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Influence of climate control strategies and the impact of visitors on the conservation of cultural heritage

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Abstract

Given the current issues surrounding the environmental control in museums, particularly revolving around hygrothermal conditions of the internal microclimate, it is important to gain perspective by looking into the past and asserting how it shaped present circumstances on defining climate control strategies. Developments witnessed in science and technology over the past century attest to new approaches and dynamic methodologies that seek to cut energy costs and move from stringent targets to more flexible specifications, opting for simpler and passive measures that intend to be more sustainable. However, differing views exist on these pertaining issues, which accounts for disparities in operating methods and applied standards all over the world that further amplifies the discussion.

Tourism can be seen be seen as one of the foremost agents for cultural exchange as well as a major vehicle in facilitating the preservation of cultural heritage with the allocation of resources for its maintenance. However, this relationship between tourism and Heritage Places can often be seen as conflicting in nature, by the fact that it can both lead to opportunities as well as potential complications. Visitors in museum buildings have therefore an impact in the preservation of cultural heritage, given that they influence the internal climate, particularly in terms of hygrothermal conditions, which could possibly induce new concerns as well as hinder their sustainable management.

For the present study, an account on the level of climate control strategies used throughout the past century was performed through an exhaustive literature review along with an evaluation of its impact on the sustainability of cultural heritage as well as an analysis of the influence of tourism on its conservation. Therefore, the current work evaluates the impact that tourism, specifically if practiced in an unsustainable way, may infer to the overall preservation of artefacts, mainly on the prediction of mechanical, biological and chemical damage risks. With the aid of a simulation software – EnergyPlus – a model of a generic room from the National Museum of Ancient Art in Lisbon (Portugal) (NMAA) was generated and virtually placed for each district of Portugal, varying also the number in visitors per hour, aiming to estimate – from a risk-based approach – the influence this concerning topic in today's society has on the internal climate and ultimately the preservation of the artefacts being displayed.

In terms of risk assessment, the results show that each increase in occupancy aggravates the potential for damage in each of the considered cases. A geographical distribution of risk is also evidenced, presented in maps, which indicates certain regions where risk is higher than others.

Keywords: Museum, Microclimate, Temperature, Relative Humidity, Thermal Inertia, Cultural Heritage, Sustainability, Mass Tourism, Building Simulation, Degradation Risk

Resumo

Devido aos problemas actuais em torno do controlo ambiental nos museus, essencialmente ligados às condições higrotérmicas no seu interior, é importante examinar o passado e avaliar de que forma é que este moldou as circunstâncias actuais, com vista a obter uma perspectiva mais abrangente sobre o assunto. Os desenvolvimentos na ciência e tecnologia atestam a possibilidade de utilizar novas abordagens e metodologias dinâmicas com o intuito de reduzir os custos de energia e progredir de estratégias de controlo rigorosas para especificações mais flexíveis por forma a alcançar a sustentabilidade. Contudo, continuam a existir diferentes pontos de vista sobre este tema, evidenciados por disparidades nos métodos operacionais e especificações aplicadas em diferentes instituições, o que amplia ainda mais a discussão.

O turismo poder ser visto como um dos maiores agentes de impulsionamento para a interculturalidade, enriquecimento pessoal e do país, ao mesmo tempo que proporciona os recursos monetários para a manutenção necessária ligada à conservação do património. Contudo, esta dinâmica pode ter uma natureza por vezes conflictuosa, nomeadamente a sua interacção com o património cultural, no sentido em que não apenas possibilita oportunidades, mas também induz algumas pressões na sua gestão. Os visitantes em museus têm um impacto no contexto da conservação, visto que influenciam o clima interior, necessariamente em relação às condições higrotérmicas, o que pode levar a comprometer a sua integridade.

O estudo apresentado avalia o impacto que o turismo, praticado de forma insustentável, pode inferir à preservação geral dos artefactos, principalmente devido aos riscos de degradação mecânica, biológica e química inerentes às condições higrotérmicas que se verificam no interior. Com a ajuda de um software de simulação – Energy Plus – foi gerado um modelo, correspondente a uma sala genérica do MNAA (Museu Nacional da Arte Antiga), o qual foi virtualmente colocado em cada distrito de Portugal Continental, também em Ponta Delgada e Funchal, variando o número de visitantes por hora com o objectivo de estimar, a partir de uma abordagem de avaliação de risco, – a qual recorre a correlações com funções de dano existentes na literatura – as implicações que esta temática, tão relevante na sociedade de hoje, tem na preservação do património cultural.

Quanto à avaliação de risco, os resultados denunciam que o aumento em número de visitantes por horas de facto induz um agravamento quanto à possibilidade de degradação de acordo com cada caso verificado. A distribuição geográfica desta consideração também é exposta, em mapas, os quais evidenciam um padrão aliado a algumas regiões que apresentam um maior risco.

Palavras-chave: Museu, Microclima, Temperatura, Humidade Relativa, Inércia Térmica, Património Cultural, Sustentabilidade, Turismo em Massa, Simulação Edifícios, Risco de Degradação

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Abbreviations and Simbology

ASHRAE	American Society of Heating and Air-conditioning Engineers, Inc
AIC	American Institute for Conservation
AAMD	Association of Art Museum Directors
CCI	The Canadian Conservation Institute
CFC	Climate for Culture
CTF	Conduction Transfer Function
EN	European Standard
ECTN	European Cultural Tourism Network
FCT	Faculdade de Ciências e Tecnologias
FEA	Finite Element Analysis
HVAC	Heating, ventilation, and air conditioning
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
ICOM	International Council of Museums
IIC	Institute for International Conservation
IPI	Image Permanace Institute
IT	Thermal Insulation
NMAA	National museum of ancient art of Lisbon (Portugal)
NGL	National Gallery of London
NMDC	National Museums Director's Conference
PAS	Publicly Available Specification
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNI	Ente Nazionale Italiano di Unificazione
UNL	Universidade Nova de Lisboa
WMO	World Meteorological Organization
A	Area [m^2]

RH	Relative Humidity [%]
$\overline{HR}$	Mean annual of relative humidity
$\bar{T}$	Mean annual of temperature
q	Heat flux [W/m^2]
ΔT	Temperature variation
ΔRH	Relative Humidity variation
T	Temperature [˚C]
v	Concentration of water vapour
U	Coefficient of thermal transfer [W/m2.˚C]
e	Thickness [m]
λ	Thermal Conductivity [W/m.˚C]
R	Thermal Resistance [(m^2.˚C)/W]
ρ	Density [kg/m^3]
C_p	Specific heat [J/(kg.K)]

1 INTRODUCTION

1.1 *Foreword*

The inherent value of cultural heritage is "to bear a unique or at least exceptional testimony to the master of the human capability, exhibiting an important c of the past as well as maintaining it for future generations to come''[1]. By being aware of its significance, a sense of involvement in assuring its conservation is induced upon entities responsible to accomplish that goal.

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, given that it stimulates the economy, especially with touristic activity [2].

The evolution of the ideals underlying the values and benefits behind the conservation of cultural heritage can be studied through developments in raised concerns and subsequent focus by several international charters. After the second world war, the Institute for International Conservation (IIC) and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) were founded, respectively in 1950 and 1959, by one of the United nation's agencies – UNESCO – formally implementing the phase described as 'scientific conservation' with the ultimate intention of promoting the preservation of cultural property. It resulted in the drafting of charters and recommendations on how to form decisions that could have a positive impact in this regard. These basic principles were firstly introduced in the Athens Charter in 1931 [3], which was used as the primary driving force for the following international movements that took place by publishing documents that asserted the invaluable necessity of preserving and caring for the world's cultural assets. The Athens charter was adequately updated by the Venice Charter in 1964 [4], which defined the basic principles and the action frameworks adequate to the protection of monuments and other structures of pieces which have acquired cultural significance with the passing of time, stressing the need to preserve the authenticity and integrity of such important historical assets, particularly with the need of proper documentation whenever an intervention was to take place.

In 1972 the World Heritage Committee was established by the UNESCO as ''an Intergovernmental Committee for the Protection of the Cultural and Natural Heritage of Outstanding Universal Value''[5]. The intangible value rooted in these cultural assets situated all over the world, sets in place an intricate form of control established by charters and operative guidelines implemented over the past years, that devise a web of policies with the intent to guarantee heritage's conservation. Concurrent to this period of attested growing awareness, it was felt the need to set conservation in its wider context by including the sustainable, economic and social concerns. In 1975 with the European Charter of the Architectural Heritage, several elements of sustainable development were introduced and associated to the protection of the built cultural heritage [6].

Sustainable Development is a well-recognized term at this point, described in [7] as ''development that meets the needs of the present without compromising the ability of future generations to meet their own needs''.

Museums have an important impact in this context. They operate within environmental, economic and social settings. From a perspective of economic frameworks, such as cultural assets are the cultural capital of the city [8].

All forms of cultural heritage can amount to forces such as tourism that can aid in its maintenance by generating revenue. Since the main concern is towards providing a safeguard indoor environment for the display of both collections and heritage, which in some cases relies upon an active form of control, resulting in an excessively high energy consumption whenever inadequate and too stringent specifications are applied.

When considering the preservation of any type of material, it is possible to find some agents of deterioration that may constitute a risk for the collections, though in this text the focus is in respect to only Temperature (T) and Relative Humidity (RH). If not properly accounted for, these agents of deterioration may jeopardize the safety of the artwork. In accordance to climate management strategies chosen for prevention of deterioration, energy costs should also be invoked in this context given the rising importance of sustainability but never jeopardizing the conservation [9]. High energy consumption may lead to unbearable costs to institution budgets, as well as the environment, however it could be avoided by an increase of knowledge and understanding that should aim towards a sustainable future in all facets – conservation, environment and economy –whilst fully respecting and maintaining the outstanding value embedded in the artwork [10]. Hence, the search for sustainability being considered a very real and current challenge for museums, as they should be able to guarantee the conservation of collections as well as visitor's comfort with low energy strategies.

Strict climate control strategies were generalized and implemented in the past [11], when energy costs were not yet a matter of concern and sustainability still had not crossed the minds of the conservation professionals, whose methods were based on stringent requirements both for temperature and for relative humidity. This indisputable correlation between rising energy costs and the strict control implemented to the indoor climate was first specified by Marion Mecklenburg at the Smithsonian and more recently confirmed with comparisons applied to a sampling of historical house museums in the work presented in David Artigas's thesis [12]. In this regard, the escalating energy costs and the need to manage the care of collections in a way that does not compromise the ideals before mentioned – of sustainable development and environmental responsibility – has led to a more complex approach to that of the already implemented, evidencing an essence that is deeply rooted in social, economic and environmental considerations.

Due to advances in technology in recent decades giving rise to the ability of a continuous measurement of temperature and relative humidity values, it is now possible to quantify each one of these factors of decay and their effect on the environment. This allows for a systematic analysis that informs the rate of deterioration, something incredibly important when considering the preservation of collections. As it is, environmental monitoring provides a better understanding of how to both efficiently preserve collections and reduce energy consumption.

These developments prompted a recent shift into more dynamic approaches such as day/night differences, seasonal variations and set points regulated without harming the collections whilst still managing to have sensibly the same conditions, regarding the duration of the year. Nevertheless, the geographical location is important to be considered for each specific case, as the external climate drives changes in the indoor environment within a building that directly affects the artwork. Thus, the suitability of more passive approaches is awarded to wherever the climate is benign enough for it to be considered.

Mass tourism is also a relevant determinant to the preservation of cultural heritage given the growing concern towards the impacts it may induce if too unsustainable, however not much research has been conducted yet in regard to this particular matter.

1.2 *Objectives and scope*

This work aims to contextualize the inherent complexity associated to the museum environment, particularly in terms of how the internal hygrothermal conditions affect the processes of degradation in the preservation of cultural heritage.

The past certainly shapes the present as well as the future. It is then important to look back at history for the understanding of how climate control in museums was established and the reason for their current specifications, particularly how it shifted along with the way in which society evolved according to social, political and economic developments. Current environmental standards had their origin in decades of compromises and limitations between the different factors that weigh in on the decision-making process of the preservation of valuable artwork, against damage inducing effects that manifest on the environment in which they are displayed. In this context, the focus regarding the agents of deterioration is on Temperature and Relative Humidity.

A case study is then presented, directed towards an assessment of the impact that a variation in the visitor's numbers per hour has on the conservation of cultural heritage. A simulation of a generic room located in a historical building that houses the MNAA in Portugal was performed, using, for that purpose, the software EnergyPlus and its available climatic data. In this regard, all the districts in the continental territory as well as two from Madeira and Açores – respectively Funchal and Ponta Delgada – were considered for each occupancy – namely 6, 12 and 18 visitors per hour.

The results were then accordingly assessed, more specifically: a statistical understanding of the mean values, seasonal variations and short-term fluctuations of both Temperature and Relative Humidity; an examination of how these conditions fared according to relevant and persisting targets present in literature, using for such end the concept of Performance Index; it was also determined whether or not the generated hygrothermal conditions in fact complied with the ASHRAE classification dedicated to museums and other cultural buildings, explicitly the estimated percentage of time that the values were within each class, for both seasonal and short-term fluctuations; and finally a risk assessment that took into account the simulated internal hygrothermal conditions for each district, in accordance to damage functions that exist in literature, which enabled an evaluation of the mechanical, biological as well as chemical processes of degradation.

1.3 *Dissertation outline*

In order to facilitate the examination of this text and with the intent of possibly providing a full comprehension of the obtained results, for the first three chapters a theoretical account of the matters discussed is established. As it is, there's a division in 5 chapters, each specified below:

The first chapter is intended to convey the importance in the continuous work of preserving these valuable remembrances of history as well as the many challenges that affect that process. An account on the many charters and operative guidelines implemented over the past years, which devise a web of policies with the intent to guarantee heritage's conservation is also presented. It identifies the two agents of deterioration considered, temperature and relative humidity as they affect the microclimate of the museum buildings in which collections are housed. It also gives a general overview on the context of climate control and how it has evolved concomitantly to the way society has, in terms social, economic and environmental considerations.

In the second chapter, a general contextualization of museum buildings as well as an assessment, particularly to do with the role that the indoor environmental parameters play, specifically temperature and relative humidity, in the internal microclimate. Is also attested the concept of thermal inertia inherent to historical buildings, a relevant type of museum building to be taken into account.

The third chapter appoints to the mechanisms of degradation – that is mechanical, biological and chemical – that constitute a problem to the preservation of cultural heritage. The internal microclimate is dependent on several factors, though the focus in this text is restricted to the two fundamental parameters of temperature and relative humidity. There is a continuous examination in the pursuit of the appropriate climate control guidelines when managing collections and where they are housed. In an attempt to minimize the damaging effects to the art-work, ranges were set regarding low, high and fluctuations about mean values for these two agents of deterioration.

In the fourth chapter, the history and developments of climate control are presented up until today's reality where sustainability is driving the search for the best and innovative methodologies in the environmental control framework. Thus, it provides a comprehensive understanding of the socio-economical as well as scientific progress that characterizes the manner in which stringent measures gave way to more flexible and dynamic approaches in the recent past.

The fifth chapter takes into account today's society, such as the adequate equilibrium between somewhat conflicting variables, mainly to do with energy efficiency, sustainability, as well as the problematics of climate change and mass tourism.

In the sixth chapter, the methodology for this work is presented, with an account of all the considerations that were made regarding the simulation of a case study specific to Portugal using EnergyPlus. Not only to do with the input information that was necessary for an accurate performance but also a detailed analysis of how the results were processed for the intended propose of the study – an assessment of what an increase in visitor's number induces in terms of preservation of the artwork, namely in regard to indoor hygrothermal conditions.

The seventh chapter presents the results, obtained from several simulations, allowing for an evaluation of the impact that each of the proposed varying visitor's numbers have on the preservation of cultural heritage, respective to each district that was considered. A statistical analysis is presented, with the intent to characterize the interior condition of both temperature and relative humidity as well as a Performance Index which indicates the percentage of time that these parameters meet the imposed static reference targets, obtained from literature. An account on risk assessment in regard to mechanical, biological and chemical degradation as well as the ASHRAE classification were also presented.

Finally, chapter eight encompasses the conclusions of what was presented in the previous chapter as well as future developments that are deemed important to further consider.

2 INDOOR ENVIRONMENTAL PARAMETERS

2.1 *Contextualizing Museum Buildings*

Museums are implemented in different types of buildings, either modern construction or old historic heritage. This is important to take into account when pondering over preservation strategies, since each have their own particularities that certainly have an influence on the internal environment. Overall, when considering the indoor environmental conditions, it is a basic understanding that they are directly affected by several external factors, namely the solar radiation, heat and moisture conduction through surfaces, air exchanges through openings, and depending on the regional climate, architecture and material composition of the envelope as well as its orientation and internal loads related to the lights, HVAC systems and human presence. In this regard, given the function that is presented in this text to the building itself – as a museum facility – it is important to realise the conflict that arises in terms of preventing both the degradation of the art-work and the inherent value in heritage buildings, that house collections, as well as taking into account the human factor and the expectations associated with thermal comfort. The latter is also an integral part of internal vapour sources, for people release moisture by the work of their regular metabolism, via breathing and transpiration, and as such can have a significant impact on the interior environment.

Apart from the recognition of being an economic resource and a substantial aid to the preservation and maintenance of the collections, mass tourism constitutes a reason for concern for the preservation of collections and buildings, particularly due to the transport of pollutants, with the emissions of water vapour and heat to the interior climate, compromising its stability. It could be a limiting factor in the use of natural ventilation, when the number of visitors is very high, as there is a demand for a refresh rate that can only be provided by mechanical aid, such as HVAC systems [13].

Given the fact that the air inside buildings comes from the outside, the purpose of these systems is to modify the external conditions to make them suitable for use indoors, certainly if the needs are that of fresh air, cooling, heating, humidifying and dehumidifying, which accounts for energy consumption. As it is, geography is a crucial factor in preservation measures, since the regional climate to a specific building will determine the environment that collections will experience and as such, the greater the difference between the desired indoor conditions and the natural climate the more demanding those systems will have to be.

There are also the condensation risks in building surfaces, that is a frequent concern most particularly in northern climates. For instances, when considering winter conditions, the necessity of humidification to balance out the drop in internal RH levels, due to heating to human comfort levels, may indeed result in such problems. It becomes evident the existence of a conflict between museum specifications for objects that require certain ranges in environmental parameters for their safe preservation, along with the need to prevent damage in building elements, human comfort as well as with energetic considerations.

In truth, the coexistence of these four issues – building, collections, visitors and energy reduction – and the fulfilment of their requirements can be deemed as problematic, and certainly any attempt to satisfy one to the detriment of the others should not be considered. The efficiency of these factors in indoor environment control is thereby a rather intricate dilemma, that lacks the possibility to fulfil their concurrent interests simultaneously, with rare exceptions. Upon consideration of a full scale building climate control, in order to preserve the collections housed in historic buildings, particularly with recognition to the building envelope’s limitations given its historic value, the New Orleans Charter for Joint Preservation of Historic Structures and Artefacts was formulated in 1991, so as to promote this philosophy [14].

As mentioned, building envelopes where collections are housed are exposed to a variety of external hazards that, if not efficiently accounted for can have serious impacts on the inside climate. So, the properties assigned to the envelope will certainly determine the potential for a more passive control approach since airtightness, insulation and hygrothermal inertia will reduce the way outdoor variations affect the interior in a manner that is specific for each type of building [15]. Seeing as modern building’s structure is substantially different from ancient ones, varied issues concerning the control of the interior environment are going to be presented. Primarily they have vast expanses of glass façade, a small ratio of wall area to volume and the thickness of the walls is much smaller, which allows for a higher sensibility regarding the daily cycles in temperature, leading to thermal stabilization being therefore compromised. Their only inherent protective quality is thermal insulation, and on the other hand their airtightness, specifically designed according to current regulated air exchange rates for air quality, that combined with heat and moisture exchangers allow for the relative humidity buffering of some materials, which uncontrolled air exchange, typical of old construction, previously made ineffective [15]. In this case, considering buildings such as museums, depending on the climate, they are usually designed with a complementary mechanic system to provide the stable conditions needed for the preservation of collections. Therefore, the thermal gains or losses are counterbalanced by mechanical aid.

2.1.1 *Historical Buildings and the concept of Thermal Inertia*

Of course, when considering another perspective, seeing as though a large amount of collections are also kept in historic houses, monuments and churches, the situation differs considerably and is indeed a concerning topic in conservation science [16], since there is a compromise between the target indoor climate and the preservation of both collections and the building elements as well as the minimum required human comfort in their operation [17].

When considering monuments and churches and the way they are affected by external temperatures, the nature of their own construction implies a considerable mass in their walls, which allows for the depiction of the concept of thermal inertia. This concept infers the quantity of heat transferred in a body with a certain mass and specific heat at any given temperature. It should therefore be understandable, that the higher the mass the more time it will take for that heat transfer occur [18]. That is precisely the case of the thick walls that characterise historic buildings, monuments and churches. This difficulty in the transfer of the external temperatures to the inside of the building is expressed in two distinct phenomena – a time gap and a lower temperature span/range in amplitude – both illustrated in Figure 2.1-d, respectively φ and μ. When the external temperature decreases, the response of the massive walls of an historic building is not instantaneous. As it is, it takes a considerable amount of time for them to respond to that alteration – a time gap. In that account, the interior air will only be affected by that decrease in exterior temperatures when the entire wall is cooled and is therefore able to transmit it to the inside. The higher the thermal inertia of a building the higher time gap will be. That is why in some cases there is delay of sensibly a season, where the lowest internal temperature is recorded in the Spring and the highest in the Autumn. The other consideration for the cases with a higher thermal inertia is the damping effect it has on the interior, from the influence of external variations in temperature. Resulting in a lower temperature span/range that is presented on the interior of the envelope, as the highest and lowest values for variation in external temperature are more prominent than the ones on the inside. These considerations are illustrated in Figure 2.1, where a) indicates the sinusoidal variations in external temperatures – T_{as} – with which an average value can be determined, assuming the internal temperature – T_i – as constant.

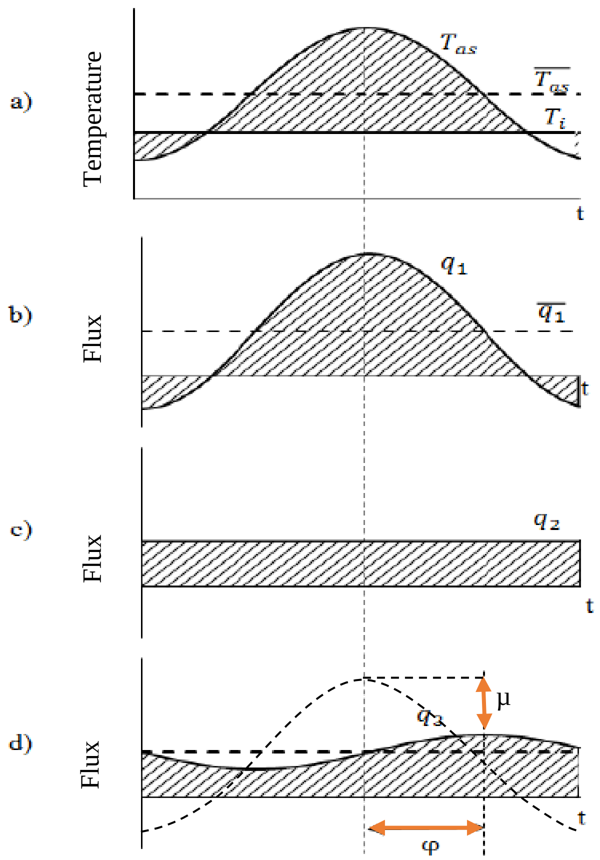


Figure 2.1 - Example of the concept of thermal inertia, adapted from [18]

These buildings, built in the past, were initially conceived to deal with climate passively, through proper design regarding materials and other considerations upon their construction, such as air leakage to an extent that allowed for the necessary exchange with the exterior, in order to maintain favourable conditions on the inside climate. Indeed, the area/volume ratio of the envelope, the use of single pane glass windows and uncontrolled air leakage are far from the cases applied in recent construction, however they were efficient enough throughout the centuries in preserving a lot of the artwork. Churches for instance, have massive structures and also contain a considerable amount of moisture absorbing materials, from porous renders to wooden works of art, which allow for effective thermal and humidity buffering processes. They are also considered to have small rates of air exchange, allowing for the internal conditions to slowly follow outdoor changes, so that the seasonal cycle is attenuated and the short-term fluctuations are significantly flattened [19]. However, as societal dynamics evolve along with the passing of time, particularly in the usage and re-usage of historical buildings, new needs arise possibly hindering the integrity of these outstanding remembrances of history.

In natural ventilated buildings, particularly when considering that most historical buildings seldom have a tightly sealed envelope [20], it can be expected that the indoor conditions will respond to the outdoor conditions. This might constitute a problem in winter, when colder temperatures from the outside air infiltrate to the inside, where they are met by a warmer climate due to the seasonal delaying effects on internal temperatures, as result of their high thermal inertia. A sudden change in outdoor temperature will affect the indoor RH, given the temperature difference presented by the incoming air and the inside surface. As a result, there is an added concern in the risk of condensation on cold indoor surfaces, especially in the spring. When the hot air from the exterior infiltrates to the inside, and comes into contact with surfaces that still retain colder conditions accumulated throughout the winter, it will be cooled, inducing an increase in relative humidity in the area close to the surface, giving rise to a potential condensation of water vapour on that cold surface. An analogue situation is presented usually in northern cold climates, that resort to humidification to balance out the drop in humidity levels caused by the use of heating, to the lower range of human comfort levels. As it is, this transfer of humidity to the interior air may result in the rise of the dew point [1]of indoor air and if it surpasses the external air temperature could potentially lead to condensation, when this warm interior air meets the cold surfaces affected by the external climate. Condensation problems are of great concern for historic buildings, to the detriment of the valuable art-work housed inside as well as their own structure, such as the rotting of wooden elements, mould growth on interior finishes, corrosion of metals and spalling of masonry [21].

Another aspect to consider is that this infiltrated air contains microorganisms as well as pollutants. These microorganisms find the adequate conditions to grow in moderate air temperatures and cold moist surfaces. If the indoor conditions and substrate are favourable to the appearance of superficial condensation in walls, or even in objects, usually more prone to appear in corners or areas where the air is more stagnant and surfaces that remain colder and moister, this constitutes an adequate environment for the development of mould. Evidently, in a museum environment this aspect leads to consequences of great extent, as the integrity of collections becomes compromised.

Over this prospect, an inherent natural variability in temperature and relative humidity conditions, most commonly induced in the term microclimate, is presented on the interior of this type of buildings – naturally ventilated ones. For several centuries that is undoubtedly what provided the vital conditions for long-term preservation of the art-work and the building itself as well as the permanence of people. Now however, given the complex requirements when considering a museum facility, specifically when this type of buildings is used for such a purpose, these factors are often seen as liabilities. Energy efficiency in historical buildings is a daunting task to ensure, either due to technical constraints or to limitations because of the cultural value associated to the envelope. Any intervention with the intent to improve its thermal performance, has the hindrance of the cultural value associated to the building, bearing in mind the integrity of the materials, as well as the unaccounted repercussions that a retrofitting of walls or windows would impose on the original climatic conditions. This could potentially give rise to other problems such as condensation on wall surfaces with either low vapour permeability or hygrothermal favourable conditions, since the excess moisture produced could be to such an extent that would compromise the previously established natural microclimate. Then, those measures could possibly be considered more unfavourable than

[1] The dew point temperature is the temperature to which a parcel of moist air must be cooled at constant atmospheric pressure and constant water vapour content in order for saturation to occur adapted from [16].

beneficial. Mechanical systems that control the internal climate and human presence may also completely change the natural equilibrium as previously mentioned.

When attempting to take a more active approach in controlling the instability that affects the environment where objects are displayed, the problems associated with the installation of air-conditioning in these massive historic buildings, which ideally requires a well-sealed envelope with appropriate levels of insulation, may compromise not only their authenticity but also their efficiency.

The installation of HVAC systems presents a risk to the structure and the building envelope, particularly with the introduction of ventilation ductwork, having to destroy walls and floors for that purpose, but also since the structure of many historic buildings is not designed to withstand the high moisture content of humidified air [22]. Furthermore, when the air that is blown intermittently reaches the walls and certain places where art-work is being displayed, gradients of moist/dry and cool/warm air are generated and moved by internal air motions, resulting in repeated cycles of temperature and relative humidity fluctuations or the transport of airborne pollutants and dust particles that may be deposited in the surfaces of objects [13]. In this account, often enormous financial and also technical efforts are required, not only investment-wise but also on ongoing expenses particularly to do with extensive maintenance and appropriate control [23].

So as to reduce infiltrations of external air and pollutants, there is a current practice in these types of buildings, mainly commercial and museums, to maintain air intake higher than air exhaust resulting in a higher indoor pressure than outdoors. Thus creating an internal artificial microclimate, not always in equilibrium with the many variables at play, particularly heat and moisture transfers when it comes to balancing the influence of visitors, air leakage and exchanges between air and surfaces [16].

The referred term *microclimate* can be understood as a more specific focus of the climate of an isolated area, as the prefix ‘micro’ suggests, a more centralized analysis of the factors that influence a particular ambient that in its own way differs from a broader context. It does not necessarily imply a precise size for the analysis, so it can range from a certain regional scope to the general indoor environment of a building and even to the level of enclosures or display cases that protect sensitive artefacts. In its full comprehension, respectively due to the world climate, it understandably deals with atmospheric conditions, mainly the transfer through heat, air and moisture that all combine to form a complex variable, determining temperature and relative humidity and their effect on organic and inorganic materials and their surroundings [16]. The indoor climate in a building is not uniform throughout its entirety, necessarily due to the existence of local diversities that can have a number of different causes. According to this perspective, it can result in concerns to the preservation of artefacts, if a particular spot indoors differs substantially to the overall conditions of the interior climate, either due to mechanical equipment or natural building physics. If there is the perception that local adverse conditions may compromise the adequate preservation of sensitive artefacts, instead of intervening on the whole building, local measures can be taken to improve the conservation of a selected group or even an isolated object, as with the examples of glazed, backed paintings and microclimatic enclosures. In his regard, the glass fronted frames and moisture impermeable backing boards are used to attenuate RH fluctuations [24]. As for the airtight display cases, which require an added concern to stabilize the microclimate, with the appliance of different techniques necessary for its control, such as the use of additional buffers as the example of silica gel [25], so that the opposite effect of what was intended in the first place, that is to rectify an unfavourable environment, does not compromise the integrity of objects.

