**Title**: Impact of climate change in cultural heritage: from energy consumption to artefacts' conservation and building rehabilitation

**Authors**: Guilherme B.A. Coelho, Hugo Entradas Silva and Fernando M.A. Henriques

**Journal**: Energy and Buildings

**DOI**: http://dx.doi.org/10.1016/j.enbuild.2020.110250

Please cite this article as: G.B.A. Coelho, H. E. Silva, F.M.A. Henriques, Impact of climate change in cultural heritage: from energy consumption to artefacts' conservation and building rehabilitation, Energy and Buildings (2020) http://dx.doi.org/10.1016/j.enbuild.2020.110250

# Impact of climate change in cultural heritage: from energy consumption to artefacts’ conservation and building rehabilitation

Guilherme B.A. Coelho*, Hugo Entradas Silva and Fernando M.A. Henriques

Departamento de Engenharia Civil, Faculdade de Ciências e Tecnologia, FCT, Universidade NOVA de Lisboa, 2829-516 Caparica, Portugal, Tel.: +351 212948580; fax: +351 212948398

* Corresponding author. E-mail addresses: g.coelho@campus.fct.unl.pt (G. Coelho)

**Abstract**: Historic artefacts must be properly preserved if they are to be transmitted to future generations. Indeed, several methodologies and guidelines that aim to safeguard artefacts by limiting the ranges in which the indoor temperature and relative humidity vary exist, which means energy consumption. This paper aims to quantify the energy consumption associated to three different setpoints and respective financial cost, as well as their future trend to demonstrate the positive outcome of passive retrofit measures, since they will be responsible for decreasing the building’s energy consumption and mitigating the effects of climate change in artefacts’ preservation. A validated whole-building hygrothermal model of a historic building was used coupled to climate change weather files to obtain the expected future indoor conditions for three types of climates, which were also assessed using a risk-based analysis. The positive potential of passive retrofit measures on the building’s energy consumption was shown, but the risk-based analysis showed that the measures performance are not universal since, for example, whilst the selected measures decrease the risk of chemical decay for Seville, they have the contrary behaviour for Oslo. To achieve these goals more than 1400 simulations were run in WUFI$^{®}$Plus, which took more than 1600 hours.

**Keywords:** climate change, preventive conservation, simulation model, historic buildings, energy consumption

## 1. Introduction

The main aim of buildings that house artefacts is to guarantee their safety, so that future generations may also have access to these objects. However, when addressing artefacts preservation it is necessary to analyse three types of decay, namely [1]: biological, chemical and mechanical, which can be accelerated by the existence of indoor air pollutants [2]. These three types of decay are governed, at different extents, by the indoor temperature and relative humidity, which vary due to several parameters, namely the building envelope, internal gains, climate control systems and outdoor meteorological conditions [2].

As in many other parts of society at the time, the industrial age brought a new beginning to climate control in cultural heritage buildings that house artefacts, such as museums, namely due to the development of air conditioning and humidity control systems. The major appeal of these systems was that they allowed to produce a uniform indoor climate or even a different indoor climate from the outdoor one. However, the set-points to which many of the museums regulated their climate at the time were not based on concrete evidence that they really safeguarded the collections [3]. It is obvious that the awareness of this limitation led to the increase of studies focussed on the collections' needs on the coming years. In time, this resulted in the creation of standards/guidelines that limit the indoor climate in order to keep the collections safe (e.g. Thomson [4], ASHRAE [2], UNI 10829 [5], EN 15757 [6], among others).

Due to the importance of maintaining historical artefacts safe many standard and guidelines that aim to mitigate the risk of deterioration by limiting the variance of the indoor temperature and relative humidity have been developed over the years. Thomson [4] suggested a guideline that is less stringent than the "magic numbers" (i.e. setpoint of 20 ºC and 50 %RH), but it still based on the variance of the indoor conditions within fixed limits. The guideline divides buildings into two major classes – class 1, which aims to mitigate the deterioration risks with the indoor conditions varying within a more stringent range and it is recommended for major museums, and class 2 that aims to avoid major deterioration risks whilst keeping costs to a minimum [4].

Another important guideline was prepared by ASHRAE [2], which is centred in a five permissible class system in which the strictness in terms of indoor conditions lessens from the first class (class AA) to the last class (class D). In other words, the energy spent so that building complies with the set-points preconized by the guideline decreases, but at the same time the risks of deterioration increase. In Europe, the standard that deals with the preservation of artefacts is EN 15757 [6]. This standard aims to reduce the mechanical risk induced by the indoor conditions to organic hygroscopic materials by maintaining the historical climate if the conditions are not harmful for the objects. If the climate is harmful, then it recommends the exclusion of the 14 % larger short-term fluctuations [7].

More recently, *Silva and Henriques* [8,9] developed a two-class guideline that aims to mitigate the risk of deterioration of artefacts housed in historic buildings for temperate climates. This guideline limits the variance of the indoor temperature and relative humidity in terms of seasonal and short-term fluctuations with a more stringent Class 1, and a more flexible class 2. This guideline was partially based on the ASHRAE guideline [2] and on standard EN 15757 [6].

In order to have the indoor climate varying within any of these ranges it is necessary that the buildings that house artefacts, such as, museums or galleries, are equipped with large mechanical systems. However, these systems can have a high energy consumption, which consequently leads to a high financial and environment costs. Additionally, due to climate change it is expected that the indoor climate of high inertia historic buildings is going to change in the future, which can result in higher energy consumptions. These changes will be translated in the increase of the free-floating indoor temperature and relative humidity in this type of buildings [10,11], but the magnitude of the changes will vary with the location [11–14]. Climate change is greatly due to the emission of large amounts of greenhouse gases into the atmosphere. These emissions are mainly due to anthropogenic activities, such as the use of fossil fuel and land-use changes [15].

Indeed nowadays, one of the main challenges for both the scientific community and society in general is to find ways to mitigate the effects of climate change and even mitigate the climate change itself, since it will negatively affect the environment, and consequently, both the human health and the world's economy [16]. Moreover, climate change will also have a negative effect on buildings [16]. According to UNESCO project 22 [17], which studied the effects of climate change in historic buildings, it is expected that the buildings' facades will deteriorate due to thermal stress and freeze-thaw/frost cycles, that the porous materials will suffer physical changes due to rising damp and that the superficial layers will suffer crack, among many other effects described in this document.

The high costs of energy associated with the stringent ranges of indoor temperature and relative humidity preconized by the mentioned standards and guidelines, and the changes that the indoor climate of high inertia historic buildings are going to suffer due to climate change will lead to an increase of the maintenance costs of these buildings, which might present a risk to their continuity. Hence, it is of great importance to study passive rehabilitation measures, active rehabilitation measures or combination of both types to decrease, as much as possible, the energy consumption of these buildings. For instance, Cornaro *et al.* [18] managed to achieve a 38% reduction of the energy consumption for Villa Mondragone in Italy with the application of a high insulating plaster, while Muñoz-González *et al.* [19] managed to reduce the energy consumption of San Francisco de Asís church by 10–21% combining active and passive measures.

Hence, this paper starts by quantifying the energy consumption associated to each of the referred standards and guidelines, as well as the associated financial cost and their future trend. Secondly, four passive retrofit measures that aim to reduce the building's energy consumption are analysed. The retrofit measures were a 10 cm interior calcium silicate board and an exterior 5 cm thermal plaster for the exterior walls, a 10 cm PUR-foam in-between the ceilings' wood slabs and the replacement of the existing windows with double-glazing windows. These measures have been used in other studies that concern historic buildings and were analysed separately.

A whole-building hygrothermal model of a historic building was used coupled to climate change weather files to obtain the future indoor conditions. This model was extensively validated against the measured indoor conditions [20,21], which were obtained through a long-term and multi-sensor campaign [8]. Additionally, and since the outdoor climate plays a prominent role in the variance of the indoor climate, three different types of climate were simulated, namely: Mediterranean (Lisbon, Portugal and Seville, Spain), Humid continental (Prague, Czech Republic and Oslo, Norway) and Oceanic (London, United Kingdom).

Furthermore, the current and future indoor conditions were assessed using a risk-based analysis that assesses the risk of biological decay using the *isopleth method* [22], the chemical decay using the *lifetime multiplier* [23] and the mechanical decay in which the method used varies depending on the type of object [1]. This methodology has been used in several other studies since its development (e.g. [10,24,25]). In a word, this paper aims to quantify how the energy consumption and, consequently, the energy costs will evolve in the future for buildings that house artefacts, but at the same time show that passive rehabilitation measures can be used to mitigate the effects of climate change in the artefacts' preservation. In order to develop this paper more than 1400 hygrothermal simulations were run in WUFI®Plus [26], which correspond to more than 1600 hours of simulations.

# 2. Methodology

## 2.1. General considerations

This section presents the tools that were used to achieve the paper's aims. It is divided into five subsections: 2.1) presents the selected case-study, the monitoring campaign performed to record the yearly variance of the indoor climate and the subsequent developed hygrothermal model; 2.2) briefly addresses the outdoor temperature and water-vapour pressure for the selected climates while taking climate change into account; 2.3) presents the passive rehabilitation measures that will be tested; 2.4) presents the temperature and relative humidity set-points for the previously mentioned standards/guidelines; 2.5) addresses the past and future trend of the electricity price in some European countries; 2.6) presents the risk-based analysis used to assess the indoor conditions.

In this paper, the term "artefact" refers to the movable cultural heritage definition specified by UNESCO [27], whilst the term "cultural heritage" encompasses both the architectural heritage buildings – i.e. the immovable cultural heritage [27] – and the historic collection – i.e. the movable cultural heritage [27].

## 2.2. Case-study

The case-study is the 13th-century church of *São Cristóvão*, in Lisbon, Portugal (Figure 1). The church has a volume of ca 5250 m$^3$ and includes a nave, a sacristy and a mortuary, among other smaller compartments. The building has thick mortared-limestone walls and limestone slabs, which makes it a good example of a high thermal inertia building and, consequently, representative of historic buildings that house artefacts. The church is not equipped with any climate control system, it is naturally ventilated, and has a ceramic tile roof and wooden frame windows.

Figure 1 – Church of *São Cristóvão*

The indoor climate of the church was monitored from November 2011 to August 2013 using a multi-sensor grid that included 17 thermocouples type T, a probe RHT2nl of Delta T and two HOBO U12-013 [8]. These sensors guarantee the accuracy limits imposed by the standards concerned with recording the indoor climate in historic buildings [28,29]. The monitoring campaign lasted for over a continuous year and had a recording frequency of 10 minutes, so that the indoor climate of the church was thoroughly characterized [7]. During the same period the outdoor temperature and relative humidity were monitored in the vicinity of the church. This allows to correlate the variance of the indoor climate with the respective variance of the outdoor conditions and, therefore, explain certain hygrothermal behaviours that occur indoors [30]. Further information can be consulted elsewhere [8].

Secondly, the recordings of the monitoring campaign were used to develop and extensively validate a whole-building hygrothermal model of the church in WUFI®Plus [26]. The model's calibration was performed using four statistical indices that compared the error between the simulated and monitoring values for both temperature and water-vapour pressure [20]: the coefficient of determination ($R^2$ - 0.99 for $T$ and 0.97 for $P_v$), the coefficient of variation of the root mean square error (CV(RMSE) - 3.2 % for $T$ and 4.4 % for $P_v$), the normalized mean bias error (NMBE - 2.7 % for $T$ and 3.4 % for $P_v$) and the goodness of fit (*fit* - 84.8 % for $T$ and 81.7 % for $P_v$). After the calibration process the simulated values very accurately overlaid the campaign values [20]. The key parameters of the whole-building hygrothermal model of *São Cristóvão* church are presented in Table 1 and Table 2. The church was only open to the public for mass services, i.e. between 18h00–19h30 from Tuesday to Saturday and between 12h00–13h30 on Sunday, and for one hour prior to each mass service. Further information can be consulted in Ref. [20].

Table 1 – Adopted internal gains and ventilation rate for the model of *São Cristóvão* church (adapted from Ref. [20])

| | |
|---|---|
| Lighting | 11.7 W/m$^2$ (30% radiant and 70% convective heat gains) |
| Person – internal loads | Human activity – 1.3 met<br>Heat load – 126 W (73% for sensible heat and 27% for latent heat)<br>Moisture load – 54 g/h |
| Ventilation rate | 0.4 h$^{-1}$ |

Table 2 – Hygrothermal properties of the building materials that compose the building envelopes of *São Cristóvão* church (adapted from Ref. [20])

| Building element | Thickness [m] | $S_d$-value [m] | U-value [W/m$^2$K] |
|---|---|---|---|
| Walls | 0.90 | 118 | 1.36 |
| Ceilings | 0.24 | 8.9 | 1.25 |
| Roof | 0.02 | 0.3 | 5.26 |
| Doors | 0.05 | 11.2 | 2.01 |

## 2.3. Rehabilitation measures

The following four retrofit representative rehabilitation measures will be tested with the goal of decreasing the energy consumption in historic buildings that house artefacts ($U_{walls, ref}$ = 1.36 W/m$^2$.K, $U_{ceilings, ref}$ = 1.25 W/m$^2$.K and $U_{window, ref}$ = 5.1 W/m$^2$.K [20]):

Retrofit 1 – Application of a 10 cm interior insulation system of calcium silicate board to the exterior walls ($\lambda$ = 0.050 W/m.K [26] and $U_{walls}$ = 0.38 W/m$^2$.K)

Retrofit 2 – Application of exterior 5 cm thermal plaster to the exterior walls ($\lambda$ = 0.045 W/m.K [26] and $U_{walls}$ = 0.59 W/m$^2$.K)

Retrofit 3 – Application of a 10 cm PUR-foam layer in-between the ceilings' wood slabs ($\lambda = 0.025$ W/m.K [26] and $U_{ceilings} = 0.22$ W/m$^2$.K)

Retrofit 4 – Replacement of the existing window for a double-glazing window with a low emissivity glass ($U_w = 1.4$ W/m$^2$.K [31])

These retrofit measures were selected since they have been used with positive outcomes in other studies that concern historic buildings [18,19,32–39] and each case is only representative of a type of retrofit, since the aim of this paper is not to assess each retrofit measures, but to show the positive effect that their application has on the energy saving potential and in terms of improving the quality of the indoor climate to house historic artefacts. Hence, and though relevant, the materials' properties and respective thickness of the selected retrofit measures will not be further examined.

