. Thus, in this thesis the results obtained for a real discount rate of 3% are highlighted.

The analysis of the results was separated according to the climate control strategy. Two reference levels were defined for each climate control strategy according the primary energy consumption and the global cost results obtained for the model with none rehabilitation scenario – the reference case.

Considering the real discount rate of 3 %, the following results were obtained for the original climate control strategy:

a) For the reference case a primary energy consumption of 159.9 kWh/m^2 and a global cost of 259.8 €/m^2 were achieved;
b) It was concluded that all the simulated scenarios contributed to the reduction of primary energy consumption;
c) Regarding to the thermal rehabilitation of the opaque envelope, a maximum energy saving of 5.4 % (8.6 kWh/m^2) was achieved applying the solution # 4 (10 cm of thermal insulation - U=0.30 W/m^2.ºC). Despite these results, it was concluded that none of the solutions contributes for the reduction of the global costs. The best scenario returns a global cost higher than the one achieved by the reference case in 2.9% (7.5 kWh/m^2). It was concluded that the exclusive rehabilitation of the opaque envelope is not economically feasible;
d) For windows, a maximum energy saving of 32.9 % (52.6 kWh/m^2) was achieved for the solution # 10 (U_w = 1.53 W/m^2.ºC and SHGC = 0.10). This solution allowed an economic saving of 5.5% (14.2 €/m^2). Focusing on the optimum cost analysis, a maximum saving of 6.7% (17.3 €/m^2) was obtained for the solution # 7 (U_w = 2.55 W/m^2.ºC and SHGC = 0.10). This solution corresponds to an energy saving of 27.9% (44.6 kWh/m^2). It was concluded that the SHGC plays a more important role than the thermal transmittance of the window to achieve the maximum economic savings. It was also concluded that the lowest thermal transmittance solutions may not return the best results;
e) The energy optimization based on the shading elements allowed a maximum saving of 19.7% (31.5 kWh/m^2) for the solution #13 (SHGC=0.14) resulting in an economic saving of 5.1% (13.2 €/m^2). The optimal cost analysis allowed to conclude that the most viable solution is

obtained for scenario #12 (SHGC=0.23) with an economic saving of 5.4% (14 €/m^2), corresponding to an energy saving of 14.2%;

f) Considering all the possible combinations, the highest energy reduction was achieved for the combination # 4 + # 10 + # 13 (U=0.30 W/m^2.ºC; U_w=1.53 W/m^2.ºC; SHGC=0.04). This solution led to an energy reduction of 51.5% (82.3 kWh/m^2) and an economic saving of 6% (15.6 €/m^2). This solution with such a low global SHGC has the drawback of almost completely excluding the visual contact from the inside to the outside;

g) By focusing on the optimal cost analysis, the best result was obtained for the combination #4 + #7 (U=0.30 W/m^2.ºC; U_w=2.55 W/m^2.ºC; SHGC = 0.10). For this combination, economic savings of 13.3% (34.5 €/m^2) and an energy reduction of 40.3% (64.4 kWh/m^2) were found.

This analysis allowed to obtain the optimal solutions regarding the energy and the economic sustainability. However, these results were obtained for a very demanding climate control strategy, which is considered outdated by many researchers around the world.

Then, the previous analysis is repeated for a less demanding climate control strategy. According several researchers, this approach does not affect the conservation of collections and the comfort of the visitors.

Considering the original reference case, obtained for the most demanding climate control strategy, it is verified that all the rehabilitation measures return lower costs. However, it was considered that this analysis would be unrealistic. Thus, it was considered that only the rehabilitation scenarios that return lower global costs than the one obtained solely by the change in the climate control strategy should be considered.