Undoubtedly, physical and ambient environments in which heritage collections are housed have a significant impact on their long-term preservation. Deterioration is not entirely unavoidable and it assuredly is a multiplier of known and controllable causes. The major agents are indeed environmental, but that is not to say there are no other causes that should not be taken into consideration, such as random occurrences that might potentially endanger the integrity of the art-work. At this point it should be relevant to mention that not only temperature and relative humidity account for the environmental problems that concern the welfare of collections. Other factors, such as light (UV or artificial radiation), indoor and outdoor airborne pollutants, microorganisms as well as time itself also bring added worries for the management of the indoor climate, that not only is supposed to safeguard the collections but that also has to do so while displaying them to the public. Given the complexity of this spectrum of parameters, which have an influence in the degradation of the art-work and the limited scope intended for the matter in this text, only the hygrothermal conditions of the environment, namely temperature and relative humidity, are going to be analysed in greater detail in the following points.

2.1.2 *Temperature in the Building Context*

The understanding of atmospheric thermodynamics in environmental diagnostics is an absolute necessity for the ability to understand the processes that affect cultural heritage, particularly how causes manifest effects and deterioration mechanisms.

When heat reaches the inside surface of a wall or window, it is transmitted to the interior climate through radiation and convection. As presented above, depending on the orientation of these elements, directly in contact with the external environment, the influence of solar radiation and other factors, a considerably different amount is going to make it through. As it is, rooms in the interior or with less external elements will have significantly different requirements than those located more outwardly, since they are better shielded and the effects can be smoothed out. Of course, this also applies to the ground floor rooms where a large portion of the heat is able to be stored there [16]. As it can be understood, there are considerable differences between museum rooms. This may be explained in part by exposure, by the construction materials employed, or the very nature and characteristics of the objects exhibited in a particular room, and also when considering mechanical climate control factors such as heating, humidifying or ventilating. Figure 2.2 ilustrates a summarized scheme of the heat gains in a museum building.

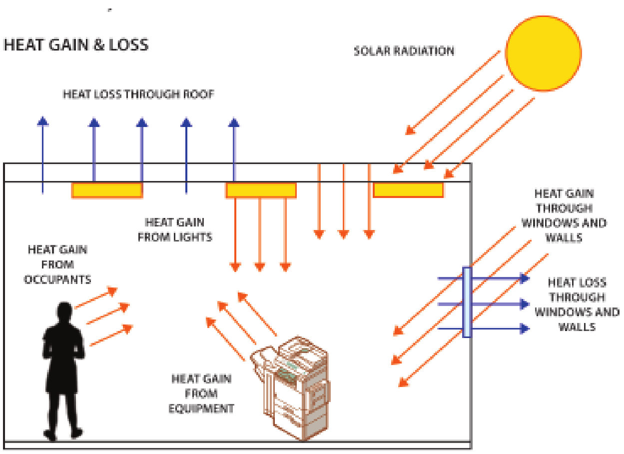


Figure 2.2 - Scheme of heat gains inside a museum building adapted from [26]

When air comes into contact with surfaces that variate in temperature, from colder to warmer conditions, it suffers a change in its density favouring the ascension of warmer air, since its less dense, and the descent of colder air, given its higher density. In buildings, the air cooling occurs in a localized area near the inside surfaces of external elements, so that when considering winter conditions lower temperatures are registered in comparison with the ambient conditions. It is important to take into account that relative humidity adjacent to that inner surface is higher in winter and spring conditions than the rest of the air in the environment. This happens due to the drop in temperature suffered by the air that comes into contact with the cooler surface [18], and of course the inverse variability that defines the connection of these two parameters.

A natural convective motion is induced, and considering a closed room with no additional sources of heat or moisture, air density regulates the distribution of the air inside, in that warm and lighter air will rise to the top, and the cold and denser air will find the floor. For this reason, a thermal layering tends to form, that is, a stable atmospheric stratification with temperature increasing with height. As might be expected, in a museum environment there are several factors and mechanisms that can impact that natural equilibrium. Apart from given assurances such as people and lighting, internal sources of heat or moisture in cases where there is an existing artificial climate control in action, whether it be with heaters, humidifiers and dehumidifiers, air-conditioning or ventilation of any sort, either forced or just the simple fact of open windows and doors, it is evident that they increase the complexity of the distribution of indoor air. There is an inherent intermittent use associated with these systems, and also the fact that they are located in specific spots, so that they continually generate discrepancies in the internal microclimate. One example are fans, that destroy the aforementioned thermal layering that is naturally established. Given that indoor temperatures are determined by the exchange of all these diverse parameters, a distinction should emerge from natural factors to the building usage and the type of climate control implemented [16].

For instances, temperature variations affecting air movements will certainly be responsible for the transport and deposition of pollutants to the detriment of art-work and monument surfaces. In the specific case where there is a radiant floor, for example, near a wall that has valuable works of art, it could be frescoes or paintings, the warm air that rises through convection forces could contain airborne particle matter or pollutants and if the surface allows for their deposition, this will undoubtedly constitute a danger to the art-work [27].

The best indoor conditions can be achieved when thermal inertia of walls, floor and ceiling are similar between them – since when they differ, the internal stability changes according to the season. For the particular case of churches, there is a shorter time-lag to the variations of seasons affecting the ceiling when compared to the ground floor. Subsequently, in the summertime, as the ceiling is warmer and the floor cooler this will generate an internal layering with a vertical thermal gradient, opposed to the situation presented in winter where the cooler ceiling and warmer floor affect the air stability, compromising it [16].

2.1.3 *Relative Humidity in the Building Context*

Atmospheric air always contains a certain quantity of water vapour mixed with other diverse gases, giving purpose to the fact that hygrometry aims to determine the moisture content of the air at a given temperature [28].

There is a subjectivity to how we perceive ambient conditions to be, varying from each individual evaluation of air quality, either on themselves or on objects, paper or cloth being the most perceptible, ranging from ‘’drier’’ to

‘’moist’’ conditions. Thus environmental monitoring and atmospheric thermodynamics are useful tools in environmental diagnostics, those being essential for the improvement of knowledge regarding the basic processes that affect cultural heritage, evidencing causes, effects and deterioration mechanisms [16]. So, for a proper measure of hygrothermal conditions it becomes necessary to find methods that best evaluate them. When considering temperature, it is fairly known that it can be expressed in either Kelvin, Centigrade or Fahrenheit, however, when it comes to defining humidity, the decision upon which parameters to use is certainly more nuanced. There are indeed several parameters to choose from, each with their own individual characteristics, but in the end, it all comes down to trying to best define the concept of humidity in a given context and ambient. In this specific field, even though other parameters such as vapour pressure or dew point temperature could potentially be used by engineers that consult on climate control systems, every content regarding the care for collections, when humidity as a factor of deterioration is concerned, it is facilitated for consultants through specifications in which relative humidity is the parameter [25].

Assuredly, there can often emerge some difficulty in the comprehension of this specific parameter, particularly in the ambiguity of its name. The term relative, in itself, induces a variability when considering the link between different quantities. It is a ratio, presented in percentage, that can be expressed either between the concentration of water vapour with the saturation value or the partial water vapour pressure to the saturation pressure at the same temperature. The fact of it being a ratio makes it indifferent to the choice of which unit of concentration to use. As it is, the reason for it being expressed as relative is the association between the actual amount of water vapour that is contained in the air, and the maximum quantity that it could possibly contain at the same temperature, which translates the dependence on the association of two variables. One that is a characteristic of the environment itself - the quantity of water vapour that exists in reality - and another that assumes the same value for a given temperature - the saturation value [18][29].

However, it should be noted that when focusing on one given temperature there is no possible indication to infer if the real amount of water vapour is either very high or very low. Still, with visual help of the psychometric chart, a graph widely used by engineers to plot the relationships between all the referred parameters, it is intelligible that 33% RH air contains much less water vapour when the temperature is low than when it is high, so that a rapid drop in temperature has the effect of immediately raising RH above 33%, tending towards the 100% level and reaching the dew point, that is the temperature to which the air must be cooled, for the excess moisture to appear as condensation [28]. In Figure 2.3 is presented the psychometric chart, the horizontal lines representing values with the same water vapour concentration (kg/m3), the vertical lines indicating values with the same temperature (ºC) and finally each of the presented curved lines is composed by values with the corresponding relative humidity (%).

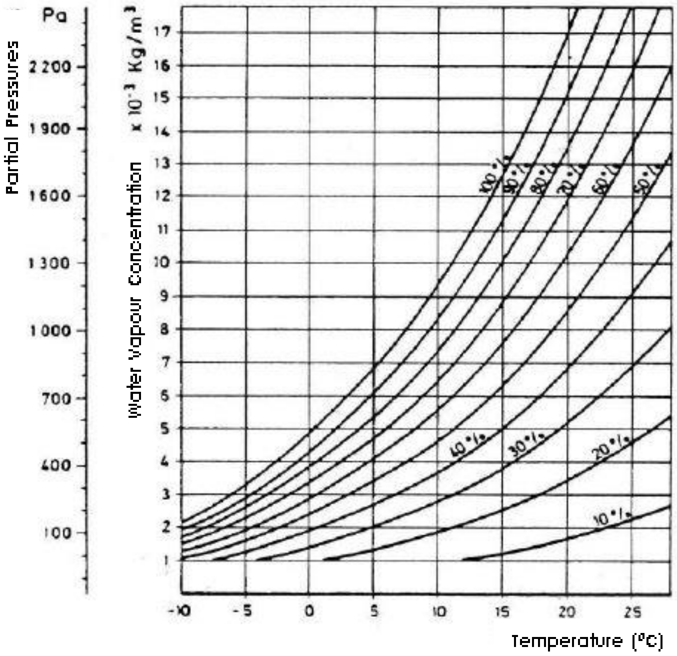


Figure 2.3 - Psychometric Chart, adapted from [18]

This represents that a change in temperature causes a change in relative humidity. Certainly, the indirect effect that temperature holds on RH is important to be aware of, given that a rise or fall in temperature causes the lowering or increasing of RH, correspondingly. Therefore, it should be obvious that most of the daily cycle of RH is intertwined with the temperature cycle, at a fairly constant water vapour content in the ambient air. So that when temperature rises, humidity immediately falls, respecting this constancy in the actual water vapour content ratio, with the steep increase in the maximum capacity of water vapour that it suffers upon the rise in temperature [30].

Knowing that temperature fluctuates along the day, there is the certainty that relative humidity will also fluctuate, a defining principle when it comes to the control of this important agent of deterioration [29]. In museums and historic buildings, the cyclical repeated fluctuation in RH may range from slow seasonal change, instigated by a decrease in RH, for example, in winter because of heating, if it applies, and a return to a higher level in summer. And even to brief fluctuations under the hour mark, resulting from the opening and closing of doors and windows, the numbers of visitors or even the intermittent operation of heating [31]. It is also important to consider the effects that humid air reaching localized cold spots in the building can have, particularly when it leads to condensation. Taking into account the regional climate, certainly as wet climates have the potential to exacerbate this situation if deficient drainage of rainwater techniques are implemented, causing possible infiltration of water. The most vulnerable places in a building associated with damp are the ones that are closer to the source of the problem, usually the basement, ground levels or attics, the latter caused by roof leaks, briefly summarized as well as illustrated in Figure 2.4, where A refers to surface drainage; B to soil drainage; C to rainwater; D in respect to attics; E to the exterior walls; and F to heating systems.

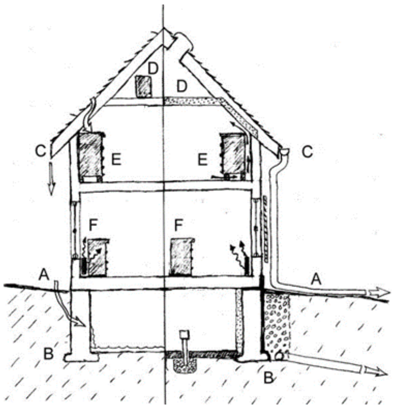


Figure 2.4 - Possible circumstances of a building affected by infiltrating water, adapted from [25]

There is a general understanding to the fact that construction materials, whether organic or inorganic both have porosities in their constitution. In open porous materials, necessarily the way they interact with different hygrothermal conditions in an indoor environment can be described in the adsorption and desorption phenomena. The first term refers to the adherence of water vapour on the surface of the porosities of solids, whereas the latter, as can easily be understood, is the opposite, that is the release of water vapour content from the porous cavities. However, a distinct hysteresis effect is observed in this process, as there is a higher moisture content exchange in the adsorption trend [31]. In most mineral binding materials, such as concrete and mortars, this effect is highly accentuated, yet on a contrast note when considering other materials, essentially wood and certain stone types, the hysteresis effect is considered to be practically null and therefore negligible in practice [18].

This is how the moisture content of organic and inorganic porous materials, used in building construction, establishes equilibrium with the values of RH and temperature in their immediate environment - these materials are named as hygroscopic. A typical porous surface will adsorb a higher amount of water vapour as the RH progressively rises. This effect is even heightened by the existence of hygroscopic salts in the pores, such as chlorate or nitrates, that have the ability to adsorb great quantities of water vapour affecting the normal behaviour of the material.

As it is, there is a considerable potential for building materials to buffer relative humidity, although it is often neglected since water vapour passes through materials much more slowly that heat does [15]. Indeed, hygroscopic walls and ceilings allow for substantial stability in the indoor RH, but there are factors that influence its performance, namely the ventilation rate exchange, provided that it is small [32], and vapour permeability of the surfaces. Modern buildings are designed with a great airtightness that results in a slower air refresh rate, moreover this allows for a better buffering and stabilisation of relative humidity by absorbent materials [15], which rapid uncontrolled air exchange previously made ineffective. This slower refresh rate could potentially affect air quality, in the way that moisture damages might occur, when the ventilation is simply not sufficient to remove the excess from the indoor air. When considering a museum there has to be a careful balance between the ventilation rate as well as thermal and humidity buffering, which has to surpass the obstacle that is combining an appropriate air exchange rate for human occupation – mainly visitors – along with the one that is appropriate for the effective buffering by the surfaces in the room. In a given space, there is a corresponding exchangeable water content in materials, so that not only when temperature changes but also when considering air transfers, the existing hygroscopic materials will buffer the RH of their environment [30][33].

Considering the possibility of the non-existence of adequate surfaces for adsorption/desorption exchanges, there must be nonetheless an equilibrium between the water vapour content in the air, either produced or transported inside. According to the mass conservation principle, the entire exterior water vapour that infiltrates a room along with the amount that is produced inside and is either condensed or evaporates from the surfaces, has to be the exact same as the amount removed by ventilation and/or diffusion through building materials along with the portion that gathers inside [18].

In unheated churches, the interior microclimate is regulated by how the building features can respond to the outside climate. It was previously mentioned that historic buildings such as these benefit from their massive walls by flattening the changes in outside temperature, with their high thermal inertia, but their interiors also accommodate large volumes of moisture-absorbing materials, in either porous renders or wood, acting as an effective temperature and humidity buffers [34]. Therefore, this buffering provided by church walls is considered to be far from negligible and assuredly beneficial to its furniture and wall paintings housed inside.

Materials such as stones, bricks, pottery, plasters and frescoes that have soluble salts in their existing pores are affected by microclimatic changes. Taking the example of an historic building being affected by rising water from a saturated terrain. Given that the building has existed long enough for that water to ascend by capillarity and if soluble hygroscopic salts exist in that soil, nitrates for instances, they will eventually be dissolved in that water and migrate through the wall. Being hygroscopic, their adsorption of water vapour is considerable, therefore they are going to be affected by cycles in relative humidity following the changes in environmental conditions that can originate their crystallization or dissolution. As it is, anomalies are going to arise in the materials and art-work, particularly derived from efflorescence and crypto florescence phenomena. The first indicates the level reached by capillary rise where water evaporates, where the salts will be deposited on the surface of the material for high levels of RH and the latter occurs when levels of relative humidity drop below a specific range and manifests itself in the underlying layer of the coating of the building, which can lead to the delamination and flaking of the material, for usually the salts occupy a volume larger than the one that can be contained within the pores of the materials, something incredibly disastrous when in a perspective of heritage conservation [16][35].

Following that same example, in the advent of the salts remaining dissolved or even if they are non-existent, the simple fact of water content infiltrating to the inside of the wall, awarded to the deficiencies in the building construction, induces the decrease in thermal resistance properties of the materials, which will therefore promote the risk of condensation, considering the decrease in temperature [35]. All these factors affect in some way or another the established microclimate on the inside of the building, particularly considering relative humidity, giving rise to problems because of that disruption, which is in no way favourable to the valuable art-work displayed on the inside.

3 MECHANISMS OF DEGRADATION TO COLLECTIONS – MECHANICAL, BIOLOGICAL AND CHEMICAL

3.1 General considerations

As specified before, buildings where museums are housed are defined by an internal microclimate that is dependent of several factors, though the focus in this text being restricted to the two fundamental parameters: RH and temperature. Following the previous broader scope of how they influence and operate inside the building context into a more concentrated approach to the object level within a collection, emerges a conflict between three distinct degradation processes that dictate how the materials are going to react. These mechanisms have a mechanical, biological and chemical origin and it is useful to individualize their analysis, given the fact that not all objects respond in the same way to climate variations. Over the prospect that most of the museums are populated by mixed collections, certainly these three processes, according to different values of temperature and RH, will have a particular and sometimes conflicting effect on different properties of objects as will be presented on the following points.

In a management perspective, there is a continuous search for appropriate climate control guidelines for collections, that are essentially formulated to define allowable ranges and fluctuations to these two parameters in an attempt to minimize the damaging effects to the art-work. Degradation in museum objects could be affected by mould growth, through the transport of microorganisms present in the air. It could also be due to inherent chemical changes, such as hydrolysis and oxidation. Since the vast majority of cultural objects are organic, their mechanical properties are also dramatically altered, swelling and shrinking whenever there are variations of temperature and relative humidity over time. It then becomes apparent the need for their control and the appliance of the best methods for their safeguard [36][17]. In accordance to that underlying principle, questions arise regarding low, high and fluctuations about mean values for both considered agents of deterioration, RH and temperature, that will be presented below.

3.1.1 Temperature as an agent of deterioration

Temperature is amongst the factors that can indeed have a serious impact on the preservation of artefacts. Variations in temperature usually appear in areas where objects are adjacent to external walls or close to heaters, lamps, air conditioning equipment and air vents or even when affected by direct sunlight. The most undesirable source of temperature is indeed direct radiation from the sun, as it cyclically reaches surfaces oriented towards it, resulting in high values that drastically surpass ambient air temperatures and can be even higher if they are enclosed by glass when considering the use of display cases or picture frames. This overheat results in thermal expansions of the materials and is relevant not only for objects but also the structural stability of monuments and buildings [16]. There is also the consideration of incandescent lamps used in display cases that result in extreme temperature fluctuations in museums. In respect to outdoor temperatures, they do not necessarily cause rapid fluctuations nor extreme temperatures in the perspective of regular objects, whereas in unstable materials summertime high temperatures are a problem, for example old film, that is best preserved in cold temperatures [37]. Although most objects are not directly affected by air temperature, there is a need for its control as variations induce differential expansions in materials and tensile strengths between the surface and the subsurface layers and can also have indirect effects in the environment within a collection space, as previously mentioned that a change in temperature causes RH changes. So that organic hygroscopic materials, that adsorb and release moisture in the air to reach equilibrium, such as wood, paper or leather, may shrink and become brittle when a rise in temperature drops the relative humidity for example. Indeed the rates of the many deterioration mechanisms increase right along with temperature, biological activity being of great concern, as well as damaging chemical processes that accelerate exponentially when temperature elevates, with an approximation for organic materials, in that reaction rate doubles with each 5ºC rise [38].

High temperatures promote the deterioration of collections by the increase of chemical reactions, they therefore assume an important role in museum climate control. The decay is mostly caused by acid hydrolysis, that affects materials that are acidic in nature such as paper – as in Figure 3.1 – photographic material, rubber and plastics or those of which become acidic from exposure to industrial pollutants, for example, as the cases of textiles and leather. Physical characteristics of materials are also affected whenever temperature is too high, some will distort irreversibly, such as many common plastics, while others may deform in the base of magnetic media tapes (analogue and digital), also waxes present in oil paintings may melt or soften.

Figure 3.1 - Embrittled low-quality paper, a chemically unstable material that deteriorates notably faster at warm temperatures adapted from [39]

On the other hand, when temperature is high enough for biological activity, mould and insects could potentially endanger collections, respectively at above ~4°C and ~10°C [37]. The spores of these microorganisms that exist in the air are not only dependent on this parameter to become active and cause one of the main concerning deterioration processes that affect museums worldwide. Indeed, mild to moderate temperatures in the range of 25-30ºC particularly play an important role but the mould germination depends also on the RH, the quality of the substrate, its structure and the chemistry, as well as further environmental variables such as air pollution, ventilation, light, in which they all have a substantial influence in defining the adequate conditions for its germination. Preventive models exist, necessarily the isopleths system, to determine fungal growth particularly given the fact that temperature, RH and substrate have to simultaneously allow, over a certain period of time, the appropriate conditions to trigger fungal growth. So that for different substrate types several graphs combining temperature, RH, germination time and growth rate are considered to determine if and at what rate fungal growth occurs [40]. This microbiological manifestation, particularly covering the surface of stones and other materials, causes not only a visual impact that should be averted, but it also favours conditions to the deposition of airborne particular matter that, along with the deposited material, create a composite layer that alters the surface characteristics, namely the thermal conductivity, water balance, porosity and water vapour diffusion inside the material, affecting in this way the established hygrothermal equilibrium of the material, with the alteration of important processes such as the adsorption and desorption of water vapour [16].

Overall low temperatures are considered to be beneficial to collections as they are effective in slowing chemical degradation especially for certain highly sensitive materials, such as newspapers, film, tapes plastics among others [37]. Moreover, low temperatures also slow water vapour diffusion, increasing the response time in materials such as wood to RH variations, so that in unheated historic buildings it is often frequent the practice of storing wooden art-works, since its preservation is favoured [31]. There are however significant limitations in allowing lower temperatures, as objects that contain plastics, painted and varnished furniture, musical instruments and polymeric materials such as paintings on wood and canvas are extremely exposed to risk in these conditions. Below the glass transition temperature such materials become very brittle and when combined with stress caused by low temperatures objects crack, and this happens as fast as it takes for the object to reach the equilibrium with a new temperature. Nevertheless, at low temperatures for wood, ivory or hide glue to either plastically deform or break they would have to be completely restrained and have high existing stresses, since if allowed to freely move dimensionally they present no structural problems. As it is, limitations to low temperatures are defined particularly by the object's ability of maintaining mechanical stability [41]. It becomes apparent that this is one of the pertaining dilemmas, when it comes to the consideration of the necessary balance between chemical, mechanical and also human comfort needs, since they are conflicting when assessing an appropriate climate control in a museum space.

Until now the consequences on objects related to both higher and lower limits in temperature and how such conditions may constitute a danger to collections were presented. However, it is also very important to take into account the transition process that objects suffer when reaching such limits. The underlying mechanism to damage in objects whenever temperature rises or falls, is their thermal expansion and shrinkage, respectively, affected by the anisotropy in their composition. This is to do with their unequal expansion in different directions, or rather by complex assemblies in materials that differ in their thermal coefficients of dimensional change, developing stresses when restrained, or even that their thermal response time is longer than surface change in any given collection item. All materials can reversibly sustain some stress and strain, though fracture and permanent deformation should be avoided in order to prevent damage to artefacts, and as such the stresses originated by changes in dimensions, that either reach fracture strength or are larger than the yield point of the material are a major factor of concern in damage control [42].

When considering the response time in materials to fast fluctuations, particularly their ability to attenuate them, it is understandable that the shorter the fluctuation the thinner the layer affected in its bulk will be. Yet, seeing as though the artistic value in museum objects and monuments lies specifically on the superficial layer, shorter temperature fluctuations, such as daily ones, are perceived as a greater threat to collections rather than seasonal ones, that even though more prolonged in time are indeed less dangerous as they have a slower rate than the penetration of heat in the material, resulting in no significant stresses between the external layer and the interior one [16]. So, if the object is subjected to a fluctuation that surpasses its ability to respond evenly, an internal temperature gradient is generated, causing internal stress and accelerating fatigue failure as it does when moisture is concerned [43], due to repeated cycles that accumulate that stress, with the result of visible damage to vulnerable materials, particularly brittle ones, that is, where there is very little or none capacity for plastic deformation, with examples such as glass, ceramics and old oil paints that fall under this category [41]. The outer layer of stones is also prone to thermal cycles by the advent of mechanical damage, beginning at the discontinuities and interfaces between the different minerals in their composition, resulting in internal tensions that damage the surface. In assessing dangerous daily fluctuations one of the most important examples are the freezing-thawing cycles that induce mechanical damage to materials.

3.1.2 Relative Humidity as an agent of deterioration

Relative humidity plays a predominant role in the conservation, due its considerable influence in the different degradation mechanisms [44] and is the remaining parameter considered in this dissertation. A recurring and already specified problem emerges since it is not possible to define universal safe ranges given the diverse effects of RH on each degradation processes and their variation in a mixed collection environment. As such, it is useful to analyse this parameter in light of individual limitations that induce damage such as lower and higher extremes and fluctuations about a mean, as made previously for temperature.

The way that indoor climate fluctuations affect the equilibrium moisture content in objects results from several factors, such the solar exposure, exposure to air flows and heat sources, or even the object constitution. The exposure to high RH values could result in the mould germination and the fluctuations can induce dimensional changes, specifically in hygroscopic organic materials, with repeated swelling or shrinking consequently leading to deformations and cracking, or even chemical reactions such as corrosion in metals that could be exacerbated if they are contaminated with salts.

As previously stated, typically historic buildings may have problems with surface condensations that lead to high moisture levels and affect the collection items adjacent to those surfaces, as one of the most frequently observed examples of damage due to those conditions is in paintings, given that the microclimate behind them is entirely different than the central gallery space. In summertime, the walls get warmer resulting in drops of relative humidity in those interior surfaces, as they conversely can be exposed to cold and moist climates, resulting in variations along the year. Moreover, the consideration that many of the traditional lining techniques using hide glues and pasta adhesives contribute even more to the increase of moisture content in paintings, as they potentially intensify the shrinkage of the original canvas and the weakening of glue size [45], especially when taking into account that the moisture diffusion coefficient in organic materials increases with moisture content, and certainly capillary wicking fabrics allow for condensate water particles to penetrate faster than vapour.

All the deterioration rates climb rapidly with increasing RH and if the objects were to be subjected to RH values above the limit of 75%, they could potentially suffer a range of diverse problems, from dimensional changes that increase significantly for every increment up to 100% RH, to germination of mould (Figure 3.2) [39]. RH causes the disintegration or discolouring of materials such as skin, leather, textiles, paper, wood, paint and glass, and also the fact that above that value there is a rapid growth of water content that is always present in the surface of metals, exponentially adding to their corrosion [46]. Some minerals deliquesce above certain critical RH values, that is, they form a salt solution by adsorbing moisture from the air, due to their hygroscopic character, which promotes the attachment of moisture to the surface of metallic objects, particularly the cases of archaeological iron and bronze, most vulnerable to this occurrence, thus determining the formation of an aggressive agent that activates and even intensifies their corrosion [25]. Other impurities such as dust, that also accumulate on those surfaces may aggravate this condition, attracting moisture as well and possibly contaminating it with the soluble acidic impurities of the atmosphere.

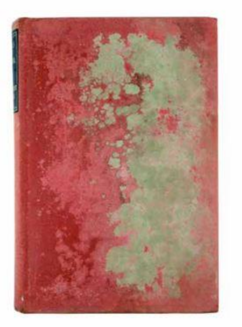


Figure 3.2 - Mould growth on a book exposed to conditions of high relative humidity, adapted from [39]

Apart from extremely vulnerable archival materials such as acidic paper, magnetic tape, film, that decay very rapidly through acid hydrolysis, and thus require extreme control to stop the reaction process to proceed, maintaining them below 0%, in regards to chemical reactions that can lead to the deterioration of materials in museums, there's certainly an added concern to maximum levels permitted to relative humidity, so as not to compromise the preservation of vulnerable and unstable objects at display, mainly due to the acceleration of metal corrosion, the fading of dye materials, the decrease of paper and cloth resistance and also the deterioration of certain glass materials [47]**.** Chemical processes in many objects are therefore dependent on or accelerated by water content, increasing reaction speed correspondingly in hygroscopic materials as RH rises.

Although low humidity does decrease this reaction speed, by lowering moisture content and therefore chemical deterioration, a conflict emerges upon consideration of another mechanism if either handling of the object or a sudden change in RH takes place – mechanical degradation. According to this, lower RH can be considered beneficial for some materials and should indeed be permissible if there is no risk of physical damage, certainly an important factor to take into account when considering brittle materials that have no capacity for plastic deformation, such as glass and ceramics for example. Very low humidity affecting organic materials will cause them to exchange some of their moisture to the environment, resulting in their fragility as they become more brittle and may shrink or, if vulnerable enough, suffer fracture.

Figure 3.3 - Loss of paint in a polychrome wooden sculpture caused by large fluctuations in relative humidity, adapted from [39]

When comparing a rapid change in RH affecting a hygroscopic collection with a certain response time, an internal RH gradient is generated, which can lead to physical damage. The fluctuations considered to be the most stressful for an item are the ones longer than its response time, but shorter than the stress relaxation time. As such, it should be noted that the different relaxation times for gesso, wood, paint and varnish all strongly increase by both low RH and temperature, leading up to possibly more damage in this regard. Indeed, a variation in RH affects the moisture content of hygroscopic materials, ranging from rigid materials such as wood, glues and ivory, to more flexible ones that include papers, parchments and textiles and also to a lesser extent gessoes and paints, resulting in a dimensional response [45]. It is important to point out at this consideration, that physical damage is particularly due to dimensional changes in materials that are restrained from movement, seeing as though no problems are presented whenever they are free to expand and contract [25]. In this respect, a slow RH change over time does lead restrained objects to a deformation stress, which can become so intense that permanent deformation occurs, whereas for short fluctuations, only the most superficial part of the object responds to this change, hence the constraint in movement that the bulk produces. As it is, variations in humidity levels not only affect severely the interior of wooden artefacts such as furniture, for example, but also induce spalling of paint (Figure 3.3), loosening of joints and surface damage in other complex assemblies of materials.