## 2.4. Outdoor climates

This subsection is divided into two sections in which the first addresses the current outdoor conditions of the selected climates to perform the hygrothermal simulations using a 1990 weather file, which is henceforth known as reference climate for each climate. The second subsection addresses how the outdoor conditions of these climates will evolve in the future in accordance with the IPCC scenarios: A1B and A2, from 2020 until 2100 using 10-year weather files. These hourly weather files were provided by Meteonorm [40].

### 2.4.1. Current weather

The outdoor climate has a very pronounced effect on the indoor climate of historic buildings [11], which means that if the same measure is applied in two different climates the result can be quite different. Hence, to determine how differently each of the selected standards/guidelines behaves in terms of energy consumption throughout Europe three types of climate were tested: Mediterranean (Lisbon and Seville), Humid continental (Prague and Oslo) and Oceanic (London).

Lisbon has mild and rainy winters, and warm and dry summers. For instance, for Lisbon's reference climate the outdoor temperature varies between 4.5 and 19.4 ºC during winter and between 12.4 and 37.2 ºC during summer. The annual outdoor temperature average is approximately 16.8 ºC and has an annual precipitation of 753 mm with the major precipitation occurring during winter [41]. On the other hand, during summer Seville reaches higher temperatures than Lisbon (for Seville's reference climate the outdoor temperature varies between 11.6 and 40.1 ºC during summer), but it also has a mild winter like Lisbon's. In terms of precipitation the trend is similar to what was described for Lisbon, but the annual sum is approximately 150 mm smaller than Lisbon's (i.e. 600 mm).

Prague has cold winters and hot summers, and a moderate annual precipitation. For instance, for Prague's reference climate the outdoor temperature varies between -12.4 and 12.1 ºC during winter and between 4.1 and 32.9 ºC during summer. The annual average of the outdoor temperature is ca 8.7 ºC and has an annual precipitation of 521 mm with the major precipitation occurring during summer. On the other hand, Oslo attains lower temperatures than Prague both during winter (temperature varies between -21.9 and 5.5 ºC) as well as during summer (temperature varies between 2.6 and 25.2 ºC) with the annual average being 3.9 ºC. The major rainfalls in Oslo are during summer in which the annual sum is approximately 338 mm higher than Prague's (i.e. 859 mm).

Finally, London also has a cold winter but not as severe as Prague's (the temperature varies between -7.8 and 13.4 ºC), a warm summer between Prague’s and Oslo’s (the temperature varies between 3.6 and 27 ºC) and it rains moderately all year long with the annual sum being 751 mm. These values correspond to London’s reference climate.

### 2.4.2. Climate change

The effects of climate change are multiple and will occur at several levels, namely in terms of the environment, the global economy, which in turn will affect the local economy, and the human health [16]. It has been reported that if proper measures are not applied, climate change will also have a significant effect on the envelope of historic buildings [17,42], which in turn will affect the indoor climate and might accelerate the deterioration processes of the housed artefacts.

Hence, in order to ensure the continuity of artefacts it is of the utmost importance to study climate change. Over the years the *Intergovernmental Panel on Climate Change* (IPCC) has developed several scenarios that translate how the climate might evolve in the future based on different assumptions which will mainly reflect on the amount of greenhouse gases (GHG) emitted into the atmosphere, namely $CO_2$ [15]. In this paper, two IPCC scenarios from the Fourth Assessment Report (AR4) were used: scenario *A1B* (mid-radiative forcing scenario) and scenario *A2* (high-radiative forcing scenario), which are based on different assumptions in how the world will evolve [43]. Both scenarios have been used in European projects that deal with historic buildings, namely *Noah’s Ark project* [44] used scenario A2 and *Climate for culture* [45] used scenario A1B. There is a correspondence of these scenarios with the more recent *Representative Concentration Pathway* (RCP) scenarios, RCP 6.0 corresponds to A1B and RCP 8.5 corresponds to scenario A2 [46].

Whilst scenario A1B rests on assumptions that will lead to an increase of the $CO_2$ emissions until 2050 but its steeply decrease until 2100, scenario A2 is based on a continuous increase of the $CO_2$ emissions throughout the 21st-century [15]. These assumptions will obviously cause the outdoor conditions to evolve differently.

The outdoor temperature in Lisbon is expected to increase for both selected IPCC scenarios with the increase varying approximately 0.6–3.0 K for the annual average between 2020–2100 in relation to 1990 (Figure 2a). However, the difference between both scenarios is only substantial from 2060 onward in which the outdoor temperature in the A2 scenario is almost 0.5 K higher than for A1B scenario. The same can be said for Seville, however, it is also visible that the increase of outdoor temperature is higher than in Lisbon’s, i.e. increase of 1.0–4.2 K from 2020-2100 (Figure 2a).

In both climates the water-vapour pressure increases with the A2 scenario reaching higher values from 2060 onward, but the increase is more significant for Seville than for Lisbon (Figure 2b). Whilst the water-vapour pressure increases between 103–460 Pa from 2020 to 2100 for Seville, it increases from 62–305 Pa for Lisbon. In conclusion, the outdoor temperature and water-vapour pressure increase in both Mediterranean climates, but Seville has a higher increase for both conditions.

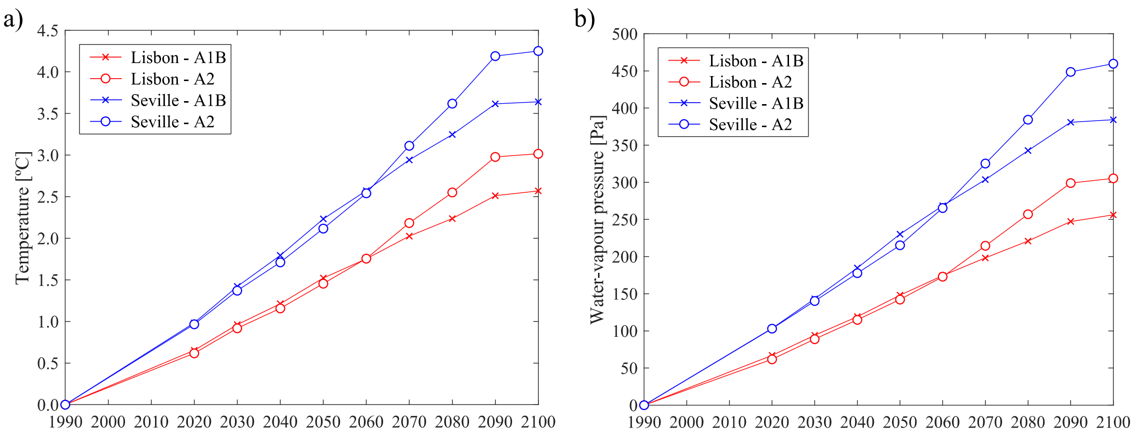

Figure 2 – Difference of the annual average of the outdoor temperature (a) and water-vapour pressure (b) for Lisbon (red) and Seville (blue) relative to the 1990-value for scenario A1B (cross) and A2 (circle)

The outdoor temperature in Prague increases substantially for both IPCC scenarios (Figure 3a). The increase of temperature varies between 1.0–3.8 K and the highest value is attained in 2100 for scenario A2, i.e. more 0.4 K than scenario A1B. In terms of water-vapour pressure it is also visible an increase trend, which ranges from 58–264 Pa with the highest value being achieved in 2100 for scenario A2, i.e. ca 40 Pa higher than scenario A1B (Figure 3b). A similar behaviour occurs in Oslo in terms of temperature but reaching higher values, since the temperature increases between 1.2–4.2 K (Figure 3a). In terms of water-vapour the increase is less substantial than Prague's, i.e. varies between 50–206 Pa (Figure 3b).

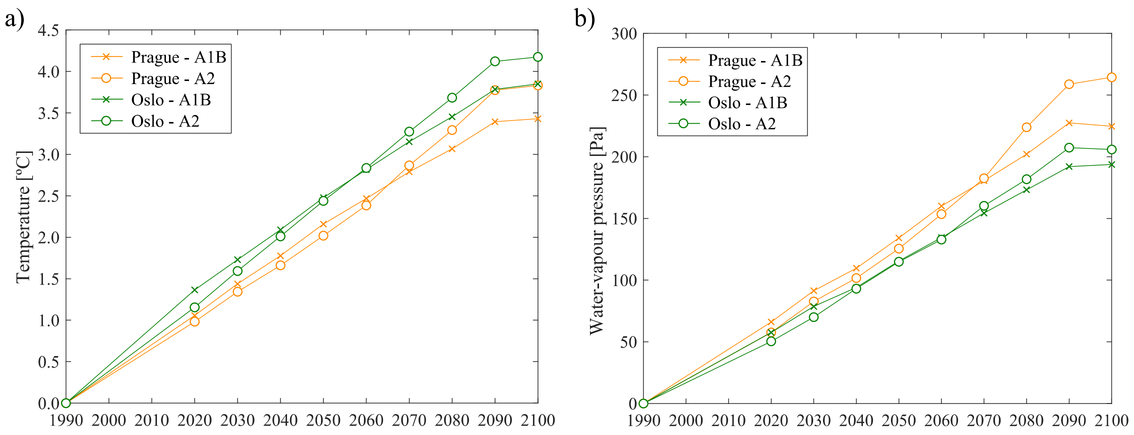

Figure 3 – Difference of the annual average of the outdoor temperature (a), and water-vapour pressure (b) for Prague (orange) and Oslo (green) relative to the 1990-value for scenario A1B (cross) and A2 (circle)

Finally, both the outdoor temperature and the water-vapour pressure in London increase 0.7–3.0 K and 41–220 Pa until 2100, respectively (Figure 4). Overall, there is an increase trend in terms of outdoor temperature and water-vapour pressure for the five selected climates and for both IPCC scenarios, with the highest increase being reached in the end of the century by scenario A2. The difference between both IPCC scenarios is only substantial from 2070 onward.

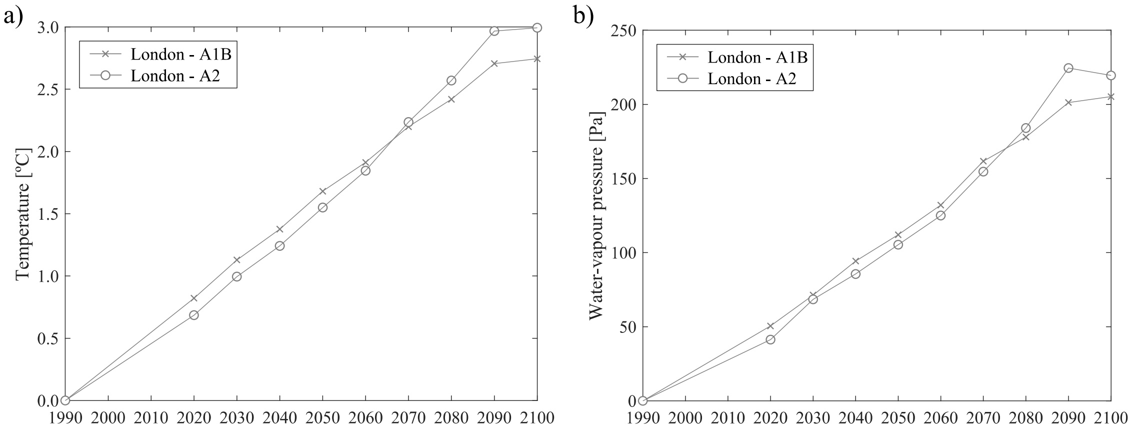

Figure 4 – Difference of the annual average of the outdoor temperature and water-vapour pressure for London (a and b, respectively) relative to the 1990-value for scenario A1B (cross) and A2 (circles)

## 2.5. Indoor climate control

The set-points that the HVAC system must ensure depend on each standard/guideline (Table 3). Due to the large number of classes that some of these standards/guidelines have, it was decided to choose only one class for each, i.e. the most demanding in terms of indoor conditions. Since the case-study is a high thermal inertia building, ASHRAE's recommended class is either B, C or D, and since its classes are organized in decreasing order of strictness, B-class was chosen.

Additionally, the range of values within which the indoor climate can vary according to ASHRAE class B and FCT-UNL class 1 were determined using the methodology presented by Kramer *et al.* [47] for each year, namely: 1)- simulate a free-floating indoor climate, 2)- determine the respective temperature setpoints, 3)- simulate the indoor climate restrained by the temperature setpoints, 4)- determine the respective relative humidity setpoints, 5)- simulate the indoor climate restrained by temperature and relative humidity setpoints. Hence, the dynamic methodologies simulations were run three times. The analysed energy consumption for these cases correspond to the last simulation. This 5-step methodology allowed to account for the acclimatization behaviour of hygroscopic materials [5–7].

Since the aim of this paper is to analyse the energy consumption associated to each of the standards and guidelines that limit the artefacts deterioration, rather than develop or optimize the HVAC system, the authors opted for an ideal HVAC system.