Considering the real discount rate of 3 %, the following results were obtained for the less demanding climate control strategy (comparing with the reference case):

a) Considering only the change of the climate control strategy, an energy reduction of 52 % (83.2 kWh/m^2) and savings of 52.5% (136.3 €/m^2) were achieved;

b) Contrary to the previous case, it was concluded that the improvement of the thermal transmittance may lead to an increase in the energy consumption. This is justified by the reduction of heat losses to the exterior;

c) It was concluded that all the refurbishment scenarios related to the opaque envelope resulted in higher energy consumes with respect to the solution described in a) and consequently in the increase of the global costs. For this particular case, it was concluded that the isolated improvement of the opaque envelope is neither energetically nor economically feasible;

d) For windows, a maximum absolute energy saving of 72.7% (116.3 kWh/m^2) was achieved for the solution # 10 (U_w=1.53 W/m^2.°C; SHGC=0.10), resulting in a global cost reduction of 45.6 % (118.5 €/m^2). Comparing this result with the one achieved for the solution #14 (the original model simulated for the less demanding climate control strategy), an energy saving of 43.1 % (33.1 kWh/m^2) was obtained. The economic feasibility study allowed to conclude that none of the solutions allowed to reduce the costs in relation to the scenario # 14;

e) The energy optimization based on the shading elements allowed a maximum absolute energy saving of 68.2% (109 kWh/m^2) for the scenario # 13 (SHGC=0.14) and 33.7 % (25.8 kWh/m^2) comparing with the solution #14, associated with an economic saving of 3.2% (3.9 €/m^2). The cost-optimal analysis allowed to conclude that the most viable solution is obtained for the scenario # 12 (SHGC=0.23) with absolute savings of 64.1 % (102.5 kWh/m^2) and 55.7 % (144.8 €/m^2) of energy and global costs, respectively. Relatively to the scenario # 14 an energy reduction of 25.2% (19.4 kWh/m^2) and a cost saving of 6.8% (8.4 €/m^2) were found;

f) Considering all the possible combinations, an optimum energy scenario was obtained for the combination #4 + #10 + #13 (U=0.30 $W/m^2.°C$; U_w=1.53 $W/m^2.°C$; SHGC=0.04). In absolute terms, this solution led to an energy reduction of 81.5% (130.3 kWh/m^2) comparing with the original case and 61.4 % (47.1 kWh/m^2) comparing with the scenario #14. However, this combination returned a cost 34.2 % (42.2 €/m^2) higher than the one verified for the scenario #14;

g) Focusing the attention on the cost optimal analysis, the best result was obtained for the scenario # 12 (SHGC=0.23). This combination achieved an energy reduction of 64.1 % (102.5 kWh/m^2) comparing with the original case and 25.2 % (19.4 kWh/m^2) comparing with the solution # 14. Based on the cost optimal analysis, a global reduction of 55.7 % (144.8 €/m^2) was achieved. By comparing with the results obtained for solution #14, a reduction of 6.8 % (8.4 €/m^2) was concluded.

For a more pragmatic analysis, the use of a 5% discount rate may be useful. Table 6.7 and Table 6.8 present all the economically viable solutions for discount rates of 3% and 5%, respectively. Only solutions with SHGC greater than or equal to 0.10 are presented, given the importance of the visual contact with the exterior for the quality of the visit.

It is often assumed that for rehabilitation scenarios with similar costs, the decision-makers should choose the one that results in a lower energy consumption. Analysing Table 6.7 for a real discount rate of 3%, it was verified that the optimal solution for the original climate control strategy was obtained for the combination #4 + #7 (U=0.30 $W/m^2.°C$; U_w=2.55 $W/m^2.°C$; SHGC = 0.10). According to Table 6.8 for a real discount rate of 5%, this is not the solution with the lowest global cost. However, it presents a cost close to the best option and a considerably lower energy consumption, which justifies the adoption of such solution.

Considering the possibility of changing the climate control strategy, the scenario changes drastically. For a real discount rate of 3%, the best result was obtained for the solution #12, resulting in an energy consumption of 57.4 kWh/m² and a global cost of 115.0 €/m². For a real discount rate of 5%, this is also the most viable solution, with an overall cost of 95.3 €/m².

