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Energy Efficiency in Historic Museums: The Interplay between Thermal Rehabilitation, Climate Control Strategies and Regional Climates

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Abstract: Museums housed in historical buildings combine the intrinsic value of the collections with the historical and architectural values of the building itself. Although usually made with thick elements with high thermal inertia, very effective in damping and delaying the heat flow, these buildings are usually characterized by elements with low thermal resistance, poor-quality windows and low area/volume ratio in the noblest buildings, which renders them ineffective at maintaining a stable indoor climate adequate for conservation, comfort and energy efficiency issues. In this paper, a simulation study was carried out to analyze the impact of the building location (weather), thermal envelope and climate control strategies by analyzing a generic room of the National Museum of Ancient Art of Lisbon. A simulation study was carried out for 15 European cities to verify the impossibility of standardizing the rehabilitation solutions in cultural heritage since energy needs depend on the location. It was concluded that the focus on climate control strategies has great potential for energy reduction and that in temperate climates of southern Europe, the improvement of thermal transmittance has a reduced effect on the building's response.

Keywords: cultural heritage; energy efficiency; energy reduction; museums; thermal rehabilitation

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1. Introduction

Traditionally, comfort and conservation in museums impose the use of tight ranges of temperature and relative humidity [1–6], sometimes with no scientific justification. Take the case of the National Museum of Ancient Art of Lisbon (NMAA), which imposes a tight climate control of 20–22 °C and 50–60% RH even though the building is unable to comply with it for percentage of time that can be considered satisfactory, as concluded by the authors in [2]. These constraints, coupled with the poor hygrothermal response of ancient buildings, lead to high energy consumption.

Rising environmental concerns and the publication of directives in the pursuit of greater sustainability and reduction of global warming that emerged over the last two decades have led to hygrothermal rehabilitation of buildings which significantly contribute to the total energy consumption in Europe [7]. The European energy policy has become more demanding and the European Union (EU) has taken energy efficiency as an urgent need, developing some ambitious directives aiming to achieve energy reduction in the building sector, where it is possible to highlight the 2018/844/CE [8]. This directive is very demanding and binding on new buildings or extensive rehabilitations, but leaves cultural heritage buildings out given their needs and specificities, namely the risk of loss of identity and historical quality induced by invasive interventions [6,9]. However, this new version specifies the following need:

"Research into, and the testing of, new solutions for improving the energy performance of historical buildings and sites should be encouraged, while also safeguarding and preserving cultural heritage" [8]

Despite these directives, the evolution of energy consumption in the services sector, including museums, does not follow the global trend of energy reduction, as can be seen in Figure 1. It is possible to see a sharp decrease during the period of the public debt crisis in the Eurozone and during the pandemic, but the global trend since 2000 is of an increase in the final energy consumption. Comparing the period before the pandemic—up to 2019—and taking the year 2000 as the reference, the EU27 presents an increase of around 23% and Portugal an increase of 68% [10].

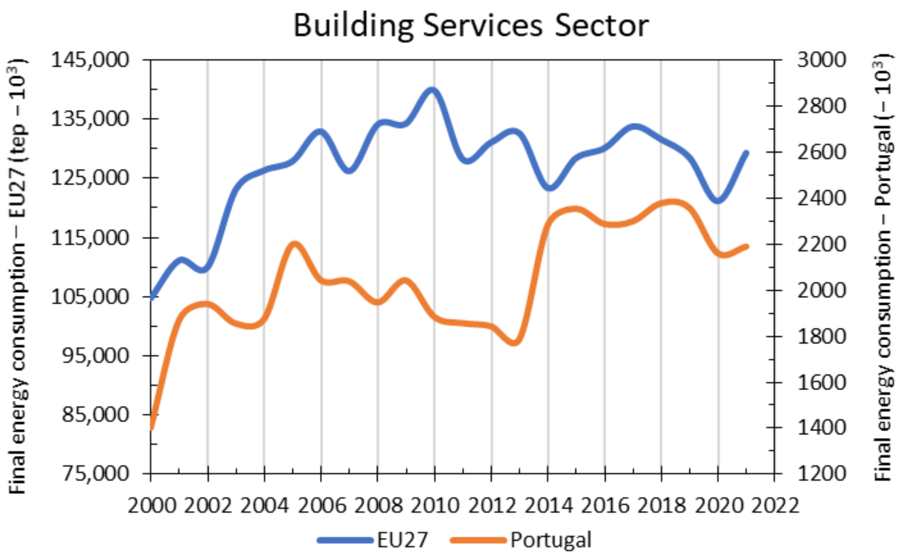


Figure 1. Energy consumption in the building services sector since 2000 [10].

The ineffectiveness of European policies to reduce energy consumption in the services sector in general, and in particular in cultural heritage, cannot be solved by the publication of new directives focusing solely on energy, since the patrimonial character associated with these buildings does not allow it, thus enhancing the need to find a balance between conservation, comfort and energy [11] rather than an incessant search for the numbers.

Despite all the evolution in the use of passive techniques in the design of new buildings and in rehabilitation, the intervention in classified buildings is not obvious and is impossible to standardize [9,12,13]. Due to the impossibility of changing the original architecture [14,15], quite often a change in the climate control strategy, window refurbishment or, in some cases, the use of thermal insulation in the interior are some of the most obvious solutions to implement. Furthermore, it is necessary to take into account the impact of climate change when making decisions about the interventions that will occur [16]. An extensive literature review on the use of thermal insulation and windows in historic buildings can be seen in [17].

The impact of thermal rehabilitation and climate control strategies on cultural heritage has been studied by several authors [7,18–23]. Interesting results were obtained by Kramer et al. [7], for example, achieving energy savings of around 77% for a Dutch museum by changing the original constant set-point of 21 °C and 48% RH to a less demanding target—40–50% RH—and a dynamic temperature set-point based on an adaptative thermal comfort model and in free-floating at the night time. This new scenario allows us to obtain a high energy reduction while significantly improving the conservation and thermal comfort.

At the level of thermal rehabilitation, the studies developed by Wang et al. [22] at the National Gallery of Edinburgh or by Sciurpi et al. [18] at the "La Specola" museum in Florence can be highlighted. Wang et al. [22] achieved energy savings of around 15% in heating needs, 28% in cooling needs, 4% in humidifying needs and 34% in dehumidifying needs by replacing the original skylight of a model of the National Gallery of Edinburgh, with a U_w of 5.67 W/m^2.°C, with a new solution with 2.25 W/m^2.°C. For a museum located in Florence, Sciurpi et al. [18] achieved energy savings of around 51% in a certain room by replacing the original windows with U_w = 4.96 W/m^2.°C and SHGC = 0.87 with new windows with U_w = 2.36 W/m^2.°C and SHGC = 0.21.

Other cases regarding museums or ancient buildings with different climate control strategy requirements can be found in the literature, namely [24–31].

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

In a second phase, the impact of the windows and opaque envelope refurbishment in parallel with the use of two different climate control strategies were evaluated for the Portuguese case through a sensitivity study composed of 128 different combinations.

This paper stands out for analyzing the energy needs and behavior of buildings that host museums in 15 European cities. This analysis allows us to conclude that management and rehabilitation solutions cannot be standardized across Europe, as the local climate has a major impact on the hygrothermal and energetic response of buildings. The result of this paper is to break down various taboos in energy rehabilitation, showing that interventions should be designed according to the local needs of each building rather than using standardized solutions.