Table 3 – Temperature and relative humidity set-points for each of the selected standard/guidelines

| Standard/ Guideline | Temperature (ºC) | Relative humidity (%) | Comments |
|---|---|---|---|
| Thomson [4] | Winter: 19 ± 1ºC<br>Summer: 24 ± 1ºC | Range: 50 or 55 ± 5 % | Class 1 – Major museums |
| ASHRAE [2] | Set-point: 15–25 ºC<br>Short fluctuations: ± 5 K<br>Seasonal cycle: Up 10 K not above 30 ºC | Set-point: 50 % or historic annual average<br>Short fluctuations: ± 10 %RH<br>Seasonal cycle: Up 10 %RH and down 10 %RH | Class B – Heavy masonry or composite walls with plaster |
| FCT-UNL [8] | Set-point: historic annual average<br>Short fluctuations: -5º/ +95º percentiles<br>Seasonal cycle: -10º/ +90º percentiles<br>Extra limits: $\lvert T - \bar{T} \rvert$ up to 10ºC not above 30ºC | Set-point: historic annual average<br>Short fluctuations: -5º/ +95º percentiles<br>Seasonal cycle: -10º/ +90º percentiles<br>Extra limits: $\lvert RH - \overline{RH} \rvert \leq 15\%$ and $RH_{max} \leq 75\%$ | Class 1 – Low risk of mechanical damage and biological attack. |

## 2.6. Energy price trend

The electricity prices in Europe have been increasing over the years. For example, the average electricity price for the European Union increased from 0.1805 €/kWh in 2007 to 0.2435 €/kWh in 2019 for band-IA [48]. This corresponds to an increase of approximately 0.063 €/kWh over a period of 13 years. Since the aim of this paper is buildings that house artefacts, which evidently are non-household, they are subjected to industrial energy prices [49]. Hence, the price of energy varies according to the amount of energy consumed by the building. However, due to the liberalisation of the energy markets, the Eurostat energy prices system was reorganized in 2007 from a 9 to a 7-level classification system that only takes the annual consumption of the building into account – *band-IA* (below 20 MWh), *band-IB* (between 20 and 500 MWh), *band-IC* (between 500 and 2,000 MWh), *band ID* (between 2,000 and 20,000 MWh), *band-IE* (between 20,000 and 70,000 MWh), *band-IF* (between 70,000 and 150,000 MWh) and *band-IG* (higher than 150,000 MWh) [49]. This system was used to determine the overall cost of maintaining the indoor climate according to each selected standard/guideline. Figure 5 presents the energy prices for all bands in each of the five selected climates between 2007-2019.

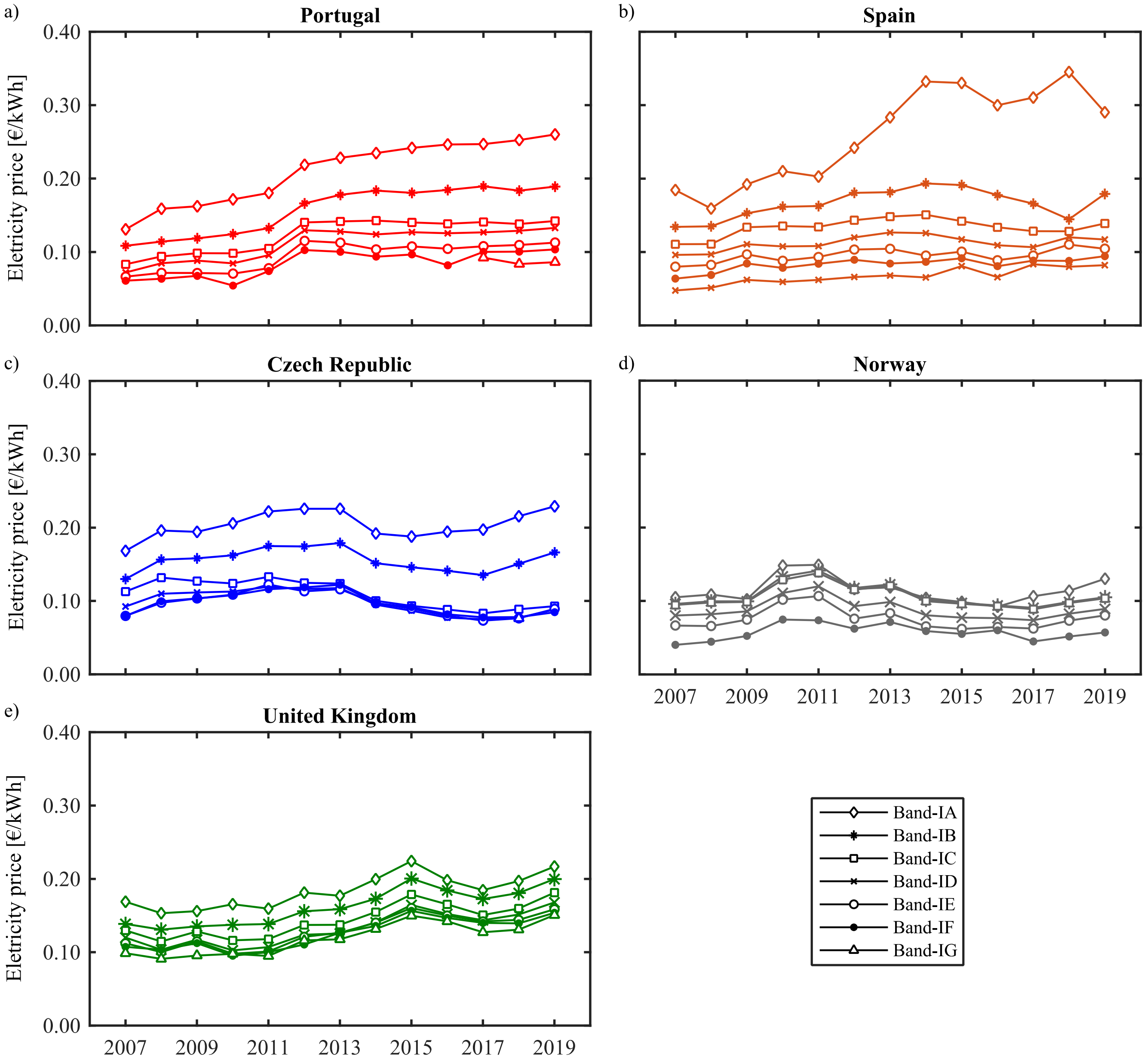

Figure 5 – Electricity price (€/kWh) for industrial users that includes all taxes and levies between 2007-2019 [48] for Portugal (a), Spain (b), Czech Republic (c), Norway (d) and United Kingdom (e) for the seven bands

Additionally, it is expected that the electricity price will increase until 2030 and only after will it decrease (Table 4). From the selected countries only in Czech Republic will the electricity price not decrease after 2030. These annual changes for the electricity prices were taken from the “EU Reference Scenario 2016: Energy, transport and GHG emissions Trends to 2050” [50], which unfortunately does not include the annual changes for Norway. Hence, the electricity price between 2020-2100 was determined using a constant annual change for Norway depending on the annual consumption, which was based on the historical values of 2007 and 2019 [48] and varied between 0.1–0.2 % per year. Additionally, and since there is no annual change for the period 2050-2100, the same percentage as the one for the 2030-50 period was adopted for Czech republic, Portugal, Spain and the United Kingdom (Table 4).

Table 4 – Annual change (%) of the electricity price for Czech Republic, Portugal, Spain and United Kingdom between 2010-2050 [50]

| | Czech Republic | Portugal | Spain | United Kingdom |
|---|---|---|---|---|
| 2010-20 | -0.7 | 3.0 | 1.5 | 2.8 |
| 2020-30 | 0.2 | 0.6 | -0.3 | 0.6 |
| 2030-50 | 0.1 | -0.2 | -0.2 | -0.3 |

## 2.7. Risk-based analysis

A methodology that assesses the indoor conditions, namely the indoor temperature and relative humidity, in terms of artefacts conservation was developed by Martens [1], evaluating the risk of biological, chemical and mechanical decay using several methods. The risk of biological decay is assessed using the *isopleth method* [22]. This method was developed by *Sedlbaeur* and determines the germination conditions depending on the temperature, relative humidity and substrate type. Mould grows if the *Lowest Isopleth for Mould* curve (LIM) is surpassed. The biological decay was analysed in terms of the amount of time the LIM curve is surpassed.

The risk of chemical decay is assessed using the *lifetime multiplier* concept [23]. This concept, which was developed by *Michalski* [23], basically determines the amount of time the material stays usable when compared to standard conditions – 20 ºC for temperature and 50 % for relative humidity. Usually, two different materials are analysed since their activation energy differs [1]: 70 kJ/mol for varnish, and 100 kJ/mol for cellulose. More recently, *Silva and Henriques* [51] introduced the *equivalent lifetime multiplier*, a concept which computes a representative value for the whole considered period.

$$eLM = 1 \Bigg/ \left( \frac{1}{n} \cdot \sum_{x=1}^{n} \left( \frac{1}{\left( \frac{50\,\%}{RH_x} \right)^{1.3} \cdot e^{\frac{E_a}{R} \cdot \left( \frac{1}{T_x + 273.15} - \frac{1}{293.15} \right)}} \right) \right) \qquad 1$$

where *eLM* is the equivalent Lifetime Multiplier (-), *n* is the number of time steps within the considered period (-), $RH_x$ is the surface relative humidity at instant x (%), $E_a$ is the activation energy of the material (kJ/mol), *R* is the gas constant (8.314 J/Kmol) and $T_x$ is the temperature at instant x (ºC).

Lastly, the method used to assess the risk of mechanical decay varies according to the type of object: a) wood sculpture (Figure 6a) – uses an adapted version of the Jakiela et al. method [52], b) wood furniture (Figure 6b) – uses an adapted version of the Bratasz *et al.* method [53], c) wood substrate of the panel paintings (Figure 6c) – uses an adapted version of the Mechlenburg *et al.* method [54], and d) pictoral layer of the panel paintings (Figure 6d) – uses an adapted version of the Bratasz *et al.* method [55]. These methods determine if the yield strain of the materials is surpassed (Figure 6). Hence, and since the performed analysis includes a great number of years, the mechanical decay was analysed in terms of the amount of time the objects are under reversible conditions in each year [11].

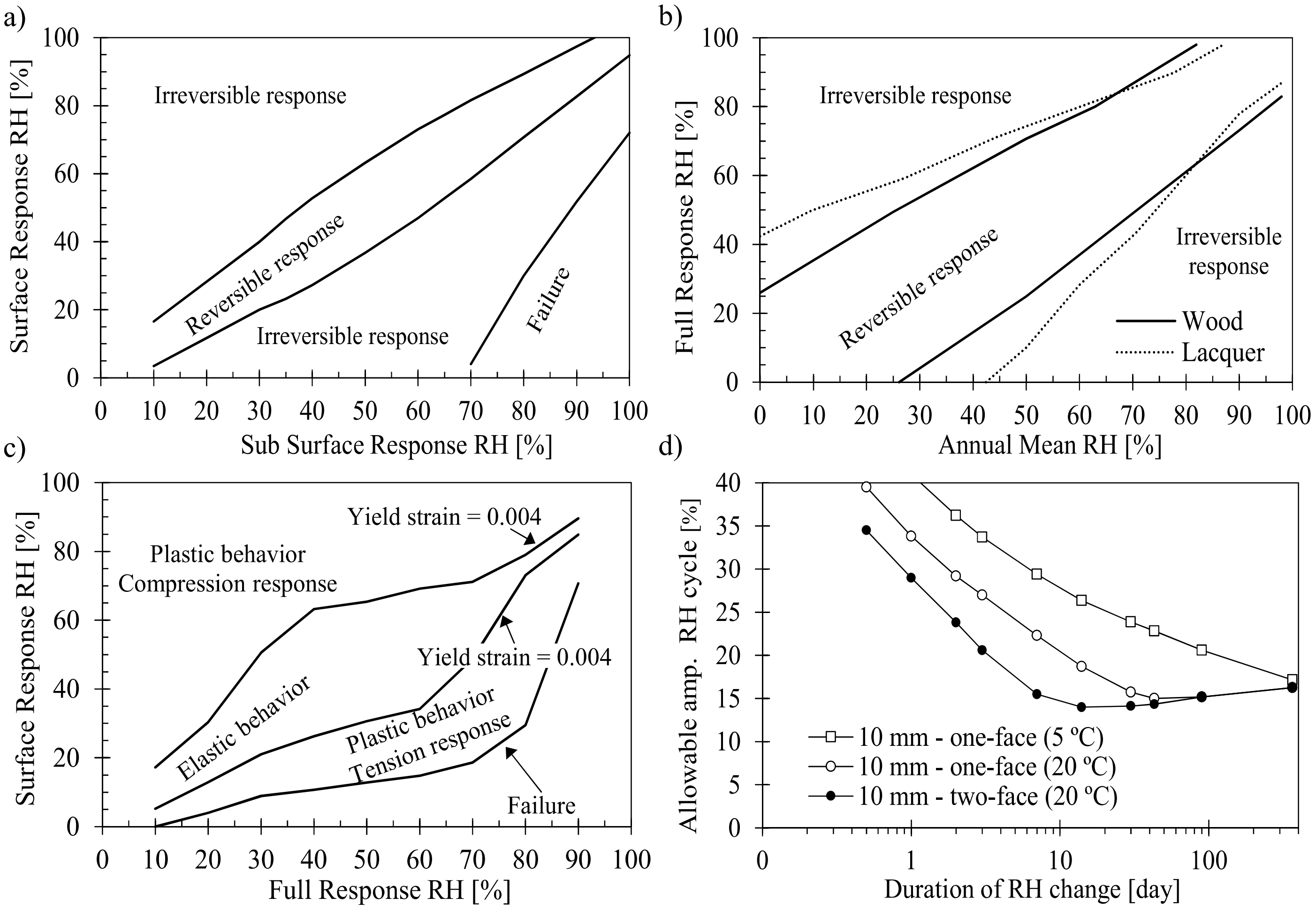

Figure 6 – Mechanical decay assessment for: a) wood sculptures, b) wood furniture, c) wood substrate - panel painting, d) pictorial layer - panel painting

## 3. Results and discussion

This section starts by addressing the amount of energy necessary to guarantee the indoor conditions established by the three selected standards/guidelines. Furthermore, future trends and the respective financial cost are also assessed. Lastly, the energy saving potential of a set of passive retrofit measures is assessed, as well as its effect on the artefacts' conservation metrics in historic buildings. In colder climates it is usual that the indoor climate of historic buildings that house artefacts is heated to ensure the thermal comfort of visitors [56–59]. However, due to the fact that the minimum temperature limit varies considerably from case- to case the authors chose a minimum temperature of 13 ºC for the methodologies that do not preconize temperature limits to guarantee that there is no embrittlement of the artefacts [60].