Table 6.7. Economically viable solutions for a real discount rate of 3 %

Real discount rate of 3 %						
Climate control strategy	Combination	U [W/m².ºC]	U_w [W/m².ºC]	SHGC [-]	Primary energy [kWh/m²]	Global costs [€/m²]
20-22ºC; 50-60 % RH	Ref.	1.36	3.63	0.38	159.9	259.8
	#4 + #7	0.30	2.55	0.10	95.5	225.3
	#3 + #7	0.37	2.55	0.10	96.9	226.3
	#2 + #7	0.49	2.55	0.10	99.2	228.3
	#4 + #13	0.30	3.63	0.14	108.6	229.4
	#3 + #13	0.37	3.63	0.14	110.0	230.5
	#1 + #7	0.64	2.55	0.10	102.0	231.9
	#4 + #10	0.30	1.53	0.10	89.9	232.3
	#2 + #13	0.49	3.63	0.14	112.3	232.5
	#3 + #10	0.37	1.53	0.10	91.1	233.1
	#4 + #12	0.30	3.63	0.23	120.9	234.3
	#2 + #10	0.49	1.53	0.10	93.1	234.6
	#3 + #12	0.37	3.63	0.23	122.0	235.1
	#1 + #13	0.64	3.63	0.14	115.1	236.0
	#2 + #12	0.49	3.63	0.23	123.9	236.5
	#1 + #10	0.64	1.53	0.10	95.6	237.6
	#1 + #12	0.64	3.63	0.23	126.2	239.20
	#7	1.36	2.55	0.10	115.3	242.5
	#4 + #6 + #12	0.30	2.55	0.12	98.4	244.7
	#10	1.36	1.53	0.10	107.3	245.6
	#3 + #6 + #12	0.37	2.55	0.12	99.7	245.6
	#12	1.36	3.63	0.23	136.2	245.8
	#13	1.36	3.63	0.14	128.4	246.6
	#2 + #6 + #12	0.49	2.55	0.12	101.9	247.5
	#1 + #6 + #12	0.64	2.55	0.12	104.6	250.8
	#4 + #6	0.30	2.55	0.20	112.8	251.3
	#3 + #6	0.37	2.55	0.20	113.8	251.9
	#2 + #6	0.49	2.55	0.20	115.6	253.0
	#4 + #9 + #12	0.30	1.53	0.12	93.7	253.3
	#3 + #9 + #12	0.37	1.53	0.12	94.8	253.9
	#2 + #9 + #12	0.49	1.53	0.12	96.7	255.3
	#1 + #6	0.64	2.55	0.20	117.8	255.6
	#4 + #5 + #13	0.30	2.55	0.11	97.5	256.1
	#4 + #6 + #11	0.30	2.55	0.17	107.2	256.2
	#3 + #6 + #11	0.37	2.55	0.17	108.3	256.9
	#3 + #5 + #13	0.37	2.55	0.11	98.8	257.0
	#1 + #9 + #12	0.64	1.53	0.12	99.0	258.0
	#2 + #6 + #11	0.49	2.55	0.17	110.2	258.3
	#2 + #5 + #13	0.49	2.55	0.11	101.0	258.9
	#4 + #5 + #12	0.30	2.55	0.18	108.6	259.1
	#3 + #5 + #12	0.37	2.55	0.18	109.7	259.8
16(18)-25ºC; 40-60 % RH	#14	1.36	3.63	0.38	76.7	123.5
	#14 + #12	1.36	3.63	0.23	57.4	115.0
	#14 + #13	1.36	3.63	0.14	50.9	119.6

Table 6.8. Economically viable solutions for a real discount rate of 5 %

Real discount rate of 5 %						
Climate control strategy	Combination	U [W/m².ºC]	U_w [W/m².ºC]	SHGC [-]	Primary energy [kWh/m²]	Global costs [€/m²]
20-22ºC; 50-60 % RH	Ref.	1.36	3.63	0.38	159.9	209.5
	#4 + #13	0.30	3.63	0.14	108.6	192.4
	#3 + #13	0.37	3.63	0.14	110.0	193.0
	#2 + #13	0.49	3.63	0.14	112.3	194.3
	#4 + #7	0.30	2.55	0.10	95.5	194.8
	#4 + #12	0.30	3.63	0.23	120.9	195.0
	#3 + #12	0.37	3.63	0.23	122.0	195.4
	#3 + #7	0.37	2.55	0.10	96.9	195.4
	#2 + #12	0.49	3.63	0.23	123.9	196.2
	#2 + #7	0.49	2.55	0.10	99.2	196.7
	#1 + #13	0.64	3.63	0.14	115.1	197.0
	#1 + #12	0.64	3.63	0.23	126.2	198.2
	#1 + #7	0.64	2.55	0.10	102.0	199.4
	#12	1.36	3.63	0.23	137.2	201.5
	#13	1.36	3.63	0.14	128.4	203.5
	#4 + #10	0.30	1.53	0.10	89.9	203.6
	#3 + #10	0.37	1.53	0.10	91.1	204.0
	#2 + #10	0.49	1.53	0.10	93.1	204.9
	#7	1.36	2.55	0.10	115.3	205.9
	#1 + #10	0.64	1.53	0.10	95.6	207.1
16(18)-25ºC; 40-60 % RH	#14	1.36	3.63	0.38	76.7	98.8
	#14 + #12	1.36	3.63	0.23	57.4	95.3