Museums galleries are indeed populated with a large variety of artefacts that tend to have complex assemblies of materials, which makes up for diverse responses in time as a result of varying environmental conditions, that could be caused by natural hygrothermal processes or due to existing heaters, air-conditioners or humidifiers, causing deformations to the structure. A very pressing example in this context are panel paintings, as they are considered to be in the category of heritage objects most vulnerable to fluctuations in the indoor climate [48]. Particularly because of their multi-layered structure, composed of hygroscopic materials that each have their own individual dimensional response rate to variations in their environment, necessarily the wood, gesso containing animal glue - applied to prepare a smooth, paintable surface - and paints. Stresses induced could be a result of the uneven moisture distribution on wood, acting as its own constraint from movement as the moisture diffusion is not instantaneous causing deformation and cracking on the wood since the outer parts respond more quickly than the interior to variations, but also of the pictorial layer on the unrestrained wood substrate due to mismatch in the dimensional response of gesso restrained in the direction parallel to the grain of the wood, resulting in subsequent cracking and flaking of the pictorial layer (Figure 3.4) [45].

Figure 3.4 - Crack variations related to climate fluctuations. Credit: Stefan Michalski, CCI, adapted from [49]

4 THE DEVELOPMENT OF ENVIRONMENTAL STANDARDS AND CLIMATE CONTROL STRATEGIES

4.1 *Early 20th Century Conservation Field Considerations*

Collections were initially exposed to similar conditions experienced by people, with limited heating from fireplaces and natural ventilation since it was yet not technologically viable, nor economical to that extent, to pursue a more elaborate and specified control of the environment.

Late 19th century saw the emergence of industrial technology, first with central heating and eventually in the transition to the 20th century with air conditioning and humidity control. These systems certainly marked the beginning of a new era in museum climate control, since they modified the interior environment either with the intention to produce uniform indoor climate or ultimately a different one from the exterior conditions. It is reasonable to assume that initially these installations were mainly integrated in accordance to human comfort rather than necessarily with the collection's safety in mind. Central heating, for instances, affected RH, by lowering it to levels never before experienced in certain interior climates, which led to the adverse effects on artefacts, mainly due to observation of flaking in paintings, cracking and warping of wood and loosening of furniture joints [50]. The most relevant causal chain was set in place – that is low RH inducing dimensional response of materials, causing strain beyond its limits leading to fracture and delamination. This of course lead to a newfound interest in furthering the understanding of the mechanical decay of hygroscopic materials, through research that focused on these mechanisms, and it soon correlated its cause to be due to these new heating systems.

The burning of coal and the industrialization of cities meant that 19th century external urban environment was highly polluted. Once electric lighting was introduced in late 19th century, concerns about internal gas lighting pollution were replaced by the infiltration of highly polluted air from the outside, which led to developments in ducted ventilation systems by filtering the air supply. In the transition to the next century early attempts regarding air washing systems became extremely attractive to museums, however problems related to humidification were found [21].

Chemical deterioration also saw some improvements with the understanding that high RH values accelerated light damage in studies conducted in the National Gallery of London and by the turn of the century a German chemist named Rathgen, considered to be the father of conservation science [51], discovered that the rapid corrosion of recently excavated bronzes, known as bronze disease, could be stopped by very low RH.

Developments in localized means of control also took place, with the adoption of passive methods such as the use of showcases particularly recommended by chemists [51], namely the coverage of oil paintings with glass in an attempt to secure the protection of their surface. Later, Rathgen as introduced the concept of RH controlled airtight cases with a sorbent, represented in his handbook for museum curators.

It is evident that, by the end of the 19th century, qualitative characteristics of the environment in museums were fully in place, namely that chemical deterioration slowed with lower RH and temperature, fluctuations in climate lead to cracks and delamination as well as the avoidance of damp to be proven beneficial. The realization in terms of moving from a fairly unheated climate, that had lower temperatures and was more humid, before the introduction of central heating, to an extremely dry environment when buildings began to be heated both day and night in the early 20th century had consequences on the artwork and certainly shaped to a great extent the environment in which museum collections were to be displayed for the rest of the century.

The Boston Museum of Fine Arts is considered to be one of the first museums to have implemented a rudimental air conditioning system in 1908, so that the intake of air was controlled with central heating, air washing and humidification. Observation by monitoring the effects of RH on objects, led to the definition of a range of values for indoor relative humidity from 55 to 60%, that supposedly best served the paintings and most of the artworks, regardless of temperature and time of the year. The engineer McCabe, responsible for the project, did not justify the obtained results that could support that assumption, but it certainly marked the development of environmental control specifications in museums, as the range appears frequently in following recommendations, such as The Cleveland Museum of Art, which, 15 years after its installation in 1915, set their humidity control from 50 to 55% [52]. Macintyre, working for the National gallery in London in early 1930s, also suggested the same targets used in the Boston Museum, albeit without specifics as to how it was derived, assumedly taking into account the local climate and feasibility. In regard to the control of temperature he suggested around 16ºC (60°F) since it was the level at which galleries were maintained during the winter months, and as Brown and Rose convincingly argue [21], that it possibly was not meant to be an all year round recommendation and that this arbitrary convention of values, particularly in respect to RH, could have been based on the system's capacity. This conviction of 16ºC and 60% RH was tentatively proposed in European literature until the early 40s, even with contradictory statements such as Coremans's, head of the Central Laboratory of Belgian National Museums, who admittedly, in a review article, also pointed out their unsuitability during summer in Europe, as humidity was believed to be too high and the cooling load too great, nonetheless embracing this values as optimum for year round control based on undetailed experiments [21].

In the end, the consensus was that there was indeed a lack of information on collections needs, so the logic that ensued and certainly that cemented a persistent ideology for many decades to come, was dependant on a balance of human comfort and cost, which would vary seasonally, as well as the reliance on the limitations of technological availability at the time.

After the first World War, the collections were evacuated to underground tunnels in both Great Britain and Germany. Even with the realization of the existing damp environment, which prompted the measures that ensued for the assurance of their appropriate preservation, via the installation of heating and ventilation, still these precautions proved to be unsuitable climatic conditions for the objects overall in the end. Part of the British Museum antiquities were discovered to have been subjected to damaging effects such as mould, corrosion and salt efflorescence, which of course contributed to the pursuit of a greater scientific input to the preservation of the collections, specifically in the establishment of research laboratories in these institutions [53].

As it is, the gathering of experience and knowledge by conservators and museum professionals on the effects that mechanical systems had on artworks, provided for the introduction and development, in the 1920s, of scientific methodologies related to environmental conditions. Most specifically with the establishment, as previously referred, of their own scientific laboratories in different museums and institutions addressing this pressing issue on the conservation of collections [54]. Therefore, research and analysis on artwork materials began to inform how they were exposed to environmental conditions, starting with the influence that hygrothermal values had on the conservation of collections and at which extent they could be controlled [55].

Thus, during the 1930s and 1940s, when as air-conditioning systems were being adopted, an active discussion on optimal values for temperature and RH took place. Some institutions both in the EU as well as the US started the evaluation of the causes of deterioration through systematic studies on objects, with the aim of applying those findings to the care of their collections. A new philosophy began to emerge, one that acknowledged the need for preservation before repair. In 1930 took place The First International Conference for the Study of Scientifics Methods for the Examination and Preservation of Works of Art, which resulted ten years later in the publication, by a panel of international experts, including Harold Plenderleith and George Stout, of the "Manual on the Conservation of Paintings". This did not necessarily account for an absolute specification of a standard, as the experts themselves took a more pragmatic explanation, regarding their proposition of the 60 to 65% figures attributed to the control of the RH, namely that "in many climates it is the nearest approach to the conditions in which a degree of stability may be easily obtained" and also that "in a temperate climate, 60% of relative humidity is the easiest standard to keep up. At normal temperatures, this represents comfortable conditions for the human organism" [56]. Rawlins, scientist at the British museum at the time, also proposed in his 1942 article, that the acceptable conditions should be 60 °F, 60% [57], nonetheless indicating that the only evidence he had regarding that proposition was appointed to the observation on the avoidance of the extremes to objects rather than a precise scientific basis, which just as Michalski points out [46], certainly led to the trap of a set target and easy to remember specification.

4.2 *Post WW II and the Generalization of Active Mechanical Climate Control*

For the second world war, such occurrences were to be avoided at all costs. Upon its emergence, plans were made throughout Europe, certainly in London for one, to protect the valuables collections from bombing, relocating them to safer places. So, collections from the Victoria and Albert, British Museum, the National Portrait Gallery and many other institutions were transported to a quarry at Westwood, approximately 27 meters below ground. Retrofitting measures were necessary in order to counteract the saturation conditions, with waterproof silica-based paint being implemented in the walls as well as air conditioning systems to guarantee the maintenance of a supposedly stable environment of 15º-24ºC and 60-65% RH [54].

The collection of nearly 2000 paintings from the National Gallery were stored in the Manod quarry in Wales (Figure 4.1). Given that the conditions in the slate caves were of extreme dampness too, brick buildings to improve the efficiency of climate control were constructed within the enormous mines along with a simple heating method found to be sufficient to reduce relative humidity without any active dehumidification to maintain an appropriate and stabilized environment for the preservation of the collections [54]. Constant conditions of 58% RH and 17ºC were obtained inside these structures and thus the paintings were kept until the war came to the end, upon which they were eventually returned to London. Before the war, and with the experience of previous occurrences of increased damage in painting panels, such as blistering and flaking in the then uncontrolled climate of the gallery

[58], investigations were conducted by the scientific laboratory of the National Gallery. They informed that the yearly average equilibrium moisture content of different species of wood in the exhibition gallery was of 11 %, corresponding to an average RH of 58%, which converged the feasibility argument with the annual average resulting in a set point for the wartime storage in this slate quarry.

Figure 4.1 - Storage of paintings at Manod during WWII, adapted from [54]

At both quarry locations, Westwood and Manod, conditions were considered to have been excellent for the storage of the collections that survived with an impeccable state of preservation during the war [21], which proved that ideal and stable storage conditions were indeed achievable with the appropriate mechanisms in place, that worked towards a somewhat specific target. However, upon return to the National Gallery after the end of the war, still not equipped with any active climate control system to date, the artworks suffered the re-occurrence of an epidemic of blisters, cracks and deformations on their panel paintings as a result of the indoor climate conditions of the museum building, that differed in a lot part from the favourable environment they experienced in the quarries. Which of course lead to the belief, certainly on the National Gallery's part that, since the average RH target of 58%, derived from pre-war experiments on the Gallery's different wood species and the London average value, had provided such good results during storage in Manod, and in the absence of data to recommend any other climate, replicating those conditions was considered to be the best approach. As it is, and after a recommendation from the Weaver Committee in 1947, air conditioning in the museum began to be introduced in 1950 [59]. However, this report dismissed problematics to do with the fact that the NGL was a 19th century museum building and the level of control that had been relatively easy to obtain in the caves at Manod could therefore not translate as smoothly to the same results there. Furthermore, this generalization of narrow control did not consider whether other artefacts indeed required such similar conditions. Nonetheless other factors also proved to be sufficient in sustaining this impending transition, particularly with the rising demand for glass enclosures to be removed from paintings, as they prompted irritating reflections, along with concerns for the highly polluted outdoor urban air in London, which lead of course, to the pursuit of a more efficient central filtration air system as well as one that could maintain the specified tight range for the preservation of collections [21].

4.3 *Since Mid-20th century – Development of Mechanic Climate Systems and Human Comfort Zone*

Following the end of the second war, as science established its place more assertively in the museum world along with a better understanding of deterioration mechanisms as well as the spread of new technical knowledge at the international level, so did the interest of experts towards, as George Stout advocated "long-range preservation". This allowed for the cost-effectiveness of constant care before repair into motion, with the ideal that the integrity of objects and certainly their conservation is best assured when preventing undue deterioration. As such, in a 1949 conference, he goes on to mention that: "this effort requires the best available knowledge of the true state of the thing that is subject to deterioration" and that "it requires further that every attempt be made to keep that state as it is" acknowledging the importance of scientific methods when dictating the appropriate preventive measures [56]. One year later, he and an assembly of many other international professionals in the field, launched a new project that would later be known as the International Institute for Conservation of Historic and Artistic Works (IIC) [54], which would give prominence to this mind-set and along with ICCROM and ICOM (International Council of Museums) be a crucial part in promoting this change.

The positive effects on collection preservation during the Second World War led to the persistent belief of the benefits associated with a stable environmental condition due to the awareness of the reduced mechanical damage. From mid-twentieth century forward, technical developments in climate systems were paralleled with the assignment of set point values for relative humidity and temperature, which influenced moisture balance in buildings and managed to disconnect, to a certain extent, indoor conditions to the outdoor climate. Therefore, precaution and the potential of available technology led to a somewhat over-simplified generalisation of target values for these two parameters.

4.3.1 *Zone of Safety*

The positive outcome of the British experience underground during the war had such an impact that it was cited and adopted in the following decades as sufficient evidence of the effectiveness of those stable and narrow values in regard to T and RH. An example was Plenderleith, a well-respected professional in the field, who quoted it in several works of his, particularly in the publication of Conservation of Antiquities and Works of Art [60], which became a useful guidance for collection care for the next two decades in the conservation community. The importance of this volume laid in the fact that it was the first systematic explanation of the aspect at the core of conservation knowledge, that is, the deterioration mechanisms. It also provided permissible limits for relative humidity, based on research carried out on the deterioration of objects by museum scientists between 1922 and 1950, stating that due to susceptibility of organic materials to damage by desiccation, a lower safety limit should be fixed at 50% RH. He takes into account mould growth by setting the upper limit at 65% RH, and allows for a temperature range of 16-25°C (60-75° F), presumably a generalization attributed to an entire collection, given the lack of information on how these values were obtained, just as the Weaver report [21] had done before based on past experiences with the storage of paintings during the second world war.

In the late of 1950s a survey was sent out to museums around the wold by the ICOM about their preferred environmental levels. It culminated in the publication of the results in an article authored by Plenderleith and

Philpott in 1960 [61]. The authors did recognize the importance of the historic climate for the objects safety and that even the best museum conditions can be dangerous for a painted panel that has been normally housed in a cold damp country house. However, a zone of safety was specified, that perhaps became too blindly accepted as the norm, and once again Plenderleith's position on the lower limit of 50% for RH was reasserted, as well as the experiences in Manod serving as proof of the security of the range of 50%-60% RH, the upper limit being to prevent mould. Not a lot of consistency was shown by the many institutions surveyed on the preferred levels of RH, apart from a general agreement in values varying from 40-70% RH, which of course then led to an approximation of the ideal condition should be around 60% RH. This preference reflected, as experts came to realize [58], how little data on experimental evidence of materials existed to date, except only with previous results from limited wood responses to moisture, to support this general recommendation as well as its acceptance on the definition of values for RH and T in institutions. It should also be pointed out that as this rationalization progressed, it was mostly focused on appropriate ranges to prevent mechanical damage of organic materials, just so that little to no data existed on chemical degradation and the needs of specific inorganic materials, such as weeping glass and ceramics with deliquescent salts.

Just as well, as practicality asserted its position in the choices for an adequate climate control, cases concerning damage to the buildings due to condensation began to emerge particularly in cold climates, where high levels of RH proved to be too difficult and expensive to maintain, as many museum collections were housed in historic buildings that were not designed for this type of humidity and thermal control. In the heating season the necessary humidification condensed on the cold surfaces in the building envelope, leading to accelerating rotting of wooden pats, so that collection's needs were being met at the expense of the building fabric [62]. In fact, comments by Richard S. Buck in the USA in 1964 reflected opposition to this standard for picture galleries as they were "so rigorous as to be almost unattainable in many American climates", acknowledging the difference of climates between Europe and North America in the adoption of these values. He then proposed lower winter temperatures and a limit to RH of 45% rather than 50% for organic collections in order to avoid condensation based on the perception of the adjustments in moisture content suffered by objects during winter before the introduction of heating. He also noted the great variability of conditions that were required to best preserve mixed collections, recommending a wider bandwidth of 20%, from 45 to 65% RH, in a table that became widely recognized by North American conservators [63].

Both Plenderleith's and Buck's visions were subsequently reproduced in conservation literature for the following decades, with questions regarding whether or not this type of control was feasible at a building level or even uncertainty surrounding its absolute necessity for the majority of objects, that were plainly left to the side. The only assurance laid in the fact that these optimum conditions for collections could not be maintained in most of buildings without a central air-conditioning. Still some measures and guidance on climate control were becoming officially established for the first time as well as an international collaboration among experts on the field even with the difference in opinions.

4.3.2 *The Museum Environment by Garry Thomson*

Thomson pointed out in 1978, with the publication of the 1st edition of his widely-cited relic within conservation community - Museum Environment: "We have a very uneven knowledge of how fast things in the museum change and what causes these changes, and yet we have to erect this framework of preventive conservation before rather than after our research has reached a dignified level of completion" [64]. He also mentioned the conformity with establishing standard specifications to eliminate damage with what could be expected of technologic equipment at the time rather than being based on a specific deep knowledge of how small variation affected exhibits, as he states quite explicitly that the standard fluctuations of ±4 or 5% RH is based air-conditioning plant capacity than on what exhibits can stand without degradation, which was not known in detail.

His attention was more devoted to measurements and control techniques and while trying to not fall into the trap of setting shallow foundations for optimum levels of climate control. He made an effort not to state specific recommendations, advising on thresholds of a safe upper limit for RH at 50-55% and following Plenderleith on the lower limit of 40% to avoid embrittlement to artefacts such as parchment. Still, his work was, to a greater extent than previous publications, a well-rounded and critical evaluation of the available scientific evidence to date, as well as denoting its limitations, taking into account the importance of considering the type of collection and local climate as determining factors on the choice of climate control.

An appreciation for the difference in requirements regarding climate control to safeguard collections housed in typical museums, historic houses and churches was also presented as well as new insights on the understanding of how microclimates could be achieved in well-sealed passive showcases, by the use of buffering agents such as silica gel. This reflected an intention of a more flexible interpretation of his qualifications on environment control, with adaptations to be made according to regional climate, typology of building and collection as well as the consideration of simpler, more reliable and cheaper techniques rather than a trend of an overly energy-consuming approach. As he remarked in the very last paragraph [64]:

"There is something inelegant in the mass of energy-consuming machinery needed at present to maintain constant RH and illuminance, something inappropriate in an expense which is beyond most of the world's museums. Thus the trend must be towards simplicity, reliability and cheapness. We cannot, of course, prophesy what will be developed, but I should guess that it will include means for stabilising the RH in showcases without machinery, use of solar energy for RH control in the tropics, improved building construction to reduce energy losses, and extensive electronic monitoring."

It is interesting to see how his original intention was disregarded in the following decades for the demand of a more convenient and precise target for recipe specifications.

As it is, the long sought out appreciation for a more direct guidance on specifications for climate control, certainly something that lacked in his previous edition, was satisfied in the second edition published in 1986, as Thomson explicitly presented two classes of control included in the appendixes. Class I, while at the same time accepting other possible set points, advised for strict control of 50-55% RH with a fluctuation of ±5%, recommending that mixed collections should stay within a bandwidth of 15%, namely a range of 45-60% RH. In respect to temperature, it stated that it "must be controlled to control RH, but the level is dictated by human comfort'' and the recommended levels were at 24°C in summer and 19°C in winter, ±1°C, though accepting a lower limit of 10°C. Class II on the other hand, recommended RH "to be kept within the danger limits 40% and 70%" and temperature "reasonably constant to stabilise RH"[64].

Surely not intending for it to be so, though before long, his recommendations turned into wide-spread practice of an over simplification of rigid specifications, denoted in the so called ‘’20/50 de facto standard’’ for museums [65], being implemented as energy cost was not yet a reason for concern as well as the generalized assumption that the greater the precision in control the less damage would be expected for collections. This unfortunately turned into convenience when deciding on which parameters would be best suited for storage, exhibitions and loans as museums worldwide were eager for facilitations and guidance in their practice, even though these conditions could not be maintained without some deviation at a great cost.

4.3.3 *The Pursuit of Maintaining Narrow Ranges in Climate Control*

The persistence of this, considered by many, needlessly strict, stable climate around 50% RH and 20ºC T, consisting of low fluctuations is found to be a focal point in conservation literature and one that seems to have been hard to let go even to current days. Given that little data existed on the effects that different values of RH variation had on individual objects, any deviation on the established levels was considered to be a cause for alarm. This stringent and often considered *ideal* targets were adopted, as Sarah Staniforth points out [66], on the grounds of the precautionary principle that, as mechanical systems increased in sophistication, why not keep the environmental parameters as constant as possible?

Still, it was also known that mid to high values of relative humidity had an impact not just on mould germination, but also on several chemical properties of materials, possibly affecting the long-term survival of thin organic materials such as paper, textiles, and photographs [21].

Taking into account the dilemma that are historic buildings, their structure being as important as the objects themselves and particularly considering northern climates, that may not be best adapted to sustain such high levels of RH, it adds even more to the complexity that surrounds this context. For instances, as Michalski recalls, CCI (Canadian Conservation Institute) advised for a reduction to 38% RH to be applied in the Canadian museums during the winter [67]. On the other hand, there are exceptions where even 50% is considered to be too low to prevent any damage to occur [68], demonstrating that a fixed standard and certainly set points defined for different materials is not wise, when considering that such diversity exists in building and climatic conditions. As institutions attempted to implement these standards and with the awareness of the potential damage to historical buildings, The New Orleans Charter for Joint Preservation of Historic Structures and Artefacts was developed in 1991 in order to promote measures which should be undertaken in either the historic structure or the artefacts so as not to compromise one at the expense of the other [69]. However, it is also important to stress that most moisture problems in this type of buildings are not limited to the active control of the environment, as they are also a result from infiltration of water through design faults in walls and roofs.

4.3.4 *Research and Developments in the late 20th Century – New Perspectives*

Given the inherent complexity of how the environment that surrounds collections can affect their preservation, it is plainly important to have a concise knowledge on the nature of the collection and the behaviour of the objects, mainly their adjustment to changes as they are daily exposed, to a certain extent, to the transition of seasons and many other factors playing in the context of a museum. So, it can be understandable that the static disposition that took place within the conservation community all these decades ago, was particularly due to lack of substantial and defining advances in science to date, that could have helped grasp a better comprehension of tolerances and adaptability of exhibits and their reasonable limitations when it came to the two fundamental agents of deterioration – temperature and relative humidity. Any perturbation was therefore considered to be undesirable which led to the adoption and generalization of strict and unwavering specifications regarding those parameters, without necessarily the appropriate evidence to support it other than an overzealous concern for the long-term preservation of collections. Or perhaps as some authors argue – due to the facilitation of loans from one climatic zone to another [70]. This of course caused an imposition to the capacity required in the mechanical systems – so that they could provide such tight conditions – as well as to the costs regarding the excessive energy consumption, which assumed a demanding position in the management of establishments for many years until they were considered to be no longer acceptable.

Thus, began to emerge in late 20th century this new collective conscience that there was yet still too much research to be done in order to define the appropriate climate for the preservation of collections. In the 1980's and 1990's new research carried out by the Smithsonian Institute in the USA and the Canadian Conservation Institute (CCI) provided knowledge on the mechanical, physical and chemical behaviour of how individual materials responded to temperature and relative humidity variations, which unveiled the possibility of setting a range of allowable fluctuations, necessarily how quickly they could change before the material being tested failed and whether or not its reaction was reversible, something that the prevailing early experiments and practical experience lacked.

Admittedly, one of the first indicators that the physical damage to artefacts, caused by environmental conditions, might be quantifiable and predictable, was in a paper presented in a congress that took place in 1982 for the IIC. One of the authors was Marion Mecklenburg, considered to be amongst the most notable propelling agents of these new findings that helped shape conservation science to this day, particularly since this signalled the start of a new phase of experimental investigation regarding the response of organic materials. This article gave an account of a method that was already well established in engineering fields but somewhat novel to conservators – a finite element analysis (FEA) – which was shown to be applicable in understanding the response of oil paintings on canvas to relative humidity, since they are regarded as requiring particularly tight climate control. Precisely the fact that this computer simulation was able to predict certain patterns of damage regarding the complex layered structure of paintings, as well as managing to produce a close correlation between theory and observation [71].

Accordingly, complementary environmental research, supported by computer modelling, proceeded in the following years. This expansion of the theme to determine the effects that different degradation mechanisms produced on different materials and subsequently applying the resulting data to predict their behaviour, namely the stresses and strains of composite objects, dictating when the elastic or reversible limit was exceeded with the introduction of failure rates. These research models are based on a conservative approach considering the restraints in composite objects by the analysis of independent RH response of each material that compose the object, assuming the one with the maximum response as the limit in allowable RH fluctuations [72]. With improving computer based monitoring of the museum environment, which made RH and T data increasingly available, fundamental studies and articles began to emerge in the 1990's.

In 1993 Michalski, working at the CCI, published the document "Relative humidity: a discussion of correct/incorrect values" [46] in which he not only summarized what was already known on the incorrect levels of RH, but also provided an account on the fact that, without constraint, many flexible and sliding assemblies were safe and the effect that repeated small variations in humidity below the critical fracture threshold would induce, that is, fatigue, shows a substantial decrease in damage per cycle as the fluctuation diminishes below the critical value, either the proofed value or analysis.

At the Ottawa congress in 1994, Ehardt and Mecklenburg, from the Smithsonian Institution, presented their "Relative humidity Re-Examined" [71], where they present a methodology for selecting appropriate RH ranges as well as the way in which it affects the degradation processes of different types of materials. An optimal value for relative humidity is disregarded for the choice of an appropriate range, that attempts to minimize the total effect of several reactions and processes. They also explored how temperature driven chemical reactions are a concern for a great variety of collections. For the calculation of allowable RH fluctuations, they go on a conservative assumption of a material that is fully restrained, being at its most vulnerable state, and determine whether a certain variation will reproduce a stress which surpasses the elastic limit for the material and if so, mechanical damage occurs even though no visible damage such as cracking is observed. From this reasoning, many charts were subsequently produced, partitioned into safe zones and others to be avoided for restrained materials under different conditions of temperature and relative humidity. Particularly to the safe zone – in terms of relative humidity fluctuations – for small organic materials acclimated at extreme levels of humidity is smaller than those acclimated at mid-levels.

The better understanding provided by this new research movement in the end of the 20th century – most notably with the contributions from Erhardt, Meclkenburg, Tumosa and Michalski, among others – suggested that many museum artefacts could safely withstand broader fluctuations in relative humidity than what had previously been accepted by many conservators, leading up to a necessary revaluation on the existing tight standards. It deemphasized strict RH control and the need for really narrow ranges regarding fluctuations as well as a more comprehensive look at the function of decay and how much risk is produced according a specific environment as well as to the type of material. In a 1994 CCI article, Michalski provided a table – Table 4.1 – with the variable risk of fracture for several objects and climate fluctuations, which resulted in a consideration of the risk to be very small at ±10 % variations of both RH. This prompted CCI's guidelines to equate risk in their specifications, assuming the limit that was associated with rapidly diminishing returns. Also in 1994, the Smithsonian adopted new recommendations for environmental control – Table 4.4 – however not all institutions were convinced in the existence of enough evidence, or knowledge for that matter, at this point to relax their strict implemented specifications. Particularly the remaining doubt of whether or not this results could indeed be extrapolated to all historical and ancient artefacts [73].

Table 4.1 - Effect of incorrect RH and Incorrect temperature on Museum Materials, adapted from Michalski 1994 [73]

Material	Stiff or brittle organic materials[a]	Flexible organic materials, Chemically stable[b]	Flexible organic materials, chemically self-destructing[c]	Inorganic materials[d]
Damp (over 75% RH)	Mould. Softening of glue, some paint, wood. Canvas may shrink	Mould. Softening of size, binders. Textiles may shrink	Mould. Softening of size, binders	Mould. Rapid corrosion of base metals
Above or Below a critical RH				For some: corrosion, crizzling, disintegration
Above 0% RH			Disintegration and yellowing. If object life is 50years: 50%; 100 years: 30%, 200-400 years: 10%	
Fluctuation around a middle RH (stresses are zero)	Rate or risk of fracture growth: ±5%: P, V, A, W: none ±10%: P: tiny W, A: none-tiny ±20%: P: small W,A: tiny-small ±40%: P: severe W,A: small-severe	If brittle image layer, as P. If restrained by frame, as W	If brittle image layer, as P. If restrained by frame, as W	Fluctuations crossing a critical RH disintegrate some contaminated ceramics, stones, metal patina
Temperature too high	Over 30°C, softening of some adhesives, waxes, pitch	Over 30°C, softening of some adhesives, waxes, pitch	Disintegration and yellowing. If object life is 50 years: 20°C, then 200 years: 10°C, 5000 years: -15°C.	Some minerals disintegrate
Temperature too low	Embrittlement, e.g., acrylics below 5°C	Embrittlement	Embrittlement	
Temperature fluctuation	Rate or risk of fracture Growth: ±10°C: P, V, A: none-tiny ±20°C: P, V, A: none- small ±40°C: P, V, A, W: none-severe Plus indirect effects if RH fluctuates	If brittle image layer, as P. If restrained by frame, etc., as W.	If brittle image layer, as P. If restrained by frame, etc., as W.	Some composites (e.g., weak enamelling), as P.

a. For example, wood (W), oil and tempera paintings and polychrome (P), varnish (V), acrylic paintings (A).

b. For example, non-acidic paper and textiles, parchment, stable B & W photographs.

c. For example, acidic paper, acetate films, colour photographs.

d. For example, metals, minerals, ceramics, glass.

It has then been considered that for most organic objects short term events are not incredibly important [46], as they are not necessarily felt by them. This conclusion was not intended to suggest that short-term fluctuations should be disregarded, however this relatively recent scientific research has been pointing to the recognition of the extremes, the longer-term averages and prolonged events, specifically in the differences imposed by the transition of seasons that are crucial in the preservation of collections. Risk increases in the extremes of environmental conditions, certainly just as previously asserted that the potential for mechanical damage exponentially rises at extreme dryness and contrarily, extreme dampness with mould damage. Furthermore, from the chemical change point of view, temperature is the crucial factor precisely for prolonged periods of time when temperature is too high, inferring that these matters are what really constitute a reason for special concern in climate control. The ultimate aim being in applying strategies that best avoid them.