In order to develop this section more than 1400 simulations were run in WUFI®Plus, which correspond to more than 1600 hours of computation on a computer with an Intel(R) Core(TM) i5-8500 CPU @ 3.00 GHz, 16 GB of RAM and a 64-bit operating system. However, to make this study time reasonable, the simulations were subdivided into 20 computers equipped with an Intel(R) Core(TM) i5-650 CPU @ 3.20 GHz, 4 GB of RAM and a 64-bit operating system, which drastically reduced the overall simulation time.

## 3.1. Energy expenditure and financial cost evolution

The energy spent to ensure a proper indoor climate for artefacts preservation will greatly depend on the adopted methodology (Figure 7). Furthermore, the effect of climate change on energy consumption will also depend on the methodology, since it can either be responsible for its increase or decrease. The following section first addresses the constant value methodology suggested by Gary Thomson (class 1) and then the dynamic methodologies – namely ASHRAE class B and FCT-UNL class 1. In addition, the calculated heating, cooling, humidification and dehumidification energy demands are presented in tables at the appendices section.

By limiting the indoor climate according to Thomson's methodology, it is visible that climate change is responsible for an energy saving for all selected climates except for Seville (Figure 7a). The decrease of energy consumption in Prague, Oslo and London is easily understood by the fact that in these climates the HVAC needs are mostly heating, which correspond to 93–96 % of the total consumed energy (Table A.1), since the free-floating indoor temperature will be very often below the 18 ºC limit. Moreover, since climate change is responsible for the increase of the free-floating indoor temperature, this will lead to energy saving. The greatest savings at the end of the century correspond to scenario A2 (Figure 7a), since the free-floating indoor temperature reaches higher values for this IPCC scenario [11].

On the other hand, Lisbon is an interesting case, because climate change is also responsible for an energy saving, but more substantially for scenario A1B. This occurs because the need to heat the room will decrease (Table A.1). For instance, the number of hours that the HVAC system is operating to guarantee the 18 ºC-limit decreases 25% between 1990–2100 for scenario A1B. However, the free-floating indoor temperature will increase more for scenario A2 than for scenario A1B [11], which means that the upper limit will be overcome for a larger period of time. For instance, the number of hours that the HVAC system has to guarantee the 25 ºC-limit when compared to the reference climate is 6 and 8 times higher for scenario A1B and A2, respectively. Hence, the HVAC system has to decrease the free-floating indoor temperature to comply with Thomson's methodology, thus increasing the cooling needs (Table A.1) and, consequently, increasing the total energy consumption. The cooling needs increase from 0.4 to 6.8 MWh between 1990 and 2100 for scenario A2 (Table A.1). The dehumidifying needs are also responsible for a substantial part of the total energy consumption that range from 7–25%, which are due to the expected increase of the indoor water-vapour pressure [11].

Finally, Seville is the only one of the selected climates in which the energy consumption increases with time (Figure 7a). Seville's indoor climate is similar to Lisbon's, however, since its free-floating indoor temperature is higher than Lisbon's and because climate change increases the free-floating indoor temperature, this will lead to the overcome of the 25 ºC-limit much more often than in Lisbon (Figure 8). Thus, increasing the cooling needs substantially (Table A.1), which goes from corresponding to 12 % of the total energy needs in 1990 to 43 % in 2100 for scenario A2, i.e. 10 % higher than heating needs for that year. This increase of the cooling needs will overshadow the decrease of heating needs (Table A.1), thus being responsible for the increase of the total energy consumption for Seville, while in the other climates the consumption decreases.

Nevertheless, the energy consumption associated to each of these climates is still very significant, and this will lead to great financial costs (Table 5). Prague has the highest overall cost to maintain the indoor conditions suggested by Thomson, although it does not correspond to the highest energy consumption (Figure 7a). This is due to the fact that currently energy costs more in Prague than in Oslo and it is expected to remain so. The overall cost of energy in Prague is closely followed by London's and Oslo's, but the selected Mediterranean climates (i.e. Seville and Lisbon) present a much lower energy cost.

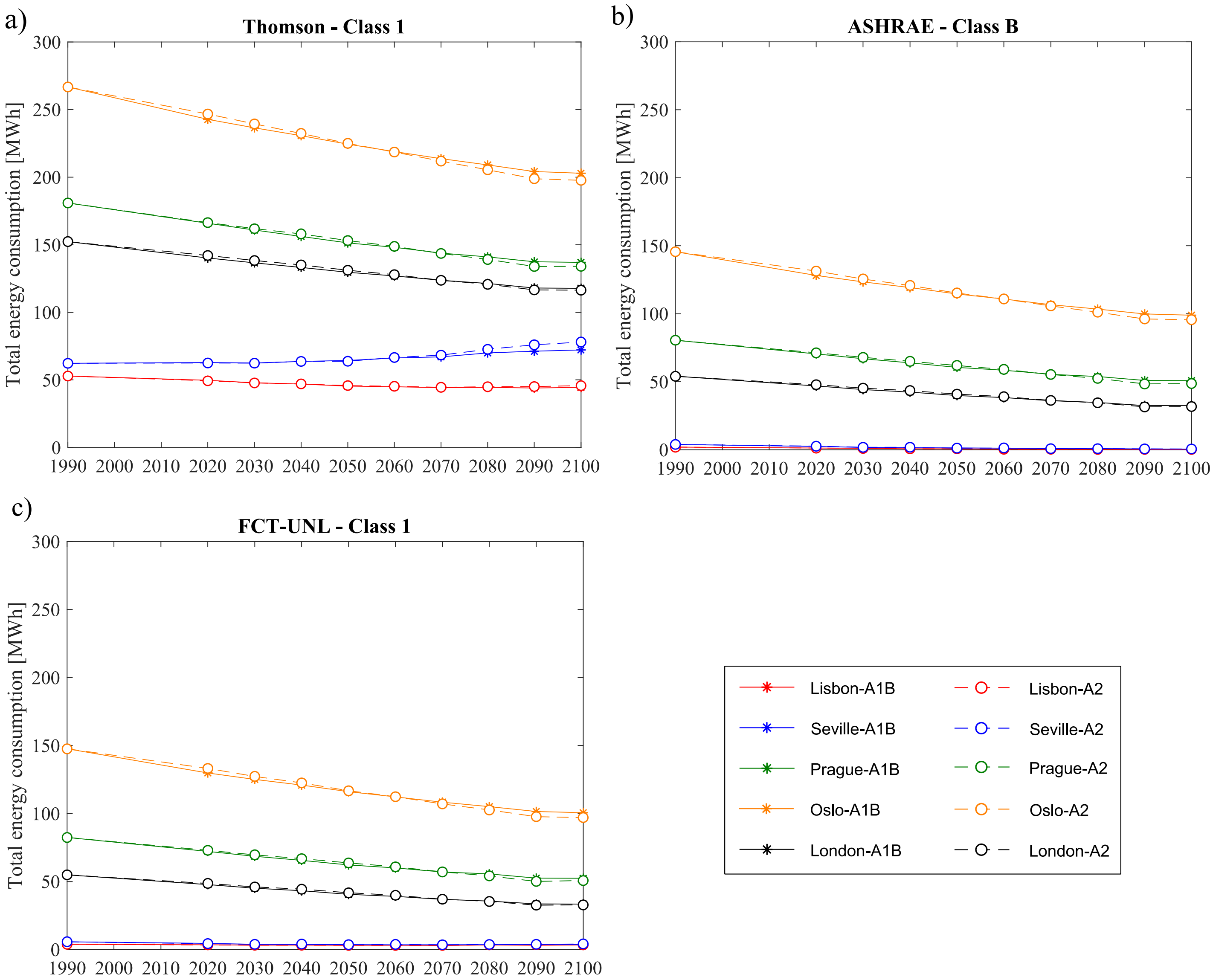

Figure 7 – Assessment of the energy consumption to guarantee the indoor conditions according to Thomson class 1 (a), ASHRAE class B (b) and FCT-UNL class 1 (c) for the five selected climate and the two IPCC scenarios (A1B and A2)

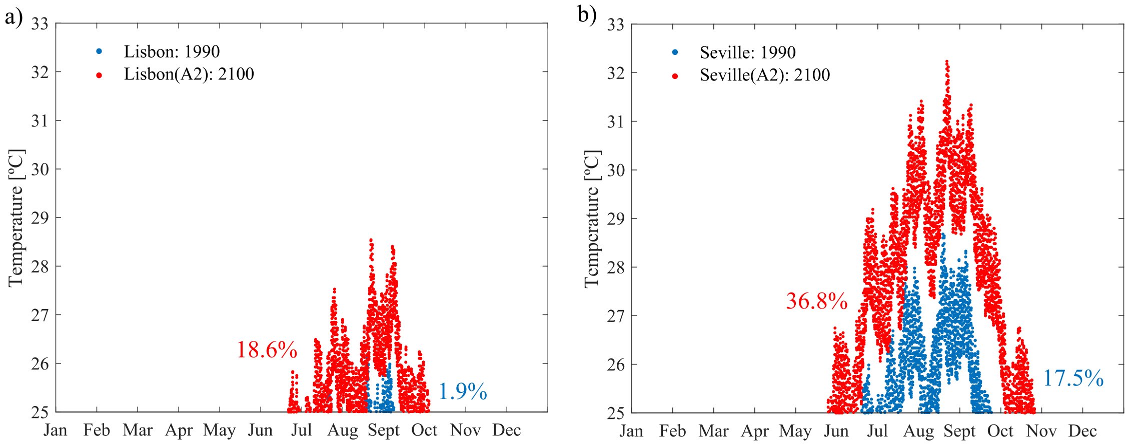

Figure 8 – Free-floating indoor temperature higher than the 25 ºC-limit for Lisbon (a) and Seville (b) in 1990 and 2100 (scenario A2), and respective percentage of the year that the 25 ºC-limit is surpassed

Both selected dynamic methodologies have a very similar energy consumption trend, i.e. the energy consumption decreases for all selected climates with the Mediterranean climates consuming a relatively smaller amount of energy (Figure 7b for ASHRAE and Figure 7c for FCT-UNT). Nonetheless, FCT-UNL methodology attains higher overall costs than ASHRAE's, which is more significantly for the Mediterranean climates (Table 5), since it preconizes a more stringent indoor climate range (Table 3).

The energy consumption necessary to limit the indoor climate according to these two methodologies is almost non-existent for the selected Mediterranean climates, i.e. Lisbon and Seville, due to their flexible ranges. For example, the annual consumption for Lisbon is 1.9 MWh in 1990 for the ASHRAE methodology, mainly heating needs, and tends to decrease with climate change (Table A.2), since the free-floating indoor temperature will increase. The same behaviour is observed for Seville although the energy spent to ensure an indoor climate according to ASHRAE class B guideline is slightly higher, e.g. the annual consumption for Seville in 1990 is 3.9 MWh (Table A.2). Whilst in terms of the FCT-UNL methodology the value for Lisbon in 1990 is 3.8 MWh and 5.7 MWh for Seville with the tendency to decrease on the subsequent years, but slightly increasing 2070-onwards until they reach respectively 3.4 MWh and 4.1 MWh for scenario A2 in 2100 (Table A.3).

On the other hand, it is also easily understandable that the energy consumption in Prague, Oslo and London decreases substantially, since the key factor for energy consumption in this type of climates is to guarantee the minimum indoor temperature. Since climate change will increase the indoor free-floating temperature, then it is evident that energy consumption will decrease. For example, the energy consumption for Oslo between 1990 and 2100 for scenario A2 decreases approximately 34% for the ASHRAE methodology, i.e. from an energy consumption of ca 146 to 96 MWh (Table A.2), and 34% for the FCT-UNL methodology, i.e. from a consumption of ca 148 to 97 MWh (Table A.3).

In terms of overall cost to guarantee the indoor climate according to ASHRAE Class B and FCT-UNL Class 1 it is obvious that for Mediterranean climates the cost is very small with climate change being responsible for its decrease, but for the other three climates the costs are much more substantial with Oslo having the highest cost, followed by Prague and then London (Table 5).

Table 5 – Overall energy cost per square meter between 2020–2100 for each of the five selected climates and the change induced by climate change in the overall energy cost (in percentage). ↓ green – means decrease of the overall energy consumption and ↑ red – means increase

|  | Lisbon |  | Seville |  | Prague |  | Oslo |  | London |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 | A1B | A2 |
| Thomson class 1 | 2768 €/m$^2$<br>↓ 13.4 % | 2791 €/m$^2$<br>↓ 12.7 % | 3503 €/m$^2$<br>↑ 6.8 % | 3579 €/m$^2$<br>↑ 9.1 % | 8039 €/m$^2$<br>↓ 17.8 % | 8022 €/m$^2$<br>↓ 18.0 % | 7491 €/m$^2$<br>↓ 17.5 % | 7462 €/m$^2$<br>↓ 17.8 % | 7872 €/m$^2$<br>↓ 16.2 % | 7905 €/m$^2$<br>↓ 15.8 % |
| ASHRAE class B | 48 €/m$^2$<br>↓ 69.5 % | 46 €/m$^2$<br>↓ 71 % | 106 €/m$^2$<br>↓ 68.3 % | 112 €/m$^2$<br>↓ 66.7 % | 3180 €/m$^2$<br>↓ 26.9 % | 3169 €/m$^2$<br>↓ 27.2 % | 3795 €/m$^2$<br>↓ 23.4 % | 3785 €/m$^2$<br>↓ 23.6 % | 2389 €/m$^2$<br>↓ 28.3 % | 2411 €/m$^2$<br>↓ 27.6 % |
| FCT/UNL class 1 | 267 €/m$^2$<br>↓ 16.7 % | 268 €/m$^2$<br>↓ 16.5 % | 321 €/m$^2$<br>↓ 34.3 % | 329 €/m$^2$<br>↓ 32.7 % | 3266 €/m$^2$<br>↓ 26.7 % | 3264 €/m$^2$<br>↓ 26.7 % | 3850 €/m$^2$<br>↓ 23.3 % | 3838 €/m$^2$<br>↓ 23.6 % | 2440 €/m$^2$<br>↓ 27.9 % | 2463 €/m$^2$<br>↓ 27.2 % |

## 3.2. Passive rehabilitation measures

Taking the previously obtained results for tested standards/guidelines into account (Table 5), it is visible that there is a need to decrease the energy consumption if we want to substantially decrease the GHG emissions, which are directly related to energy consumption [15]. This behaviour is more substantial for the constant valued standards/guidelines, such as Thomson's. Obviously, if we choose a dynamic methodology (e.g. FCT-UNL), the energy consumption decreases considerably (Figure 7). Moreover, this energy saving can be heightened if a less stringent indoor climate methodology is combined with a proper set of passive retrofit measures.