6.4. Conclusions

The analysis carried out in this chapter with the simulation of a room of the National Museum of Ancient Art for 15 European cities with different climatic conditions allowed to conclude that the energy needs vary strongly with the building location. For the climate control strategy 20-22ºC and 50-60% RH, it was concluded that the lowest consumptions were obtained for Oporto and Lisbon with 44.9 kWh/m² and 64.5 kWh/m² per year, respectively, while the highest consumptions were obtained for Oslo and Krakow with 134.7 kWh/m² and 117 kWh/m², respectively. It was also found that the distribution of energy needs varied strongly. For Lisbon, Seville and Athens, the cooling needs account for more than half of total consumption, while for Oporto, Madrid and Rome a balanced distribution was obtained. For the remaining cities the heating needs accounted for more than half of the total energy consumed.

From a thermal rehabilitation point of view, it was found that the greatest losses occur through windows, while for example the losses by the opaque envelope are practically negligible for the southern Europe cities. It was concluded the impossibility of standardizing the rehabilitation solutions since the building response is strongly influenced by the local weather conditions.

These evidences led to a sensitivity study to improve the energy consumption for the building located in Lisbon, considering the improvement of the windows and the opaque envelope for two climate control strategies. For the set-point 20-22ºC and 50-60 %RH, the best results were obtained for a solution combining a U-value equal to 0.30 $W/m^2.ºC$, a U_w-value of 1.53 $W/m^2.ºC$ and an SHGC equal to 0.10, resulting in savings of 44 %. Considering the hypothesis of changing the climate control strategy, the combination of the set-point 16(18)-25ºC and 40-60 %RH with a U-value of 0.30 $W/m^2.ºC$, a U_w-value of 2.08 $W/m^2.ºC$ and a SHGC of 0.10 allowed a reduction of 75.3 % (48.20 kWh/m^2) referring the reference case.

Finally, a cost-optimal analysis was performed to evaluate the economic feasibility of each of the thermal rehabilitation scenarios. This analysis was performed for a macroeconomic panorama considering two different real discount rates.

The cost-optimal analysis has led to the conclusion that not all rehabilitation scenarios result in sufficient savings to support the cost of their implementation. It was concluded the importance of the climate control strategy for the energy consumption and economic sustainability. Considering the hypothesis of changing the climate control strategy, the best result was obtained by only refurbishing the shading system, resulting in a cost-reduction of 55.7 % (144.8 €/m^2) for a real discount rate of 3 % and 54.5 % (114.2 €/m^2) for a real discount rate of 5 %.

Significant findings have been obtained that can contribute to the sustainable management of the cultural heritage of southern European countries in the future. It was concluded that "more" is not always "better". That is, the application of the most advanced rehabilitation solutions may not present a result that justifies their application.

It is obvious that these results cannot be extrapolated to other cases with different properties. The purpose of this chapter was not to achieve an ideal combination. With this chapter, the opposite was pretended, aiming to demonstrate in a sustained way the impossibility of standardizing solutions.

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7. Conclusions and future work

7.1. Conclusions

The work developed in this thesis allowed to prove the validity of some approaches recently defended on the built cultural heritage area to achieve a balance between conservation and sustainability, but which are still far from being consensual. The evolution of science regarding preventive conservation and the growing concerns about environmental, energetic and economic sustainability have made it possible to suggest alternative climate control strategies to those traditionally used. However, the results obtained so far are not yet sufficient to change the paradigm. In many cases constant and absolute strategies that have arisen in the past with no scientific justification still remain in use, as it was the case of the National Museum of Ancient Art (NMAA) of Lisbon that imposes limits of 20-22ºC for temperature and 50-60% for relative humidity, even though the HVAC system is unable to meet them in a satisfactory percentage of time.