4.4 *From Rigid Specifications to More Flexible Approaches*

The ideology shared by many professionals in this field regarding what constitutes a safe environment for heritage, as one that is undeviating, where both temperature and RH remain constant, has been altered given that it is inherently unsustainable. Seeing as it ignores some of the fundamental facts about deterioration in that, an ideal environment for a collection does not exist. Certainly, due to the fact that distinct climatic regions create environments that have differing effects in a mixed collection, where objects with distinct materials and constructions present different needs. That is not to say that a steady environment is not beneficial or even to be preferred, however, it needs to be taken into account the reality of managing the same condition for an entire year, particularly the considerable energy consumption and maintenance efforts it demands. This idea has been extensively debated, beginning when advances in research, since the 1980's, allowed for a better understanding of the different dependencies that relative humidity had in a mixed collection and convincingly argued for more rational and flexible set points for RH and T in museums, in order to balance collection needs with historic building needs and energy consumption in times of reduced funding and increased environmental awareness.

This further broadening of allowable ranges in environmental parameters, might also result from practical observations of many objects that have survived fairly well in conditions deemed not ideal. As it is, climate specifications based on the acclimatisation concept remain very prominent still, especially given the advancement in electronic monitoring as it is able to provide long-term historic climate data in great detail.

4.4.1 *Historical Climate and the Acclimatization Concept*

There have been developed two approaches when establishing allowable ranges in climate control, necessarily to do with an analysis of the mechanical response of vulnerable artefacts to variations in RH and T, as well as the consideration of the historic climate within which heritage objects have been acclimatised.

Every historical building has been subjected to its own particular historical climate, determined of course by external regional conditions, its envelope, use, among other factors. If artefacts were conditioned to this specific microclimate, mainly in the way they have interacted with RH and T, it becomes important to address that it implies the possible resulting internal tensions to which they have adapted to, either with reversible or irreversible shrinkage or swelling, leading to functional fractures that respond to the microclimate variability [17].

The acclimatisation concept was traditionally expressed in the understanding that, a particular care in vulnerable collections should be considered when moving them from their usual location to another, that did not necessarily reflect the same conditions and it has then been explicitly expressed in standards, developed since the turning of the century, upon recommendation of the choice for indoor environmental conditions, examples being the Italian UNI 10969 [74] and later the EN15757 [75].

It reflects the individual needs that organic hygroscopic materials have on the environment in which they have been exposed for a considerable period of time. Particularly as changes in RH and T induce internal stresses over time that could result in fracture, allowing for a wider range of acceptable fluctuations.

A key assumption in this approach has therefore been the harmlessness of past climatic conditions, as physical damage can be cumulative rather than catastrophic, so that fluctuations even when not exceeding the historic levels can involve risk of damage, this of course contributing to the debate on its validity [31].

4.4.2 *Michalski's Proofed Fluctuation Concept*

Derived from the resonating factor that collections do indeed acclimatize, lies the concept of Proofed Fluctuations. Michalski first introduced this term in 1993 [46], defining it as the pattern of the largest RH or T fluctuations to which the object has been exposed to in the past. This concept eliminates the need for any elaborate mechanical response, assuming a risk based approach, in that it considers the risk of physical damage to be extremely low whenever the worst proofed fluctuation has already caused all possible damage, providing a benign region of future climate. In other words, future fluctuations equal or smaller than the proofed ones are supposed to not cause further mechanical damage. It certainly shortcuts through more complex scientific analysis, using only historical data that has become increasingly easier to obtain as well as more insightful, given the technological advances of the recent past in monitoring measurements and computer algorithms. However, it can also be used in situations where climatic data is not accessible, as long as enough historical evidence is presented concerning the stability of the collection, simply by judging the way the museum has been operating for many years, necessarily with simple heating systems and little to no humidification. It is important to consider some of its limitations, particularly in it not being applicable when the objects have chemically aged or conservation treatments have taken place, as they remove the effects of past fluctuations and also considering that fatigue or relaxation of the materials could potentially reduce the limits for the safe fluctuations [76].

4.4.3 *The Advent of a Risk Management Approach*

Any material exposed to varying conditions either dampness or dryness are going to be at risk primarily based on individual characteristics such as its nature and overall assembly as well as its climate history. When it comes to the nature of objects, they can be hygroscopic, mostly organic and some inorganic materials, exchanging moisture with their surroundings so that different effects could be expected accordingly. When evaluating the potential for damage in face with such diversity within any given collection, it is important to consider how differently they might react to changes in T or RH, for instances, metals corroding, efflorescence in ceramics and the cracking and embrittlement of paper. Not only the different types of materials are to be taken into account, since their history also defines how their condition was affected throughout their existence in a particular environment.

A tendency towards a more objective appraisal of the many threats concerning collections came about in the remaining years of the 20th century, resulting in the quantification of risk and the integration of a risk analysis methodology to the complexity that is conservation practice, keeping in mind that it requires a technical knowledge about the artefacts and the many factors that cause damage. Much of this pioneering work is associated with contributions from Waller, Michalski and Ashley-Smith, who argued for a framework of systemizing collection care for a decision based model capable of assessing risk of loss when balancing the preservation of collections with the use of limited resources [77]. According [44], the general concept of risk can be defined as "the chance of something happening that will have a negative impact on our objectives", which can also be applied to cultural heritage, as several hazards can arise necessarily affecting the objective underlying the use and preservation of both heritage collections and buildings. In this case, the risk is expressed in terms of the expected loss of value to the heritage asset. For instances, unintended consequences regarding the need for an increase in RH of a given space must consider contingencies such as the type of building, risk of condensation and limitations with current mechanical systems. The risk management approach certainly informed proceeding standards, the new chapter in the 1999 ASHRAE handbook being an example, as it assesses risks to a collection when climate control is considered to be not appropriate.

4.4.4 *New Guidelines and Standards in 1990s*

More examples of this shift in flexing existing practices of climate control towards the end of the century were with the publication, in 1999, of two standards, the Italian UNI 10829 [74] and the new chapter dedicated to design guidelines for the indoor climate in museums, libraries and archives by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE handbook) [78], which is revised every 4 years. Both aimed at a more sophisticated, flexible, realistic and risk-management based approach, specifically according to the latter, to the choice of T and RH specifications.

The UNI 10829 provides a methodology of monitoring procedures and climate control recommendations for the preservation of 33 categories of organic, inorganic and mixed materials and objects, taking into consideration the historic climate to which they have been subjected to and current state of degradation, Table 4.2. Ranges of hygrothermal conditions for each of these different categories of objects were reported not only in respect to seasonal changes but in restricting daily cycles excursions as well.

Table 4.2 - Thermo-hygrometer values recommended to ensure the optimum conditions of chemical-physical preservation of the artefacts, adapted from UNI 10829 [74].

Material	T (ºC)	ΔT (ºC)	RH (%)	Δ RH (%)
Artistic artefacts of paper, paperboard, veline upholstery	18 - 22	1,5	40 - 55	6
Fabrics, curtains, rugs, religious costumes, materials made from natural fibres	19 – 24	1,5	30 - 50	6
Leather clothing and artefacts	19 – 24	1,5	45 - 60	6
Canvas paintings, oil paintings, tempera and gouache	19 – 24	1,5	40 - 55	6
Files on paper or parchment, 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
Polychrome sculptures made of wood, painted wood, wooden clocks, wooden musical instruments	19 – 24	1,5	50 – 60	4
Unpainted wood 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, collections of shells, bone	19 – 24	1,5	40 – 60	6

The ASHRAE specification accepted that collections can acclimatize to local historic average RH as an annual set point, not simply the 50% value for international consistency, as well as the wider permissible temperature ranges not simply dictated by human comfort [76]. A wider range of short-term fluctuations, seasonal adjustments and permissible levels of both indoor RH and T was considered within five classes (AA, A, B, C, and D) along with their associated risks and benefits, in respect to different building types and climatic conditions. Each class had their own description of the estimated risks to varying types of objects, with AA having the strictest control in RH and T variations and D the most relaxed, ranging respectively from lowest to highest risk expectations.

These considerations were inserted in a table, which assumedly was regarded as the centrepiece of the whole publication, given the recurring demand for simple and practical advice on target indoor specifications for climate control – see Table 4.4 – even though the text contained an excellent review of known deterioration mechanisms and how to best take them into account, so as to reduce the risk damage on different artefacts within the bigger context of the building. This possibly reflected an intention for providing tools for a framework based on risks and benefits to be considered as a reference in the individual decision making process, emphasizing the negotiability aspect intrinsic in the end result [44].

The concern for the preponderance of collections housed in historic buildings have, particularly in their ability to accommodate museum climate control, was also taken into consideration as presented in Table 4.3, where each class of control is evaluated according to various building types, based on construction characteristics and occupancy determinants, regarding the fundamental issue of whether or not the building could in fact support them, in terms of thermal and moisture performance. For instances, Class IV informs the most adequate classes of control to be applied to heavy masonry buildings or composite walls with plaster, storm windows, for limited occupancy, with performance characteristics including low to moderate air and moisture exchange, high thermal mass and moderate moisture buffering as well as radiant solar gains. The possible climate control advised for this type of buildings are B, C and D, contrasting with the ones in Class V associated with insulated structures, vapour retardant, double glazed, where the materials are thin and light compared to those in the previous class. This infers in low air and moisture exchange rates, low to moderate thermal mass, recommending the higher restrictive classes of control, namely AA, A and then B.

Table 4.3 - Classification of Climate Control Potential in Buildings (adapted from ASHRAE) [78]

Category of control	Build-ing Class	Typical building construction	Typical type of building	Typical building use	System used	Practical limit of climate control	Class of control possible
Uncontrolled	I	Open structure	Privy, stocks, bridge, sawmill, well	No occupancy, open to viewers all year.	No system.	None	D (if benign climate) Exhaust
	II	Sheathed post and beam	Cabins, barns, sheds, silos, icehouse	No occupancy. Special event access	Exhaust fans, open windows, supply fans, attic venting. No heat	Ventilation	C (if benign climate) D (unless damp climate)
Partial control	III	Uninsulated masonry, framed and sided walls, single- glazed windows	Boat, train, lighthouse, rough frame house, forge	Summer tour use. Closed to public in winter. No occupancy. Staff	Low-level heat, summer exhaust ventilation, humidistatic heating for winter control	Heating, ventilating	C (if benign climate) D (unless hot, damp climate)
	IV	Heavy masonry or composite walls with plaster. Tight construction; storm windows	Finished house, church, meeting house, store, inn, some office buildings,	Staff in isolated rooms, gift shop. Walk-through visitors only. Limited occupancy. No winter use.	Ducted low-level heat. Summer cooling, on/off control, DX cooling, some humidification. Reheat capability	Basic HVAC	B (if benign climate) C (if mild winter) D

Table 4.3 - Classification of Climate Control Potential in Buildings (adapted from ASHRAE) [77] (continuation)

Category of control	**Build-ing Class**	**Typical building construction**	**Typical type of building**	**Typical building use**	**System used**	**Practical limit of climate control**	**Class of control possible**
Climate controlled			storage rooms				
	VI	Metal wall construction, interior rooms with sealed walls and controlled occupancy	Vaults, storage rooms, cases	No occupancy. Access by appointment.	Special heating, cooling, and humidity control with precision constant stability control.	Special constant environments	AA A Cool Cold Dry

The new formulations clearly point to the inherent difficulty in proposing adequate universal ranges for vulnerable objects, particularly when based on individual studies carried out usually on samples of new material and the determination of their mechanical behaviour. This is mainly due to the uncertainty surrounding the limitations of this approach, as it is argued that it did not consider the historic properties of individual works of art that have been adapted over many decades to a particular indoor environment. Moreover the fact that adaptation might have involved an uncertain level of permanent change, reflecting the complexity of their specific problems when compared to average properties in materials and microclimatic conditions used to define safe intervals to damage processes [79].

4.5 *New Millennium and a Re-examination of Museum Practice*

From early 2000s on, and still persisting nowadays, a further re-examination of many aspects related to the environmental control in museums has been stimulated by concerns about sustainability as well as the recent economic downturn. Several international conferences, debates and roundtables have taken place in recent years with the participation of experts in the field, discussing the most pressing matters in conservation science. Necessarily transcriptions from “Climate Change and Museum Collections” in 2008 [11] and “The Plus/Minus Dilemma: The Way Forward in Environmental Guidelines” in 2010 [80], “Climate For Collections: Standards And Uncertainties” in 2012 [23] and “Summit on the Museum Preservation Environment” in March 2013 [51], demonstrate the problems discussed as well as recent studies and methodologies concerning this topic.

The consensus on the relaxation of environmental conditions in order to reduce energy consumption, whilst not compromising the preservation of collections has yet to be reached, as polarising views in regard to its efficiency are still strongly held. Still, the replacement of a universal standard for a more localized approach that considers the specifics of the climate, building and identified risks as well as available resources has mostly become generalized.

4.5.1 *Lack of consensus in the field*

These differing views on what can safely been implemented, that is whether keeping conditions as they are at the current recommended levels or in promoting a more flexible and broadening of parameters. For instances, the N'L's position is very much involved in the conditions already chosen for their permanent conditions [65], as one that is unwavering, justifying this level of control as the safest practice particularly for their most vulnerable paintings, undermining much of the advances in experimental research by conservation scientists stating that "real paintings are very much more fragile than experimental test models which significantly over- simplify the nature of the problem, particularly with regard to their complex mechanical behaviour". Still, they actively pursue energy reduction strategies, though the efforts are more directed towards other areas of the NGL's operation. This precautionary safety of the "Stable is Safe" approach has also been endorsed by the Doerner Institut, which considers that the state of research, as advanced as it is, has yet to reach a point where "robust general statements can be made on climate fluctuations and their effects" and that the "scientific investigations to date on mechanical behaviour describe individual cases, but are not (yet?) in a position to claim general validity" [81]. They also state that the air conditioning is optimized to current climate specifications that is, the persisting set point of 20ºC/50% in most general cases.

There is a direct opposition to the other side of the debate, namely the position presented primarily by proposition of the Interim Guidelines by the NMDC (National Museums Director's Conference) in 2008, that were later adopted by the Bizot Group in 2009 as well as the AIC (American Institute for Conservation), AAMD (Association of Art Museum Directors) and AICCM (Australian Institute for the Conservation of Cultural Materials) [9], which aimed for a broadening in fluctuations, particularly to be within a particular corridor of 40-60%. This prompted the Doerner Institut to affirm that it is only possible with adjustments to the control systems, possibly increasing energy consumption. It is important to point out that the interim term associated with these guidelines may reflect the existing uncertainty with its suitability given the opposing views on the subject.

Also in support of this more liberal approach is Jim Reilly from the Image Permanence Institute (IPI), who states that "… it's time to put a stake in the heart of the zombie of 20/50 … for all collections, all the time" [82]. Indeed, the stance on experimental over experiential data has been criticised for being far to limiting and artificial, though given the current circumstances particularly the lack of experiential data for a great diversity of material types, supports the importance that such information is certainly of more use than no data.

4.5.2 *The Guiding Principles defined by Environmental Standards and Guidelines*

Upon regarding the gradual development of environmental control in museums, it can be understood the several ways in which institutions can be advised to best prevent damages from occurring to artefacts and the building fabric. Over the decades, as previously mentioned, specifications, standards and guidelines were presented recommending mainly on three principal elements by which the internal climate is statistically represented – those are usually the annual average, the seasonal cycles and short-term fluctuations. Of course, throughout the years and with advances in science as well as a newfound collective consciousness on the pertaining issues around sustainability, that influence all facets of today's society, it can certainly be understood that a progressive tendency towards a more rational, science-based approach with a flexible and dynamic nature takes place. Which definitely contrasts the early stringent mentality, where generalized narrow ranges for T and RH persisted. In Table 4.4 is presented a selection of recommendations for both T and RH formulated from different authors and institutions since the 1970s.

Table 4.4 - Summary of Standards and Guidelines formulated since 1970s until recently.

Source of specification	Temperature (ºc)	Relative humidity (%)			Considerations
		Long-term average	Seasonal cycle	Short-term fluctuations	
Garry Thomson ‘’The Museum Environment’’ (1978/1986)	Winter: 19 Summer: Up to 24	50 or 55	-	± 5	Class 1 – appropriate for major national museums, old or new, and also for all important new museum buildings
	Reasonably constant to stabilise RH	[40 – 70]			Class 2 – aimed at avoiding major dangers whilst keeping costs and alteration to a minimum, for example, climate control in historic houses and churches may have to be limited to class 2 specifications
Canadian Conservation Institute 1979	21 (Seasonal variation from 20 to 25 allowed)	[47 – 53]	[38 – 55]	± 2	The allowed seasonal changeover of the set points is 1 °C and 5 % RH per month, respectively Occasional variations of ± 5 % RH are tolerable if these are the exception
National Trust 1994	Winter: [5 – 18] Summer: [5 – 22]	58	First level alarm: outside [50 – 65] Second level alarm: outside [40 – 75]		The RH control was to be achieved by adjusting heat input or by dehumidification. RH was the priority control variable unless a temperature limit was reached: a lower temperature limit was specified of 5oC to prevent

Table 4.4 - Summary of Standards and Guidelines formulated since 1970s until recently (cont.)

Source of specification	Temperature (ºc)	Relative humidity (%) Long-term average	Relative humidity (%) Seasonal cycle	Relative humidity (%) Short-term fluctuations	Considerations
					water freezing, and upper temperature limits in winter and summer were specified to limit the energy consumption and visitor discomfort
UNI 10829 1999*					*See table 4.2
ASHRAE (1999 – 2011)	[15 – 25] ± 2 Winter: – 5 Summer: + 5	50 or historic yearly average	None	± 5	Class of control AA – No risk of mechanical damage to most artefacts and paintings
	[15 – 25] ± 2 Winter: – 10 Summer: + 5		None	± 10	Class of control A – Small risk of mechanical damage to high-vulnerability artefacts; no mechanical risk to most artefacts, paintings
			Summer: +10 Winter: – 10	± 5	
	[15 – 25] ± 5 Winter: Dependent on RH Summer: Up 10; <30		Summer: +10 Winter: – 10	± 10	Class of control B – Moderate risk of mechanical damage to high-vulnerability artefacts; tiny risk to most paintings
	[15 – 25] Rarely > 30 Usually <25		[25 – 75]		Class of control C - High risk of mechanical damage to high-vulnerability artefacts; moderate risk to most paintings

Table 4.4 - Summary of Standards and Guidelines formulated since 1970s until recently (cont.)

Source of specification	**Temperature (°c)**	**Relative humidity (%)**			**Considerations**
		Long-term average	**Seasonal cycle**	**Short-term fluctuations**	
	[15 – 25]		< 75		Class of control D - High risk of sudden or cumulative mechanical damage to most artefacts and paintings because of low-humidity fracture
National Trust 2006	[5 – 22]	[50 – 65]	-	-	The earlier fixed set point of 58 % RH was replaced with a target range. The RH set point should be adjustable in each room and depend on the conditions to which the collection has acclimatised
Smithsonian Institution, Erhardt et al. 2007	21 ± 4	45	-	± 8	All museums of the Smithsonian Museum are located on the west coast of the United States and are exposed to the same humid subtropical climate. The conclusions are drawn based on the different museums.

Table 4.4 - Summary of Standards and Guidelines formulated since 1970s until recently (cont.)

Source of specification	**Temperature (°c)**	**Relative humidity (%)**			**Considerations**
		Long-term average	**Seasonal cycle**	**Short-term fluctuations**	
UK's NMDC 2009	[16 – 25]		[40 – 60]		No more than ±10% RH per 24 hours within this range. For many classes of objects containing hygroscopic material (such as canvas paintings, textiles, ethnographic objects or animal glue). More sensitive objects will require specific and tighter RH control, depending on the materials, condition, and history of the work of art.
European standard EN 15757:2010	None	Historic yearly average	Historic seasonal cycle*	± 10 or target range calculated from the historic climate** (whichever greater)	* This cycle is obtained by calculating, for each RH reading, the central moving average (MA), which is the mean of RH readings taken 15 days before and after the time at which the average is computed ** The lower and upper limits of the target range of RH fluctuations are determined as the 7th and 93rd percentiles of the fluctuations recorded in the monitoring period respectively

Table 4.4 - Summary of Standards and Guidelines formulated since 1970s until recently (cont.)

Source of specification	Temperature (ºc)	Relative humidity (%)			Considerations
		Long-term average	Seasonal cycle	Short-term fluctuations	
					A fluctuation is calculated relative to MA, i.e., the seasonal cycle rather than the yearly average value
PAS 198:2012*	[5 – 30] *	[35 – 65] *			* Determined by a process best described as a risk-managed, holistic approach to environmental management. No ideal standard is presented – the goal is to help users make their own judgments based on local climates, an under-standing of material vulnerabilities within the collection to agents of deterioration, the capabilities of the mechanical system and the building envelope, and the move towards energy reduction
Bizot Group Interim Guidelines 2014	[16 – 25] ± 10/day	[40 – 60]	-	± 10/day	These guidelines do not necessarily indicate the best conditions, just consistent ones to facilitate international loans. This information would then be related to local climates and climate histories
AIC, AAMD Interim Guidelines 2014	[15 – 25] ± 4/day	[45 – 55]	-	± 5/day	

Table 4.4 - Summary of Standards and Guidelines formulated since 1970s until recently (cont.)

Source of specification	Temperature (ºc)	Relative humidity (%)			Considerations
		Long-term average	Seasonal cycle	Short-term fluctuations	
AICCM Interim Guidelines 2014	[15 – 25] ± 4/day	[45 – 55]	-	± 5/day	Refers specifically to storage and display. Where storage and display environments experience seasonal drift, RH change to be managed gradually across a wider range limited to 40% – 60%
FCT-UNL methodology 2014*					*See Table 4.5

There has been a gradual shift in recent developments of standardizations, from static and universal guidance to more flexible approaches. Such an example is the European EN15757: Conservation of Cultural Property-Specifications for temperature and relative humidity to Limit Climate-Induced Mechanical Damage in Organic Hygroscopic Materials, published in 2010 [75]. Its recommended specifications for both temperature and relative humidity in order to limit the mechanical damage in organic materials, was considered a more innovative stance as it addressed the historic indoor climate as reference for the establishment of the allowable short-term fluctuations. Namely, based on less vulnerable artefacts that have safely withstood such conditions in the past, precisely when conserved for more than a year in a specific environment. The mean target value for RH is calculated as a moving average over a 30-day period, informed by measurements of at least one year. It considers remaining within this historical climate in order to avoid any risk of damage to objects, further recommending that fluctuations of 10% in RH are accepted and that the seasonal average is also calculated on a moving average of 30 days around which they should be limited. The sustainable upper and lower limits based on the historical climate are determined by the 7th and 93rd percentiles of short-term fluctuations recorded in the monitoring period, respectively. As such, 14% of the more dangerous fluctuations are excluded. This standard was complemented by the EN 15758: Procedures and instruments for measuring temperatures of the air and the surfaces of objects [83], which was later followed by EN 15759-1 2012: Guidelines for heating churches, chapels and other places of worship [84], though both not specifying any numbers for the control of the indoor climate but rather describing a procedure on how to establish the target indoor climate and the implementation of technical solutions.

Recent standards indeed reflect a more methodological indication on their content rather than a prescriptive one, focusing on a decision-making framework informed by a risk assessment approach. For instances, the PAS 198, a British Specification published in 2012 [38], allows 35–65% RH and 5–30°C for temperature, and aims to inform users on the choice for the most appropriate strategy to be based on local climates, with the understanding about the vulnerabilities of the collections in regard to the agents of deterioration. It prioritizes the mechanisms of decay as well as the capabilities of the mechanical system and limitation of the building envelope, ultimately moving toward energy reduction.

4.6 *Recent Developments*

More recently in 2014, Hugo Silva and Fernando Henriques developed a new methodology for the microclimatic analysis of historic buildings in temperate climates, proposing a climate range that is much more adequate to this type of climate, a pertaining issue that has yet to meet substantial research and developments for its context. This method named FCT-UNL [85] is based on EN 15757 and influenced by the ASHRAE specification and UNI 10829 as well as being supported by the concepts of acclimatization as well as the proofed fluctuations. It does not consider extreme registered values reducing the past fluctuations in terms of seasonal and short-term fluctuations, surpassing the impediments of fatigue and relaxation of objects. Rather than being completely innovative, it asserts its position in that, it improves its applicability, particularly in the possibility of further comparison with several other studies. It considers two classes with differing ranges for both seasonal and short-term fluctuations, the first class and the strictest one and is meant to be applied to buildings with higher requirements, such as museums, whereas the second class allows for a more flexible approach for microclimates and may be applied in churches for example. The specifications for seasonal cycles as well as short-term fluctuations is summarized in Table 4.5.

As it was previously presented, the research developments of recent decades led to the realization that objects can generally sustain temperature changes without damage, and even at a certain extent RH changes – considered to be the most sensible parameter. Indeed, given that most objects and their configurations can survive days, weeks and sometimes months to fully feel the impact of that alteration. Hence, there are several beneficial, sustainable as well as less energy demanding scenarios that are possible for their long-term preservation. For instances, in moving to more dynamic approaches such as day/night differences, seasonal variations and set points regulated without harming the collections whilst still managing to have sensibly the same conditions all year round. This of course depends on the geographical location for each specific case, as the external climate drives changes in the indoor environment within a building that directly affects the artwork. It then infers on the suitability of more passive approaches wherever the climate is benign enough for it to be considered.

There are many places and studies beginning to adopt such a dynamic approach to the control of the internal climate, experimenting with different set points for both Winter and Summer and gradually moving from those during the transition seasons [86].

With respect to the acclimatization concept, when assessing to which extent historic conditions have induced safety in vulnerable objects, it has in recent years become increasingly supported by scientific methods that are non-invasive, simple, economic and have a practical application in the context of direct tracing the climate induced damage in museums and historic buildings. In 2007, Kozłowski introduced an acoustic measurement, based on monitoring the energy released as sound waves during fracture processes in materials which opened a possibility of predicting damage caused by fluctuating temperature and relative humidity [42]. Another option are laser techniques for mapping paint layer damage which provide information of the surface of the object at the micro-level before damage is observable [31].

Table 4.5 - Temperature and relative humidity specifications according to FCT-UNL, adapted from [85].

Reference value	Daily cycles(1)	Seasonal cycles(2)	Short-term fluctuations(3)	Extra limits	Notes
T & RH: Buildings Historic yearly Average	90º percentile ($\Delta T \cap \Delta RH$) ≥ UNI 10829 limits	T and RH: -10%/+90º percentiles	T and RH: -5%/+95º percentiles	$\|RH - \overline{RH}\|$ $RH_{max} \leq 75$ % $\|T - \overline{T}\|$ up to 10ºc but not above 30ºc	Class 1 - low risk of mechanical damage and biological attack. T and RH: 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: -10%/+90% percentiles	T and RH: -5%/+95º percentiles	-	Class 2 - Moderate risk of limits 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) Values defined by the 90th percentile of the recorded daily cycles if higher than the UNI 10829 limits;

(2) 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;

(3) 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.

In the pursuit of appropriate conditions for the environment, mainly that have minimal impact on the global climate, as they aim for energy efficiency and low maintenance costs while at the same time being as favourable as they can be for the collections and their particular needs, one of the most important aspects to consider is to measure how environment is affecting the artefacts. With developments in technology in recent decades giving rise to the ability of a continuous measurement of temperature and relative humidity values, it is now possible to quantify each one of these factors of decay and their effect on the environment, which allows for an analysis that informs the rate of deterioration. The preservation of collections through environmental monitoring provides a better understanding of how to both efficiently preserve collections and reduce energy consumption [87].

5 SUSTAINABILITY AND TOURISM

5.1 *Sustainability and Management*

Currently, everyone should be able to understand the importance of protecting the environment from excessive carbon emissions and the overall usage of non-renewable resources. It is indeed one of the most pressing issues human kind is facing right now, given the concern with climate change and all that it encompasses with great magnitude repercussions if society proves to be unable to develop measures to mitigate them.

The consideration of a sustainable development in cultural heritage has surfaced in the recent past given the current state of socio-economic and political awareness to environmental responsibility, which creates new challenges but also opportunities to the climate management with the intent to serve the collections, environmental and economic needs[88]. It is important to bear in mind that there is the possibility to achieve sustainability without jeopardizing the conservation.

Sustainability in museums and all cultural heritage needs to be a centrepiece underlying the extensive debate of which environmental standards to implement in management strategies [51], since institutions should endeavour in reducing their energy usage, with the intent of mitigating climate change so as not to compromise the future of generations to come.

In 2011 the World Heritage Committee, at its 35th Session in Paris, made several additions to its Operational Guidelines concerning the concept of sustainable development which aimed at not only being able to ensure that any use of World Heritage properties be sustainable, consistent with the Outstanding Universal Value, but also that ‘’sustainable development principles should be integrated into the management system’’[1]. Additionally, the Agenda 2030, implemented in 2015 by the UN, 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’’[89].

5.2 *Climate Change and Worldwide Energy and Resource Deficiency Problems*

In 2015 the world came together and made history with the first ever global agreement on a path to low carbon footprint and environmental friendly future for generations to come – The Paris Agreement – a remarkable step but also one that brings much more pressure into the scope of a more comprehensive management vision for cultural heritage, establishing it as a focal point for countries in a more sustainable future [90]. Allied with the ‘’2030 Agenda for Sustainable Development’’ [91], these two international accords are a representation of mostly global consensus on the concept of countering climate change, as well as inducing a sustainable development providing new framework that steers governments towards a main goal – sustainability. This will certainly help to support the requirements needed to protect World Heritage and cultural tourism destinations for future generations. Considering the prospects already presented, with the problematic of adapting to climate change and growing energy costs, the future assuredly holds even stricter demands on energy efficiency and sustainability overall in this sector.

The projections of a global climate change infer an even greater uncertainty from helpful predictions of what can be expected in the future. Granted, the frequency and severity of climatic phenomena characterized by an erratic pattern may hinder not only the condition of both collections and historical buildings fabric, because of the alterations imposed to the external as well as internal microclimate, but also could potentially be problematic to the evaluation and accurate assessment of future hazards associated with risks to collections, in studies regarding simulations for the prediction of future climatic data.

Recently the EU has funded the project 'Climate for Culture'. In this projected, which ran from 2009 to 2014, researchers from several countries investigated the impacts of climate change on cultural heritage, assessing damage risks and economic consequences as well as developing mitigation strategies for their long-term preservation. Recent climate and building simulation tools allow to predict future outdoor and indoor climate conditions affected by the potential impact of climate changes, assessing their consequences on historical buildings and the vast collections they contain. The innovation lies on the correlation between a more systematic and reliable damage risk assessment and the future climate data obtained by building simulation models that may lead to a more efficient preventive strategy to preserve the collections and reduce energy consumption [92].