Hence, four retrofit measures were tested to determine their energy saving potential (see section 2.3). The indoor climate was limited according to a constant and a dynamic methodology to determine to which extent the energy saving potential would differ. Additionally, the simulations were run for the two most demanding climates of each climate type: Seville and Oslo.

### 3.2.1. Energy saving potential

Table 6 presents the energy consumption of the four retrofit measures for Seville and Oslo, and the respective saving potential, which is calculated based on the correspondent reference case, i.e. the case-study that does not have any retrofit measure. Although the energy saving potential for the retrofit measures in the Mediterranean climates is in the same range of values as the ones described in Table 6, its overall energy saving is small (see section 3.1). Therefore, it was discarded from the analysis performed in this subchapter.

Based on this table it is clear that the four selected retrofit measures are responsible for a reasonable energy saving. Furthermore, it is also clear that both indoor climate limiting methodologies attain close energy saving potentials, although evidently Thomson attains much higher consumptions in both climates, since it is a constant value methodology with a much stringent indoor temperature/relative humidity range than those obtained with the FCT-UNL methodology (subchapter 2.5).

The application of an interior insulation system (R1) reaches the highest energy saving potential – between ca 20 and 32%, followed by the application of an exterior thermal plaster (R2) – between ca 16 and 20%, and then by the application of an insulation foam in the ceilings of the case-study (R3) – between ca 13 and 20%. The replacement of the windows (R4) has the lowest energy saving potential – i.e. between ca 4 and 6% – due to the low window/wall ratio of the case-study [51].

Nonetheless, the obtained values demonstrate that a less stringent climate limiting methodology decreases the energy consumption considerably, but this effect can be heightened if an individual or a set of passive retrofit measures is applied to the building. However, the selected passive retrofit measures should take into account the special requirements of both historic buildings, since insufficient studied retrofit measures can lead to irrecuperable damages [61], and the artefacts housed on those buildings, which need that the indoor conditions vary within certain values for preservation purposes [2].

Table 6 – Total energy consumption (in MWh/m$^2$) and energy saving potential (in percentage) between 2020–2100 for Seville and Oslo for the four retrofit measures: ↓ green – means decrease and ↑ red – means increase of the energy consumption compared to the reference case

| | Total energy consumption (MWh/m$^2$) | | | | | |
|---|---|---|---|---|---|---|
| | Seville – Thomson | | Oslo –Thomson | | Oslo – FCT-UNL | |
| | A1B | A2 | A1B | A2 | A1B | A2 |
| Reference | 21.0 | 21.5 | 69.3 | 69.1 | 35.7 | 35.5 |
| Retrofit #1 | 16.8<br>(↓ 20.8%) | 17.1<br>(↓ 20.2%) | 51.4<br>(↓ 25.8%) | 51.3<br>(↓ 25.8%) | 24.2<br>(↓ 32.2%) | 24.1<br>(↓ 32.2%) |
| Retrofit #2 | 18.1<br>(↓ 16.7%) | 18.5<br>(↓ 16.7%) | 58.3<br>(↓ 16.0%) | 58.1<br>(↓ 16.0%) | 28.7<br>(↓ 19.5%) | 28.6<br>(↓ 19.6%) |
| Retrofit #3 | 18.2<br>(↓ 13.5%) | 18.6<br>(↓ 13.3%) | 58.3<br>(↓ 15.9%) | 58.1<br>(↓ 15.9%) | 28.7<br>(↓ 19.5%) | 28.6<br>(↓ 19.5%) |
| Retrofit #4 | 20.1<br>(↓ 4.4%) | 20.6<br>(↓ 4.4%) | 66.1<br>(↓ 4.6%) | 65.9<br>(↓ 4.6%) | 33.6<br>(↓ 5.8%) | 33.5<br>(↓ 5.8%) |

### 3.2.2. Risk-based analysis

The effect of these retrofit measures in the artefacts' conservation metrics was also assessed using the risk-based analysis presented in section 2.7. Note that all figures presented in this subsection have, as reference, a case without any retrofit measure but with the indoor climate limited by the corresponding standard/guideline, which are either named Ref-A1B and Ref-A2 depending on the IPCC scenario. This reference allows to determine the effect that applying a certain rehabilitation measure has on the indoor climate of the case-study.

It was observed that the risk of *biological decay* for Thomson climate control strategy is non-existent for both climates (e.g. Figure 9a for Seville), since the recommended temperature and relative humidity set-points do not surpass the LIM curve. For the temperature range preconized by Thomson – i.e. 18 to 25 ºC, the LIM curve varies between 80.5 and 79.6 %RH. Since the highest allowed relative humidity in Thomson's methodology is 60 % (Table 3), then it is clear that for this methodology the LIM curve is never surpassed.

The risk of *biological decay* is also non-existent for the FCT-UNL methodology. Although the preconized temperature ranges vary with the historic climate, the first class of this methodology limits superiorly the relative humidity (Table 3). Since the maximum admissible value is 75 %, the LIM is never surpassed because its minimum value is approximately 79.2 %RH for 30 ºC. This is the reason why Oslo does not have nor will it ever have a risk of biological decay, which was also shown for free-floating conditions [11]; and why Seville, which substantially and gradually surpassed the LIM curve for free-floating conditions [11], now that is limited by the FCT-UNL methodology, does not show risks of biological decay (Figure 9b).

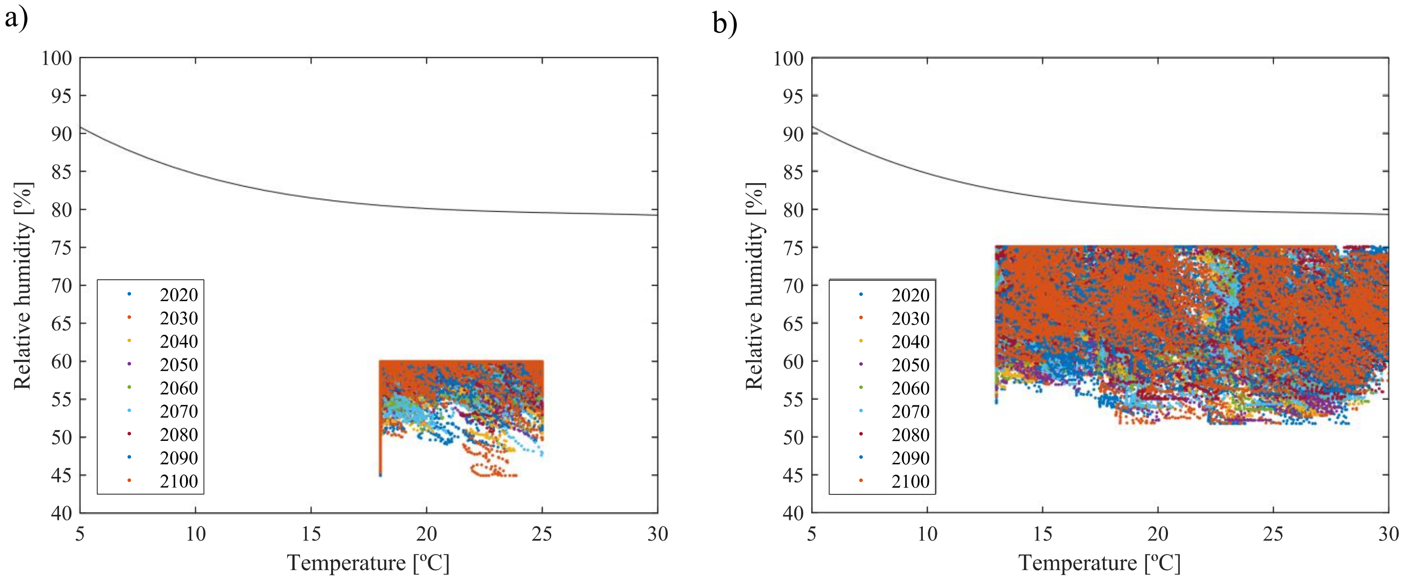

Figure 9 – Spore germination for the reference case of Seville between 2020 and 2100 for scenario A2 for Thomson's methodology (a) and for FCT-UNL methodology (b)

It is expected that the risk of chemical decay increases over the years for both IPCC scenarios [11], with the highest risks being reached at the end of the century by scenario A2. On the other hand, the application of retrofit measures to this kind of buildings can have two different effects, which are greatly dependent on the type of the outdoor climate. Whilst for Seville the application of the retrofit measures improves the quality of the indoor climate (Figure 10), for Oslo it has the opposite effect, i.e. it decreases the quality of the indoor climate to preserve artefacts that are susceptible to chemical decay (Figure 11). In Seville, the application of the retrofit measures improves the quality of the indoor climate because they are able to reduce the increase of the free-floating temperature that occurs mainly in summer significantly, which is the season that mainly limits the Mediterranean climates. This lowering of the indoor temperature is beneficial to avoid chemical decay, because chemical processes are slowed by lower temperatures [1]. On the other hand, in Oslo the retrofit measures are responsible for an overall increase of indoor free-floating temperature, but more significant during the spring and summer seasons. Evidently, that this higher temperature level will increase the risk of chemical decay [1].

In addition, the best performing retrofit measure for Seville is the application of the interior insulation system – R1 (Figure 10), followed by the application of the exterior thermal plaster – R2. The application of the PUR-foam layer in-between the ceilings' wood slabs (R3) or the replacement of the existing window (R4) lead to a small improvement of the indoor conditions in terms of chemical risk, although a slightly more significant for the FCT-UNL methodology (e.g. Figure 10a and c). These observations show that the performance of each retrofit in terms of decreasing the risk of chemical decay is slightly affected by the methodology chosen to control climate.

Furthermore, it is also observable that whilst the Thomson methodology is responsible for a significant increase of the risk of chemical decay, the FCT-UNT methodology manages to maintain the same level of risk if the indoor climate was already appropriate to preserve artefacts susceptible to chemical decay. This occurs, for example, for Oslo (Figure 11), whose free-floating conditions were already deemed appropriate to preserve artefacts susceptible to chemical decay [11]. This particularity of the FCT-UNT methodology and other dynamic methodologies (such as, ASHRAE [2] and EN 15757 [6]) is due to the fact that they are based on the acclimatization concept, which allows to obtain an indoor climate adequate for the preservation of the artefacts based on the historic climate. Note that since the previously described behaviours also occur for varnish, the authors chose to leave it out so as not to duplicate the same analysis.

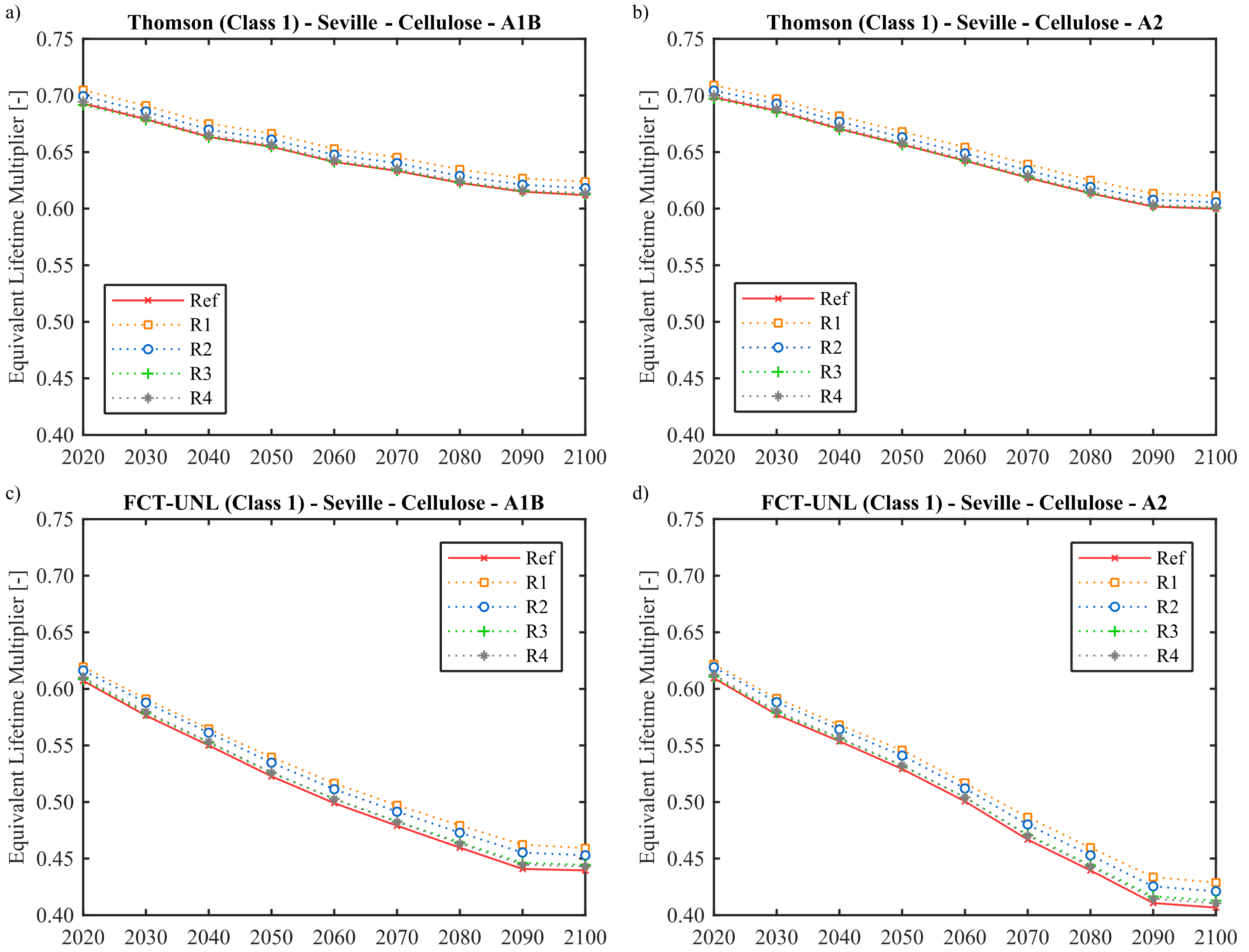

Figure 10 – Equivalent lifetime multiplier for the reference case and retrofits #1–4 following Thomson' methodology for IPCC scenario A1B (a) and A2 (b), and following FCT-UNL methodology for IPCC scenario A1B (c) and A2 (d) between 2020-2100 for cellulose in Seville climate

