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Indoor Parameters of Museum Buildings for Guaranteeing Artworks Preservation and People's Comfort: Compatibilities, Constraints, and Suggestions

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Abstract: Since people tend to spend more and more time visiting museums, more accurate requirements are needed for the indoor environmental conditions of these confined spaces where two primary requisites coincide in defining their optimal indoor microclimate: the need for the appropriate artwork preservation and suitable levels of indoor comfort conditions for people visiting the exhibition buildings and/or working there. Regrettably, people and artwork requirements are sometimes characterized by different reference limits of the environmental parameters that, not rarely, could potentially conflict. Another important point to consider is that museums hosted by heritage buildings (particularly in Mediterranean climates, as is often the case in Italy) are often not equipped with climatization systems because of difficulty in installing generally bulky equipment such as HVAC systems. This circumstance represents another important limit for achieving suitable conditions for the two requisites. In addition, the recent pandemic-related occurrences are pushing technicians and designers to rethink the criteria for controlling the microclimate of public buildings, and museums among them. In this paper, this issue is addressed by reviewing current regulations, standards, and handbooks (and by means of a real case example related to the Italian context) in order to ascertain whether such documentation could facilitate the development of effective rules/guidelines for proper management of indoor parameters in museums.

Keywords: artwork preservation; human comfort; cultural heritage; indoor microclimate; technical standards and regulations; indoor quality; museums; museum buildings; energy optimization

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1. Introduction

In enclosed exhibition spaces, two primary requirements interact to define the indoor microclimate conditions, that is, the need for adequate artwork preservation and people's comfort demand [1,2]. Indeed, people tend to spend more and more time visiting museums for their classical cultural demands and for the enhanced range of services provided by these institutions (such as recreational activities, conferences, bookshops, etc.) [3,4]. This calls for greater attention toward the comfort conditions of people visiting and working in these buildings, without forgetting the aspects related to improving energy and environmental sustainability [5–8].

Unluckily, people's and artworks' needs are sometimes conflicting, since people's well-being refers to environmental parameters and values that, in some cases, diverge from those that should be maintained for the protection of the artworks [9–11]. These problems are generally addressed and solved by means of suitable management and design of the heating, ventilation, and air conditioning (HVAC) system (as regards thermal-hygrometry and indoor air quality (IAQ) requirements) and by a proper selection and placements of the lighting fixtures [12–14].

On the other hand, especially in countries with relevant cultural heritage, historical buildings are often operated as exhibiting spaces, as opposed to being considered artworks themselves. Therefore, such buildings, also due to aesthetic and artistic reasons, are usually not equipped with a climatization system. It would indeed be difficult to hypothesize and/or install conventional (and bulky) equipment for the mitigation of indoor climate pressure, particularly in Mediterranean areas characterized by a mild climate [15,16]. Nevertheless, the microclimate requirements for preserving cultural heritage demand special attention, given the vast array of artworks displayed in museums and the diverse materials they are made of (including stone, marble, wood, textiles, and more) and considering that these objects are of significant importance, often representing unique examples of human art [17,18].

Various studies have been undertaken globally for the purpose of evaluating the environmental conditions [19–21] and proposing optimal features and/or guidelines [22–25] relating to museums' indoor climate, with particular attention to the risks of deterioration for materials [26–29]. However, ultimate and generalized limits and benchmarks for microclimate conditions in museum buildings have not been established yet [30,31], despite that microclimate parameters (and their variations in space and time) play a crucial role in the deterioration of materials that make up artworks (often leading to cumulative and irreversible chemical and/or physical alterations) [32–34].

Chao Guo et al. [35] compare the environmental criteria for the conservation and storage of artifacts in different territories such as Europe, Asia, America, America, Australia, and Africa. In particular, Italy is one of the countries in Europe that has issued specific regulations for the conservation of heritage goods in museums and, additionally, some technical standards have also been released referring to the definition and to managing microclimatic conditions to conserve cultural heritage in indoor settings. Such documents are characterized by an intrinsic validity that appears to go beyond the strict applicability to the Italian context.

In September 2010, the European Committee for Standardization, CEN (Comité Européen de Normalisation), issued two standards, namely, "EN 15758" [36] and "EN 15757" [37]. The first standard is essentially a guideline related to methodologies and tools for the evaluation of the air temperature and surface temperature of artworks exposed in confined and/or open environments, specifying the measuring minimum requirements. The second standard gives some specifications for temperature and relative humidity in order to limit damage to organic materials, and, in particular, it suggests maintaining the current preservation environmental conditions (even if they do not seem optimal for the preservation of the object) when the object has reached a stable condition. Later, in November 2021, CEN issued the standard "EN 16242" [38], which outlines methodologies and tools to measure air humidity and moisture interchanges between the air and artworks in both enclosed and open spaces or environments.