There are some alternative methodologies that allow to define dynamic strategies adapted to the local climate and thus contribute to achieve a compromise between conservation and sustainability, but their application is not yet widespread and needs to be validated before applied to climates and cases different from those for which they have been defined.

Before proceeding with any intervention, it is necessary to identify the risks and their causes and to tailor the solutions on a case-by-case basis. Although qualitative risk assessment for conservation is a science used since the early days of preventive conservation, only the use of quantitative methods can contribute to the assessment of the impact of climate control strategies and to define efficient solutions. In addition, it is important to combine the conservation requirements with the thermal comfort and indoor air quality concerns, since visitors are an integral part of the heritage conservation strategies.

Another solution to reduce energy consumption can be the rehabilitation of buildings. Again, as identified for the climate control strategies, the use of standard solutions should be avoided, since the needs vary according to the building characteristics, type of use and external climate.

In this thesis, climate data recorded from the church of São Cristóvão, the National Museum of Ancient Art and the Jeronimos Monastery were used to assess the impact of climate control strategies on conservation and energy consumption, to test the impact of tourism on the interior climate and to evaluate the possibility of rehabilitating the built cultural heritage.

The use of dynamic climate control strategies was tested and a new methodology adapted to temperate climates was proposed. This new methodology was validated according to the climatic data obtained and evaluated with the proposed tools. It has been found that the increase in tourism in an uncontrolled way is clearly affecting the conservation conditions of the Jeronimos Monastery and the indoor air quality. Finally, the possibility of thermally rehabilitating a room of the National Museum of Ancient Art was evaluated. The model was simulated for 15 European cities, which allowed to conclude that energy needs vary clearly with the location, which makes it impossible to use similar strategies for different locations. It was possible to define objective functions to achieve the best solutions regarding the energy and conservation and to study the economic feasibility of each scenario.

The following conclusions were obtained trying to answer to the objectives that the author proposed for this thesis:

1. What is the impact of the climate control strategy on conservation, comfort and energy consumption in cultural heritage?

    a. The impact of climate control strategies on conservation, comfort and sustainability has been tested for a naturally ventilated building

The influence of four climate control strategies (20ºC and 50% RH; PAS 198; EN 15757 and the natural climate) was accessed for the climate data of the church of São Cristóvão evaluating the mechanical, biological and chemical response of the collections, the thermal comfort of the visitors and the natural capacity of the building to meet the respective strategies.

It was possible to conclude that the more demanding set-points allow the best conditions for the conservation, but they are only complied by the natural climate of the building in short periods. The evaluation of the natural climate recorded in the church and that obtained from the application of the dynamic climate control strategy defined by the EN 15757 allow to conclude the possibility of optimizing the indoor climate with less demanding strategies that do not result in high risks for conservation. This approach can be used to achieve a serious compromise between the conservation and energy reduction.

It was concluded that a detailed knowledge about the hygrothermal response of each building and a risk-based analysis to quantify the risk are essential to optimize the indoor climate and to take any decision.

b. A new dynamic method to define climate control strategies to be adopted in cultural heritage buildings in temperate climates

The applicability of the climate control methodology described in the standard EN 15757 was evaluated and a high potential to achieve a compromise between conservation and sustainability was found.

Then, the analysis of the method was deepened and it was found that it presents some limitations when applied to temperate climates since its genesis was based on colder climates in which the presence of heating systems is usual. The method described in EN 15757 assumes that the short-term fluctuations cause a higher risk, and limits their range significantly; however, it has no limitations for seasonal cycles. When applying this methodology in temperate climates with no heating system it is clear that seasonal cycles are still large, but short-term fluctuations are limited too rigidly.

Based on this analysis, a new method based on the one recommended by the EN 15757 and influenced by the ASHRAE specification is proposed by the author. As the short-term fluctuations are low it is possible to lighten their limits, while the seasonal variations were limited. It was also considered the risk of biological attack and the fact that some materials require greater stability conditions than others. So, two classes of analysis were defined, one for less demanding buildings such as churches and other more demanding for museums.

A simulation model of the Jeronimos Monastery, developed and validated against the measured data within the scope of this thesis was used to validate the proposed methodology. The less demanding class shares the concerns presented by the EN 15757, and requires lower energy consumption for the same risk level. The most demanding class, which imposes extra measures and presents an attached methodology to avoid mould germination on surfaces, has proved to be effective in controlling mechanical and biological risks. If temperature and relative humidity were to be controlled, any of the proposed classes presented lower energy consumptions than those obtained by the application of the EN 15757, concluding its better suitability to temperate climates.