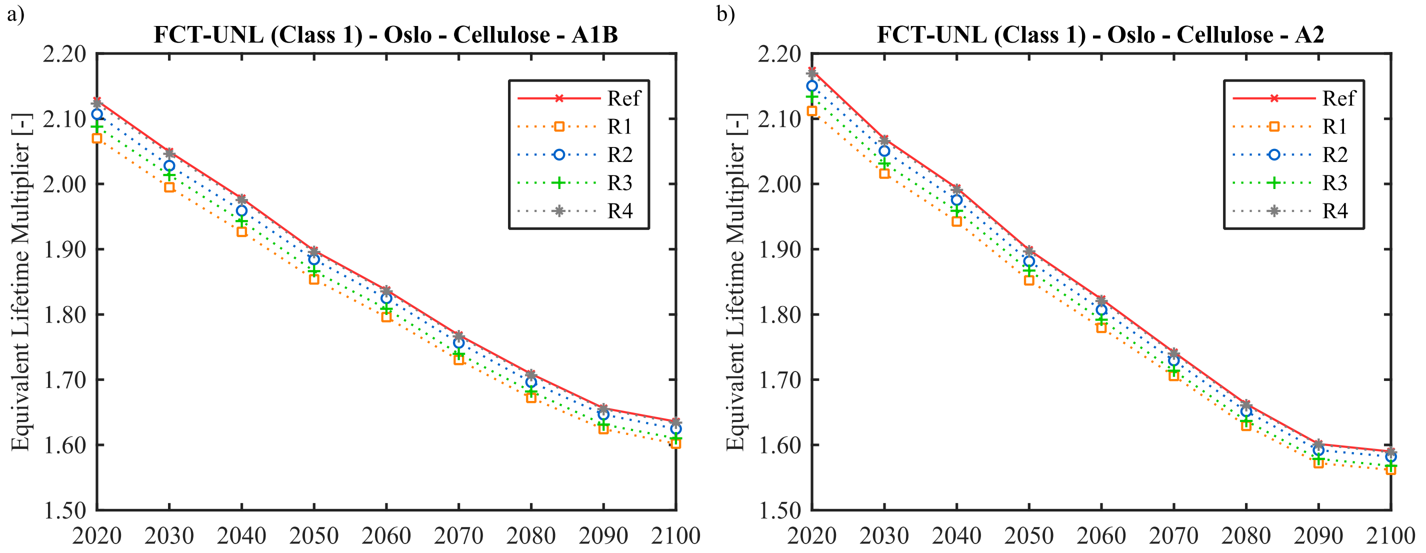

Figure 11 – Equivalent lifetime multiplier for the reference case and retrofits #1–4 for IPCC scenario A1B (a) and A2 (b) between 2020–2100 for cellulose in Oslo climate and following the FCT-UNL methodology

Thomson's methodology will not lead to the mechanical decay of furniture, sculptures pieces or panel paintings in nowadays conditions nor will it lead to mechanical decay in the future. These observations are valid for both selected climates. In addition, the application of any of the four selected retrofit measures will not decrease the quality of the indoor climate to safeguard these artefacts.

On the other hand, the FCT-UNL methodology can cause the mechanical decay of the base layer of panel paintings in Seville (Figure 12a and b) and the mechanical decay of the pictorial layer of panel paintings in Oslo (Figure 12c and d), since the 14%-limit is surpassed. Whilst the first observation worsens with time and it is heightened by the application of the retrofit measures, the second behaviour is attenuated by the application of these retrofit measures since they manage to reduce the amplitude of the RH cycles. Regarding Seville, the application of the retrofit measures decreases the free-floating indoor temperature mainly during the summer and spring, as was previously mentioned. This decrease will increase the relative humidity values, since the water-vapour pressure does not change significantly due to the rather low moisture impregnability capacity of the selected measures. This will inevitably increase the amount of time that the yield strain is surpassed. These observations show that the performance of retrofit measures is dependent on the climate.

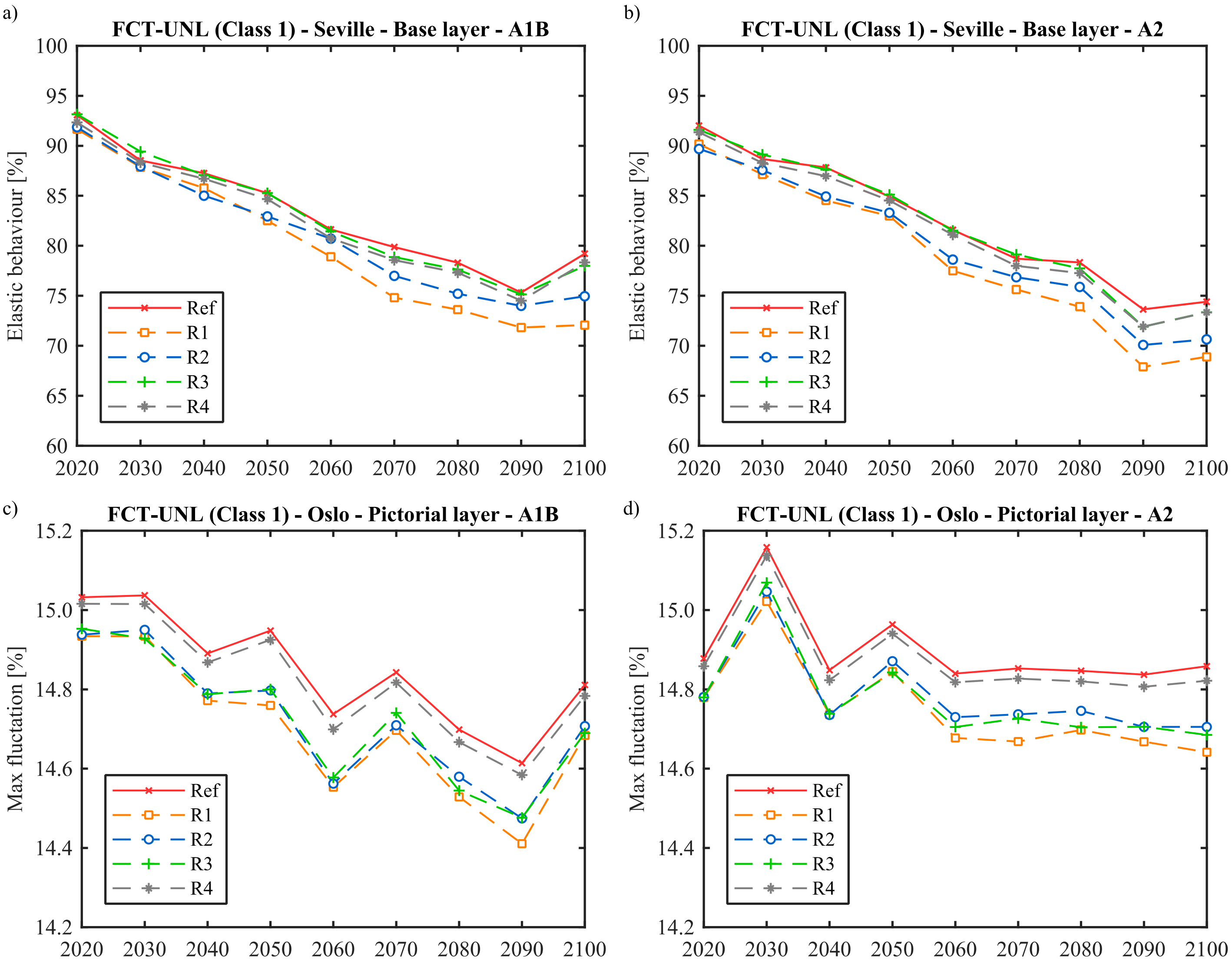

Figure 12 – Risk of mechanical decay in the base layer of panel paintings according to the FCT-UNL methodology for Seville for scenario A1B (a)

and A2 (b), and the risk of mechanical decay in the pictorial layer of panel paintings according to the FCT-UNL methodology for Oslo for scenario A1B (c) and A2 (d)

## 4. Conclusions

The present paper aimed to determine the energy consumption associated to three of the most used standards/guidelines to limit the indoor climate in buildings that house artefacts. It also aimed to determine how this consumption will evolve in the future due to climate change and how much it will cost to guarantee each standard/guideline for three types of climate in Europe. Additionally, four representative passive retrofit measures were tested to determine their energy saving potential.

In order to achieve these aims a validated whole-building hygrothermal model of a historic building (Church of *São Cristóvão* in Lisbon, Portugal) was used coupled to future weather files based on two IPCC scenarios – A1B and A2 – for five climates, namely: Lisbon (Portugal), Seville (Spain), Prague (Czech Republic), Oslo (Norway) and London (United Kingdom). Lastly, the indoor climates were also assessed in terms of biological, chemical and mechanical decay using a methodology based on several validated methods.

This paper intends to reinforce the idea that passive retrofit measures can be used to decrease the energy consumption of buildings that house artefacts considerably and, consequently, the financial and environmental costs, associated to guaranteeing the indoor climate adequate for artefacts in the future. It was also shown, that if the passive retrofit measures are combined with a more adequate relative humidity and temperature set-point strategy the energy savings are even higher. This paper allowed to test the impact of a representative set of passive retrofit measures on conservation, which highlighted the potential of various rehabilitation strategies in the studied climates.

Based on the shown data it is clear that some of the existing methodologies that aim to preserve artefacts will lead to high energy consumption in the future, but there are other methodologies in which the opposite occurs. Evidently, the magnitude of these behaviours varies with the methodology and the climate. For instance, the highest energy consumptions were attained by Oslo using Thomson's methodology, ca 267 MWh in 1990, but it tends to decrease in the future. Whilst the lowest energy consumptions were attained by Lisbon and Seville using ASHRAE methodology, ca 0.2 and 0.5 MWh in 2100 for scenario A1B respectively, as well as the FCT-UNL methodology, ca 3.3 and 3.7 MWh in 2100 for scenario A1B, respectively.

It was also shown that for the constant valued methodologies the key factor for the colder climates is the minimum temperature limit whilst for the Mediterranean climates is the maximum limit. However, this latter factor will gain even more importance in the future since it is expected that the indoor free-floating temperature is going to increase substantially. The overall energy costs for the dynamic methodologies will be quite significant for climates like Oslo, Prague and London mostly due to the minimum temperature limit.

It was demonstrated the positive outcome of implementing retrofit measures in historic buildings for future conditions in terms of energy saving potential. The application of an interior insulation achieved the highest saving potential which varies between 20–32%, followed by the application of an exterior thermal plaster which varies 16–20%, application of a thermal insulation layer in the ceilings which varies 13–20 % and lastly by replacing the existing windows which varies 4–6%. The energy saving potential of the case-study could be even higher if these retrofit measures would be properly combined. However, this is a complex challenge due to the large variability of the input parameters. It is important to bear in mind that the energy saving potentials can vary significantly from case to case, since they are dependent on a large number of variables, such as the building's volume, window/wall area ratio, among many others.

The risk-based analysis showed that, although retrofit measures are an interesting tool to significantly decrease the energy consumption in historic buildings that house artefact, their choice must be thoroughly studied prior to application, since their improvement potential can greatly differ according to the outdoor conditions. Hence, a more detailed analysis concerning these measures need to be performed.

In conclusion, it was shown that the standards/guidelines that buildings that house artefacts follow to preserve their content will lead to rather high financial costs for most of the tested cases, which shows the importance of studying ways to counteract this trend. In addition, it was shown the positive potential that applying passive retrofit measures can have on the energy consumption of these buildings, but a risk-based analysis should be performed to assess if the indoor conditions in terms of artefacts conservation really improve.

Despite the obtained results and conclusions, this study must be performed for other historic buildings with different geometries and building assemblies, as well as other outdoor climates before it can be used as a reference to support decision makers indisputably. Ultimately, this will make the analysis more comprehensive and founded.

## Acknowledgments

The authors acknowledge the FCT – *Fundação para Ciência e a Tecnologia* – for the financial support through the PhD scholarship PD/BD/127844/2016 and PD/BD/52654/ 2014. The first author acknowledges Hugo Bento Rebelo for his assistance with MATLAB.

## Appendices

In these three tables, the green colour means that the energy consumption diminishes, whilst the red colour means that the energy consumption increases. Plus, the value of the colour translates the magnitude of the decrease or increase, i.e. the light green means that the decrease is small and the dark green means that the decrease is substantial, while the light red means that the increase is small and the dark red means that the increase is substantial.