2. Methodology

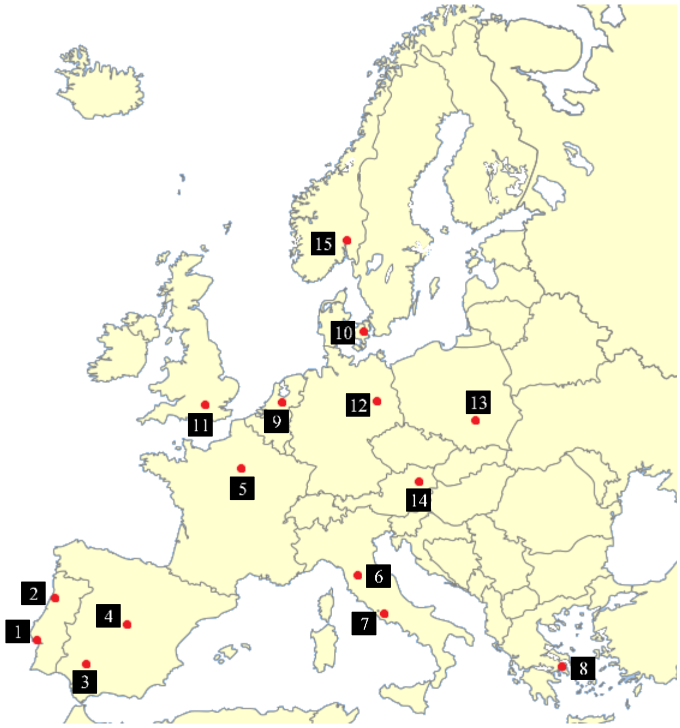
2.1. General Overview

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

Trying to prove that the energetic rehabilitation solutions cannot be generalized to all climates and situations, a simulation model of a generic room of the National Museum of Ancient Art of Lisbon was developed with the software WUFI®Plus and simulated for 15 European cities. The WUFI®Plus v3.1.1.0 is an hygrothermal simulation software based on the calculation model presented in Ref. [32]. The software has been extensively tested and validated [33–35] and has several applications for cultural heritage [35–38], in particular within the European project "Climate for Culture" [39].

The model was simulated for the climate control strategy used by the National Museum of Ancient Art which follows the more conservative values used in museums: 20–22 °C and 50–60% RH.

The 15 cities chosen for this analysis, their geographical location and Köppen classification [40] can be seen in Figure 2. The temperate climates are classified as type C and characterized by an average temperature of the coldest month being between 0 and 18 °C. Cold climates are classified as type D and present an average temperature of the coldest month below 0 °C. The subtype "s" shows the presence of a markedly dry periods during the summer and the subtype "f" shows the absence of a dry season. The last letter of the classification depends on summer: the subtype "a" characterizes hot summers with the average temperature of the hottest month exceeding 22 °C and the subtype "b" characterizes mild summers with the average temperature of the hottest month equal to or lower than 22 °C. Thus, the Csa classification applies to temperate climates with dry and hot summers; the Csb classification applies to dry temperate climates with mild summers; the Cfb classification applies to temperate climates without a dry season and with mild summers; and the Dfb classification applies to cold climates without a dry season and with a mild summer.



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

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

Figure 2. Geographical location of the 15 European cities studied.

For Lisbon, a test reference year (TRY) was developed in accordance with the international standard ISO 15927-4 [41] for the hourly climatic data provided by the Portuguese Institute for Sea and Atmosphere (IPMA) for the Geofisico weather station from 2005 to 2015. For more details, please see [42].

The Oporto weather file was provided by the Laboratório de Física das Construções (LFC) of the Faculty of Engineering of the Oporto University. The weather files of the remaining 13 cities under analysis were taken from the EnergyPlus weather database [43]. These files represent typical climatic years for energy calculations mostly of type IWEC (as a result of the ASHRAE Research Project 1015 by Numerical Logics and Bodycote Materials Testing Canada for ASHRAE Technical Committee 4.2 Weather Information)—Vienna, Berlin, Copenhagen, Paris, London, Athens, Amsterdam and Oslo—and by files created by agencies of each country such as the SWEC (Grupo de Termotecnia of the Escuela Superior de Ingenieros in Seville)—Madrid and Seville; IGDG (Italian Climatic data collection "Gianni De Giorgio")—Rome and Florence; and IMGW (Polish Ministerstwo Infrastruktury)—Krakow.

The climatic classification according to Köppen, the annual averages of temperature and relative humidity, the annual global solar radiation and the typical range between the 5th and 95th percentile for temperature and relative humidity for the 15 cities can be seen in Table 1. The climatic extremes were analyzed according to the percentiles instead of using the absolute maximum and minimum values because it is considered of greater utility for the typical understanding of the climate of each city.

Table 1. Climatic characterization of the fifteen cities under analysis.

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

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

To highlight the differences in climate, the daily cycles of temperature, relative humidity and global horizontal radiation were analyzed for a typical winter and summer day. In Figure 3, this analysis is presented for Lisbon, Amsterdam, Krakow, Madrid, Berlin and Florence.