It is well known that energy consumption around the world is ramified into different economic sectors – industry, transport, households, services, agriculture, etc. The one with the most obvious concern in this text is the building sector, in which, it was reported that around 35 to 40% of total energy was consumed in the developed countries, ranging from 50 to 60% of electricity consumption [93][94]. Now, on the subject regarding energy consumption in the 28 countries that are part of the EU, it was possible to gather data from Eurostat [95], specifically for the service and residential sectors that make up for the bulk in the buildings energy consumption. The important factor to consider here is that a significant portion of the electricity supplied for institutions to meet their functions, comes from power stations using non-renewable combustibles. Since sustainability is at the centre of the current European agenda, a reduction in energy consumption is paramount in every sector considered. The overall evaluation of the presented statistical values in the selected period, for the final energy consumption of the 28 countries integrated in Europe, accounts for a reduction in the last few years as can be observed in Figure 5.1. This indicator is a Sustainable Development Indicator and has been chosen for the assessment of progress regarding the objectives and targets of the EU Sustainable Development Strategy [96] with the intent to prevent an exacerbation to climate change, an aim was set of an overall saving of 9% of final energy consumption until 2017, achieved through a combination of several measures. It is related to climate change and energy security [95], two important sustainable development goals.

Figures 5.2 and 5.3 show the distribution of energy consumption from 1990 to 2015, specifically the role that both residential and service buildings account for in the overall results. A slight decrease in the residential sector in recent years could either reflect the influence of the economic crisis that took place concurrently to that shift in the trajectory or prove, perhaps even more recently, that the added pressures previously mentioned are indeed gradually being integrated with the ultimate aim at a more sustainable future. On the other hand, a divergence is verified in the services sector as can be seen in Figure 5.2, where an increase was attested in the selected period which raises the question if indeed the efforts applied have been sufficient to the necessary change.

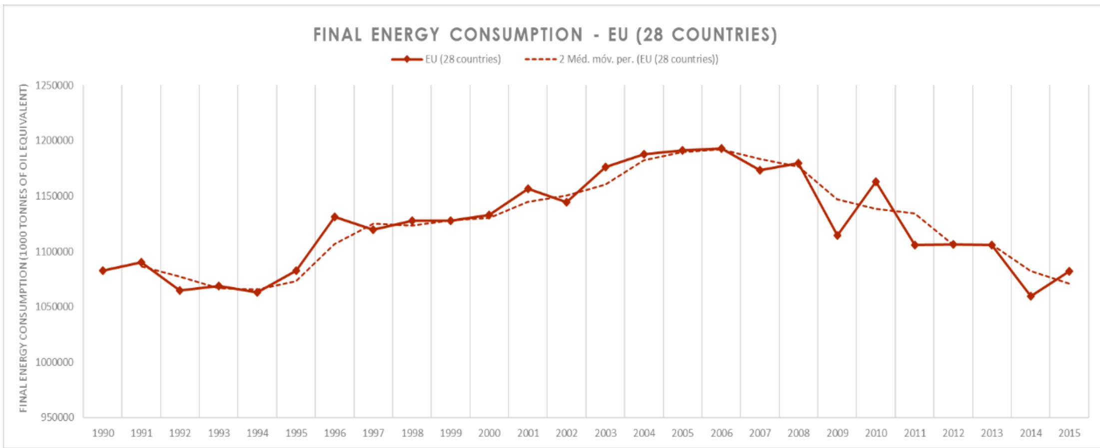


Figure 5.1 - Final Energy Consumption for 28 countries in EU, data obtained from [95].

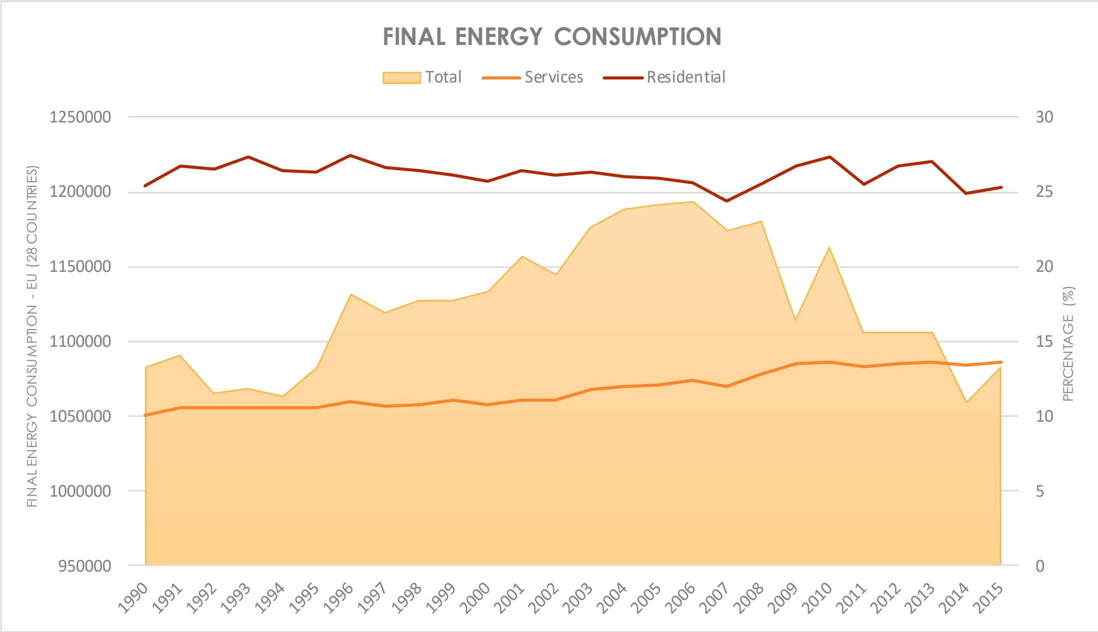


Figure 5.2 - Final Energy Consumption according to sectors data obtained from [95]

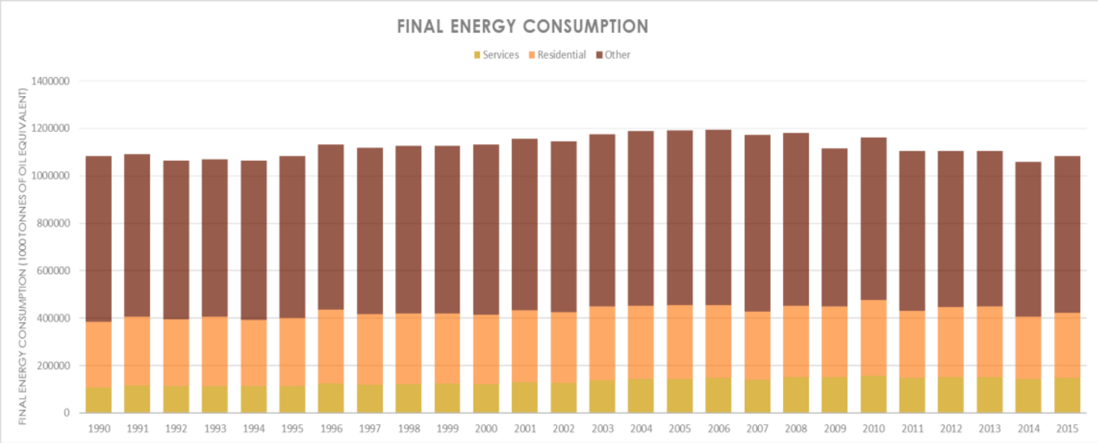


Figure 5.3 - Final Energy Consumption for considered sectors, data obtained from [95].

Focusing the analysis in the Portuguese situation, it is possible to see an increasing tendency in the energy consumption by the services sector over the last two decades just as it is verified for all the other EU countries (Figure 5.4). With regard to cultural Heritage, particularly museum buildings, not only their long-term survival depends on reducing high energy costs, due to traditionally established rigid specifications regarding the indoor control of both temperature and relative humidity in order to assure the safeguard environment of collections, but also their contribution towards low carbon economies, respective to the sustainable goals previously presented, should be taken into account.

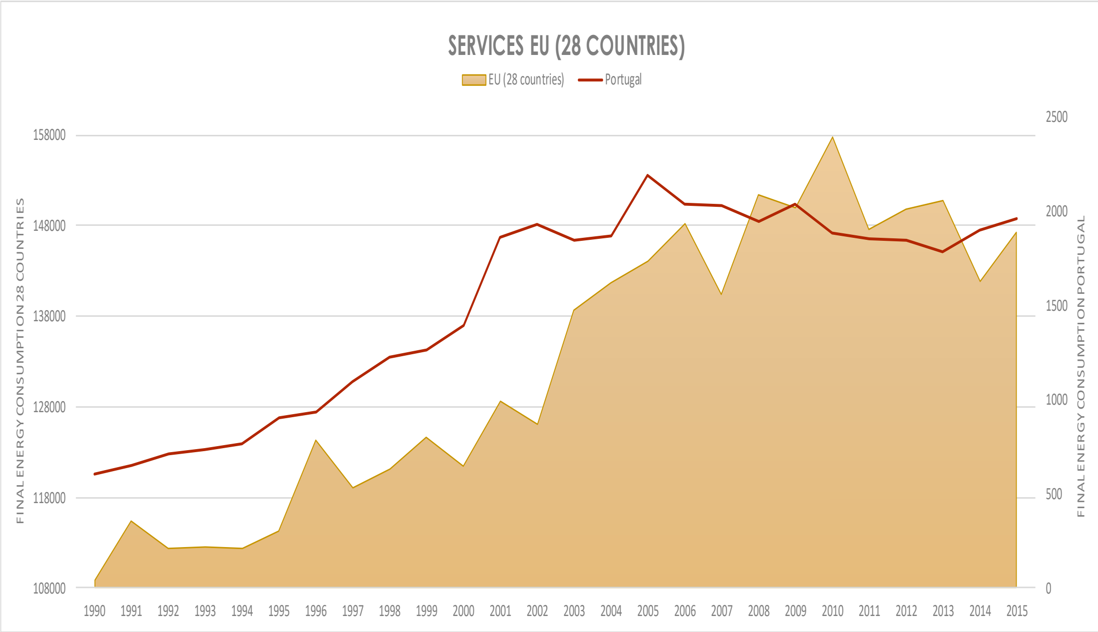


Figure 5.4 - Final Energy Consumption in Portugal, data obtained from [95].

5.3 *The Dynamic Interaction Between Tourism and Cultural Heritage*

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 seen as a major contribution for the economy of each country, as well as a potential vehicle in facilitating the preservation of cultural heritage, if managed properly. In the International Cultural Tourism Charter ‘’Managing Tourism at Places of Heritage Significance’’, first presented in 1999 by ICOMOS [97], it was reckoned that tourism is indeed among the foremost agents for cultural exchange. However, this relationship between tourism and Heritage Places can often be seen as conflicting in nature, by the fact that it can both lead to opportunities as well as potential complications.

A compromising aspect to the protection of places and collections of heritage significance is the disturbance of the indoor climate due the increasing number of visitors and the new added pressures to guarantee both their comfort as well as health necessities. The term 'sustainable tourism' had its origin due to a previous disregard of that sector when considering the spectrum of cultural exchange between countries, with visitor numbers now becoming paramount concern to both the economy and heritage management conservation [98]. Tourism is considered to be one of the world largest and fastest-growing economic sectors, responsible for 10.2% of gross domestic product globally in 2016 [99]. If not properly managed, it can have a negative impact on sites with relevant cultural value, compromising the role that agencies responsible for its preservation play in establishing a safeguard environment. Tourism can play a vital role in supporting the Sustainable Development Goals adopted in 2015, with promotion and enhancement of practices applied in protecting the authenticity of countries, monuments and collections [90].

Europe is entitled to some of the most extraordinary examples of intangible heritage value in the world. In fact, 'cultural tourism' accounts for around 40 % of European tourism, representing a key economic sector in terms of potential for growth [100]. By gathering to its own accord the economic characteristics associated with places of cultural significance, it makes for a potentially advantageous way of generating revenue that further supports the ultimate purpose of heritage management – it's long-term preservation. In regard to the Thessalia Charter, adopted in 2016 in its second edition, as a means to influence practices and initiatives that encourage ‘’sustainable and responsible tourism policies and actions across Europe and beyond, through engaging culture and heritage with innovation and cohesion’’[101]. It also grants contribution by the European Cultural Tourism Network (ECTN) to both the 2017 International Year of Sustainable Tourism for Development [102] and European Year of Cultural Heritage 2018. It becomes clear the trajectory in which policies and goals are being set by inter-governmental entities and policy makers in recent years, when considering the management of places identified by their great heritage significance.

The concept of tourism is being integrated in the agenda for a more sustainable future at a cultural heritage level, reflecting the growing worldwide concern for such an integrated approach.

6 Methodology

6.1 *General Considerations*

6.1.1 *Climate in Portugal*

Portugal consists of two archipelagos – Madeira and Açores – as well as its continental territory. According to the Köppen[2] classification – one of the most widely used climate classification systems – the latter is considered to be a Mediterranean climate, however with two separate climatic regions: one that is temperate, with rainy Winter and dry or hot Summer (Csa) and the other that is temperate, with rainy Winter and dry or temperate Summer (Csb) [103]. Situated in the southeast extreme of Europe, the climate is greatly influenced by its proximity to the Atlantic Ocean. On the basis of latitude/longitude distribution ratio it is a region that extends more latitudinally with the most interior locations remaining at a distance long enough for the climatic characteristics to be considered continental. Moreover, in regard to its orography, the regions of the North as well as the Centre have significant altitudes surpassing the 1000 m height. The differentiability of all these factors induces crucial variations both in temperature as well as in precipitation. As it is, the North-eastern region is one of Europe's areas that registers the highest values of precipitation [104]. On the other hand, some locations in the interior of Alentejo are known to have the lowest mean annual precipitation of the country, however this specific region presents considerable interannually variations in this regard, making it vulnerable to extreme phenomena of drought as well as floods.

As agreed upon by the World Meteorological Organization (WMO), the climate is characterized by the average values of the various climatic elements over a reference time-period of 30 years, which is a standard for calculating climate normal[3] values. The first period was established from 1st of January 1901 to 31st December 1930. Though, the WMO recommends for the climatological normal to be updated at the end of each decade, hence obtaining interim normals such as the 1971-2000, the latest available.

Figures 6.1 and 6.2 show the mean annual and seasonal temperature as well as the accumulated seasonal precipitation for the continental territory in the reference period of 1971 to 2010. The highest annual average value for mean temperature, for the considered period and regarding the continental territory, is registered in Faro with 17,5 ºC – Figure 6.1a. In figure 6.1b the average minimal temperature registered for the months of December, January and February, demonstrates that the lowest temperature is inferior to 0ºC in the region of Serra da Estrela – with the highest altitude in the continental territory – and it has values below 2ºC in some regions of both the North and the Centre of the territory. The highest values are around 10ºC and are verified in the more southern regions such as Faro and Setubal. In respect to the average maximum summer temperature for the months of June,

[2] Created almost 100 years ago, continues to be one of the most widely used classification systems for climate studies in the world. The Köppen climate classification system defines distinct types of climate using average monthly values for precipitation and air temperature, adapted from [104].

[3] Climatic normals refer to statistical calculations performed on climatic values of meteorological quantities observed in a given location and within a given time period and are used as background information in the classification of the climate of a specific region, adapted from [104].

July and August, the highest values are registered mostly in the central and southern regions towards the interior of the territory, with temperatures reaching above 32ºC.

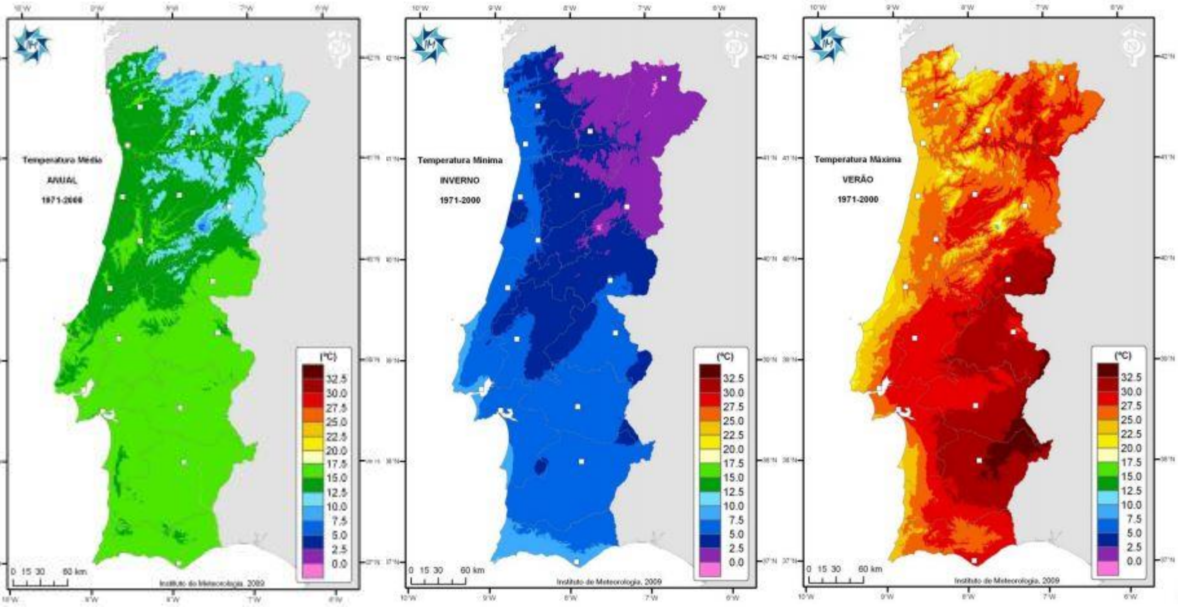


Figure 6.1 Air temperatures registered from 1971 to 2010: a) Mean annual, b) Average minimum temperature in Winter, c) Average maximum temperature in Summer, adapted from [105]

The mean annual precipitation in the continental territory is around 900mm [104], and the highest values are, as previously stated, verified in the north-eastern region of the country (Figure 6.2a).

In terms of total precipitation, and as would be expected, the season with the highest values is the winter – Figure 6.2b – specifically for the months of December, January and February. On the other hand, the season with the lowest precipitation is the summer, in respect to June, July and August, with the presented distribution for the continental territory.

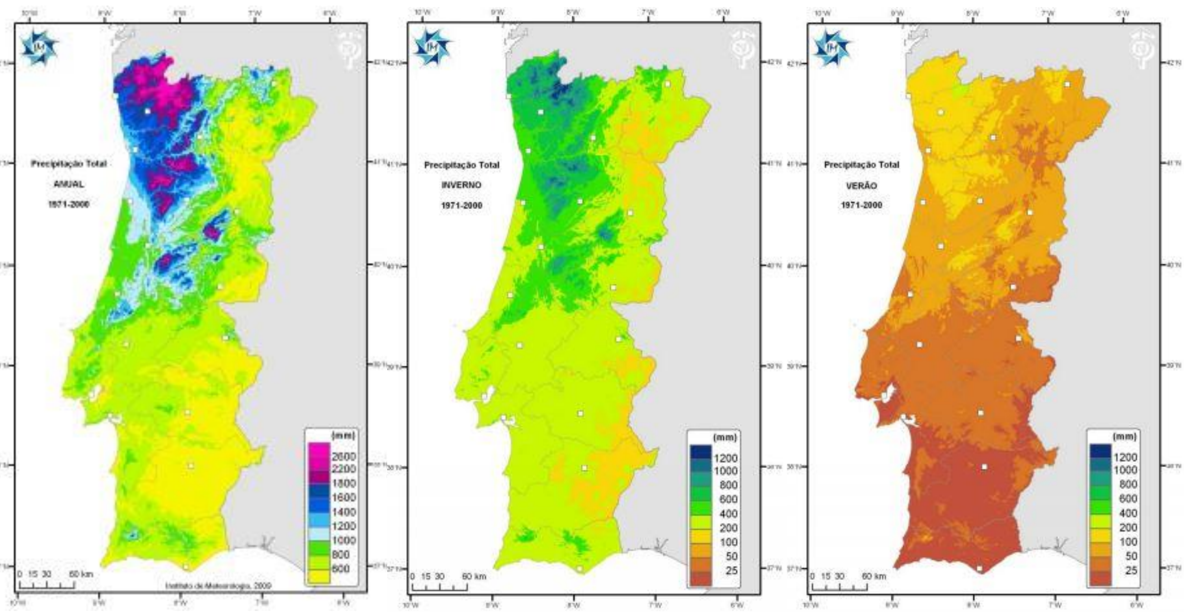


Figure 6.2 Total Precipitation from 1971-2010: a) Annual, b) Winter, C) Summer, adapted from [105]

Madeira is characterised by the Csa type in the Köppen classification, considered to have a temperate climate with hot, dry summers [106].

The average annual air temperature in both Madeira and Açores is dependent on the altitude of the area that is considered and decreases with the increase in altitude – Figure6.3a. Therefore, the registered averages values vary between 14ºC and 18ºC in coastal regions and between 6ºC and 12ºC in areas with a higher altitude. The summer average maximum air temperature values have a range of between 17ºC and 26ºC and occur in coastal regions of Madeira – Figure6.3c. Contrarily the lowest winter average values of the minimum air temperature – that is below 8ºC – occur in areas of higher altitude (Figure 6.3b).

The eastern group of Açores, in which S. Miguel is located, is considered to be type Csb that is a temperate climate with dry and mild summer [106]. One of the most important factors that define the climate in Açores is its geographical location in the centre of the Atlantic Ocean, in the anticyclonic zone with relatively consistent high pressures. Since it is distant enough from the continent, its climate is regulated by the ocean in terms of temperature as well as being affected by a significant amount of humidity [104]. The average maximum temperature in summer varies between 18ºC in regions of higher altitudes and 24ºC in lower regions – Figure 6.3c.

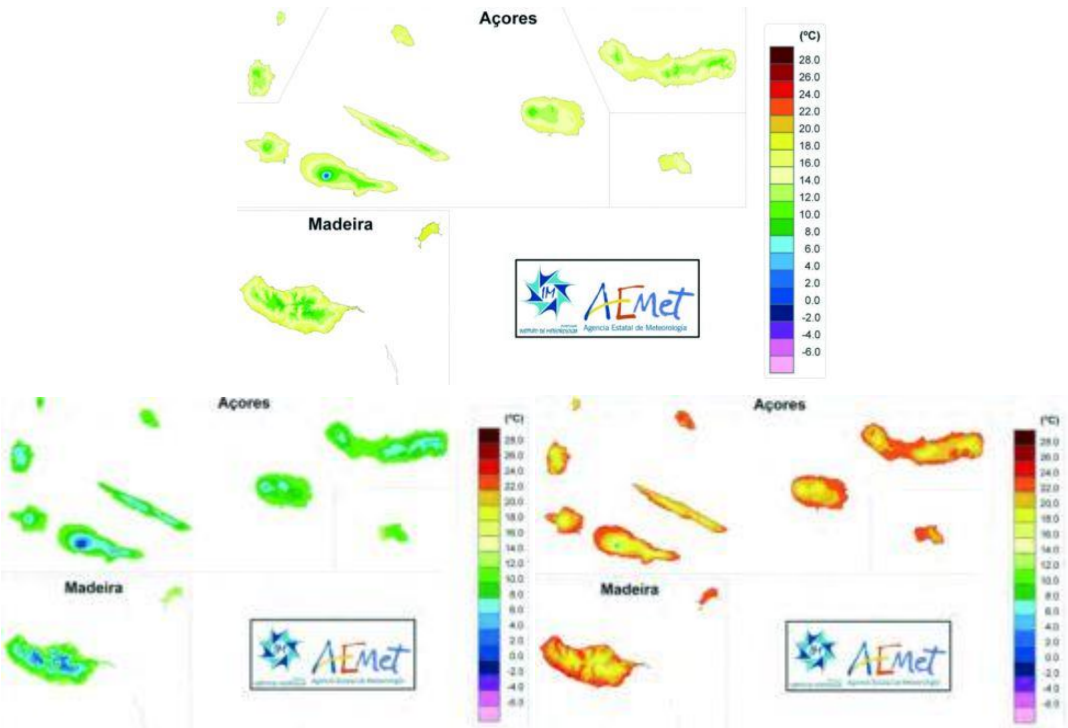


Figure 6.3 Distribution of temperature in the island of S. Miguel in the period of 1971-2010: a) Annual average; b) Average minimum temperature in winter; c) Average maximum temperature in summer, adapted from [107]

The annual average precipitation shows that it is most abundant on the island of Madeira than any of the others that are part of the archipelago, registering an average of 596.4 mm in Funchal – Figure 6.4. Topography is an important factor when it comes to this consideration as there is a higher amount of precipitation in higher altitudes on the island. The months of December and January are the ones with the highest precipitation values, specifically in Funchal with 109.4 mm. During summer – June, July and August – the values of the average amounts of precipitation are overall low [107].

In regard to Açores, topography also influences the abundance of precipitation, as the areas with higher altitudes register higher values, mainly the island of Pico with values of average annual precipitation greater than 4000 mm/year. The moths of November, December and January also register a great abundance of precipitation, with an average greater than 500mm [107].

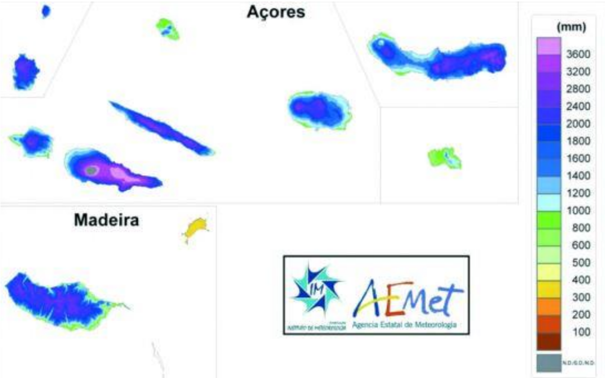


Figure 6.4 Average total precipitation in the archipelagos, adapted from [107]

6.1.1.1 Outdoor climate according to the simulation performed

As a simulation of the internal climate in a specific case study is going to be presented in the following points, with the intent of evaluating the risk of damage that an increase in occupancy induces, specifically in terms of temperature and relative humidity, an account of the external climate for each district is therefore interesting to consider. Particularly in correlating it with the results so as to facilitate the analysis. For that purpose, Table 6.1 represents the outdoor climate in each district according to the specific weather files used [108].

Table 6.1 The external climate considering the climatic data used in the simulation

District	Temperature [ºC]			Relative humidity [%]		
	Annual mean	Minimum	Maximum	Annual mean	Minimum	Maximum
Aveiro	15,47	32,24	0,94	79,32	98,00	37,00
Beja	17,87	38,38	2,14	76,08	98,00	15,00
Braga	15,02	30,84	0,14	79,15	98,00	30,58
Bragança	16,16	38,18	0,08	75,02	98,00	15,00
Castelo Branco	17,41	40,08	0,23	69,18	98,00	15,00
Coimbra	15,65	31,54	0,84	80,94	98,00	26,58
Evora	17,41	38,98	1,64	76,21	98,00	20,58
Faro	17,41	34,88	3,34	74,48	98,00	22,58

Table 6.1 The external climate considering the climatic data used in the simulation (cont.)

District	Temperature [ºC]			Relative humidity [%]		
	Annual mean	Minimum	Maximum	Annual mean	Minimum	Maximum
Funchal	17,40	27,74	7,84	77,61	98,00	45,00
Guarda	14,12	34,94	-1,96	75,54	98,00	20,58
Leria	15,27	30,74	1,84	81,92	98,00	33,58
Lisboa	16,56	31,98	3,74	78,41	98,00	32,58
Ponta Delgada	17,78	29,44	7,40	82,23	98,00	46,00
Portalegre	17,24	38,88	1,44	73,80	98,58	15,00
Porto	15,75	32,64	2,24	81,27	98,00	37,58
Santarem	16,50	37,25	1,48	78,27	98,00	23,00
Setubal	17,19	34,78	2,64	77,06	98,00	27,58
Viana do Castelo	14,52	33,28	0,24	78,70	98,00	27,58
Vila Real	14,96	36,28	-2,66	75,68	98,00	15,00
Viseu	14,57	34,48	-1,86	76,14	98,00	19,58

6.1.2 *Touristic activity*

From an analysis standpoint, Figure 6.5 denotes that a much higher influx of visitors to national monuments and palaces is registered in comparison to museums, however both suggest an increase throughout the considered period. Figure 6.6 shows the evolution of tourism visitor's numbers in Portugal, which attests for a continuous growth in the past few years, with the highest contribution being from foreigners. This increase accounts for the added concern in the influence that it might have on the internal climate, where collections are housed, as well as the assurance of their preservation. Nevertheless, as previously mentioned, there is also a positive aspect to this overall rise of visitor's influx seeing as though it helps to generate a revenue for the management and improvement of the conditions that are representative of each establishment. One specific example is the case of the National Palace of Ajuda in Lisbon and the recently imposed touristic rate by the mayor of Lisbon, which managed to allocate the required financial aid for its conclusion, that for so many decades was lacking and consequently prevented the impending and needed rehabilitation of the palace [109]. This certainly accounts for perhaps the major driving contribution from tourism in the preservation of existing cultural heritage. Still, if unsustainable, it can be an unwanted and hindering force, that goes against the crucial and underlying principle of managing the conservation of these important remembrances of history.