Another important (Italian) regulation is the standard "UNI 10829" [39] that the non-profit Italian association UNI (Italian National Standards Body) issued in July 1999, which was titled "ambient conditions for the conservation". It gives an exhaustive methodology for measuring in the field of the environmental parameters that can be assumed as significant for the conservation of artworks of historical importance. Specifically, some types of objects and materials that are most frequently found in museums and for which it is recommended the conservation in stable climatic conditions are singled out. These categories belong to three main groups, that is, objects/materials of inorganic nature, objects/materials of organic nature, and mixed objects/materials. Within the standard for each kind of object, suggested values of the physical environmental parameters are reported, under the hypothesis of a stable (steady-state) climate condition; the reference values of environmental parameters to be used for the design of new climatization equipment are suggested as well. Moreover, a form is included in the standard, where the "climatic history" of the handicraft should be reported. Finally, the proper measurement procedures, along with the algorithms to be utilized to statistically analyze the obtained data, are indicated.

The causes of degradation considered in the above-cited UNI 10829 are the air thermal-hygrometer conditions and the electromagnetic radiations coming from natural and/or artificial lights. The standard recommends the monitoring of some particular physical parameters; it singles out the preferred values of these parameters, the daily maximum excursions, the allowable maximum limits, and the absorbed energy yearly dose.

With regard to environmental conditions for people's well-being, besides several scientific studies, there are specific and established regulations that indicate the optimal values to be maintained within environments depending on the intended use [1,14,40,41].

In general, any perturbation in the environment, including the presence of people, could contribute to the artworks' degradation process. That is why the existence of technical standards and regulations designed to evaluate the optimal values of physical parameters in exhibition spaces is highly significant. However, given the fragmented nature of these documents, the values proposed are often misaligned with each other [9,10,30,35].

To try to contribute to covering this gap (or at the least to bring some more clarity on this matter) the aim of this work is to examine the current (up-to-date) literature on standards, regulations, and handbooks in order to determine whether such documentation would make it possible to propose a useful set of rules/guidelines to follow for a proper management of indoor parameters in museums.

In the following sections of this paper, the optimal conditions of indoor parameters for the preservation and display of artworks (Section 2) and those related to the comfort of both visitors and workers in museums (Section 3) will be considered separately at first. In detail, thermo-hygrometric, lighting, and air quality characteristics, referring to both Italian standards and other international regulations, will be taken into consideration. Thereafter, the identification of possible compatibility ranges of these parameters that meet both requirements (i.e., artwork preservation and human well-being) will be discussed (Section 4). Lastly, some conclusions will be given, and possible future research insights will be drawn (Section 5).

2. Indoor Parameters of Museums Required for Artworks Preservation

Based on the literature, handbooks, and standards mentioned above, the major causes of degradation and/or damage of artworks are related to environmental parameters belonging to three main categories, that is, thermo-hygrometric, lighting, and indoor air quality (IAQ). Therefore, by referring to the main reference documents currently in force, this section will briefly review the suggested values for such parameters inside museums; specifically, taking into account the artwork materials most commonly, and in larger numbers, found in the majority of museums.

2.1. Thermo-Hygrometric Parameters

As reported earlier, although this topic has been addressed by various scholars in different countries, there are no agreed unified values. Most existing regulations and handbooks usually provide generic reference values to follow for preventing artworks from possible damage. For instance, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [42] proposes for the category of buildings referred to as "general museums, art galleries, libraries and archives" to use temperature values in the 15–25 °C range and a relative humidity rate of 50 (±10)% as borderline conditions between the safety and danger regions.

From this point of view, Italy appears to be one of the countries that have historically made the most effort in trying to better detail thermo-hygrometric conditions, not only within museums as a specific category of buildings but also in reference to the specific categories of artworks contained within such environments.

As a result, the thermal hygrometer parameters that are to be considered as the most relevant ones that need monitoring and controlling in museums [39,43] are as follows: air temperature mean value θ_0 [°C] (usually estimated monthly), daily range of air temperature $\Delta\theta_{max}$ [°C], artworks surface temperature θ_S [°C], indoor air relative humidity mean value rh_0 [%] (usually estimated monthly), and daily range of air relative humidity Δrh_{max} [%]. Specifically, the suggested values for these parameters are indicated in the cited Italian UNI 10829 standard [36] and Decree of May 2001 [43], as reported in Table 1, where the recommended values for optimal conservation are reported for a selection of the most relevant materials of which the artworks exhibited in museums are mainly composed.

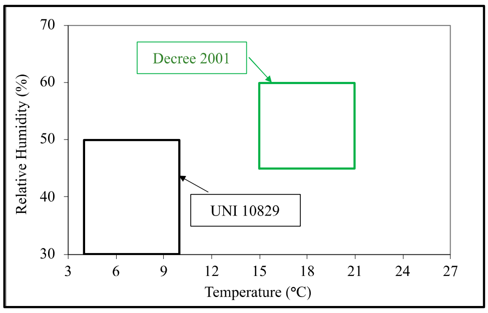
Table 1. Recommended values for proper conservation of certain relevant artworks in steady-state microclimate conditions according to Italian regulations.