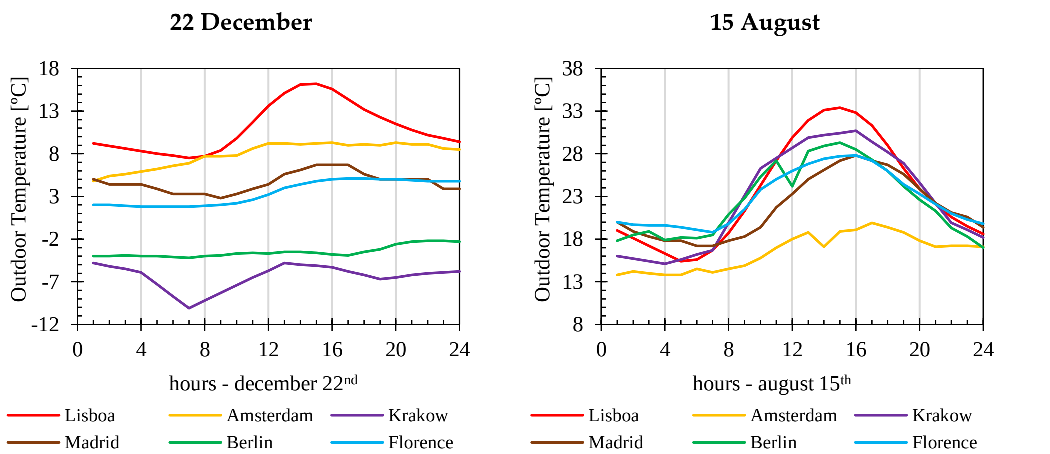


Figure 3. *Cont.*

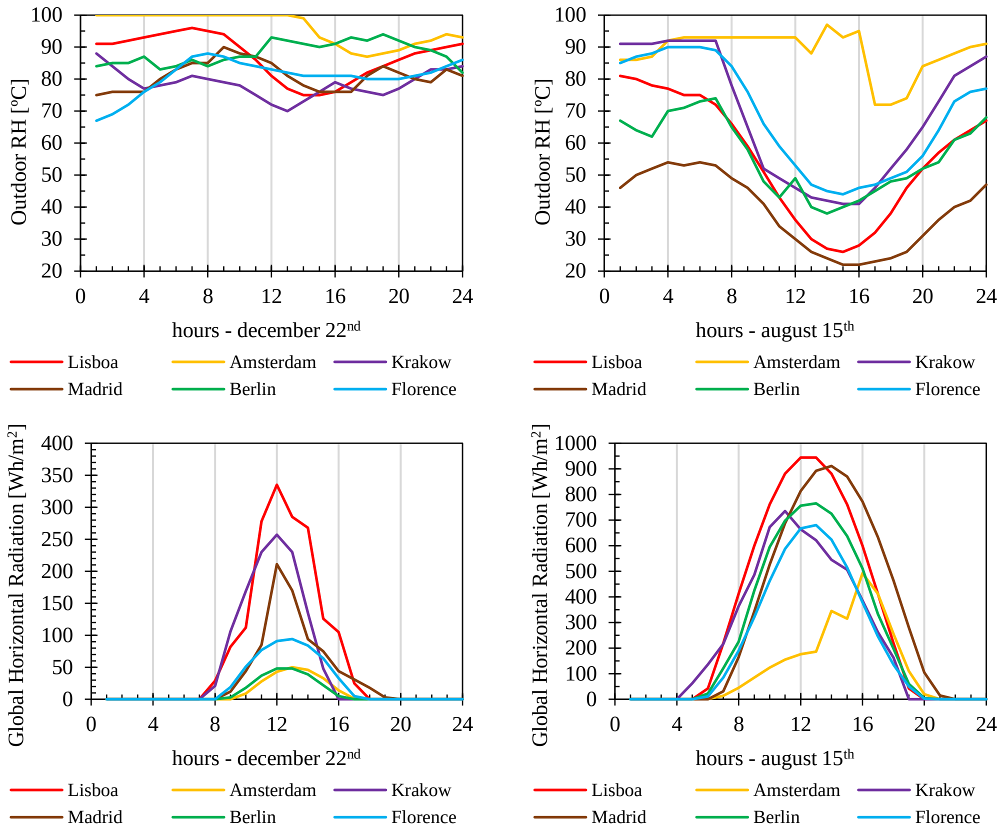


Figure 3. Daily cycles of outdoor temperature, relative humidity and global horizontal radiation for typical days of winter and summer for Lisbon, Amsterdam, Krakow, Madrid, Berlin and Florence.

2.2. Simulation Model

2.2.1. Building Geometry

A generic room of the National Museum of Ancient Art of Lisbon (NMAA) south-oriented with ca. 590 m^3 (22.5 × 7.5 × 3.5 m^3) was used for this study (see Figure 4). All surfaces were considered to be adiabatic except for the south façade.

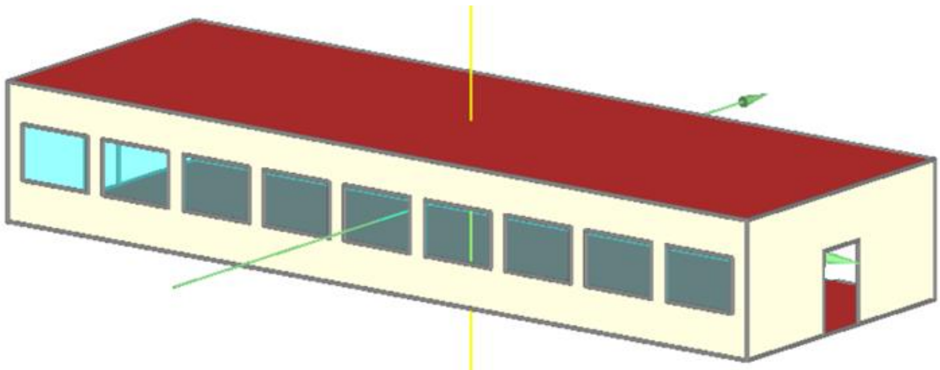


Figure 4. Model geometry.

The building is characterized by mortared limestone walls with lime renderings on both sides with a total thickness of 0.90 m. The reinforced concrete floor has a wood flooring layer on top. The room is composed of nine aluminum-framed double-glazed windows resulting in a window/floor ratio of 0.15 and a window/façade ratio of 0.31. The windows include clear and transparent interior shading elements and are characterized by a total solar heat gain coefficient (SHGC) of 0.38 [44].

All building assemblies considered in the simulation study (i.e., exterior and interior walls, the interior ceiling and floor and windows) as well as the respective properties of the materials can be seen in Table 2. The material properties were collected from the refs. [44,45].

Table 2. Assemblies and respective material properties used in the model [45,46].

Building Component	Materials	d [m]	λ [W/m.K]	ρ [kg/m³]	C [J/kg.K]
Walls Outside → Inside	Lime mortar	0.03	0.70	1785	850
	Mortared limestone	0.84	1.76	2122	850
	Lime mortar	0.03	0.70	1785	850
Ceiling Outside → Inside	Wooden layer	0.02	0.15	740	1400
	Concrete	0.25	1.70	2322	850
	Lime mortar	0.03	0.70	1785	850
Floor Outside → Inside	Lime mortar	0.03	0.70	1785	850
	Concrete	0.25	1.70	2322	850
	Wooden layer	0.02	0.15	740	1400
Windows	Double-glazed aluminum frames		U_w = 3.63 W/m^2.°C		SHGC = 0.38

2.2.2. Internal Gains and Ventilation

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

Parameters reporting internal gains are shown in Table 3. For more information, please see [42,47].

Table 3. Internal gains and ventilation used in the model [42,48–50].

Visitors' Impact	
Average occupancy	10 visitors/h (open hours)
Sensible heat	88 W/(person.h) (60% emitted by radiation and 40% by convection) [42,47]
Latent heat	39 W/(person.h) (converted into 61 g/(person.h) according to [42,47]
CO_2 generation rate	34 g/(person.h) [42,48,49]
LPD (lighting power density)	4.8 W/m^2 [32]
Ventilation	
Open hours	456 m^3/h of fresh air [42,49]
Night period	61 m^3/h of fresh air [42,50]

2.3. Sensitivity Study

A sensitivity study was designed to attest the impact of the windows and the opaque envelope on the energy demand in museums for two different climate control strategies for the case of Lisbon. Four solutions for the windows' thermal transmittance, four solar heat gain coefficients and four solutions for the thermal transmittance of the opaque envelope were analyzed through the use of a sensitivity study to correlate all the hypotheses, performing a total of 128 simulations.

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

For the windows, the U_w values were estimated according to CIBSE Guide A [51]: 6.01 W/m^2.°C for single-glazed and aluminum frames without thermal cut; 3.63 W/m^2.°C for double-glazed with an air layer of 6 mm and aluminum frames with 4 mm of thermal shear; 2.55 W/m^2.°C for double-coated glazes (ε = 0.2) with an air layer of 12 mm and aluminum frame with 12 mm of thermal shear; and 1.53 W/m^2.°C for double-coated glazes (ε = 0.05) with an argon layer of 16 mm and PVC frames with three hollow chambers. The use of windows with 1.4 × 2.0 m^2 and a ratio of 0.185 between the frame area and the total area were considered.

As regards the solar heat gain coefficient (SHGC), a minimum theoretical value of 0 was used to simulate a window totally covered by a plasterboard and a maximum SHGC of 0.75 to simulate a double-glazed window with no shading elements [43]. SHGC can be obtained through various combinations of glazed and shading elements—more details can be found in [51,52].