Table A.1 – Heating, cooling, humidification and dehumidification energy demand (kWh) for Thomson's methodology for IPCC scenario A1B and A2 between 1990 (reference case) and 2100 for Lisbon, Seville, Prague, Oslo and London

| Climate | | Ref | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lisbon | Heat | **48,897** | 43,958 | 40,940 | 39,080 | 36,245 | 34,844 | 32,599 | 31,755 | 29,708 | 29,713 |
| | | | 43,736 | 41,064 | 39,512 | 36,830 | 35,133 | 32,033 | 30,054 | 27,174 | 27,522 |
| | Cooling | **392** | 915 | 1,437 | 1,694 | 2,272 | 2,565 | 3,287 | 3,862 | 4,716 | 4,841 |
| | | | 934 | 1,278 | 1,647 | 2,071 | 2,732 | 3,840 | 4,937 | 6,542 | 6,762 |
| | Humid. | **15** | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Dehumid. | **3,627** | 4,862 | 5,524 | 6,176 | 6,945 | 7,563 | 8,372 | 8,879 | 9,647 | 9,916 |
| | | | 4,671 | 5,436 | 5,977 | 6,934 | 7,439 | 8,657 | 10,031 | 11,447 | 11,446 |
| Seville | Heat | **49,958** | 43,723 | 40,356 | 38,250 | 34,856 | 33,397 | 30,943 | 30,043 | 27,720 | 28,206 |
| | | | 43,134 | 40,125 | 38,469 | 35,728 | 33,900 | 30,357 | 28,466 | 25,389 | 25,809 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cooling | **7,655** | 12,452 | 14,407 | 16,615 | 18,820 | 21,161 | 23,188 | 25,752 | 27,919 | 28,464 |
| | | | 12,381 | 14,088 | 16,220 | 18,174 | 20,990 | 24,414 | 28,549 | 32,459 | 33,688 |
| | Humid. | **345** | 81 | 80 | 50 | 31 | 23 | 3 | 1 | 2 | 2 |
| | | | 55 | 75 | 54 | 35 | 15 | 7 | 1 | 1 | 0 |
| | Dehumid. | **4,343** | 6,636 | 7,730 | 8,793 | 10,653 | 11,655 | 12,973 | 14,193 | 15,589 | 15,537 |
| | | | 6,923 | 8,080 | 8,999 | 9,933 | 11,686 | 13,601 | 15,691 | 18,124 | 18,570 |
| Prague | Heat | **170,305** | 155,830 | 151,078 | 146,907 | 142,198 | 138,805 | 135,164 | 132,054 | 128,344 | 128,341 |
| | | | 156,803 | 152,320 | 148,641 | 143,761 | 139,712 | 134,463 | 130,289 | 125,088 | 124,869 |
| | Cooling | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 13 | 20 |
| | | | 0 | 0 | 0 | 0 | 0 | 3 | 20 | 97 | 171 |
| | Humid. | **9,495** | 8,272 | 7,856 | 7,410 | 6,906 | 6,551 | 6,213 | 5,821 | 5,486 | 5,445 |
| | | | 8,338 | 7,920 | 7,469 | 7,093 | 6,607 | 6,206 | 5,583 | 5,083 | 5,172 |
| | Dehumid. | **1,139** | 1,820 | 1,965 | 1,869 | 2,258 | 2,739 | 2,507 | 3,137 | 3,522 | 3,166 |
| | | | 1,290 | 1,715 | 1,937 | 2,304 | 2,523 | 2,906 | 3,284 | 3,736 | 3,851 |
| Oslo | Heat | **251,316** | 229,359 | 223,466 | 218,024 | 212,166 | 207,005 | 202,130 | 197,765 | 192,944 | 191,864 |
| | | | 232,738 | 226,234 | 219,372 | 212,996 | 206,889 | 200,392 | 194,626 | 188,213 | 187,556 |
| | Cooling | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Humid. | **14,963** | 12,970 | 12,400 | 11,947 | 11,380 | 10,869 | 10,377 | 9,810 | 9,518 | 9,462 |
| | | | 13,273 | 12,652 | 12,115 | 11,311 | 10,886 | 10,346 | 9,700 | 9,072 | 8,902 |
| | Dehumid. | **425** | 411 | 693 | 734 | 799 | 1,083 | 1,193 | 1,433 | 1,691 | 1,581 |
| | | | 655 | 474 | 909 | 747 | 778 | 1,168 | 1,081 | 1,554 | 1,173 |
| London | Heat | **145,903** | 134,247 | 130,422 | 127,220 | 123,645 | 121,020 | 117,484 | 115,276 | 111,913 | 111,555 |
| | | | 136,019 | 132,150 | 129,018 | 125,215 | 121,960 | 117,682 | 114,343 | 109,942 | 109,938 |
| | Cooling | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Humid. | **4,927** | 3,961 | 3,743 | 3,385 | 3,137 | 2,841 | 2,486 | 2,266 | 2,023 | 1,914 |
| | | | 4,168 | 3,768 | 3,502 | 3,220 | 2,999 | 2,616 | 2,331 | 1,974 | 2,028 |
| | Dehumid. | **1,503** | 2,043 | 2,426 | 2,670 | 2,858 | 3,084 | 3,747 | 3,821 | 4,093 | 4,346 |
| | | | 1,882 | 2,403 | 2,569 | 2,759 | 2,936 | 3,436 | 4,035 | 4,638 | 4,413 |

Table A.2 – Heating, cooling, humidification and dehumidification energy demand (kWh) for ASHRAE's methodology for IPCC scenario A1B and A2 between 1990 (reference case) and 2100 for Lisbon, Seville, Prague, Oslo and London

| Climate | | Ref | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lisbon | Heat | **1,770** | 1,120 | 859 | 589 | 443 | 273 | 254 | 153 | 118 | 93 |
| | | | 1,091 | 839 | 600 | 482 | 271 | 204 | 111 | 62 | 29 |
| | Cooling | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Humid. | **13** | 15 | 19 | 8 | 27 | 8 | 20 | 12 | 4 | 5 |
| | | | 0 | 22 | 3 | 42 | 9 | 4 | 3 | 9 | 5 |
| | Dehumid. | **124** | 68 | 166 | 123 | 214 | 139 | 122 | 140 | 150 | 82 |
| | | | 108 | 126 | 92 | 168 | 55 | 144 | 156 | 172 | 170 |
| Seville | Heat | **3,362** | 2,067 | 1,442 | 1,117 | 754 | 535 | 396 | 278 | 224 | 191 |
| | | | 1,968 | 1,321 | 1,210 | 844 | 613 | 386 | 235 | 100 | 129 |
| | Cooling | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Humid. | **127** | 77 | 77 | 74 | 154 | 187 | 131 | 135 | 87 | 50 |
| | | | 114 | 154 | 166 | 80 | 163 | 140 | 120 | 143 | 130 |
| | Dehumid. | **425** | 286 | 224 | 309 | 464 | 359 | 330 | 448 | 291 | 221 |
| | | | 507 | 317 | 466 | 260 | 504 | 268 | 416 | 386 | 312 |
| Prague | Heat | **80,037** | 69,977 | 66,245 | 63,537 | 60,128 | 57,675 | 55,042 | 53,057 | 50,312 | 50,235 |
| | | | 70,704 | 67,309 | 64,496 | 61,377 | 58,554 | 54,800 | 51,921 | 47,873 | 48,049 |
| | Cooling | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Humid. | **208** | 208 | 269 | 177 | 208 | 236 | 214 | 257 | 273 | 202 |
| | | | 258 | 226 | 201 | 279 | 204 | 261 | 227 | 276 | 229 |
| | Dehumid. | **290** | 353 | 439 | 240 | 266 | 526 | 223 | 540 | 348 | 370 |
| | | | 294 | 380 | 324 | 316 | 345 | 301 | 304 | 219 | 398 |
| Oslo | Heat | **144,827** | 127,626 | 122,828 | 118,698 | 113,952 | 110,165 | 106,150 | 102,827 | 99,093 | 98,306 |
| | | | 130,689 | 125,085 | 120,121 | 114,751 | 110,454 | 105,115 | 100,606 | 95,432 | 95,167 |
| | Cooling | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Humid. | **330** | 298 | 344 | 289 | 309 | 286 | 335 | 313 | 392 | 359 |
| | | | 279 | 313 | 301 | 325 | 293 | 316 | 309 | 392 | 324 |
| | Dehumid. | **478** | 226 | 322 | 249 | 220 | 378 | 248 | 244 | 358 | 234 |
| | | | 398 | 156 | 386 | 197 | 132 | 296 | 253 | 363 | 134 |
| London | Heat | **53,933** | 46,768 | 44,100 | 42,220 | 39,688 | 38,140 | 35,789 | 34,591 | 32,287 | 32,331 |
| | | | 47,731 | 45,054 | 43,382 | 40,750 | 38,855 | 36,120 | 34,284 | 31,331 | 31,593 |
| | Cooling | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Humid. | **13** | 13 | 44 | 21 | 21 | 29 | 35 | 38 | 33 | 100 |
| | | | 38 | 52 | 21 | 39 | 51 | 36 | 79 | 52 | 53 |
| | Dehumid. | **104** | 92 | 164 | 186 | 156 | 141 | 182 | 157 | 197 | 193 |
| | | | 92 | 174 | 81 | 125 | 119 | 96 | 180 | 128 | 137 |

Table A.3 – Heating, cooling, humidification and dehumidification energy demand (kWh) for FCT-UNL methodology for IPCC scenario A1B and A2 between 1990 (reference case) and 2100 for Lisbon, Seville, Prague, Oslo and London

| Climate | | Ref | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lisbon | Heat | **2,011** | 1,260 | 1,150 | 764 | 738 | 468 | 549 | 373 | 443 | 314 |
| | | | 1,272 | 1,109 | 850 | 719 | 480 | 560 | 413 | 504 | 362 |
| | Cooling | **1,176** | 1,326 | 1,172 | 1,299 | 1,129 | 1,254 | 1,183 | 1,447 | 1,187 | 1,373 |
| | | | 1,269 | 1,079 | 1,258 | 1,290 | 1,340 | 1,155 | 1,324 | 1,207 | 1,243 |
| | Humid. | **161** | 153 | 81 | 153 | 161 | 116 | 130 | 213 | 152 | 163 |
| | | | 33 | 139 | 107 | 165 | 168 | 91 | 90 | 83 | 101 |
| | Dehumid. | **525** | 694 | 880 | 978 | 1,071 | 1,283 | 1,191 | 1,377 | 1,382 | 1,456 |
| | | | 819 | 783 | 967 | 919 | 1,032 | 1,239 | 1,564 | 1,683 | 1,731 |
| Seville | Heat | **4,046** | 2,712 | 2,201 | 1,654 | 1,383 | 1,063 | 1,106 | 826 | 896 | 835 |
| | | | 2,587 | 2,083 | 1,808 | 1,535 | 1,258 | 1,035 | 738 | 883 | 852 |
| | Cooling | **951** | 1,013 | 916 | 1,241 | 870 | 1,144 | 1,019 | 1,165 | 1,045 | 1,166 |
| | | | 999 | 852 | 1,162 | 1,012 | 1,167 | 1,017 | 1,318 | 963 | 1,094 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Humid. | **71** | 145 | 119 | 135 | 160 | 243 | 184 | 234 | 232 | 173 |
| | | | 81 | 327 | 241 | 170 | 220 | 252 | 111 | 227 | 286 |
| | Dehumid. | **636** | 609 | 613 | 731 | 1,148 | 1,071 | 1,134 | 1,423 | 1,564 | 1,491 |
| | | | 662 | 566 | 781 | 816 | 1,101 | 1,177 | 1,518 | 1,766 | 1,855 |
| Prague | Heat | **80,231** | 70,143 | 66,384 | 63,726 | 60,362 | 57,850 | 55,242 | 53,179 | 50,474 | 50,324 |
| | | | 70,812 | 67,498 | 64,770 | 61,495 | 58,695 | 54,932 | 52,134 | 48,056 | 48,170 |
| | Cooling | **329** | 268 | 313 | 424 | 354 | 393 | 355 | 656 | 343 | 613 |
| | | | 564 | 416 | 492 | 373 | 493 | 520 | 528 | 561 | 891 |
| | Humid. | **815** | 735 | 815 | 653 | 721 | 614 | 660 | 673 | 702 | 578 |
| | | | 795 | 768 | 674 | 804 | 619 | 745 | 675 | 771 | 664 |
| | Dehumid. | **1,027** | 1,018 | 1,099 | 790 | 765 | 1,115 | 761 | 1,078 | 951 | 825 |
| | | | 777 | 966 | 886 | 1,006 | 1,027 | 877 | 813 | 730 | 975 |
| Oslo | Heat | **144,809** | 127,641 | 122,849 | 118,689 | 113,947 | 110,166 | 106,200 | 102,877 | 99,197 | 98,409 |
| | | | 130,729 | 125,092 | 120,108 | 114,744 | 110,446 | 105,117 | 100,709 | 95,633 | 95,293 |
| | Cooling | **161** | 149 | 70 | 77 | 55 | 73 | 59 | 87 | 32 | 88 |
| | | | 123 | 94 | 76 | 40 | 113 | 16 | 163 | 31 | 83 |
| | Humid. | **1,182** | 1,024 | 1,098 | 1,031 | 1,030 | 955 | 1,036 | 1,012 | 1,079 | 1,036 |
| | | | 1,058 | 1,105 | 1,055 | 997 | 974 | 966 | 945 | 1,021 | 941 |
| | Dehumid. | **1,438** | 1,045 | 1,125 | 1,085 | 998 | 1,091 | 1,077 | 1,111 | 1,176 | 995 |
| | | | 1,275 | 1,024 | 1,281 | 956 | 863 | 995 | 804 | 996 | 732 |
| London | Heat | **54,026** | 46,811 | 44,159 | 42,334 | 39,738 | 38,177 | 35,925 | 34,627 | 32,394 | 32,358 |
| | | | 47,772 | 45,103 | 43,476 | 40,829 | 38,897 | 36,172 | 34,349 | 31,496 | 31,662 |
| | Cooling | **275** | 347 | 345 | 241 | 262 | 356 | 250 | 328 | 372 | 360 |
| | | | 328 | 291 | 375 | 319 | 438 | 235 | 292 | 322 | 432 |
| | Humid. | **221** | 259 | 238 | 199 | 164 | 209 | 227 | 202 | 188 | 229 |
| | | | 229 | 236 | 197 | 226 | 228 | 237 | 204 | 261 | 203 |
| | Dehumid. | **383** | 309 | 387 | 434 | 383 | 378 | 453 | 469 | 542 | 504 |
| | | | 279 | 397 | 299 | 321 | 313 | 350 | 502 | 512 | 512 |

# References

[1] M. Martens, Climate risk assessment in museums: degradation risks determined from temperature and relative humidity data (PhD dissertation), Technische Universiteit Eindhoven, Eindhoven, 2012. doi:10.6100/IR729797.