This methodology can be a useful tool to manage the indoor climate in cultural heritage buildings, reducing energy demands without jeopardizing conservation.

c. Applying the risk-based analysis and the proposed methodology to optimize the indoor climate of a major national museum

Museum managers sometimes impose very strict climate control strategies, often with no scientific justification, that require the use of powerful HVAC systems. Despite the exacerbated consumption of energy, sometimes these limits are not met.

The capacity of the HVAC system of the National Museum of Ancient Art to meet the intervals defined by their managers was evaluated in three controlled rooms (room 12, room 25 and room 41) and in one naturally ventilated room (Chapel of Albertas): 20-22ºC for temperature and 50-60% for relative humidity. Despite the imposition of such tight limits, it was concluded that they are not met in a percentage of time that can be considered satisfactory. Through the risk-based analysis and the thermal comfort tools described in this thesis, it was concluded that although the imposed limits were not being met, there were no risks for conservation and comfort.

A high potential for optimizing the climate control was found. The relative humidity limits were optimized according to class 1 of the FCT-UNL methodology proposed by the author and the temperature was optimized based on the Matias' adaptive model. For the current level of risk, the existing limits were replaced by dynamic ranges that vary between 18 and 28ºC in all rooms. As regards the relative humidity, new limits were obtained: 45-66% RH for the room 12, 39-64% RH for the room 25 and 40-64% RH for the room 41. For the chapel, only RH limits were defined since the room is naturally ventilated and closed to visitors: a RH target of 55-70% was obtained.

It was possible to test and validate the application of a dynamic optimization method to improve the conditions for conservation and thermal comfort, which results in less demanding targets. It was also concluded that the use of appropriate climate control strategies can contribute significantly to reduce the energy consumptions without putting conservation at risk.

2. What is the impact of cultural tourism for the conservation of the buildings and the health and comfort of the visitors?

Recurrent complaints from visitors with headaches, indisposition, dizziness and other symptoms in periods of greater affluence drew attention for possible problems related to an exaggerated number of visitors inside the Jeronimos Monastery. The number of annual visits increased 154 % between 2005 and 2017.

The indoor climate recorded in the Jeronimos Monastery was evaluated and a simulation model was developed and validated to test the impact of the increasing number of visitors on the building conservation and on the thermal comfort and indoor air quality.

a. Indoor climate monitorization

An extensive monitoring campaign of the indoor climate of the Jeronimos Monastery was performed using prototype sensors developed by the author with low-cost and open-source components based on the Arduino Technology. The use of this type of sensors allowed to reduce drastically the costs of the monitoring campaign. The sensors were calibrated and validated in laboratory to ensure their reliability. The indoor temperature and relative humidity were measured during 15 months with a frequency of 10 minutes through a sensor grid including seven data loggers, 13 thermistors and 9 RH sensors installed both in plan and in height to accurately characterize the indoor climate of the monastery.

It was concluded the viability of performing an extensive and long-term monitoring campaign in cultural heritage buildings through the use of low-cost and open-source data loggers. Additionally, it was also shown the importance of calibrating the sensors in order to obtain accurate measures and at the same time correlate the values between different sensors.

b. Developing and validating a hygrothermal simulation model of the Jeronimos Monastery

An hygrothermal simulation model of the Jeronimos Monastery was developed using WUFI®Plus. The simulation model was validated against the measured data. A graphically comparison was made, as the comparison between the annual mean, the maximum and minimum values, the percentiles 2º, 25º, 50º, 75º and 98º and the water vapour pressure excess. To corroborate the robustness of the model, three different statistic indices (R^2, CV(RMSE) and NMBE) were used for the temperature, relative humidity and water vapour pressure.