The impact of the U, U_w and SHGC in the energy consumption was simulated for two different climate control strategies: (a) the first one simulating the actual conditions used in the museum (20–22 °C and 50–60% RH); (b) and the second using a less demanding target of 16–25 °C during the closing hours and 18–25 °C during the opening hours to guarantee the visitors' thermal comfort. For the relative humidity, a set point of 40–60% RH was implemented. This less demanding strategy is in accordance with the targets argued by the Group of Organizers of Large-scale Exhibitions (Bizot Group, which comprises the directors of the world's leading museums and galleries), the Australian Institute for the Conservation of Cultural Materials (AICCM) and the Association of Art Museum Directors (AIC) for loan collections [53–56]. An ideal HVAC system (i.e., 100% efficiency) was adopted since the aim of this study is to compare the energy consumption of a set of conditions and not to analyze the absolute consumption. The simulation diagram can be seen in Figure 5.

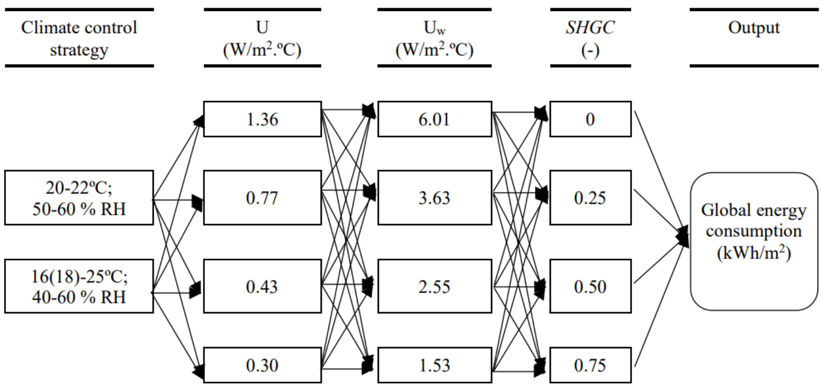


Figure 5. Sensitivity study to assess the impact of the climate control strategy and window refurbishment on energy consumption.

3. Results and Discussion

3.1. The Impact of the Climatic Zone on Energy Consumption

The results of the energy simulation for the 15 cities can be seen in Figure 6. This analysis allowed us to conclude that the cities of Oporto and Lisbon (in Portugal) present the lowest energy requirements with 45 kWh/m^2.year and 64 kWh/m^2.year, respectively, while Oslo and Krakow are at the opposite extreme with consumptions of 135 kWh/m^2.year and 117 kWh/m^2.year, respectively. Separating the analyzed cities into three main groups ordered by the total energy consumption, Oporto, Lisbon, Seville, Rome and Madrid can be classified in the first group; London, Athens, Amsterdam, Paris and Florence in the second group; and Berlin, Copenhagen, Vienna, Krakow and Oslo in the third group. The first group of cities are all located in southern Europe.

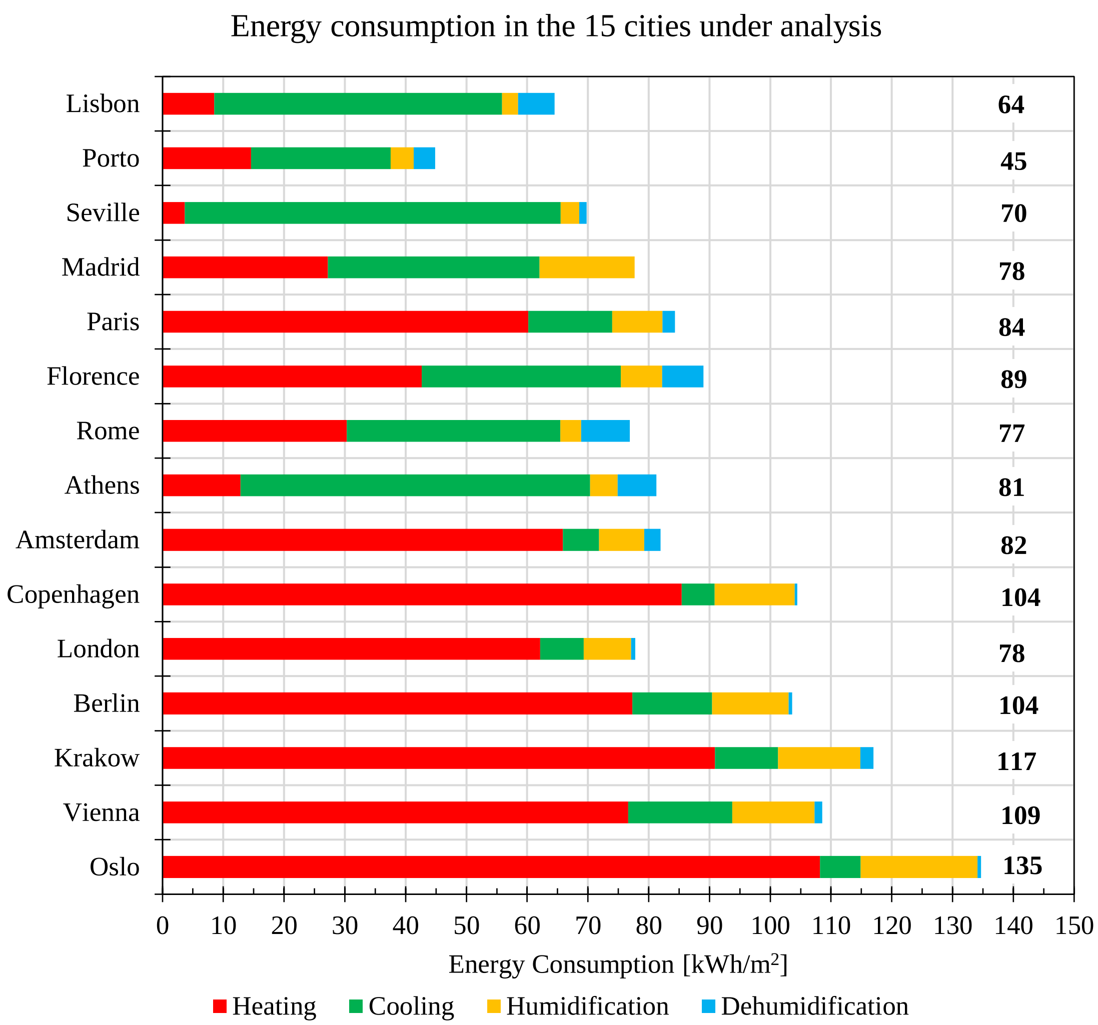


Figure 6. Energy consumption in the 15 cities under analysis.

However, this analysis can be reductive since it only focuses on absolute consumption. Consider for example the case of Athens, which, although classified in the second group with 81 kWh/m^2.year, behaves differently to London, also in the second group with a consumption of 78 kWh/m^2.year. In Athens, the cooling demand assumes 71% of the global energy consumption, while heating needs in London account for 80% of the global consumption.

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

By analyzing the energy consumed to maintain the temperature set-point, it can be observed that the cooling needs are higher than the heating needs in three cities, accounting for more than 70% of the total consumption: 71% in Athens, 74% in Lisbon and 89% in Seville. Oporto, Madrid, Rome and Florence show more balanced behavior, while for the remaining cities, the heating needs are responsible for most of the energy consumption. These results allow us to conclude the impossibility of defining a global policy for conservation and energy reduction in Europe, since the necessities of the different locations are quite different.

To define an efficient and adjusted rehabilitation strategy for each case, an analysis of heat gains and losses between the building and the surrounding environment was carried out. The results are presented in Figure 7 for the heat losses in the heating season and in Figure 8 for the heat gains in the cooling season. Heat losses from cooling the room (C), from ventilation (V), from the opaque envelope (O.E.) and from the windows (W) were analyzed. Heat gains to heat the room (H), from ventilation (V), from the opaque envelope (E.O.), from the windows (W), due to internal gains (I.g.) and due to solar gains were also analyzed.