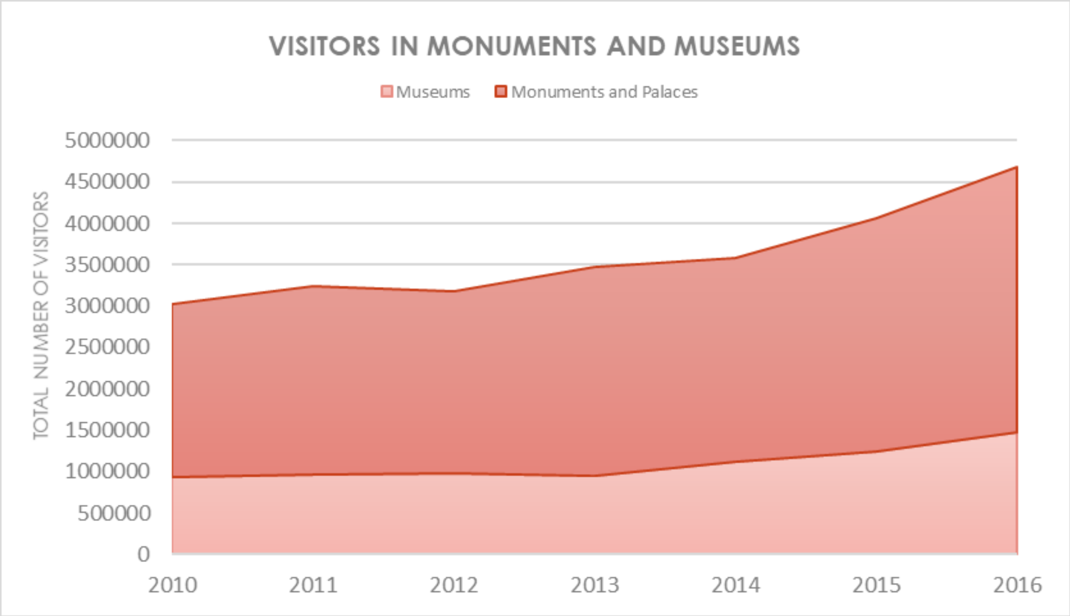


Figure 6.5 Total number of visitors in both Museums and Monuments, data obtained from [110]

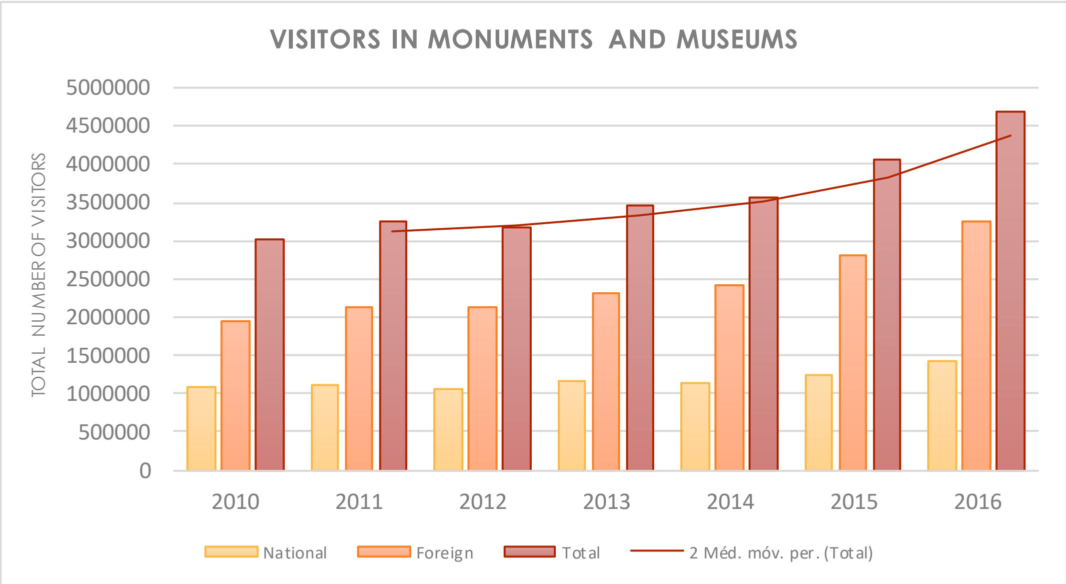


Figure 6.6 National and Foreign visitors in monuments and museums from 2010 to 2016, data obtained from [110]

Even though several studies are being carried out concerning the preservation of cultural heritage in Portugal, with many aspects that affect the indoor environment inside museums undergoing relevant considerations – such as referred in [111], [112], [113], [114], [115], [116] – however until now, none of those have studied the impacts of tourism in cultural heritage.

Tourism can not only represent a valuable generator of revenue for the continuous work of preservation, an indispensable requirement in maintaining a safeguard environment to cultural heritage, but can also be considered a hindrance to the same accord, given the fact that if not sustainable, negative impacts can arise, possibly affecting the established conditions and ultimately harming the artwork. Considering that people contribute to the internal heat and moisture gain by the work of their natural metabolism, it then becomes apparent that large fluctuations in arrivals and excessive influxes in number of visitors for a prolonged time constitute a problem that needs to be addressed. The use of a building accounts for thermal and moisture gains within the envelope, in respect to lighting, equipment and occupants, the latter resulting in the need for exterior air ventilation to meet the desired and healthy hygrothermal conditions, that are to be expected in current days. Thus, the requirements on climate control – resultant from regulated ventilation rates so as to prevent health risks given the high values of CO_2 – and the minimal limits for thermal comfort have to be met. A conflict emerges when a museum environment is to be considered, necessarily to do with the fact that these requirements are not isolated when taking into account the needs of the collections. It is then alleged [117] that information should reach to visitors, with the intent to present the intelligible value of cultural heritage as well as the exceptional need for its safe preservation, which then leads to the assumption that if it makes for a less comfortable visit, but on the other hand allows for a positive outcome in the sustainable climate control strategy chosen for the conservation of that specific environment, then it should indeed be considered. Degradation, when balancing all the agents at play in this context, is a complex subject as was also pointed out in previous chapters. As it is, a risk analysis of such environments must be undertaken so as to mitigate possibly permanent damage to affect the artwork.

6.1.3 *Importance of simulation in this context*

With the above context in mind, simulation models of museum buildings can help to predict the indoor climate conditions when they are virtually subjected to diverse factors applied to control strategies. In this particular case, it allowed for the evaluation of the potential damage that the varying of numbers in visitor's influx has on the degradation mechanisms – namely mechanical, biological and chemical – of valuable historical objects.

Within building physics, these computer simulation models have become an excellent tool to help in the process of risk assessment regarding dangers to collections, as they have been developed to calculate the expected indoor climate of buildings exposed to the respective regional climate, constructed from data files from outdoor climate estimates provided by the software, as it was in this specific case. The simulated indoor climate will then create the input for the risk evaluation, as it is then coupled with damage functions that are already present in literature, derived from experimental results, in order to be able to predict the risks of damage to the objects as well as produce statistical analysis of the obtained results. This study will necessarily be based on this modelling approach, conducting a comparative analysis on the potential for damage to objects – that is mechanical, biological, and chemical that different numbers of visitors per hour – specifically 6, 12 and 18 – can induce when considering a modelled representative room of a historic building – in this case the NMAA – which was virtually placed in 20 different districts of Portugal. The weather data was used according to Ref. [108] which considers a period of 30 years, as reference years. All the 18 districts of the continental territory as well as two from the islands, namely Ponta Delgada and Funchal, were considered in the weather generator program in order to assess the simulated impact of touristic activity in each region and inform on further developments when evaluating the best suited control strategies in museums.

When modelling a building, several considerations must take place in order to create an approximation very close to what is observed in reality, so as to efficiently conduct the analysis that is going to take place. In the cases of historic buildings this process becomes more complicated due to the inherent complexities associated them, sometimes making it impractical to find the appropriate correlation to a particular parameter. Moreover, when modelling buildings several variables are dynamic throughout the day as it is the case with occupancy. This of course greatly influences the output resultant from the year in analysis, namely because of the resultant indoor variations in temperature as well as in relative humidity.

As it is, it becomes necessary to schedule the hours of operation of certain parameters, seeing as though they vary in reality during the day. For instances, museums are generally closed at night, resulting in an occupancy of zero people which then affects the internal microclimatic conditions differently than when considering the opening hours period. These differences are implicitly represented in the defined model's schedule for occupancy as well as lighting.

For this specific model, the occupancy was defined by the fractions of both sensible and radiant heat per person (W), lighting in W/m^2 and the ventilation rate in ach.

It should also be stressed that even though these tools are useful, they are applied with the awareness that the assumptions and approximations with which these models in simulation software are based on, are indeed an idealized perspective and do not fully represent the real context of variations with precision in envelope construction.

6.2 *Computational Modelling – Energy Plus*

The analysis presented in this study was performed by the dynamic simulation software EnergyPlus 8.6. This software started being developed in 1996 based on two already existing programs – DOE-2 and Building Loads Analysis and System Thermodynamics (BLAST) – and it includes a number of innovative simulation features such as variable time steps, user-configurable modular systems that are integrated with a heat and mass balance-based zone simulation as well as input and output data structures in order to facilitate third party module and interface development – open source code – making EnergyPlus an international repository for algorithms that can be made available to all interested parties [118].

This is an energy analysis and thermal load simulation program, necessarily in terms of the hygrothermal performance in buildings, the energy consumption – for the heating, cooling, ventilation and lighting – as well as the internal generated pollutants. It is supported by the fundamental principles of heat balance. However, this modelling approach induces that the heat balance is established considering that in each zone the air volume is well-mixed at a uniform temperature, and also that the heat conduction is unidirectional, which is not correct. Future developments in computer modelling are being made regarding this particular misconstruction of how the physics inside of buildings happens in reality, and given its structure soon it will be possible to introduce those improvements in Energy Plus [119].

This software takes inputs – both building description and weather – a necessary first step in defining as accurately as possible the model that is going to be considered. As such, a characterization of materials, activities and geometry are required to allow the user to create construction solutions and then associate them to each element – floor, ceiling and walls for instances – as well as in defining schedules and occupancies for each activity and zone individually.

Since the external elements are taken into account for the simulation, it then becomes necessary to define the climate respective to where the reference building is located – namely using the weather file. The weather data can be inserted manually with on-site measurements or via an auxiliary program. The data associated with the latter is obtained according to WMO – grants information on temperature, humidity, wind as well as solar radiation for each specific location.

It is also important to specify the type of algorithm used for both heat and moisture transfer as well as for convection of internal and external surfaces. There are four possible choices: the CFC (*Conduction Transfer Function)* which is a sensible heat only solution and does not take into account moisture storage or diffusion in the construction elements; the Moisture Penetration Depth Conduction Transfer Function that needs additional moisture material property information since it adds to the previous algorithm an inside surface moisture storage; the remaining two algorithms are of advance usage, namely the Conduction Finite Difference and the Combined Heat and Moisture Finite Element (HAMT). The first uses a one-dimensional finite difference solution in the construction elements and is a sensible heat only solution contrarily to the second which is a coupled heat and moisture transfer and storage solution.

When defining surfaces convection, there is the possibility of defining a specific algorithm for the interior as well as the exterior. The model specified in this field is the default algorithm for the inside all the surfaces – that is TARP – and as for the external surfaces it also recommends a default algorithm – that is DOE-2 – which uses correlation from measurements by Klems and Yazdanian for rough surfaces.

When the simulation is completed the program originates the outputs in several different formats, such as the CAD file and the data related to parameters such temperature and relative humidity.

6.2.1 ***Simulation Model***

In this section, an account of how the simulations were performed is formulated, for the specific case study, necessarily of which inputs were considered – such as the specific parameters as well as algorithms necessary for its accurate performance.

The chosen heat balance algorithm was the CFC, for both heat and moisture transfer. As for convection, either on the exterior or interior surfaces, the selected algorithms were the default – respectively TARP and DOE-2.

The building for this model is considered to be naturally ventilated with no climate control.

The geometry for the model was based on a representative room located in the historical building that houses the NMAA, according to [116], with the respective building construction and material components. In the south façade, it was considered an area of 10% of the floor for the glazing elements. It appears illustrated on Figure 6.7. A single zone was considered, with no interior partitions, along with the respective elements that define it – such as the walls, floor, ceiling and windows. The considered area and volume for the model are 22.5m x 7.5m x 3.5m. Each element was inserted via the cartesian coordinates of the four point that define it, clockwise starting in the lower left corner, considering that the viewer is in the exterior side. In this model, all elements were considered adiabatic – that is all heat transfer into the surface is a result of the dynamic response of the construction to varying inside boundary conditions – with the exception of the external south wall.

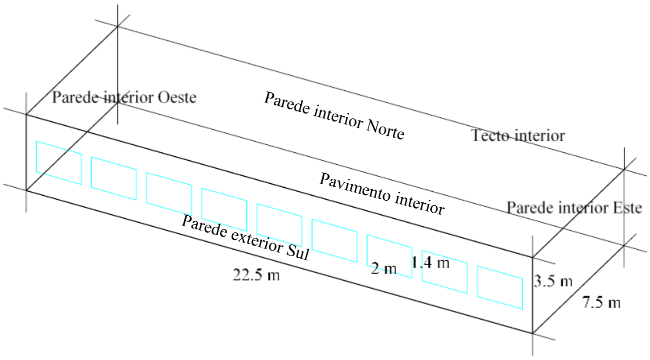


Figure 6.7 Geometric Model used for the simulation using EnergyPlus, adapted from [116]

To be able to identify each component with their respective material construction it was necessary to insert the individual characteristics that define them, distinguishing the opaque elements from the existing windows. Table 6.2 shows the material characteristics that were used respective to each element – walls, ceiling, floor and windows – in order produce the simulation of this specific model.

Table 6.2 Defined characteristics for the simulation of the model

Component	**Material**	**e (m)**	**λ [W/(mºC)]**	**ρ [kg/m³]**	**C_p [J/(kg.K)]**
Walls (Exterior -> Interior)	Lime Mortar	0.03	0.7	1785	850
	Masonry	0.54	1.76	2122	850
	Lime Mortar	0.03	0.7	1785	850
Ceiling/Floor (Exterior -> Interior)	Oak	0.02	0.15	740	1400
	Concrete	0.25	2.3	2322	850
	Lime Mortar	0.03	0.7	1785	850
Windows	Metallic frame	Simple glazing	Drapes	U_w = 5.1 [W/(m².ºC)]	g = 0.25

A ventilation rate of 0,3 ach was specified – Table 6.3 – as well as internal gains resultant from lighting, 9 W/m² during opening hours and 2 W/m² selected for the remaining period. Regarding occupancy, different numbers were chosen – necessarily for 6, 12 and 18 per hour – in distinct simulations so as to conduct a rounded analysis of the possible impacts on the indoor environment only for operation hours, as would be expected.

Considering each visit to have a duration of 15 min and a typical year with 308 days of being open to the public, it results in 59136 visitors annually – which is equivalent to NM Soares dos Reis – 118272 visitors – in respect to NM Arqueologia – and also 177408 visitors – in regard to the NMAA.

Table 6.3 Ventilation flow respective to each case of occupancy

Case	Ventilation [ach]	Ventilation [m^3/h]	Visitors/h	Ventilation by visitor [m^3/visitor]
1			6	30
2	0.3	177	12	15
3			18	10

For the definition of the internal gains it was necessary to define the interval of time respective to each specific gain in Schedule: Compact (Figure 6.8). So as to construct a complete definition of the considered parameters, a first field was completed in order to inform the program that these gains are according to 24 hours/day.

The selected hours of operation ranged from 10:00 to 18:00 and the only day closed for visitors was considered to be Monday.

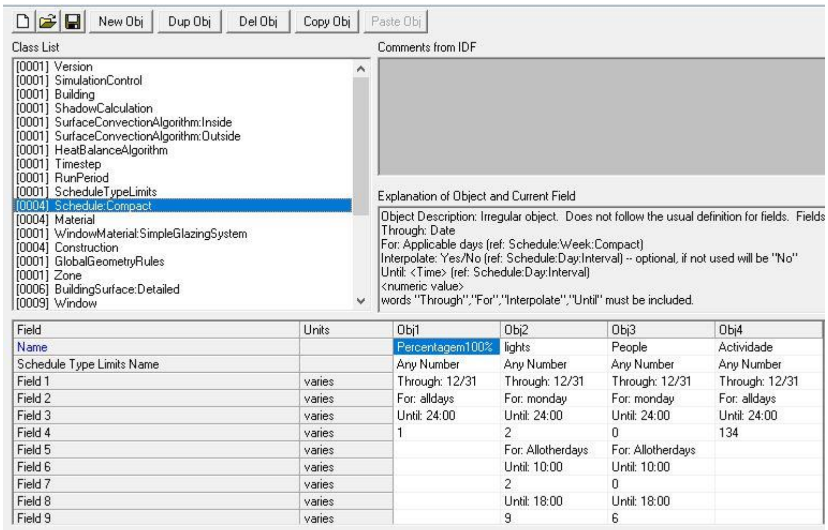


Figure 6.8 Definition of Schedule: Compact for this model

According to Silva and Henriques [120], several parameters were used so as to obtain the internal gains, namely a metabolic rate of 1,28 met, a heat gain of 134 W, in which 60% is sensible heat and 40% is latent heat. Sensible heat is directly related to temperature and is divided into two fractions, of 50% radiant and 50% convective (Figure 6.9).

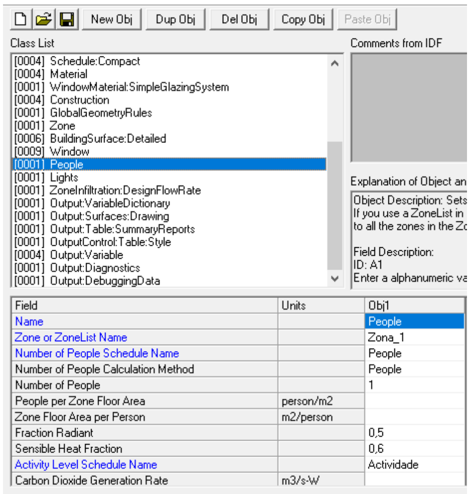


Figure 6.9 Definition of occupancy in respect to its radiant and sensible heat.

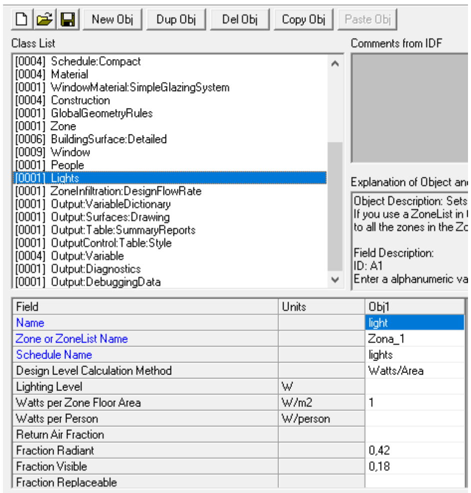


Figure 6.10 Definition of lighting in this model

Considering the ventilation flows previously presented in Table 6.3 and taking into account that each visitor releases 70 g/h [BS 5250:2011] of water vapour in the duration of 8 h, as well as applying the concept of hygrometry – Table 6.4 – which links the internal water vapour gain with ventilation:

$$\frac{n \cdot \omega \cdot h}{ach \cdot V \cdot 24} \quad (6.1)$$

in that n is the number of visitors, ω the water vapour produced by each visitor, h the number of hours of the visit, ach the ventilation rate, V the volume and 24 the factor used to obtain the mean hygrometry. According to French literature [121], a classification of low hygrometry is resultant from this consideration respecting the three cases of occupancy and as such, it is possible to theorically infer that none of the considered cases will cause high risks of superficial condensations.

Table 6.4 Hygrometry according to each of the cases of visitor's number considered

Case	Ventilation [ach]	Visitors/h	Hygrometry [g/h]
1	0.3	6	0.8
2		12	1.6
3		18	2.4

6.3 *Results Processing*

6.3.1 *Statistical Analysis*

On the basis of understanding the indoor climate generated in this simulation model, a general analysis was performed, specifically concerning the indoor temperature (ºC) and relative humidity (%) values.

The indoor climate is defined by average levels and variability of both temperature and RH. These are statistically represented in terms of an average level over a selected period – for instances one year – seasonal cycles as well as short-term fluctuations.

So, to support the statistical analysis of the values resulting from the performed simulations as well as to provide a better account of the variations throughout the year, a running average of 30 days was considered, in accordance to what is asserted in EN 15757. This value is determined considering data 15 days before and after the desired value and can be calculated with the equation 6.2:

$$X_i = \frac{1}{n+1} \sum_{i-0,5n}^{i+0,5n} X \qquad 6.2$$

where X_i is the 30-day running average centred in the point *i*, *n* is the number of records during 30 days, *i* is the central point around which the calculation is being produced and *X* can either be temperature (ºC), relative humidity (%) or water vapour concentration (g/m^3), corresponding to what it is to be considered.

As for the seasonal variation of both RH and T, another parameter that was used to evaluate the results was the maximum variation of the dynamic movable average of relative humidity ($\Delta\overline{RH}_{sazonal}$) and temperature ($\Delta\overline{T}_{sazonal}$), which represents the difference between the maximum and minimum values of the 30 day running average, respectively in the following equations, 6.3 and 6.4:

$$\Delta \mathrm{RH}_{sazonal} = máx\left(\overline{RH}_{i,sazonal}\right) - mín\left(\overline{RH}_{i,sazonal}\right) \qquad 6.3$$

$$\Delta\overline{T}_{sazonal} = máx\left(\overline{T}_{i,sazonal}\right) - mín\left(\overline{T}_{i,sazonal}\right) \qquad 6.4$$

For the calculation of the short-term fluctuations a maximum limitation of the 90º percentile of the obtained results, for both temperature and relative humidity, was considered and applied to the following equations, 6.5 and 6.6:

$$\Delta_i = RH_i - \overline{RH}_{i,sazonal} \qquad 6.5$$

$$\Delta_i = T_i - \overline{T}_{i,sazonal} \qquad 6.6$$

where Δ_i refers to the short-term fluctuations, RH_i and T_i the hourly values of both relative humidity and temperature, $\overline{RH}_{i,sazonal}$ and $\bar{T}_{i,sazonal}$ the 30-day running average of the values respective to temperature and relative humidity.

6.3.2 *Performance Index*

Given the great concern awarded to the preservation of collections, often the choice for extremely strict ranges of T and RH takes place even though it may not necessarily be the best suited for a specific context due to unwarranted consequences such as the unnecessarily high energy consumption as well as what certain limitations in the building envelope itself imposes. In order to assess if the parameters are in conformity with the static reference targets, present in literature, a method named as Performance Index developed by Corgnati et al. [122] was used. It expresses the percentage of time the imposed limits are met by the hygrothermal parameters, it does not however evaluate the risk of degradation.

The selection for the static targets was based upon a previous literature review, presented in greater detail on Chapter 4, with the choice resulting in the limits such as the Magic Numbers of the 70s, Garry Thomson's classes published in 1986, the Smithsonian ranges from 2007 as well as the interim guidelines adopted by the Bizot Group recently divulged in 2014, all summarized in Table 6.5:

Table 6.5 Static Targets used and their respective Temperature and Relative Humidity ranges

Source		**T (ºC)**	**RH (%)**
Magic Numbers		18 – 22	45 – 55
Garry Thomson	Class 1.1	18 – 25	45 – 55
	Class 1.2		50 – 60
	Class 2	-	40 – 70
Smithsonian		19 – 23	37 – 53
Bizot		16 – 25	40 – 60

The values of both temperature and relative humidity resultant from the performed simulations, that took into account the variation in occupancy – that is 6, 12 and 18 visitors per hour – as well as the specific data respecting the different climates associated with each district, were then accordingly evaluated with respect to the imposed ranges from the considered static targets. Thus, an estimate of the percentage of time that both hygrothermal values are within the reference target's specifications is presented in the next chapter.

6.3.3 *ASHRAE Specification*

ASHRAE's chapter 21 specifically designated for Museums Libraries and Archives, defines an average range for both temperature and RH at 15-25ºC and 50%, respectively, or the annual average for permanent collections. Depending on the damage risk of biological, mechanical and chemical degradation to the collection, it also presents six classes of control for general museums (See Table 4.4 in chapter 4), each with its own specific ranges of seasonal cycles and short-term fluctuations for both hygrothermal parameters. The strictest class is the AA, as it limits very closely the variations for T and RH with the seasonal cycle at ± 5ºC and no variation for RH as well as short-term fluctuations respectively at ± 2ºC and ± 5%, presenting no risks of mechanical damage to most artefacts and paintings. Class A is divided into two subclasses, both sharing the collection degradation risk and allowed temperature variations but with differing seasonal cycles and short-term fluctuations for RH, respectively one with no seasonal variation and ± 10%, as for the other, the As, with seasonal changes of ± 10% and smaller daily fluctuations of ± 5%. Furthermore, it refers to small risk of mechanical damage for some highly vulnerable artefacts. The most adequate class for masonry historic buildings and certainly the one that is verified for the majority of times in this type of buildings if not mechanically climatized – given the limitations associated with their particular construction as well as the preservation aspect in respect to their fabric – is class B, with recommendations for the indoor temperature seasonal cycles to be at an upward limit of 10ºC though not above 30ºC, and ± 10% for RH. The short-term fluctuations for temperature and RH are ± 5ºC and ± 10%, respectively, also indicating a moderate risk of mechanical damage to extremely vulnerable artefacts, very small to most paintings and photographs. The remaining two classes are the less stricter ones, with C limiting temperature at 30ºC and recommending RH to be within 25-75% as well as considering a high risk of mechanical damage to highly vulnerable artefacts and moderate to others, and finally the Class D only limiting the RH at below 75% in order to avoid the risk of mould germination and rapid corrosion, with, of course, elevated risk of either immediate or cumulative mechanical degradation to most artefacts.

This specification is dedicated to design the indoor climate, though it can also be applied as a method of classification to already existing buildings. Rather than assuming the acceptance for each class at only 100%, a more comprehensive analysis has therefore been conducted in this study, through the validation of the estimated percentage of the values that are within the imposed ranges of both seasonal and short-term fluctuations, specific for each class [42], allowing for possible alterations to be considered.

Further details of this method are presented in its respective specification [78] as well as in Ref. [123].

6.3.4 *Risk Assessment and Damage Functions*

The presented risk assessment was based on the evaluation method defined in [113], with a microclimatic classification of 5 categories, from high risk - 1, to no risk - 5. The functions used within this study were in accordance to mechanical, biological and chemical damages, identified in the following points, expressing quantitatively the cause and effect dynamic between environmental influences and changes in materials, converting the obtainable data into a prediction of the risk it implies.

6.3.4.1 Mechanical Degradation

Changes in Relative Humidity affect the dimensional response and some physical properties of organic hygroscopic materials. If those materials are in any form restrained from movement, for instances when considering complex assemblies of different materials with differing response rates of adsorption and desorption which generates strains, due to swelling or shrinking, that if larger than the material's yield point can lead to mechanical degradation. It is also important to point out that these responses are not instantaneous, varying in accordance to different materials, taking hours, days or even weeks reaching a new equilibrium in moisture content.

For this reason, in this risk-based analysis, in order to obtain the equivalent relative humidity, considering the response time of the materials, equation 6.7 was used [42], as referred in Ref. [115], only valid for undamaged objects, as cracks significantly decrease the response time, and with a focus on the indoor climate as it is experienced by the object:

$$RH_{response,i} = \frac{a \cdot RH_i + a^2 \cdot RH_{i-1} + a^3 \cdot RH_{i-2} + a^4 \cdot RH_{i-3} + ... + a^n \cdot RH_{i+1-n}}{\frac{a}{(1-a)}} \quad 6.7$$

where *RHresponse,i* represents the RH equivalent to the moisture content of the object in every instance calculated from the response factor *a* obtained according to equation 6.8:

$$a = e^{\frac{-3 \cdot \Delta t}{\tau_{response}}} \quad 6.8$$

where *Δt* is the time interval between two successive records and *response* accordingly the response time.

As stated previously, mechanical damage is predominantly linked to dimensional changes in materials that are restrained from movement. According to the specific response time for each material, the construction of the entire object can hinder the induced dimensional changes. On the other hand, for shorter fluctuations in RH usually only the superficial layer is affected, given the short amount of time that they occurred in, thus creating a difference in moisture equilibrium content between the surface and the bulk of the material, as the latter constrains the movement from the other.

In the present work two methods were used to evaluate the risk of degradation in painted panels and in sculptures. To assess the mechanical risk-damage in the wooden substrate of painted panels a method based on the experimental work from Mecklenburg et al. [72] was used. With respect to sculptures, a method developed by Jakieła et al. was used [124] which modulated the response of a lime wood cylinder according to different levels of RH, particularly the influence of the moisture gradient from the inner surface of the object rather than its full response. The results from this study are presented in graphs – Figure 6.11 – and were used respective to the instantaneous response, which allowed for a conservative approach in the evaluation, as they represent the worst scenario [115].

If the climate conditions exceed the allowable fluctuations, the object begins to deform permanently informing the damage risk for these considerations. As such, a classification of a 5-points scale is established, ranging from 1, which corresponds to high risk, to 5 representing an ideal response. According to what is described in [113] in terms of mechanical risk, class 5 is always in the elastic region while class 1 represents the failure obtained when subjected to tension strengths. Class 4 is identified as a good response, showing a plastic response though only in compression and in less than 10% of the time. Class 3 accounts for some risks and extends the limitation and the last class allowing a plastic response both in compression as well as in tension. Class 2, represents a potential risk and constitutes a behaviour in the plastic region in more than 10% of the time, however without reaching failure. The final class represents a high risk of failure.

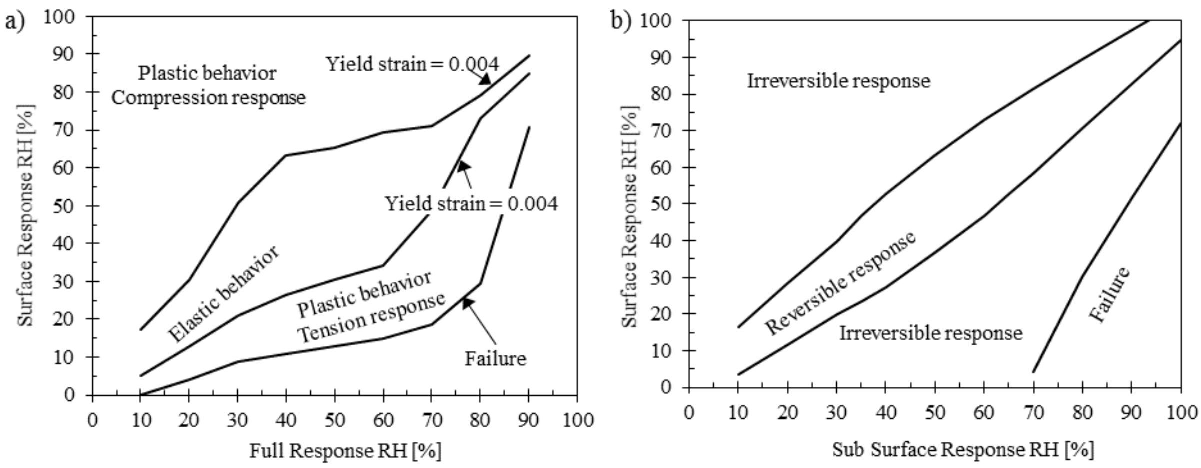


Figure 6.11 Mechanical risk-assessment: a) wooden substrate of painted panels; b) sculptures , adapted from [115]

6.3.4.2 Biological Degradation

Mould growth is considered to be a significant problem that affects museums all around the world, generally induced by the presence of high RH conditions for a prolonged time, however other factors such as temperature and the substrate material also contribute to its development, as previously specified in chapter 3. Thus, the assessment of biological degradation is necessarily connected to the occurrence of germination on the object.