It was possible to conclude that the model represents the reality. It was concluded that the use of hygrothermal simulation models can be an important tool for the study of several scenarios, since the model validity is proven.

c. Evaluating the impact of visitors at the conservation of the building and collections and on the health and comfort of themselves

The model was simulated for various past occupancies and applied for four future scenarios until 2027. Regarding to conservation, it was concluded the 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). As regards the pictorial layer, only the future scenarios triggered the degradations risks. Concerning the biological degradation, the influence of the number of visitors is clear on the increase of the mould risk factor. For the influx of visitors verified in 2017 the risk is already a reality. In terms of thermal comfort, it was found that the increase of the number of visitors has a positive impact, albeit slight, as the indoor temperature increases. Regarding to air quality, it was verified that the first problems appear for the occupancy of 2017 with CO_2 concentrations higher than the comfort limit during the periods of greatest occupancy (2.4% of the time). For the fastest growing scenario, it was estimated that the indoor air quality will be unacceptable in 72.3% of the time.

Since it is not plausible to install climate control and mechanical ventilation systems in the building, an obvious solution to control the conservation and the indoor air quality could be to limit the number of visitors. Although it is not possible to achieve a maximum limit of visitors based on conservation requirements since there are other factors with strong influence such as the external climate, it is clear that the increase in tourism contributes to the degradation of the internal conditions. As far as indoor air quality is concerned, the inevitability of limiting access to the interior of the church was noted, suggesting as a more feasible method the use of CO_2 sensors inside and outside the church, preventing new visitors from entering whenever CO_2 concentration reaches undesired values.

Despite the economic benefits that tourism can bring to cultural heritage, this chapter made it clear that its management should be done considering the risks to conservation and to the comfort and health of visitors.

3. May the thermal rehabilitation be the solution for the energy and economic sustainability of museums?

    a. Evaluating energy necessities of museums in the Europe

A dynamic hygrothermal simulation model of a generic room of the National Museum of Ancient Art was developed using the WUFI®Plus software and simulated for the climate of 15 European cities with the goal of verifying the energy needs and evaluating the application of rehabilitation strategies according to the location. The model was simulated for the climate control strategy currently used in the NMAA. It was found that the distribution of energy needs varied strongly with the location. It was concluded that for Seville, Lisbon, Athens and Oporto the cooling needs account for more than half of total consumption; for Madrid, Rome and Florence a more balanced distribution was obtained and for the remaining cities the heating needs accounted for more than half of the total energy consumed.

In order to proceed to a thermal rehabilitation, it was found that the greatest losses occur through windows, while for example the losses by the opaque envelope are practically negligible for the countries of southern Europe. It was concluded the impossibility of standardizing the rehabilitation solutions to be adopted since the building response is strongly influenced by the exterior weather conditions.

    b. Optimizing the energy consumption for the case of Lisbon

To optimize the energy consumption for the case of Lisbon, a sensitivity study considering the hypothesis of replacing the actual climate control strategy, improving the thermal transmittance of the opaque envelope and the windows and changing the solar heat gain coefficient (SHGC) of the windows was carried out, resulting in a total of 128 simulations.

It was once again concluded that the use of appropriate climate control strategies has a high energy reduction potential without compromising the safety of the collections. As regard the thermal rehabilitation, the importance of using low SHGC values was concluded. Only for the lower range of SHGC, the thermal transmittance of the opaque envelope and the windows return a positive impact.

Two objective functions were derived from the simulation results to obtain the best solutions. For the set-point 20-22ºC and 50-60 %RH, the best results were obtained for a solution combining a U-value equal to 0.30 W/m^2.ºC, a U_w-value of 1.53 W/m^2.ºC and an SHGC equal to 0.10, resulting in savings of 44 %. Considering the hypothesis of changing the climate control strategy, the combination of the set-point 16(18)-25ºC and 40-60 %RH with a U-value of 0.30 W/m^2.ºC, a U_w-value of 2.08 W/m^2.ºC and a SHGC of 0.10 allowed energy savings of 75.3 % (48.20 kWh/m^2) referring the reference case.

It was concluded that the impact of the various rehabilitation scenarios varies drastically according to the climate control strategy. It was concluded that the thermal transmittance of the envelope only has a positive effect on the energy consumption with the reduction the solar gains. For high solar gains, the increase in thermal transmittance makes it impossible the heat out and contributes to the overheating of the indoor environment.

c. The cost-optimal analysis

Focusing the study of the rehabilitation of the cultural heritage only in the energy may lead to solutions with exaggerated costs that do not contribute to the economic sustainability of buildings.