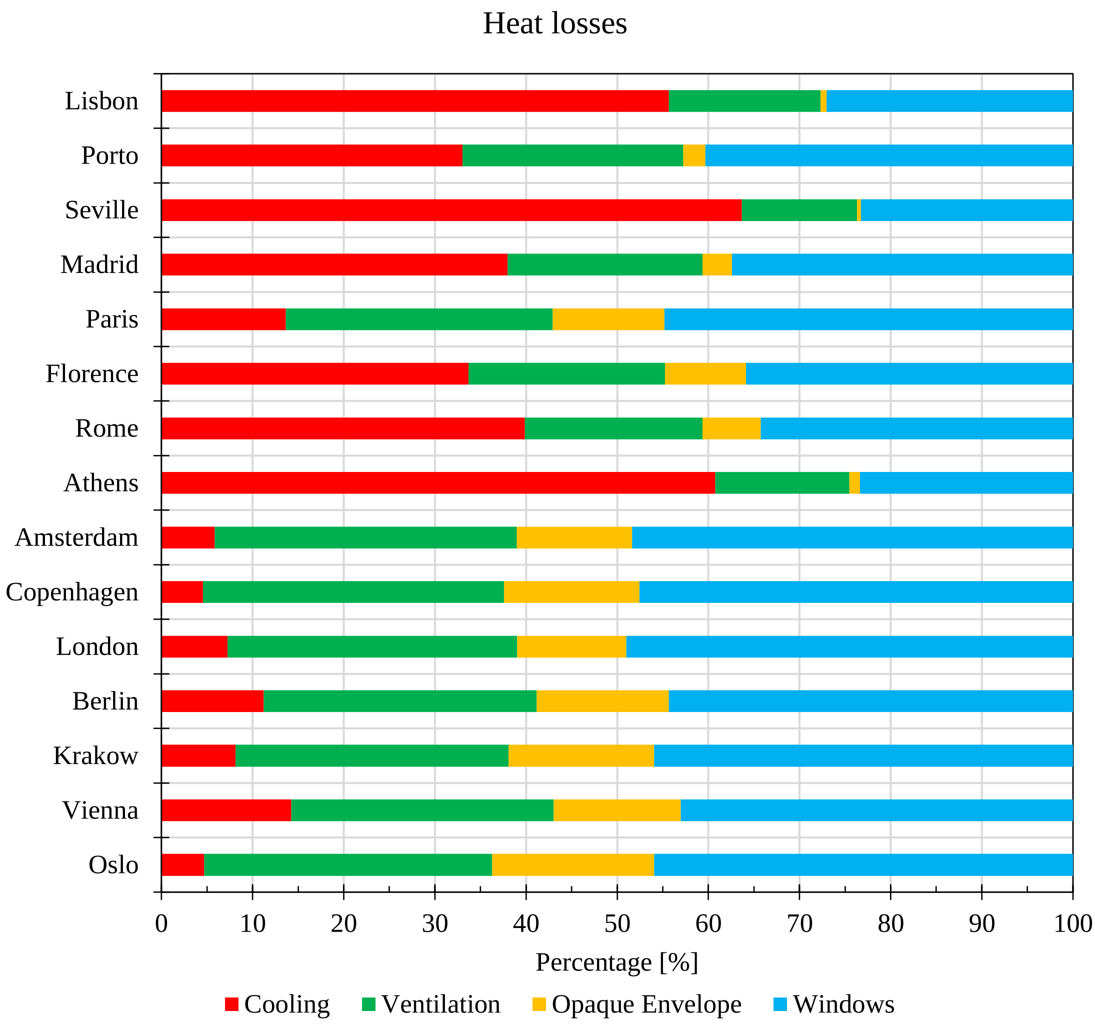


Figure 7. Heat losses during the heating season.

As far as losses are concerned, it is possible to observe different behaviors for the 15 cities. For Lisbon, Seville and Athens, the loss of heat through the HVAC system to cool the room plays a prominent role and is responsible for ca. 56%, 64% and 61% of the total losses, respectively. Following this, the losses through the windows and ventilation can be found. The cities of Oporto, Madrid, Rome and Florence present losses relatively well distributed by the HVAC system, the windows and the air exchanges with the exterior. It is interesting to note that for all the cities of southern Europe, the losses through the opaque envelope are practically negligible. For the remaining cities, located in central and northern Europe, the panorama changes. Losses through the HVAC system lose their preponderance and the losses through windows and ventilation assume a prominent position. The losses through the opaque envelope take values that can justify their improvement with losses ranging from ca. 12% in Paris and London to ca. 18% in Oslo.

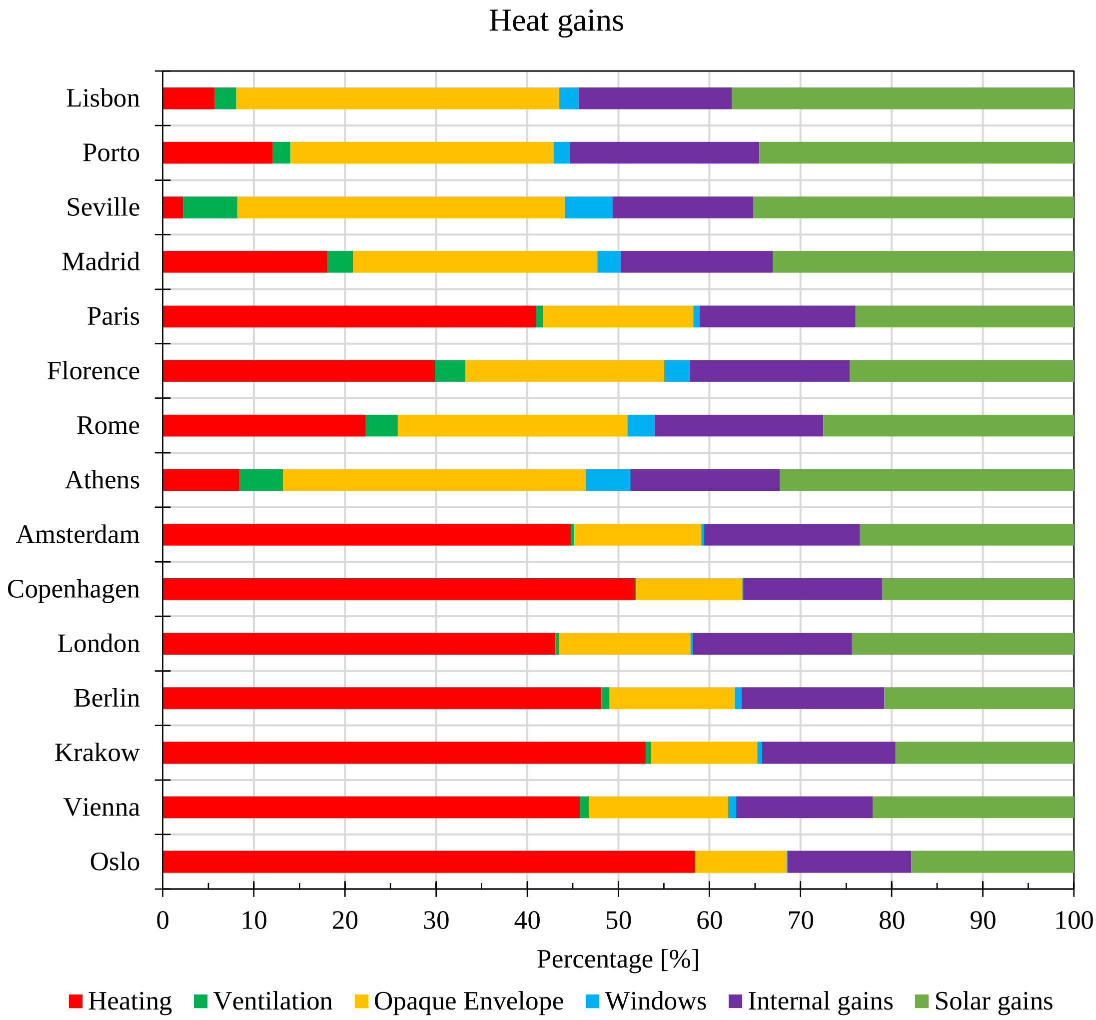


Figure 8. Heat gains during the cooling season.