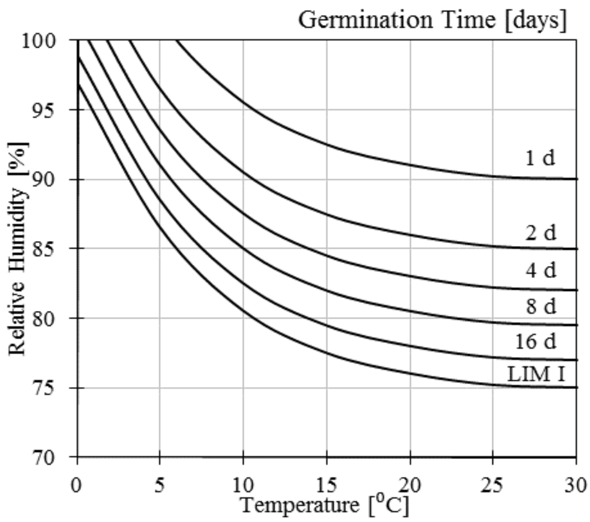


Figure 6.12 Risk assessment of biological degradation according the isopleth method defined by Sedlbauer for the substrate type, adapted from [40]

For the qualification of the risk of biological degradation in the indoor environment, Sedlbauer's isopleth method was used [40]. According to this method and as previously stated in chapter 3, the substrate materials also play an important role in determining fungal growth conditions, that is when temperature, RH and substrate are all exposed over a minimum period of time and for certain hygrothermal levels. As a result, a model is presented combining temperature, RH and germination time and growth rate on different substrate types, being the most extensive model available in this context to date, Figure 6.12. In addition to the conservative use of the isopleth graph for substrate type I, the concept of mould risk factor (MRF) was used, as referred to in [113], to quantify the biological risk, namely considering that the value 1 indicates that germination occurs and that the value 0 indicates an ideal condition represented by category 5, according to the 5-scale point used. As it is, Class 1 for a MRF higher than 1 represents a high risk, Class 2 for a value 1 corresponds to a potential risk, Class 3 has limits that may be sufficient in order to prevent biological growth and lastly Class 4 is the less demanding, allowing germination levels to be exceeded for short periods as long as MRF is lower than 0.5.

6.3.4.3 Chemical Degradation

In order to evaluate the chemical degradation, Michalski's Lifetime Multiplier was used [125]. The following equation, established for the Lifetime Multiplier, instead of setting an absolute life-time defines the number of time spans an object remains usable when compared to the standard of 20ºC and 50% RH:

$$LM_i = \left(\frac{50\%}{RH_i}\right)^{1.3} \times e^{\frac{E_a}{R} \times \left(\frac{1}{T_i + 273.15} - \frac{1}{293.15}\right)} \qquad 6.9$$

where LMi is the Lifetime multiplier at point i, Ea the activation energy (J/mol) – 70,000 for the yellowing varnish and 100,000 for degradation of cellulose [42], R is the gas constant (8.314 J/mol K), RHi (%) and Ti (ºC) the relative humidity and temperature respectively at point i.

If the multiplier returns a value greater than 1, it indicates that the corresponding conditions decrease the chemical risks.

In order to derive an encompassing global value that takes into account the records from all year-round the method presented in [113] was used, that defines an equivalent Lifetime Multiplier from which returns a single value for the entire year, obtained from the average of the resulting values of the Lifetime Multiplier as specified in [115]

$$eLM = \frac{1}{\frac{1}{N} \times \sum_{i=1}^{N} \left(\frac{1}{LM_i}\right)} \qquad 6.10$$

where the eLM is the equivalent Lifetime Multiplier and N the number of data points.

The considered classification was defined around the mid value of 1 corresponding to the attribution of Class 3 in this regard, that represents some risks. Classes 4 and 5 correspond to an increase of life expectancy and contrarily the other two, namely Class 1 and 2, account for shorter life expectancies.

In accordance to [115], response times of 24h and 30 days were used, for temperature and relative humidity, respectively, so as to respect the necessary response of the material, as previously mentioned, concerning the mechanical degradation in that, objects do not instantly reach equilibrium with the environment.

In this study, the evaluation of biological risk corresponded to the yellowing of varnish.

6.3.5 *Final classification*

According to what was previously described and considering the evaluation that were selected, the final classification system used in this study is as follows in Table 6.6:

Table 6.6 Microclimatic classification, adapted from [112].

Category		Painted wood - Base material	Sculptures	MRF [-]	eLM [-]
Ideal	5	Elastic	Elastic	0	>2.2
Good	4	Plastic: Only compression. % of time in plastic region < 10%	Plastic: Only compression. % of time in plastic region < 10%	<0.5	[1.7;2.2[
Some Risk	3	Plastic: Compression and/or tension. % of time in plastic region < 10%	Plastic: Compression and/or tension. % of time in plastic region < 10%	[0.5;1[	[1;1.7[
Potential Risk	2	Plastic: % of time in plastic region > 10%	Plastic: % of time in plastic region > 10%	1	[0.75;1[
High Risk	1	Failure	Failure	>1	<0.75

7 Results

7.1 *Indoor climate characterization*

With the intent to present a summarized account of the indoor climate characterization, specifically concerning temperature and relative humidity, in order to better perceive the implications associated with the performed simulations, Tables 7.1 and 7.2 are the result, respectively evidencing the statistical analysis of the hygrothermal conditions with the inclusion of the annual mean value, the seasonal variation and also the 90º percentile of the short-term fluctuations.

Table 7.1 Statistical Analysis of Temperature values for each district and visitors per hour

District	**Temperature [ºC]**								
	Annual mean value			**Seasonal fluctuations**			**Short-term fluctuations (90º percentile)**		
	Visitors per hour			**Visitors per hour**			**Visitors per hour**		
	6	**12**	**18**	**6**	**12**	**18**	**6**	**12**	**18**
Aveiro	24,56	24,14	24,81	9,96	12,43	12,45	1,73	2,04	2,22
Beja	25,76	26,39	27,04	13,16	13,15	13,15	1,96	2,13	2,32
Braga	22,98	23,63	24,30	13,26	13,25	13,25	1,89	2,07	2,25
Bragança	23,11	23,73	24,37	17,35	17,34	17,32	1,86	2,04	2,23
Castelo Branco	25,37	26,02	26,68	17,43	17,42	17,42	1,97	2,15	2,33
Coimbra	23,79	24,43	25,10	11,86	11,86	11,88	1,90	2,09	2,27
Evora	25,40	26,03	26,69	14,18	14,16	14,16	1,86	2,04	2,23
Faro	25,21	25,84	26,49	10,99	10,96	10,95	1,91	2,08	2,27
Funchal	23,87	24,51	25,18	7,05	7,06	7,07	1,46	1,67	1,88
Guarda	21,95	22,59	23,25	17,39	17,38	17,38	1,85	2,02	2,21
Leria	23,19	23,82	24,48	11,16	11,17	11,19	1,81	2,00	2,19
Lisboa	24,56	25,19	25,85	9,96	9,95	9,94	1,73	1,91	2,10
Ponta Delgada	23,95	24,56	25,21	8,69	8,72	8,75	1,46	1,67	1,88
Portalegre	25,22	25,86	26,51	15,67	15,66	15,66	1,96	2,12	2,30
Porto	23,46	24,09	24,75	12,38	12,38	12,38	1,74	1,92	2,11

Table 7.1. Statistical Analysis of Temperature values for each district and visitors per hour (cont.)

District	Temperature [ºC]								
	Annual mean value			Seasonal fluctuations			Short-term fluctuations (90º percentile)		
	Visitors per hour			Visitors per hour			Visitors per hour		
	6	12	18	6	12	18	6	12	18
Santarem	24,65	25,28	25,95	12,85	12,83	12,83	1,93	2,11	2,30
Setubal	25,35	25,99	26,65	12,90	12,87	12,87	2,01	2,19	2,37
Viana do Castelo	22,23	22,87	23,53	13,08	13,06	13,05	1,84	2,02	2,20
Vila Real	22,43	23,06	23,71	18,24	18,23	18,23	1,89	2,07	2,25
Viseu	22,76	23,41	24,09	14,76	14,74	14,74	1,79	1,98	2,18

In view of Table 7.1 and considering the annual average values of temperature, it is apparent that the overall results indicate a not very significant increase in temperature along with the rise in occupancy. For instances, nearly every district has an increase from 6 to 18 visitors per hour, namely in 5-6% – from 22,76 ºC to 24,09 ºC in Viseu for example – the remaining cases only increasing 5% with the exception of Aveiro that only alters in 1%. As to the season differences, the general analysis of the results indicates no alterations with the increase in occupancy, except for Aveiro which verifies a rise of 25% when the visitors number per hour rise from 6 to 12. In regard to the short-term fluctuations the districts with the biggest increase are Aveiro, Funchal and Ponta Delgada, each with nearly 29%, when considering the increment from 6 to 18 visitors per hour. The overall distribution of the results for each district, when comparing the increase from 6 to 12 and 12 to 18 visitors an hour is relatively the same in that they rise accordingly, the only exception being Aveiro that registers a more significant increase when comparing the rise in occupancy. Namely, from 6 to 12 visitors an hour it increases 18% and only 9% considering the case of 12 to 18 visitors.

Considering the values presented in Table 7.2, a general increase in the selected three statistical parameters regarding relative humidity is evidenced for each district given the increase in hourly occupancy. The parameter that shows to be the one that is most affected by this imposition is the one which considers the short-term fluctuations, indicating for several districts a considerable increase of the values along with the one respecting the visitor’s numbers, particularly in Viseu, when the visitor’s number change from 6 to 18 per hour, with an increase of 93% - from 12,64% RH to 24,38% RH - practically twice the amount of the initial value. With respect to the increment form 6 to 12 visitors, it appears slightly higher than the case from 12 to 18 visitors – for instances Guarda with a 45% increase regarding the first and only 28% considering the latter. As to the seasonal variation every district presents an increase concomitant with the increase in visitor’s numbers per hour with the exception of Funchal which suffers a reduction of namely 4% when considering the rise from 6 to 18 visitors. For this case, the district with the highest increment is Setubal with 28% - from 13,90% RH to 17,76% RH. On the other hand, Lisboa appears to have the lowest increase in RH for this case as well – from 6 to 18 visitors an hour – specifically with only 5%. For the annual average, the districts all have a similar increase in RH between 3-5% in both 6 to 12 and 12 to 18 visitors per hour and of 8-10%, which follows the rise in visitor's number from 6 to 18 per hour.

Table 7.2 Statistical Analysis of Relative Humidity values for each district and visitors per hour

District	Relative Humidity [%]								
	Annual mean value			Seasonal fluctuations			Short-term fluctuations (90º percentile)		
	Visitors per hour			Visitors per hour			Visitors per hour		
	6	12	18	6	12	18	6	12	18
Aveiro	52,55	55,05	57,34	15,39	15,29	16,34	12,97	17,95	23,33
Beja	50,07	52,21	54,18	20,15	21,83	23,19	12,94	16,92	21,66
Braga	52,58	55,19	57,47	14,03	16,35	17,28	13,41	18,80	24,66
Bragança	52,66	55,39	57,42	22,84	25,72	25,77	14,28	19,91	24,91
Castelo Branco	45,42	47,88	50,13	24,49	27,39	29,18	12,52	16,88	21,76
Coimbra	53,16	55,53	57,70	15,49	15,40	16,75	13,16	18,00	23,18
Evora	49,78	51,99	54,06	15,99	18,23	20,22	11,85	16,52	21,26
Faro	49,63	51,88	54,00	11,67	12,88	14,21	11,97	16,35	21,03
Funchal	56,76	58,92	61,03	16,81	16,45	16,19	11,57	16,18	21,44
Guarda	50,85	53,86	56,13	25,72	28,29	28,11	14,00	20,23	25,98
Leira	54,56	57,03	59,26	12,71	14,39	15,11	12,60	17,93	23,22
Lisboa	52,02	54,29	56,43	15,03	15,39	15,85	12,13	16,58	21,36
Ponta Delgada	61,08	63,20	65,07	13,48	14,07	14,58	12,77	17,22	22,13
Portalegre	48,51	50,84	53,01	18,24	20,66	22,57	12,97	17,41	22,17
Porto	54,84	57,26	59,41	10,75	13,00	14,04	13,24	18,28	23,58
Santarem	50,94	53,23	55,35	13,25	14,95	16,39	13,38	17,69	22,40
Setubal	50,21	52,36	54,40	13,90	15,91	17,76	11,80	16,34	21,05
Viana do Castelo	53,14	55,93	58,30	16,46	18,51	18,90	13,97	19,80	25,54
Vila Real	51,60	54,47	56,61	24,68	27,21	26,63	14,18	20,14	25,42
Viseu	49,92	52,71	55,12	17,40	20,07	21,11	12,64	18,60	24,38

7.2 *Performance Index*

As presented in Table 7.3, which considers the case of 6 visitors per hour, it should be clear that the target that represents the best performance, considering the percentage of time that both values of temperature and relative humidity stay within its recommended ranges, is Garry Thomson's Class 2. Given that it grants no imposition regarding the control of temperature to be within any specific range and, on the other hand, the suggested range for RH is very wide, it should be expected that this flexibility in specifications would indeed result in an overall better performance for the hygrothermal conditions in this specific context, verified for each district, with ranges varying from 70% to 93%. From comparison with the author's remaining two classes – that is 1.1 and 1.2 – it is perceivable that they are somewhat equitably distributed, all districts having an overall poor performance in the percentage of time that the generated indoor climate is within the predefined limits, their highest performances reaching, respectively, only 25% in Lisbon and 27% in Funchal. The Bizot reference target demonstrates a general average performance regarding the compliance of both T and RH to its limitations, with values ranging from around 30% to 47%. As to the Smithsonian target, it presents results somewhat similar to those of one of Garry Thomson's least favourable classes in this context – namely 1.2 – in the majority of the districts, the only exceptions being Bragança, Guarda and Ponta Delgada whose values demonstrate a closer approximation to the performance of the Magic Number's target, which was necessarily adopted due to their persistence in literature and appears as the overall worst performance in the selected group – its highest performance value being observed in both Lisboa and Leiria with only 15%. This target, arguably the least favourable one for this specific context, presents the strictest ranges awarded for both temperature and relative humidity which contrasts greatly with Thomson's class 2, the one with the most flexibility in its imposed specifications.

From a geographical point of view, the district/location with the lowest values in overall performance, considering most of the selected static reference targets, is Ponta Delgada, the only two exceptions being Garry Thomson's Class 1.2 and 2, where it registers an accordance to the resulting values of the remaining districts. Conversely, the district with the best performance in general, that is, the one that shows the highest values in percentage for most of the chosen reference targets, is Leiria closely followed by Lisboa.

When evaluating the case of 12 visitors per hour – Table 7.4 – it becomes apparent that a similar distribution of performances to those previously observed takes place, however with a minor decrease in the overall values, a notable consequence when considering the effect of what an increase in occupancy has in this context. Garry Thomson's second class remains the target that verifies the hygrothermal conditions to be within its specifications in the largest percentage of time, having once again, for that reason, the overall best performance when comparing with the other selected targets. The least adequate target is still the one respecting the Magic Number's, closely followed by the Smithsonian and Thomson's Class 1.2, as it maintains the lowest percentages of time where the values of both temperature and RH comply with the indicated ranges in its specification.

The final consideration to be made, regarding this performance index evaluation, is the case of 18 visitors per hour, whose resulting values are demonstrated in Table 7.5. Once again, a general reduction in performance of the selected reference targets for all districts is observed, with yet another increase in visitor's numbers per hour since the previous case, as well as Thomson's class 2 remaining the target with the overall best performance. In regard to the least percentages of time that the indoor climate conditions aren't verified within the imposed specifications, the Magic Number's target once more appears to be the one with the lowest observable performance in the different districts. When comparing with the previous cases of 6 and 12 visitors per hour, the gap between the ranges of this target with Thomson's least favourable classes – namely 1.1 and 1.2 that are closely concomitant with the Smithsonian target in most districts – now appears to have reduced, indicating a greater drop in performance from the latter targets than the former, as it presents a slighter decrease along with the increase in visitor's numbers.

Table 7.3 Performance Index considering 6 visitors per hour

District	**Global Performance Index [%]**					
	Magic Numbers (since 70s)	**Garry Thomson (1986)**			**Smithsonian (2007)**	**Bizot (2014)**
		1.1	**1.2**	**2**		
Aveiro	12,9	20,7	19,8	89,6	18,9	42,8
Beja	12,0	21,1	19,3	82,5	16,2	35,6
Braga	14,2	20,8	19,0	89,7	16,4	43,2
Bragança	9,3	13,3	14,0	78,1	9,8	30,2
Castelo Branco	11,7	17,3	13,0	66,9	17,9	36,9
Coimbra	14,1	21,5	20,3	91,1	18,1	43,4
Evora	12,4	22,5	19,7	87,0	16,7	41,3
Faro	12,6	24,2	20,6	87,4	20,0	41,8
Funchal	14,0	23,8	26,7	92,3	17,7	41,0
Guarda	8,2	12,2	11,5	77,5	7,8	31,6
Leira	15,4	24,6	25,5	92,8	16,4	47,3
Lisboa	15,2	24,7	23,0	91,2	23,1	42,4
Ponta Delgada	5,9	12,6	21,3	84,4	6,6	26,8
Portalegre	13,4	22,2	18,4	80,2	18,7	41,3
Porto	14,0	21,1	20,5	92,3	16,3	42,5
Santarem	13,7	21,7	19,2	87,4	18,5	41,6
Setubal	8,7	23,6	20,5	88,4	17,6	41,4
Viana do Castelo	13,0	16,7	16,3	88,5	11,2	39,6
Vila Real	9,9	15,4	13,7	80,4	13,2	33,7
Viseu	13,2	19,2	31,3	83,7	14,5	40,8

Table 7.4 Performance Index considering 12 visitors per hour

District	Global Performance Index [%]					
	Magic Numbers (since 70s)	Garry Thomson (1986)			Smithsonian (2007)	Bizot (2014)
		1.1	1.2	2		
Aveiro	10,1	16,3	13,6	78,7	15,7	33,6
Beja	8,9	16,2	13,0	76,4	15,3	27,6
Braga	11,1	16,1	12,6	77,9	15,7	34,8
Bragança	8,5	11,5	10,8	71,3	9,0	24,9
Castelo Branco	8,2	13,0	9,7	63,2	15,3	29,1
Coimbra	11,3	18,2	14,9	80,6	16,2	35,3
Evora	9,0	17,6	13,6	79,4	15,7	32,0
Faro	8,1	17,6	13,6	80,4	17,3	31,6
Funchal	10,7	19,8	19,7	81,7	15,8	33,5
Guarda	6,7	9,6	8,5	68,9	7,2	24,9
Leira	12,2	21,1	18,2	81,0	16,3	38,1
Lisboa	11,4	19,1	15,4	82,1	20,6	32,3
Ponta Delgada	5,5	11,9	18,2	74,2	5,9	23,7
Portalegre	9,3	17,1	13,0	74,0	15,8	32,1
Porto	12,4	18,1	14,9	81,8	14,8	34,7
Santarem	10,8	17,1	13,8	78,1	17,0	32,5
Setubal	6,2	18,1	13,4	80,9	13,5	31,1
Viana do Castelo	10,4	13,5	12,3	77,0	12,5	32,9
Vila Real	6,7	11,4	8,9	72,7	12,2	27,4
Viseu	9,3	14,5	10,7	74,4	13,9	33,2

The application of dynamic methodologies such as the ones used in EN 15757 by Silva and Henriques [85] as well as the application of the ASHRAE specification, namely in Marten's work [42], might produce better results in terms of PI and consequently lower energetic consumption, however as this is a matter beyond the limited scope of this text it was not considered.

Table 7.5 Performance Index considering 18 visitors per hour

District	Global Performance Index [%]					
	Magic Numbers (since 70s)	Garry Thomson (1986)			Smithsonian (2007)	Bizot (2014)
		1.1	1.2	2		
Aveiro	6,9	13,8	10,8	68,6	14,4	29,5
Beja	7,1	13,3	9,9	68,3	13,7	23,3
Braga	8,7	13,4	9,6	67,2	15,2	30,0
Bragança	7,4	11,1	9,4	65,7	9,4	23,6
Castelo Branco	5,7	10,3	7,0	57,3	14,4	23,8
Coimbra	7,9	15,5	11,2	70,2	15,8	30,0
Evora	7,1	14,8	10,2	70,7	13,9	26,6
Faro	4,3	13,1	9,0	71,0	15,0	24,7
Funchal	6,2	17,6	16,4	71,3	13,5	30,4
Guarda	6,7	8,6	7,1	61,5	8,2	21,4
Leira	10,0	18,1	13,9	71,0	15,9	32,7
Lisboa	7,6	15,5	11,2	71,7	17,7	26,9
Ponta Delgada	4,8	11,9	17,6	67,1	5,9	23,5
Portalegre	7,3	14,2	9,0	66,1	14,1	26,1
Porto	10,2	16,7	12,5	71,9	14,2	30,9
Santarem	7,9	14,2	10,4	68,3	16,7	27,0
Setubal	4,3	14,3	9,5	71,0	9,8	25,2
Viana do Castelo	9,5	12,8	10,4	67,3	13,9	30,6
Vila Real	5,8	10,3	7,5	65,9	10,4	25,0
Viseu	7,7	11,9	8,0	65,3	14,2	30,2

7.3 *ASHRAE Classification*

The following tables and maps illustrate how the results from the simulated model fared for each district's regional climate as well as the three different occupancies considered, regarding the numbers of visitors per hour – that is

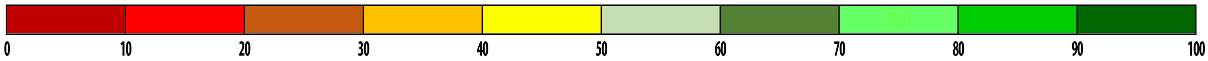
6, 12 and 18 – necessarily in terms of the percentage of time that their resulting internal hygrothermal values are within the limits associated to each of the individual classes of control formulated by the ASHRAE.

As can easily be observed in Table 7.6, which corresponds to the simulation model with 6 visitors per hour, from the comparison between the three most stringent classes – that is the AA, and the two subclasses from A – the one that manages to verify, for the vast majority of districts, an acceptance above 50% of the time according to their limits, regarding the variations in the resulting internal temperature and relative humidity, is class A. On the other hand, class B, the one that is generally most suitable for historical buildings, presents an acceptable performance for this first consideration, with percentages in every district ranging closely from 75% to 85% of permanence within its imposed specifications, for both temperature and RH control.

Table 7.6 ASHRAE Classification considering 6 visitors per hour

District	**Climate Classes ASHRAE (%)**					
	AA	**A**	**As**	**B**	**C**	**D**
Aveiro	36,9	66,9	40,8	78,3	94,0	99,1
Beja	33,1	60,4	39,3	79,3	71,6	99,0
Braga	33,4	62,7	38,0	77,3	91,6	98,6
Bragança	22,2	47,3	30,7	75,4	73,8	95,7
Castelo Branco	28,0	54,8	35,8	77,5	70,6	99,5
Coimbra	36,1	65,3	39,5	77,8	91,7	98,7
Evora	34,5	65,3	42,4	83,2	71,2	99,5
Faro	40,8	70,2	44,6	82,6	84,0	99,7
Funchal	41,9	74,9	49,8	84,6	97,3	97,8
Guarda	20,9	49,0	29,6	75,4	84,1	96,5
Leira	40,6	70,5	42,2	79,9	95,3	98,6
Lisboa	42,3	71,7	45,9	82,2	92,2	99,5
Ponta Delgada	43,5	74,5	49,4	80,4	91,7	93,5
Portalegre	31,2	57,1	37,4	76,3	75,5	99,6
Porto	39,1	70,1	41,9	78,6	92,6	97,8
Santarem	33,9	63,0	37,4	76,8	81,3	99,0
Setubal	37,7	66,9	43,2	83,2	82,1	99,8
Viana do Castelo	31,8	60,7	36,8	76,0	93,6	97,5
Vila Real	22,6	50,2	32,7	77,0	79,7	96,1

Viseu	31,9	61,7	39,3	81,0	88,3	98,7

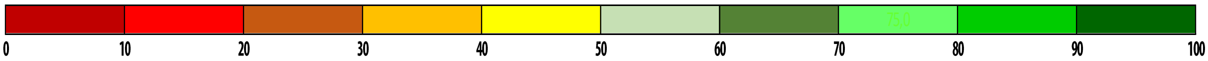


As it was to be expected, the increase in visitor's number to 12 per hour, presented in Table 7.7, inflicts a decrease in acceptance for the presented classes of climate control. Class A, the one that had previously – with 6 visitors – corresponded to a moderate performance, now presents a below average percentage of time that both temperature and RH values verify the imposed limits integrated in that class. Even Class B now infers ranges of permanence within its specifications of only 50-67% of the time for both temperature and relative humidity, a satisfactory yet decreased performance.

Table 7.7 ASHRAE Classification considering 12 visitors per hour

District	**Climate Classes ASHRAE (%)**					
	AA	**A**	**As**	**B**	**C**	**D**
Aveiro	25,8	51,0	26,8	59,5	84,5	92,9
Beja	24,6	48,0	27,4	63,2	64,7	94,7
Braga	22,7	46,9	24,3	58,1	81,5	91,6
Bragança	16,3	38,7	20,7	59,4	63,5	88,2
Castelo Branco	19,2	45,3	24,5	61,9	65,0	95,9
Coimbra	25,2	49,6	26,2	60,3	82,5	92,4
Evora	24,8	52,0	30,6	66,3	64,4	94,7
Faro	30,1	55,7	31,2	67,2	75,3	96,7
Funchal	30,2	58,4	33,0	65,7	89,0	90,7
Guarda	14,0	36,0	18,6	57,3	72,5	89,4
Leira	25,5	51,9	26,6	59,9	85,4	90,9
Lisboa	30,0	56,3	31,1	65,7	83,4	95,0
Ponta Delgada	32,1	60,0	34,0	64,9	79,6	83,9
Portalegre	23,9	46,5	24,8	61,5	68,9	95,4
Porto	24,9	52,5	27,7	59,8	82,0	90,6
Santarem	24,3	48,5	25,8	60,3	71,7	94,2
Setubal	27,8	52,8	30,2	66,6	73,8	96,4
Viana do Castelo	21,6	44,2	24,4	57,1	82,2	89,4
Vila Real	14,5	38,2	20,3	60,2	69,1	89,1

	AA	A	As	B	C	D
Viseu	20,9	46,3	23,7	61,4	77,8	92,9

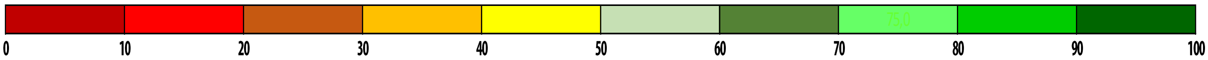


The final evaluation is to do with the resulting values from the simulation model with 18 visitors per hour – Table 7.8 – which yields to the evidence of the impact that this increase in number of occupancy produces in the control of the internal climate, necessarily the fact that not even Class B amounts to be adequate enough in guaranteeing risks from occurring with the corresponding conditions. The percentage of time that the generated values for temperature and RH verify the exigencies of this specific class, generally suitable for the cases of historical buildings, is below 50%, with the exception of two districts – Faro and Setubal – possibly the regions that can provide the most benign climate affecting the overall performance.

Table 7.8 ASHRAE Classification considering 18 visitors per hour

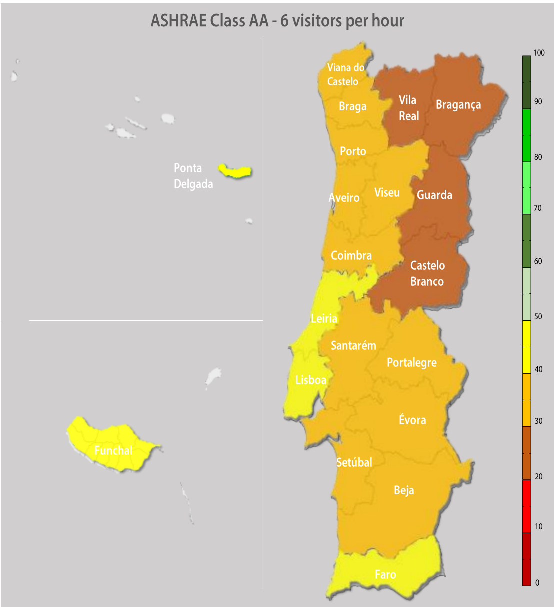
District	Climate Classes ASHRAE (%)					
	AA	**A**	**As**	**B**	**C**	**D**
Aveiro	17,1	37,2	17,7	43,9	72,8	84,3
Beja	17,4	37,1	19,5	47,2	56,0	88,4
Braga	15,4	33,6	16,5	42,2	69,8	83,4
Bragança	11,5	31,5	13,5	44,1	56,5	82,9
Castelo Branco	13,0	35,1	16,9	46,2	57,4	90,4
Coimbra	16,6	35,9	17,2	44,5	70,2	84,1
Evora	16,9	38,3	20,2	49,1	56,5	88,4
Faro	20,4	41,9	21,2	51,4	64,3	89,9
Funchal	21,1	43,3	20,2	48,2	77,5	80,7
Guarda	9,8	27,6	12,4	42,8	61,7	83,0
Leira	16,7	35,3	16,6	43,1	74,5	81,9
Lisboa	20,1	42,1	20,7	48,9	68,9	87,1
Ponta Delgada	22,1	44,7	21,3	49,3	70,1	75,6
Portalegre	16,8	36,6	16,6	46,4	59,5	89,1
Porto	16,5	36,6	18,0	43,9	70,1	82,4
Santarem	17,1	36,1	18,2	45,1	61,2	86,7
Setubal	19,1	40,2	19,9	50,5	62,7	89,7
Viana do Castelo	14,4	32,2	15,7	41,4	71,9	82,1

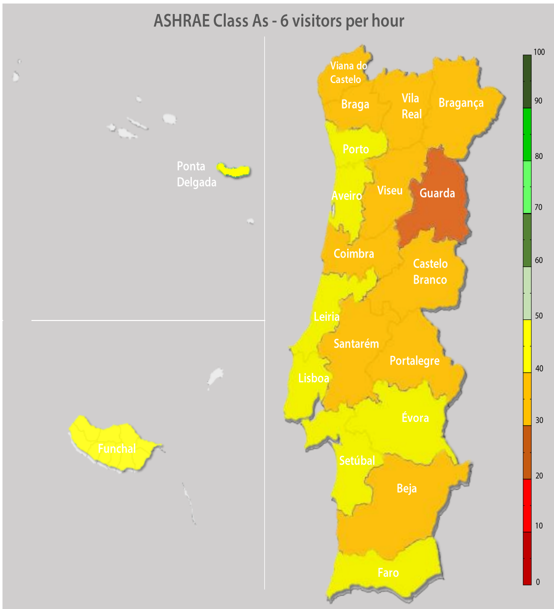
Vila Real	10,4	28,1	12,9	44,1	60,4	83,2
Viseu	13,1	33,3	15,3	43,8	65,5	85,4



Regarding Figure 7.1, presented below, it is possible to better examine the geographical distribution of the general acceptance for the selected two strictest classes AA and As, as it is evident that it favours the districts located more towards the south as well as the islands, since the northern ones show an overall lower account in this analysis. None of the districts in this verification have a classification higher than 50%.