[2] American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), ASHRAE Handbook-HVAC Applications, Atlanta, USA, 2015.

[3] M. legnér, On the Early History of Museum Environment Control - Nationalmuseum and Gripsholm Castle in Sweden, c.1866-1932, Studies in Conservation. 56 (2011) 125–137. doi:10.1179/sic.2011.56.2.125.

[4] G. Thomson, The Museum Environment, Butterworth-Heinemann, 1986.

[5] Ente Nazionale Italiano di Unificazione (UNI), UNI 10829:1999, Beni di interesse storico e artistico - Condizioni ambientali di conservazione - Misurazione ed analisi, (1999).

[6] European Committee for Standardization (CEN), EN 15757:2010, Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials, (2010).

[7] D. Camuffo, Microclimate for Cultural Heritage: Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments, 2nd Ed., Elsevier, New York, USA, 2014.

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

[9] H.E. Silva, F.M.A. Henriques, Hygrothermal analysis of historic buildings, Structural Survey. 34 (2016) 12–23. doi:10.1108/SS-07-2015-0030.

[10] Z. Huijbregts, R.P. Kramer, M.H.J. Martens, A.W.M. van Schijndel, H.L. Schellen, A proposed method to assess the damage

risk of future climate change to museum objects in historic buildings, Building and Environment. 55 (2012) 43–56. doi:10.1016/j.buildenv.2012.01.008.

[11] G.B.A. Coelho, H.E. Silva, F.M.A. Henriques, Impact of climate change on cultural heritage: a simulation study to assess the risks for conservation and thermal comfort, International Journal of Global Warming. 19 (2019) 382. doi:10.1504/IJGW.2019.104268.

[12] Z. Huijbregts, M.H.J. Martens, A.W.M. van Schijndel, H.L. Schellen, The use of computer simulation models to evaluate the risks on damage to objects exposed to varying indoor climate conditions in the past, present, and future, in: Proceedings of the 2nd Central European Symposium on Building Physics, 2013: pp. 335–342.

[13] Z. Huijbregts, M.H.J. Martens, C.M.H. Conen, I.M. Nugteren, A.W.M. van Schijndel, H.L. Schellen, Damage risk assessment of museum objects in historic buildings due to shifting climate zones in Europe, in: Proceedings of the 5th International Building Physics Conference, Kyoto, 28-31 May 2012, 2012: pp. 1271–1278.

[14] C. Turhan, Z.D. Arsan, G.G. Akkurt, Impact of climate change on indoor environment of historic libraries in Mediterranean climate zone, International Journal of Global Warming. 18 (2019) 206. doi:10.1504/IJGW.2019.101083.

[15] N. Nakicenovic, J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Griibler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, Z. Dadi, Special Report on Emissions Scenarios - A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2000.

[16] P. de Wilde, D. Coley, The implications of a changing climate for buildings, Building and Environment. 55 (2012) 1–7. doi:10.1016/j.buildenv.2012.03.014.

[17] World Heritage report 22, Climate Change and World Heritage: Report on predicting and managing the impacts of climate change on World Heritage and Strategy to assist States Parties to implement appropriate management responses, (2007) 1–55.

[18] C. Cornaro, V.A. Puggioni, R.M. Strollo, Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study, Journal of Building Engineering. 6 (2016) 17–28. doi:10.1016/j.jobe.2016.02.001.

[19] C.M. Muñoz-González, A.L. León-Rodríguez, J. Navarro-Casas, Air conditioning and passive environmental techniques in historic churches in Mediterranean climate. A proposed method to assess damage risk and thermal comfort pre-intervention, simulation-based, Energy and Buildings. 130 (2016) 567–577. doi:10.1016/j.enbuild.2016.08.078.

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

[21] G.B.A. Coelho, H.E. Silva, F.M.A. Henriques, Development of a hygrothermal model of a historic building in WUFI®Plus vs EnergyPlus, in: 4th Central European Symposium on Building Physics (CESBP 2019), Prague, Czech Republic, 2019. doi:10.1051/matecconf/201928202079.

[22] K. Sedlbauer, Prediction of mould fungus formation on the surface of and inside building components (PhD dissertation), Fraunhofer Institute for Building Physics, 2001.

[23] S. Michalski, Double the life for each five-degree drop, more than double the life for each halving of relative humidity, in: Thirteenth Triennial Meeting ICOM-CC, Rio de Janeiro, 22-27 September 2002, 2002: pp. 66–72.

[24] V. Rajčić, A. Skender, D. Damjanović, An innovative methodology of assessing the climate change impact on cultural heritage, International Journal of Architectural Heritage. 12 (2017) 1–15. doi:10.1080/15583058.2017.1354094.

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

[26] WUFI®Plus, Version 3.1.1.0, Fraunhofer Institute for Building Physics, (2017).

[27] UNESCO - What is meant by “cultural heritage”?, http://www.unesco.org/new/en/culture/themes/illicit-trafficking-of-cultural-property/unesco-database-of-national-cultural-heritage-laws/frequently-asked-questions/definition-of-the-cultural-heritage/ (access, (n.d.).

[28] European Committee for Standardization (CEN), EN 15758:2010, Conservation of cultural property. Procedures and instruments for measuring temperatures of the air and the surfaces of objects, European Committee for Standardization (CEN), (2010) 19.

[29] European Committee for Standardization (CEN), EN 16242:2012, Conservation of cultural heritage - Procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property, (2012).

[30] H.E. Silva, G.B.A. Coelho, F.M.A. Henriques, Climate monitoring in World Heritage List buildings with low-cost data loggers: The case of the Jerónimos Monastery in Lisbon (Portugal), Journal of Building Engineering. 28 (2020) 101029. doi:10.1016/j.jobe.2019.101029.

[31] Daylighting and window design- Lighting Guide LG10: 1999, The Chartered Institution of Building Services Engineers (CIBSE), (1999).

[32] G. Ciulla, A. Galatioto, R. Ricciu, Energy and economic analysis and feasibility of retrofit actions in Italian residential historical buildings, Energy and Buildings. 128 (2016) 649–659. doi:10.1016/j.enbuild.2016.07.044.

[33] C.D. Şahin, Z.D. Arsan, S.S. Tunçoku, T. Broström, G.G. Akkurt, A transdisciplinary approach on the energy efficient retrofitting of a historic building in the Aegean Region of Turkey, Energy and Buildings. 96 (2015) 128–139.

doi:10.1016/j.enbuild.2015.03.018.

[34] F. Ascione, N. Bianco, R.F. De Masi, F. De'Rossi, G.P. Vanoli, Energy retrofit of an educational building in the ancient center of Benevento. Feasibility study of energy savings and respect of the historical value, Energy and Buildings. 95 (2015) 172–183. doi:10.1016/j.enbuild.2014.10.072.

[35] P. Blecich, M. Franković, Ž. Kristl, Energy retrofit of the Krsan Castle: From sustainable to responsible design—A case study, Energy and Buildings. 122 (2016) 23–33. doi:10.1016/j.enbuild.2016.04.011.

[36] C.M. Muñoz-González, A.L. León-Rodríguez, M. Campano-Laborda, C. Teeling, R. Baglioni, The assessment of environmental conditioning techniques and their energy performance in historic churches located in Mediterranean climate, Journal of Cultural Heritage. (2018). doi:10.1016/j.culher.2018.02.012.

[37] F. Ascione, N. Cheche, R.F. De Masi, F. Minichiello, G.P. Vanoli, Design the refurbishment of historic buildings with the cost-optimal methodology: The case study of a XV century Italian building, Energy and Buildings. 99 (2015) 162–176. doi:10.1016/j.enbuild.2015.04.027.

[38] F. Ascione, F. De Rossi, G.P. Vanoli, Energy retrofit of historical buildings: Theoretical and experimental investigations for the modelling of reliable performance scenarios, Energy and Buildings. 43 (2011) 1925–1936. doi:10.1016/j.enbuild.2011.03.040.

[39] D. Milone, G. Peri, S. Pitruzzella, G. Rizzo, Are the Best Available Technologies the only viable for energy interventions in historical buildings?, Energy and Buildings. 95 (2015) 39–46. doi:10.1016/j.enbuild.2014.11.004.

[40] Meteonorm, Version 7, Meteotest Genossenschaft, (2014).

[41] G.B.A. Coelho, F.M.A. Henriques, Influence of driving rain on the hygrothermal behavior of solid brick walls, Journal of Building Engineering. (2016). doi:10.1016/j.jobe.2016.06.002.

[42] F. Antretter, T. Schöpfer, R. Kilian, An approach to assess future climate change effects on indoor climate of a historic stone church, in: 9th Nordic Symposium on Building Physics, 2011.

[43] S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller, eds., Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

[44] C. Sabbioni, P. Brimblecombe, M. Cassar, The Atlas of Climate Change Impact on European Cultural Heritage: Scientific Analysis and Management Strategies, Anthem Press, 2012.

[45] J. Leissner, R. Kilian, L. Kotova, D. Jacob, U. Mikolajewicz, T. Broström, J. Ashley-Smith, H.L. Schellen, M. Martens, J. van Schijndel, F. Antretter, M. Winkler, C. Bertolin, D. Camuffo, G. Simeunovic, T. Vyhlídal, Climate for Culture: assessing the impact of climate change on the future indoor climate in historic buildings using simulations, Heritage Science. 3 (2015) 38. doi:10.1186/s40494-015-0067-9.

[46] T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley, eds., Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013. doi:10.1017/CBO9781107415324.

[47] R. Kramer, H. Schellen, J. van Schijndel, Energy Impact of ASHRAE's Museum Climate Classes: A Simulation Study on Four Museums with Different Quality of Envelopes, Energy Procedia. 78 (2015) 1317–1322. doi:10.1016/j.egypro.2015.11.147.

[48] Eurostat - Electricity prices for non-household consumers - bi-annual data (from 2007 onwards), accessed November 2019, https://ec.europa.eu/eurostat/web/energy/data/database?p_p_id=NavTreeportletprod_WAR_NavTreeportletprod_INSTANCE_QAMy7Pe6HwI1&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_p_col_id=column-2&p_p_col_count=1.

[49] Eurostat - Energy statistics - electricity prices for domestic and industrial consumers, price components, accessed November 2019. https://ec.europa.eu/eurostat/cache/metadata/en/nrg_pc_204_esms.htm.

[50] EU Reference Scenario 2016: Energy, transport and GHG emissions Trends to 2050, Directorate-General for Energy, (2016) 1–221. doi:10.2833/9127.

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

[52] S. Jakieła, Bratasz, R. Kozłowski, Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions, Wood Science and Technology. 42 (2008) 21–37. doi:10.1007/s00226-007-0138-5.

[53] L. Bratasz, R. Kozlowski, A. Kozlowska, S. Rivers, Conservation of the Mazarin Chest: structural response of Japanese lacquer to variations in relative humidity, 15th Triennial Conference, New Delhi, 22-26 September 2008: Preprints/ICOM Committee for Conservation NV - 8 Figs. (2 Color), Refs. II (2008) 1086–1093.

[54] M.F. Mecklenburg, C.S. Tumosa, D. Erhardt, Structural response of painted wood surfaces to changes in ambient relative humidity, Painted Wood: History and Conservation. (1998) 464–483.

[55] Ł. Bratasz, R. Kozłowski, Ł. Lasyk, Allowable microclimatic variations for painted wood: numerical modelling and direct tracing of the fatigue damage, ICOM CC 16th. (2011).

[56] R. Kramer, J. van Schijndel, H. Schellen, Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe, Building and Environment. 118 (2017) 14–31. doi:10.1016/j.buildenv.2017.03.028.

[57] J. Ferdyn-Grygierek, Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems, Building and Environment. 107 (2016) 113–126. doi:10.1016/j.buildenv.2016.07.024.

[58] J. Ferdyn-Grygierek, Indoor environment quality in the museum building and its effect on heating and cooling demand, Energy and Buildings. 85 (2014) 32–44. doi:10.1016/j.enbuild.2014.09.014.

[59] A. Sadłowska-Sałęga, J. Radoń, J. Sobczyk, K. Wąs, Influence of microclimate control scenarios on energy consumption in the Gallery of the 19th-Century Polish Art in the Sukiennice (the former Cloth Hall) of The National Museum in Krakow, IOP Conference Series: Materials Science and Engineering. 415 (2018) 012026. doi:10.1088/1757-899X/415/1/012026.

[60] M.F. Mecklenburg, Determining the acceptable ranges of relative humidity and temperature in museums and galleries. Part 2, Structural Response to Relative Humidity, Smithsonian Institute. (2007) 1–29. doi:10.1103/PhysRevB.90.165140.

[61] F. Roberti, U.F. Oberegger, A. Gasparella, Calibrating historic building energy models to hourly indoor air and surface temperatures: Methodology and case study, Energy and Buildings. 108 (2015) 236–243. doi:10.1016/j.enbuild.2015.09.010.