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

The gains from the opaque envelop take also a prominent role. This can be justified by the high thermal inertia of the elements and the tightness of the indoor climate control which makes the surface temperature of the opaque elements often higher than the air temperature, triggering heat flows over large periods. Data referring to Lisbon are presented in Figure 9: the comparison between the indoor air temperature and the internal surface temperatures of the southern wall, the three internal walls, the floor and the ceiling in (a) and the density of the heat flow rates in the surfaces in (b). The density of the heat flow rate in the surfaces was obtained from Equation (1) [57]:

$$q_x = \frac{\left(T_{amb} - T_{surface,x}\right)}{R_s} \tag{1}$$

where q is the density of heat flow rate (W/m^2) of the element x; Rs means the internal surface resistance ($m^2 \cdot °C/W$); T_{amb} means the indoor air temperature (°C) and $T_{surface,x}$ means the internal surface temperature of the element x (°C). Following the standard EN 6946 [57], for the walls, an internal surface resistance of 0.13 $m^2 \cdot °C/W$ was adopted. For the floor and the ceiling, surface resistances of 0.1 and 0.17 $m^2 \cdot °C/W$ were considered, respectively.

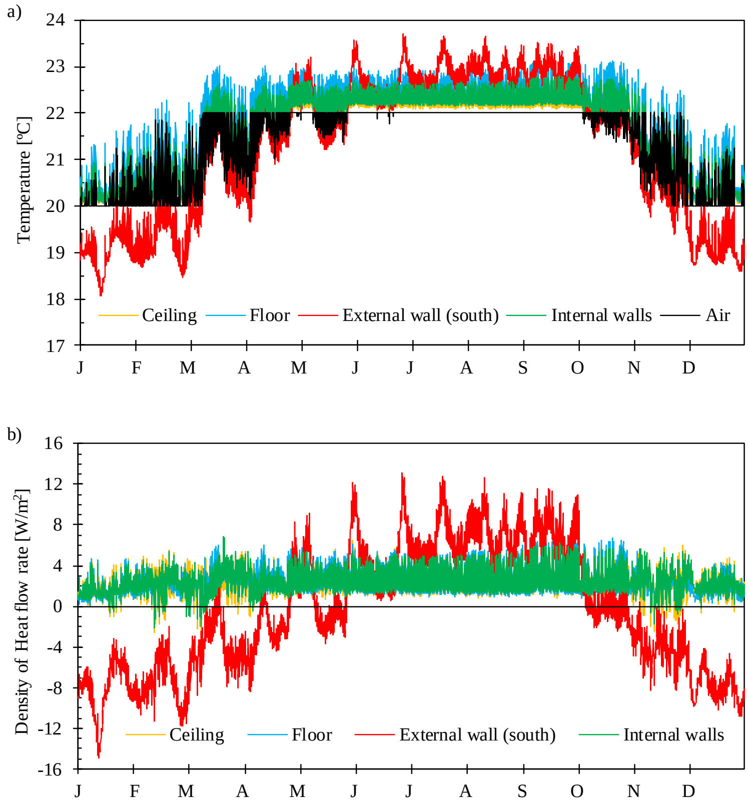


Figure 9. Comparison between the indoor air and the surface conditions: (**a**) indoor air temperature and internal surface temperatures; (**b**) density heat flow rate of the between the surfaces and the interior environment.

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

This analysis allows us to conclude that energy reduction can be obtained firstly by changing the climate control strategy, since conservation and comfort are not compromised. In warmer cities, considerable reductions may be achieved by reducing the solar heat gain coefficients of the windows or by including openings in the interior walls to reduce heat storage. In these cases, where the cooling needs are higher than the heating needs and where the contribution of the opaque envelope in the losses is reduced, the implementation of thermal insulation can be hardly seen as an efficient way to reduce the energy demand. In cases where heating needs are the main contribution to global energy consumption, the solution may be the refurbishment of the windows, increasing the SHGC and the implementation of thermal insulation in the opaque envelope. However, it is necessary to consider that the increasing incident radiation causes important hygrothermal variations and may compromise the artefact's conservation. A situation like this must be carefully studied.

3.2. Energetic Analysis

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

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

The results of the sensitivity study relating the impact of the climate control strategies, U, U_w and the SHGC on the global annual energy consumption for the case of Lisbon can be seen in Figure 10. The reference energy consumption is also presented, allowing us to effectively analyze the impact of each one of the rehabilitation scenarios in the final result.