For both cases the initial acceptance – considering 6 visitors per hour – is similar in terms of its geographical distribution, though class AA with a lower classification as it has more north-eastern districts with 20-28% comparing to As that manages to have a higher account, specifically with 30-45% considering the same districts – Vila real, Bragança, and Castelo Branco. Considering the increase in visitors per hour to 12, the same pattern is observed in that those northen-eastern districts continue to have the lowest acceptance as well as the general reduction in terms of classification. In the case of 18 visitors per hour a repeated aggravation of the resulting values is verified, with only Lisboa, Faro and the islands having acceptances around 20-22% in accordance to Class AA, as well as Évora considering Class As, as the remaining districts all have overall lower acceptances.





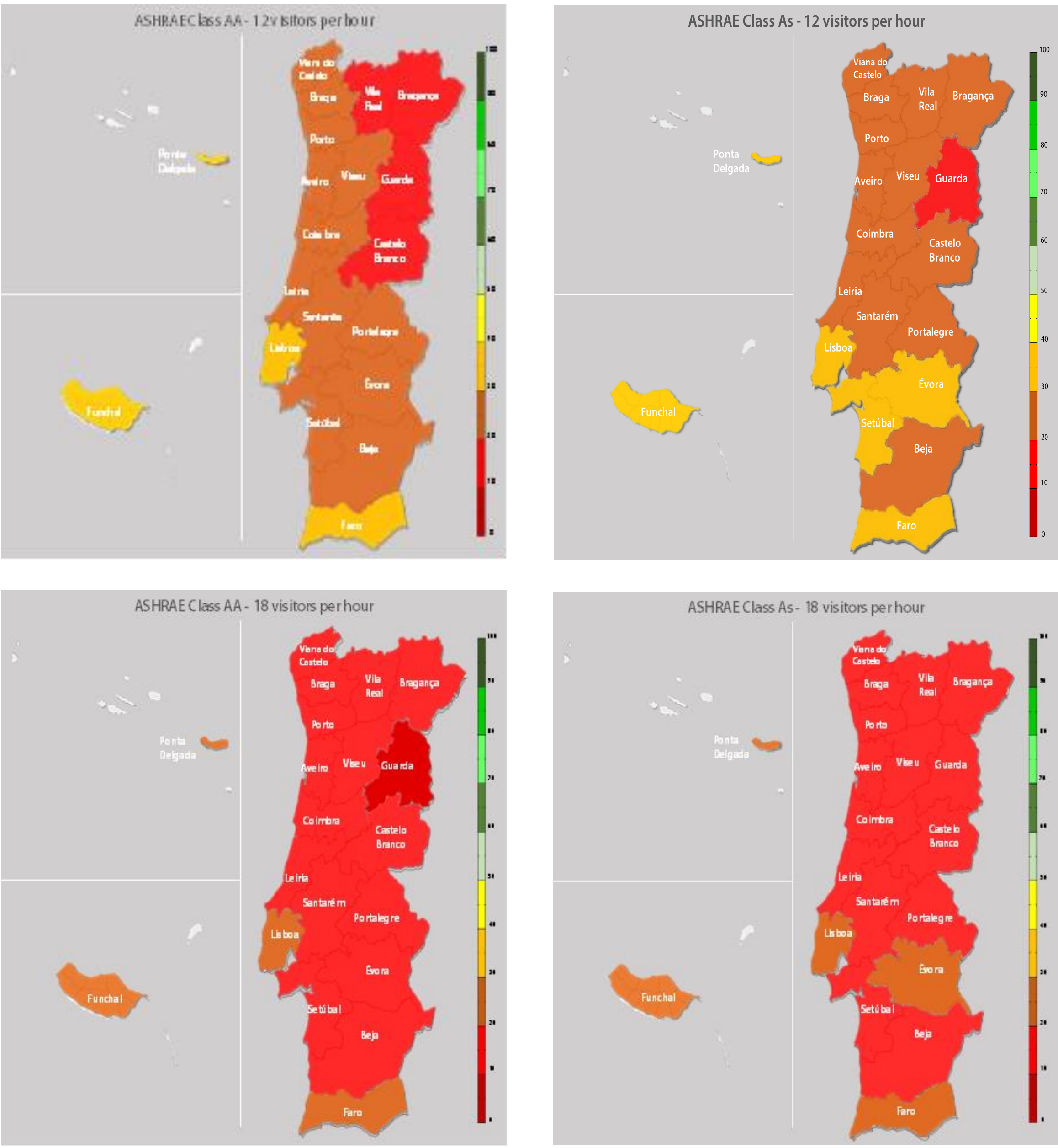
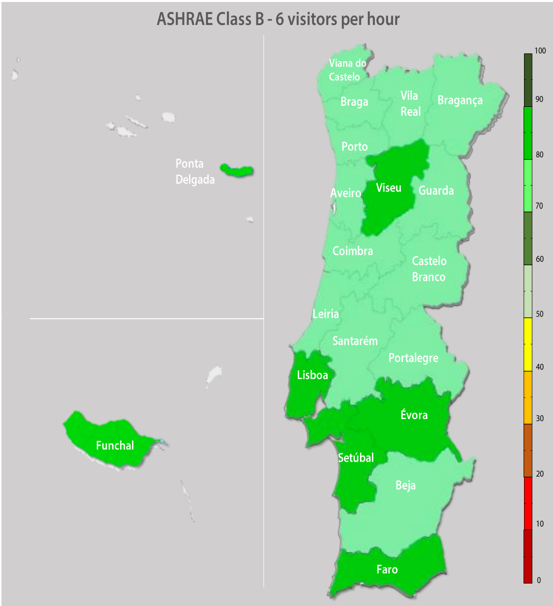
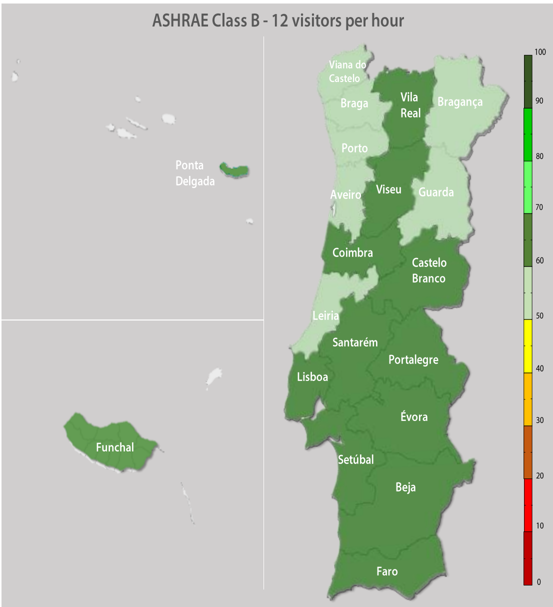


Figure 7.1 Geographical distribution of the acceptance of Classes AA and As for the three cases of 6, 12 and 18 visitors per hour

As can be observed in Fig. 7.2, the same accord for the geographical distribution of the general acceptance of Class B is verified in that, the more central-southern – Lisboa and Faro for instances – districts have better classifications for each of the three cases of visitors per hour. The cases of 6 and 12 visitors an hour albeit the reduction concerning the increase from one to the other, all districts manage to have values above average. However when considering the case of 18 visitors per hour the decrease in acceptance evidences a below average performance, where only two southern districts – Setubal and Faro – maintain percentages of acceptance above 50%, respectively with 50,5 and 51,4%.


ASHRAE Class B - 6 visitors per hour
Viana do Castelo
Braga
Vila Real
Bragança
Porto
Viseu
Aveiro
Guarda
Coimbra
Castelo Branco
Leiria
Santarém
Portalegre
Lisboa
Évora
Setúbal
Beja
Faro
Ponta Delgada
Funchal
100
90
80
70
60
50
40
30
20
10
0


ASHRAE Class B - 12 visitors per hour
Viana do Castelo
Braga
Vila Real
Bragança
Porto
Viseu
Aveiro
Guarda
Coimbra
Castelo Branco
Leiria
Santarém
Portalegre
Lisboa
Évora
Setúbal
Beja
Faro
Ponta Delgada
Funchal
100
90
80
70
60
50
40
30
20
10
0

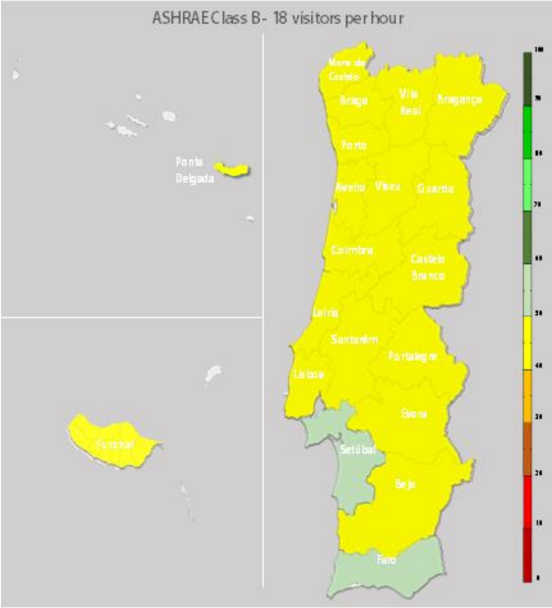


Figure 7.2 Geographical distribution of the acceptance of Class B for the three cases of 6, 12 and 18 visitors per hour.

7.4 *Risk-Assessment*

7.4.1 *Mechanical Degradation*

As can be observed in Figure 7.3, there's a general good performance in terms of mechanical response from the analysis of the base material of paintings for all districts, affected of course by the increase in visitor's number, with a decline in the behaviour for the different occupancies. In the case of 6 visitors per hour most of the central and southern continental districts present ideal classifications, as the remaining ones including the islands have a slightly lower account overall with a good response. When comparing the cases of 6 and 12 visitors an hour, it is evident that the base material suffers a general decrease in performance, though a slight one as it still remains with a good classification where no risk is to be expected, in all districts. However, upon consideration of the case of 18 visitors per hour with respect to the base material, Ponta Delgada falls into a potential risk of mechanical degradation contrasting with the overall good performance of the remaining districts. This possibly indicates that the RH fluctuations do not persist within the elastic response during the year in analysis.

As for the sculptures, there is some risk to all districts in the case of 6 visitors per hour, as it is assigned with category 3 which indicates a plastic response though in compression and/or tension and in less than 10% of the time. An aggravation of the potential risk is verified for the case of 12 visitors as it increases to potential risk – category 2 – mainly in all the northern districts as well as central and Ponta Delgada, indicating the possibility that the RH fluctuations are large enough to remain in the plastic region more than 10% of the time. This last classification is extended to every district in the case of 18 visitors per hour, presented in Figure 7.3.

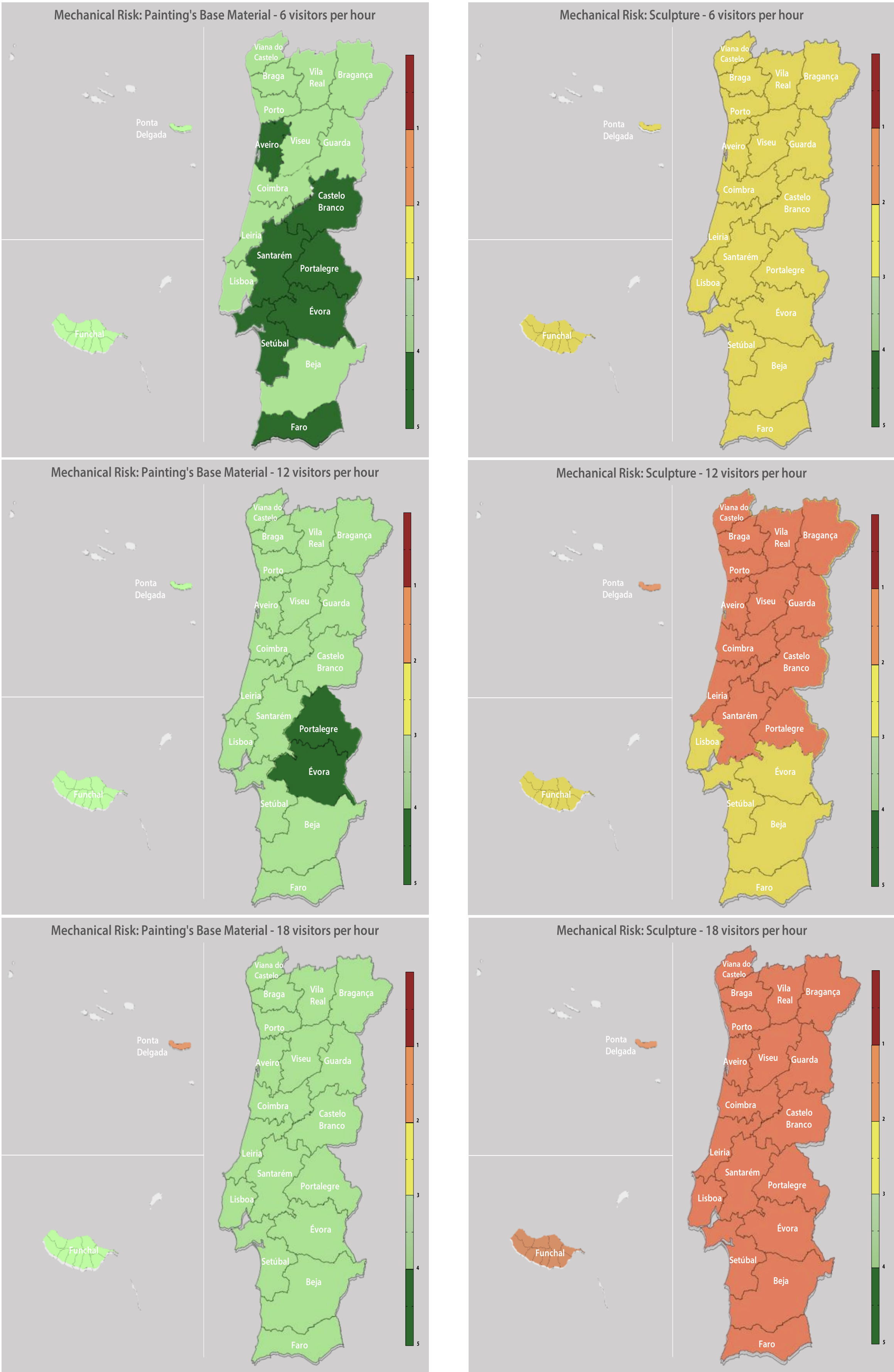
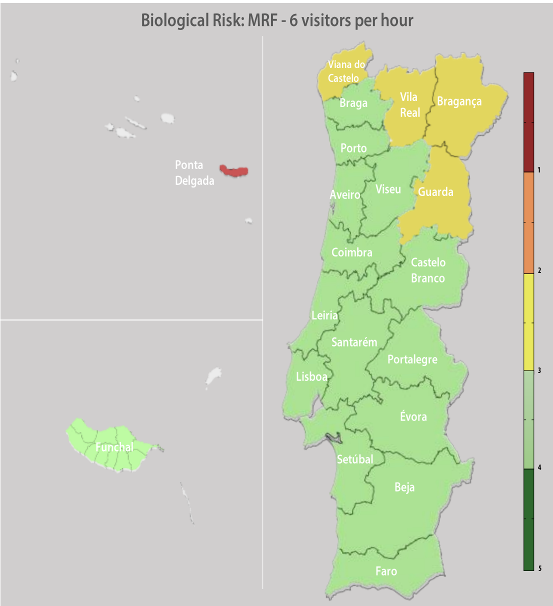
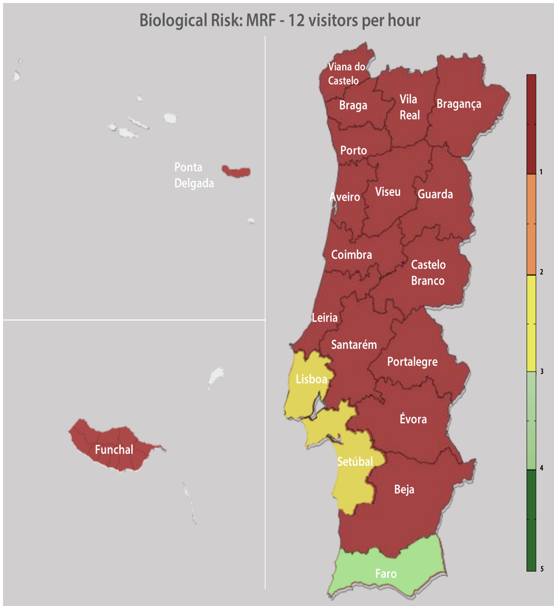


Figure 7.3 Mechanical Risks to paintings and sculptures considering 6,12 and 18 visitors per hour

7.4.2 *Biological Degradation*

The analysis of the results for each simulation allows for the conclusion that primarily, for the case of 6 visitors per hour, only Ponta Delgada demonstrates a condition of high risk for the occurrence of germination, indicating that both temperature and RH surpass the defined limits isopleth, which is concurrent to the fact that – as previously presented in Tables 6.1 and 7.2 – it also exhibits, out of all the districts, the highest overall mean values in indoor as well as outdoor Relative Humidity, resultant from the simulated model. In that same consideration, it is possible to infer the localized distribution in the category of some risk – that is 3 – which may be sufficient in order to prevent biological growth, being awarded to the more northern regions. Over the prospect that the risk rises with the increase in number of occupancy, in this case considering precisely 12 visitors per hour, it quickly becomes apparent, from the observation of Figure 7.4, that it indeed aggravates drastically for the majority of the simulated districts. With an exception of both Lisboa and Setubal, which attest the likelihood of some risk, being category 3, only Faro represents a good estimation in that, the remaining districts all decrease in rating, having a possibility of high risk of germination to occur – category 1. The latter is, as expected, what finally takes place upon consideration of the case of 18 visitors per hour, as all the districts appear to be at high risk in this biological degradation evaluation.





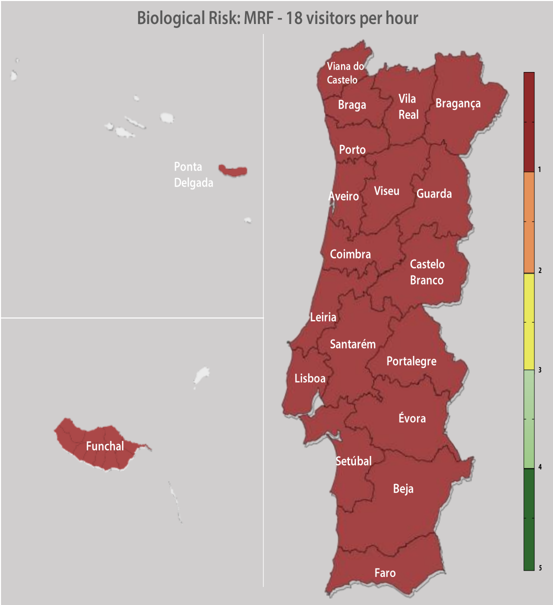
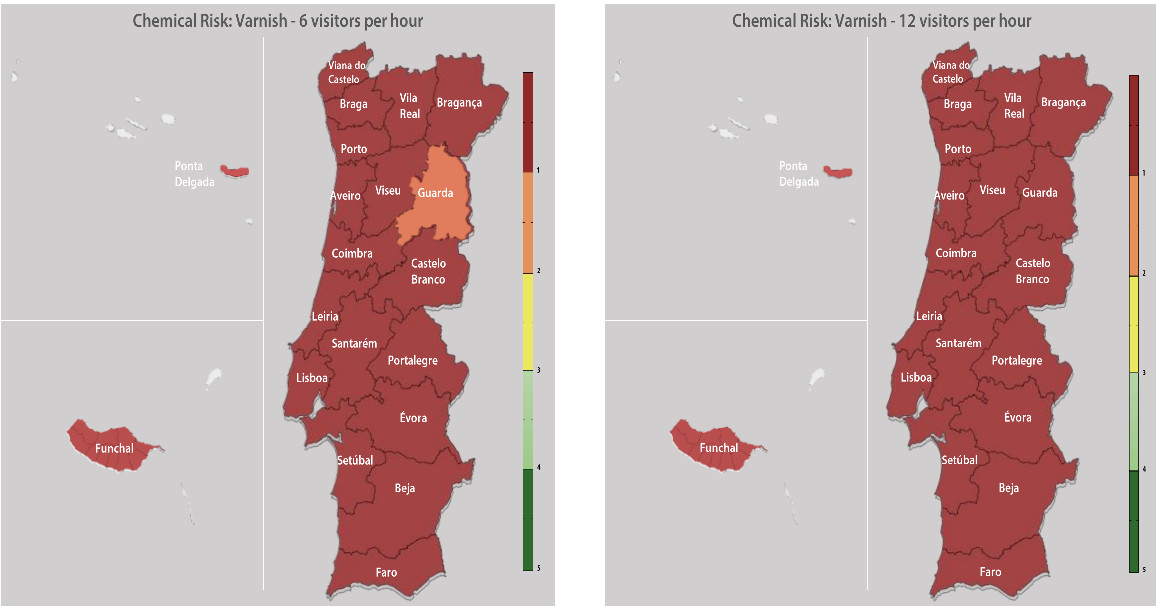


Figure 7.4 Overall display of the biological risk considering 6, 12 and 18 visitors per hour

7.4.3 *Chemical Degradation*

The results for each case of occupancy as well as district are presented below, and as can easily be observed in Figure 7.5 there appears to be only one district, specifically with 6 visitors per hour, that retains a classification above 1, necessarily with a value of 2 – Guarda – indicating a potential for risk in regard to varnish, accounting for a shorter life expectancy. Considering previous estimates of temperature values, Guarda has the lowest temperatures out of all the districts which could explain why it is the only one that manages to have a classification higher than 1, since chemical deterioration is more prone to appear as temperatures increase. However, for the remaining cases – namely 12 and 18 – they demonstrate the permanence of a high-risk classification for chemical degradation in every district.



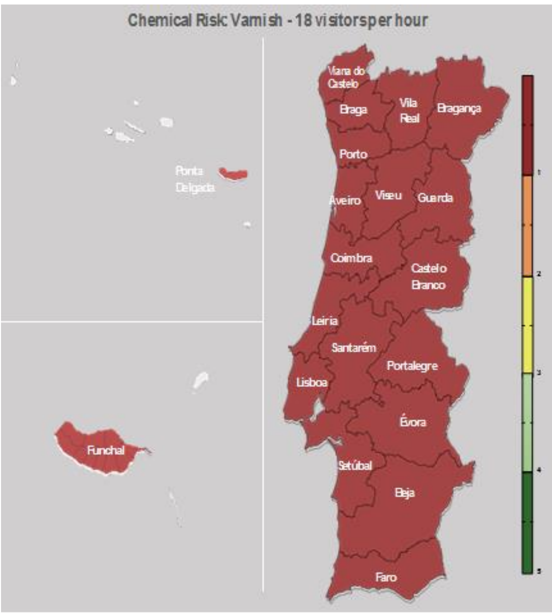


Figure 7.5 Chemical risks for varnish considering 6, 12 and 18 visitors per hour

8 FINAL REMARKS

8.1 *Conclusions*

In this work, a case study was performed in order to assess the impact that an increase in visitor's numbers induces on the preservation of artefacts given the context of a museum. The results were obtained using the simulation software EnergyPus, considering a generic room of an historical building that houses the National Museum of Ancient Art located in Portugal as well as its available exterior climatic files, using the specified weather generator program. As such and for each district, several analyses were considered so as to not only best characterize the resulting hygrothermal indoor conditions and evaluate how these conditions fared according to relevant and persisting targets present in literature, using the Performance Index, as well as an account on whether or not these complied with the ASHRAE classification and a risk assessment of the mechanical, biological as well as chemical processes of degradation.

The statistical analysis was presented regarding the mean values, seasonal variations and short-term fluctuations of both temperature and relative humidity. In regard to temperature, the results according to the annual average were not significantly affected by the increase in visitor's numbers. The seasonal differences also did not register significant alterations with the exception of one district – Aveiro – which managed to verify a slight rise in temperature along with the increase in occupancy – namely from 6 to 12 visitors per hour. As to the short-term fluctuations a general increase is evident for each case, though the districts that are most affected are Aveiro, Funchal and Ponta Delgada, respective to the rise in occupancy from 6 to 18 visitors per hour. In respect to the Relative Humidity an overall increase in the three considered statistical parameters is evidenced, however the one with the most significant alterations is respective to the short-terms fluctuations. In this case Viseu manages to verify the highest increase, considering the rise from 6 to 18 visitors per hour, of nearly twice the initial value. In terms of seasonal fluctuations Lisbon appears to have the lowest variation, regarding the increase in visitor's numbers per hour from 6 to 18, out of all the districts.

With the intent to also assess how these conditions fared according to relevant and persisting targets that exist in literature, a Performance Index was used, based on a method developed by Corgnati. Out of all the static targets considered – Magic Numbers, Garry Thomson's classes, Smithsonian and Bizot – the one that managed to have the best overall performance was Thomson's Class 2, given the distinguishing flexibility in its undefined temperature limits as well as a wider range in relative humidity, which certainly accounts for this positive outcome. On the other hand, the one with the strictest ranges for both hygrothermal parameters, namely the Magic Number's target, appears as the worst overall performance, therefore evidencing the contrast with its counterpart in this specific case, particularly to do with the matter of flexibility in specifications.

Another interesting analysis had to do with determining whether or not the generated hygrothermal conditions in fact complied with ASHRAE's classifications, specifically the estimated percentage of time that the values were within the imposed and distinct ranges of each class, for both seasonal and short-term variations. The results evidenced that, indeed, as the visitor's numbers increased the percentage of acceptance for each class diminished. Geographical location also played an important role in determining which regions were most favourable to the acceptance of the simulated internal hygrothermal conditions for each class, exhibiting a pattern concurrent to the three considered cases of different occupancies, that denoted an overall inferior performance in northern districts. Considering the three strictest classes – AA, A and As – only class A had a positive performance in the first case of 6 visitors per hour, which decreased with the increase in visitor's numbers for the remaining two cases – of 12 and 18. With respect to Class B, the one generally considered to be most suitable for historic buildings, only in the case of 18 visitors per hour did its acceptance in most districts reach values below average, as the former two cases of occupancy denoted a moderate to high percentage of time that the hygrothermal conditions were within its limits. In terms of the geographical distribution associated with these results, a similar pattern followed in that, lower acceptances were evident in more northern regions for all classes considered.

With respect to the risk assessment that took into account the simulated internal hygrothermal conditions for each district in accordance to damage functions that exist in literature, an evaluation for mechanical, biological as well as chemical degradation was also presented. Accounts of the projected risks associated with the different processes of degradation considered, denote that, indeed, the increase in number of visitors per hour rises the majority of the corresponding risks to objects, in some districts more severely than others. For instances, as is the case with biological damage considering mould germination, that appears to be more susceptible to the northern regions of the country as well as Ponta Delgada, which also presented the higher levels of mean relative humidity in respect to the obtained statistical values. The generated interior conditions were satisfactory to prevent mechanical damage to the base material of paintings, however when it came to sculptures some risk appeared instantly in the first case of 6 visitors per hour, which then aggravated as the numbers increased to higher risks and the possibility of damage. The latter was also verified for the paintings, though with damage risk only apparent for the case of Ponta Delgada, considering 18 visitors per hour. As for chemical degradation regarding varnish, the highest risk classification was awarded to every case considered, which could possibly be evidence of resulting values in previous estimates of relative humidity and temperature levels.

It should also be acknowledged the usefulness of simulation modelling in predicting the indoor climate conditions, necessarily with its correlation to the existing damage functions in literature, which allows for a risk assessment approach, and as such takes into consideration the many factors that presently identify distinct concerns, with the ultimate aim at the development of strategies on how to best avoid possible subsequent repercussions for the preservation of cultural heritage.

8.2 *Future Developments*

Further developments as well as extrapolations that complement this study are important to consider, particularly to reinforce with a more encompassing analysis that considers adjustments in the ventilation rate, as well as thermal comfort expectations for visitors, seeing as though it contributes to a compromise between that and the preservation of collections. In that respect, the development of an algorithm that is able to integrate both collection and thermal comfort requirements could potentially prove to be of great interest to this analysis.

An assessment of energy demands associated with these considerations also needs to be taken into account, given the exigencies that such alterations might induce for the climate control systems as it too contextualizes in the pivotal matter underlying the overall theme in this thesis – that is, sustainable approaches in preventing damage to reach cultural heritage.

As these results were met by previous expectations of the consequences that an increase in visitor's numbers has on preservation of collections, and as various directions for future research are identified to complement this analysis, however it should be noted that this was a specific case in a specific region and hence extrapolations are important to validate these findings in other buildings as well as climates.

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