To achieve a balance between energy and economy, a cost-optimal analysis was carried out for a 30-year period considering two different real discount rates. Globally, 560 combinations were evaluated.

Finally, a cost-optimal analysis was performed to evaluate the economic feasibility of each of the thermal rehabilitation scenarios. This analysis was performed for a macroeconomic panorama considering two different real discount rates. It was possible to conclude that not all the rehabilitation scenarios result in sufficient savings to support the cost of their implementation.

The great impact of the climate control strategies for energy consumption and economic sustainability was concluded once again. The best result was obtained using the set-point 16(18)-25 ºC and 40-60 %RH and applying a new shading system allowing a global SHGC of 0.23. A cost-reduction of 55.7 % (144.8 €/m^2) was achieved for a real discount rate of 3 % and 54.5 % (114.2 €/m^2) for a real discount rate of 5 %.

It was concluded that the most demanding rehabilitation solutions may not present a result that justifies their application. It was possible to conclude the importance of carrying out a sensitivity study for each case, considering several rehabilitation strategies and several economic scenarios. It was confirmed the impossibility of standardize solutions.

7.2. Future works

Despite the quantitative methods presented for assessing the internal climate of the cultural heritage, the risks induced by tourism on heritage buildings, the proposal and validation of climate control methods and the presentation of an optimization methodology that can be replicated in hygrothermal rehabilitation of buildings, this thesis should not be seen as an arrival point, but rather as the starting point for a long journey in search of an adequate management of the Portuguese heritage and in the achievement of a balance between conservation and sustainability. A list of future works that can contribute in a clear way to the advancement of this science is presented:

- The mechanical damage functions presented in chapter 2 have been applied by several authors and are important for the quantitative classification of risk and useful in the decision-making process. However, they were defined based on mechanical tests in new materials. Some objects have remained inside the buildings for several centuries under conditions far from those assumed to be ideal and may have lost their initial elasticity. It is considered that the testing of old materials may increase the plausibility of the methods and approximate the actual behaviour of the collections. In addition to the mechanical tests, it is also important to characterize the time that the old objects take to reach the balance with the surrounding environment in order to obtain the duration of the fluctuations that most affect them;
- Visitors of naturally ventilated historic buildings are expected to ignore issues regarding thermal comfort and to show reduced expectation levels. There are several adaptive models that try to exploit this situation, and some of them defined for the cultural heritage. Since adaptive models are based on questionnaires and in-field measurements, it is impossible to apply them to other sites unless they have been validated for the particular climate and level of expectation. In order to overcome these limitations, a model defined in Portugal for naturally ventilated buildings and air-conditioned buildings was adopted. In spite of its use, the application of the model to the heritage presents some limitations: thermal comfort in cultural heritage building was not considered in the genesis of the model; it is considered important to define a model adjusted to the cultural heritage;
- In Chapter 3 it was concluded that the increase in tourism is having a negative effect on the conservation of the Jeronimos Monastery and on the indoor air quality. The analysis focused on the study of the number of visitors and adopted the same weather file for all situations. It is suggested that in future the scenarios of growth of the number of visitors should be evaluated with climate files that include the previsions for climate changes to obtain long-term management guidelines that may avoid unforeseen surprises;
- In Chapter 4, a method to define a dynamic climate control strategy adjusted to the outdoor climate was proposed. The methodology was validated and applied to three buildings in Lisbon with

promising results. However, the methodology needs further testing before its validity can be unequivocally defended. It is recommended to simulate validated simulation models for all districts of Portugal in order to validate their application. At a later stage, the practical application of the methodology to a building in use with the monitoring of energy consumption and the impact on conservation and comfort is suggested;

- In chapter 6, the model of a museum room was simulated for several cities and optimization equations were defined to choose the best options to rehabilitate the building. It is recommended the replication of the study for a simulation model of a complete building duly validated and in the future the implementation of the obtained scenarios in a real building, monitoring the degradation risks, the thermal comfort, the indoor air quality and the energy consumption.

Finally, it is considered that the increase in the number of monitored buildings is indispensable for the definition of methods and policies aiming to guarantee the conservation and the energy reduction. Despite the usefulness of the simulation models, the monitoring of buildings in service should be used to complement the studies and to validate the models. It is recommended that a serious commitment be established among all stakeholders and that academia, which would be a central part for the development of studies and the science associated with preventive conservation.