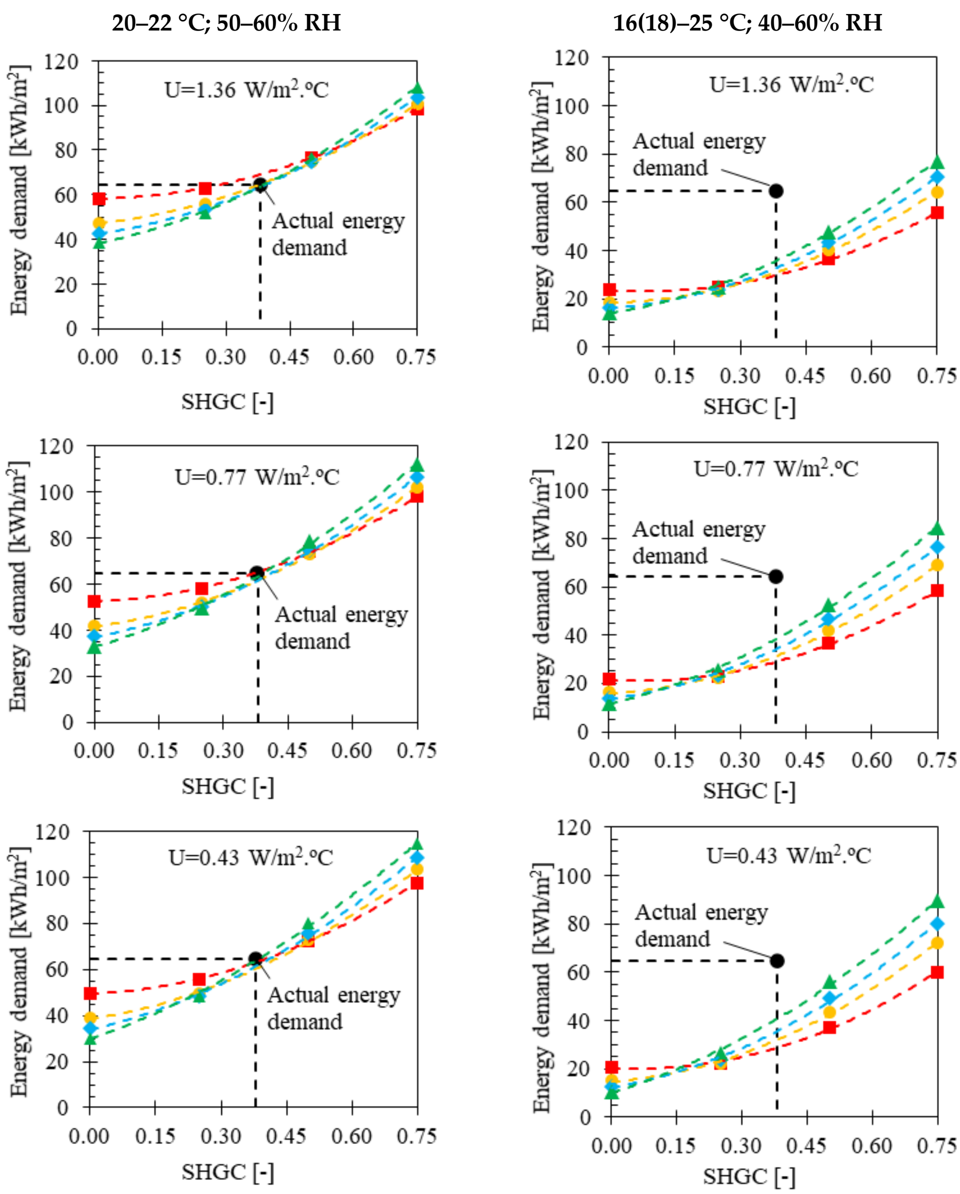


Figure 10. *Cont.*

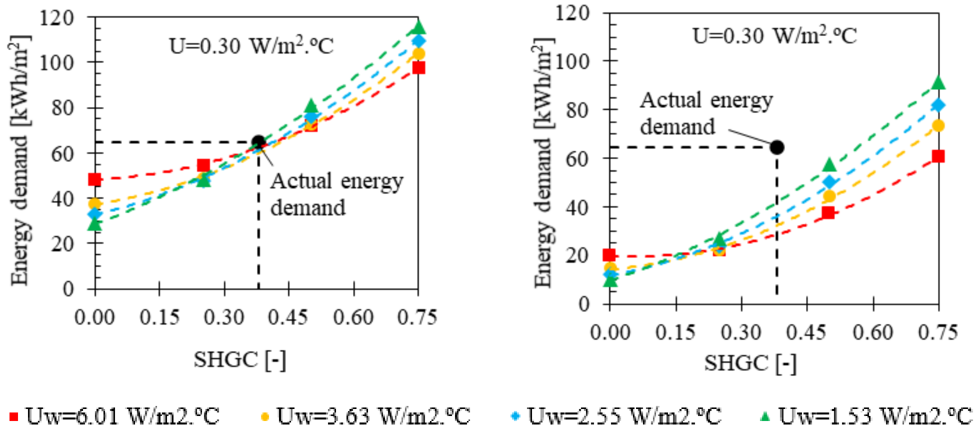


Figure 10. Impact of the climate control strategy, the rehabilitation of windows and opaque envelope on the energy consumption of a museum room—the case of Lisbon.

The improvement of the thermal transmittance of the opaque envelope and windows provides better results as lower as the SHGC values. With the increase in the SHGC, the improvement of the U and U_w coefficients provides an opposite result about that expected with the increase in the energy demand. This phenomenon is most evident for the less demanding climate control strategy in which the heating needs are less evident.

To quantify the impact of the rehabilitation and climate control strategies on energy consumption, a mathematical model was designed to physically approach the simulated results: Equation (2) for the original climate control strategy and Equation (3) for the less demanding climate control strategy.

Equations R^2

20–22 °C; 50–60% RH

$$E = \left[\left(-7.65\cdot U^3 + 16.61\cdot U^2 - 9.07\cdot U + 1.44\right)\cdot {U_w}^3 + \left(83.59\cdot U^3 \pm 182.15\cdot U^2 + 102.66\cdot U - 19.09\right)\cdot {U_w}^2 + \left(-269.29\cdot U^3 + 592.01\cdot U^2 - 354.38\cdot U + 82.03\right)\cdot U_w + \left(257.54\cdot U^3 - 581.89\cdot U^2 + 383.18\cdot U - 35.37\right)\right]\cdot SHGC^2 + \left[(18.51\cdot U - 51.47)\cdot \ln(U_w) + (-35.37\cdot U + 99.20)\right]\cdot SHGC + \left[(0.03\cdot ln(U) + 4.46)\cdot U_w + (9.20\cdot U + 18.77)\right] \quad 0.98 \tag{2}$$

16(18)–25 °C; 40–60% RH

$$E = \left[\left(0.31\cdot U^2 - 0.33\cdot U + 0.08\right)\cdot U_w^3 + \left(-4.39\cdot U^2 + 6.79\cdot U - 4.04\right)\cdot U_w^2 + \left(21.02\cdot U^2 - 43.85\cdot U + 33.11\right)\cdot U_w + \left(-34.46\cdot U^2 + 78.39\cdot U + 19.90\right)\right]\cdot SHGC^2 \cdot\left[(19.50\cdot U - 55.58)\cdot ln(U_w) + (-35.76\cdot U + 88.68)\right]\cdot SHGC + \left[(-0.11\cdot U + 2.31)\cdot U_w + (4.18\cdot U + 4.88)\right] \quad 0.97 \tag{3}$$

These equations were used to optimize each parameter individually and all the possible combinations to obtain the lowest energy consumption. The model optimization was made with the aim of minimizing the total energy consumption. For this, several criteria were defined so that the feasibility of the model was not extrapolated. Regarding the SHGC, given the importance of daylight and visual contact with the outside for the quality of museum visits, total window occlusion was not considered—the use of a minimum SHGC of 0.10 was adopted. The optimization equation and the various criteria can be seen in Equation (4).

$$\min\left(E_{20-22^{\circ}C;50-60\%RH}; E_{16(18)-25^{\circ}C;40-60\%RH}\right) \tag{4}$$

$$1.36\ W/m^2{\cdot}^{\circ}C \geq U \geq 0.30\ W/m^2{\cdot}^{\circ}C$$

$$6.01\ W/m^2{\cdot}^{\circ}C \geq U_w \geq 1.53\ W/m^2{\cdot}^{\circ}C$$

$$0.75 \geq SHGC \geq 0.10$$

Focusing the attention on the improvement of the thermal transmittance of the opaque envelope, it was concluded that this refurbishment scenario has a reduced impact on the total energy consumption. Using the optimization model, an ideal U-value of 0.30 W/m^2.°C was obtained, but only resulting in a reduction of 5.40% in the annual energy consumption (3.45 kWh/m^2 per year).

The replacement of the current windows with thermal transmittances of 3.63 W/m^2.°C has an even a lower impact on the energy reduction, resulting in a maximum energy saving of 1.25% (0.80 kWh/m^2.year) for the optimum thermal transmittances of 2.35 W/m^2.°C. As regards the SHGC, the panorama is slightly different, achieving savings of 22% (14 kWh/m^2.year) by replacing the original windows with a global SHGC of 0.38 with ones with a global SHGC of 0.1.

It is interesting to note that for the higher values of SHGC, the window refurbishment results in higher energy consumptions compared with the reference case: above an SHGC of 0.52 for a U-value equal to 1.36 W/m^2.°C or above 0.35 for a U-value equal to 0.30 W/m^2.°C. These values were obtained by the interception between the curves for a U_w equal to 3.63 W/m^2.°C and that for a U_w equal to1.53 W/m^2.°C. This fact is justified by the reduction of losses which contributes for the increase in the internal temperature and consequently the increase in the cooling needs. For the less demanding set-point, this inversion occurs for a lower SHGC: 0.24 for a U-value of 1.36 W/m^2.°C and 0.16 for a U-value of 0.30 W/m^2.°C.

Analyzing the impact of the climate control strategy was purposely left to the end as it could lead to significant savings without any initial investment. Savings of 52% in the energy consumption (33.30 kWh/m^2.year) were achieved by replacing the original set-point of 20–22 °C for the temperature and 50–60% for the RH with the set-point of 18–25 °C during the opening hours and 16–25 °C in the nighttime concerning temperature and 40–60% for the relative humidity without any further intervention. This change led to savings ca. 10 times higher than those obtained for the opaque envelope refurbishment, ca. 42 times higher than those achieved by the window refurbishment and ca. 2.4 times higher than the one obtained for an SHGC equal to 0.1.

Optimizing the other three parameters for this less demanding climate control strategy, the following results were obtained: as regards the opaque envelope, the best result was obtained for the reference thermal transmittance, i.e., the improvement of the opaque envelope is not expected to improve the energy consumption of the model; as regards the windows' thermal transmittance, an interesting result is achieved—an optimum U_w of 5.85 W/m^2.°C was obtained showing that even in buildings with windows with poor thermal response, their replacement from an exclusively energetic point of view can be not justified. Regarding the SHGC optimization, an optimal value of 0.1 was obtained for the two set-points.

Despite the analysis performed for each of the parameters, the analysis of Figure 10 makes it obvious that by simultaneously optimizing more than one parameter, the results can be considerably different. The savings for all the possible combinations comparatively to the reference case, such as the optimal values for each parameter estimated from the application of the achieved mathematical model represented by equations 2 and 3, within the limits defined by Equation (4), can be seen in Table 4.

This analysis led to the conclusion that only the scenarios involving the SHGC and/or the change in the climate control strategy provide considerable energy savings. Combining all the four parameters under analysis, a maximum saving of around 75% was obtained referring to the reference case, which corresponds in absolute terms to a saving of around 48 kWh/m^2.year. This result was obtained for the following combination: set-point 16(18)–25 °C and 40–60% RH; U-value equal to 0.30 W/m^2.°C; U_w-value equal to 2.08 W/m^2.°C and an SHGC equal to 0.10. This result shows that the analysis performed individually for each parameter does not reflect the way they interact together. However, it should be noted that the change in the climate control strategy plays a leading role in optimizing the energy consumption in museums. If the rehabilitation of the opaque envelope and windows were excluded, a reduction of 70% was obtained, representing an absolute saving of around 44.50 kWh/m^2.year. From an economic point of view, this second option can lead to a best result, since the initial investment would be much smaller.

Table 4. Optimal solutions and energy savings.

Optimizing Parameters	Optimal Values/Energy Savings	
	20–22 °C; 50–60% RH	16(18)–25 °C; 40–60% RH
Climate control strategy	-	52%
U	(U = 0.30 W/m^2.°C) 5.4%	(U = 1.36 W/m^2.°C) 52%
U_w	(U_w = 2.34 W/m^2.°C) 1.2%	(U_w = 5.85 W/m^2.°C) 53.8%
SHGC	(SHGC = 0.1) 21.9%	(SHGC = 0.1) 69.6%
U + U_w	(U = 0.3 W/m^2.°C; U_w = 3.32 W/m^2.°C) 5.5%	(U = 0.3 W/m^2.°C; U_w = 6.01 W/m^2.°C) 56.3%
U + SHGC	(U = 0.3 W/m^2.°C; SHGC = 0.10) 35.3%	(U = 0.3 W/m^2.°C; SHGC = 0.10) 74%
U_w + SHGC	(U_w = 1.53 W/m^2.°C; SHGC = 0.10) 33%	(U_w = 1.53 W/m^2.°C; SHGC = 0.10) 72.8%
U + U_w + SHGC	(U = 0.3 W/m^2.°C; U_w = 1.53 W/m^2.°C; SHGC = 0.10) 44%	(U = 0.3 W/m^2.°C; U_w = 2.08 W/m^2.°C; SHGC = 0.10) 75.3%

4. Conclusions

The analysis carried out in this paper with the simulation of a room of the National Museum of Ancient Art of Lisbon for 15 European cities with different climatic conditions allowed us to conclude that the energy needs vary strongly with the building location. For the climate control strategy using 20–22 °C and 50–60% RH, it was concluded that the lowest consumptions were obtained for Oporto and Lisbon with 45 kWh/m^2 and 64 kWh/m^2 per year, respectively, while the highest consumptions were obtained for Oslo and Krakow with 135 kWh/m^2 and 117 kWh/m^2, respectively.

It was also found that the distribution of energy needs varied strongly. For Lisbon, Seville and Athens, the cooling needs accounted for more than half of total consumption, while for Oporto, Madrid and Rome a balanced distribution was obtained. For the remaining cities, the heating needs accounted for more than half of the total energy consumed.

From a thermal rehabilitation point of view, it was found that the greatest losses occur through windows, while, for example, the losses by the opaque envelope are practically negligible for the southern European cities. Thus, the impossibility of standardizing the rehabilitation solutions was concluded, since the building response is widely influenced by the local weather conditions.

This evidence led to a sensitivity study to improve the energy consumption for the building located in Lisbon, considering the improvement of the windows and the opaque envelope for two climate control strategies. For the set-point 20–22 °C and 50–60% RH, the best results were obtained for a solution combining a U-value equal to 0.30 W/m^2.°C, a U_w-value of 1.53 W/m^2.°C and an SHGC equal to 0.10, resulting in savings of 44%. Considering the hypothesis of changing the climate control strategy, the combination of the set-point 16(18)–25 °C and 40–60% RH with a U-value of 0.30 W/m^2.°C, a U_w-value of 2.08 W/m^2.°C and a SHGC of 0.10 allowed a reduction of 75.3% referring the base model.

Significant findings have been obtained that can contribute to the sustainable management of the cultural heritage of southern European countries in the future. It was concluded that "more" is not always "better". That is, the application of the most advanced rehabilitation solutions may not present a result that justifies their application.

It is concluded that in the case of Lisbon, which can be followed, with due care, to other cities in southern Europe with similar climates, that changing the climate control strategy plays a fundamental role in energy reduction. Regarding the rehabilitation of the envelope, it is concluded that the opaque envelope has a reduced impact on energy consumption. The main differences are obtained by the different window solutions; however, it is important to highlight that for southern European climates, the cooling needs for this type of building can play a preponderant role and that only interventions aimed at reducing solar gains can have a significant impact on the energy behavior of museums.

These results cannot be extrapolated to other cases with different properties. The purpose of this paper was not to achieve an ideal combination. With this study, the opposite was pretended, aiming to demonstrate in a sustained way the impossibility of standardizing solutions.

In the future, the continuation of climate studies in museums is essential for defining standards that can contribute to conservation, but without forgetting economic and energetic sustainability. It is important to deepen knowledge related to the impact of climate change, ventilation strategies and monitor the real impact of refurbishment measures to improve the environment in case studies.

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