<table>
<tr><th rowspan="2">Artworks Materials</th><th colspan="2">Decree of 10 May 2001</th><th colspan="2">UNI 10829 Standard</th></tr>
<tr><th>θ_0 (°C)</th><th>rh_0 (%)</th><th>θ_0 (°C)</th><th>rh_0 (%)</th></tr>
<tr><td>Artistic paper artifacts and papier-mâché</td><td>19–24</td><td>50–60</td><td>18–22</td><td>40–55</td></tr>
<tr><td>Fabric, veils, drapery, carpets, fabric tapestry, arras, silk, costumes, dresses, religious vestments, natural fiber materials, sisal, jute</td><td>-</td><td>40–60</td><td>19–24</td><td>30–50</td></tr>
<tr><td>Ethnographic collections, masks, leather, leather clothes</td><td>19–24</td><td>40–60</td><td>19–24</td><td>45–60</td></tr>
<tr><td>Painting on canvas, oil painting on cloth and canvas, tempera, gouaches</td><td>19–24</td><td>35–50</td><td>19–24</td><td>40–55</td></tr>
<tr><td>Bindings of books with leather or parchment</td><td>-</td><td>50–60</td><td>19–24</td><td>45–55</td></tr>
<tr><td>Polychromatic wood carvings, painted wood, paintings on wood, icons, wood pendulum-clocks, wood musical instruments</td><td>19–24</td><td>45–65</td><td>19–24</td><td>50–60</td></tr>
<tr><td>Unpainted wood carvings, wickerwork, wood or bark panels</td><td>19–24</td><td>40–65</td><td>19–24</td><td>45–60</td></tr>
<tr><td>Furs, feathers, stuffed animals, and birds</td><td>15–21</td><td>45–60</td><td>4–10</td><td>30–50</td></tr>
<tr><td>Mosaics</td><td rowspan="2">6–25 (1.5 °C/h)</td><td rowspan="2">45–60</td><td>15–25</td><td>20–60</td></tr>
<tr><td>Murals, frescoes</td><td>10–24</td><td>55–65</td></tr>
<tr><td>Mineralogical collections, marbles and stones (stable porous stones, rocks, minerals, meteorites)</td><td>≤30</td><td>45–60</td><td>19–24</td><td>40–60</td></tr>
</table>

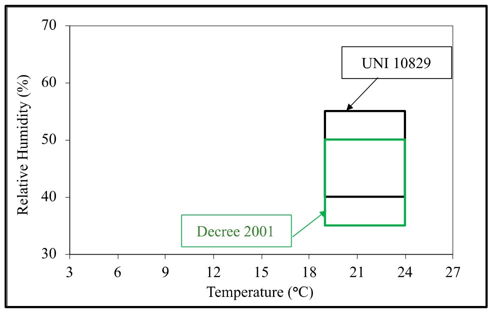
As it can be observed from the comparison of such suggested values, some differences can be found in the two documents. These differences (which have been better highlighted in Figure 1) might be significant, particularly for certain types of materials, with non-negligible consequences for the design and management of HVAC systems, as well as, more generally, for the evaluation of indoor climatic conditions in which artworks may be exposed [44,45].

Specifically, Figure 1a (regarding furs, feathers, stuffed animals, and birds) represents one of the most emblematic cases, where the air temperature and relative humidity limits proposed by the UNI standard [39] and those given by the Decree 2001 [43] appear to be completely divergent; thus making it impossible to identify common zones on which to base the sizing of air conditioning systems. Conversely, in Figure 1b–d (for painting on canvas, painting on wood, murals, and frescoes, respectively) as well as Figure 1e (for mineralogical collections, marbles, and stones) there are areas of overlap that allow common temperature and air relative humidity values to be considered that HVAC systems should be able to guarantee.

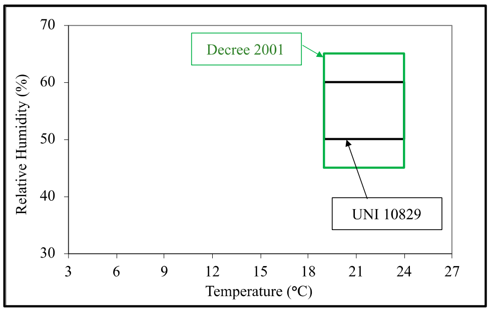
The above-cited values refer to the conservation conditions. Regarding prevention from microbiologic damage, the preferred microclimatic conditions of the exhibition environments should be those indicated in Table 2, which contains other values of microclimatic parameters, also including the daily variations ranges [39,43].



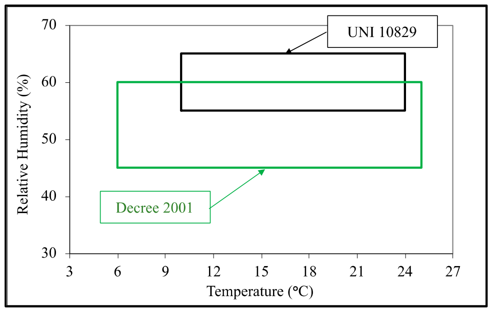
(**a**)



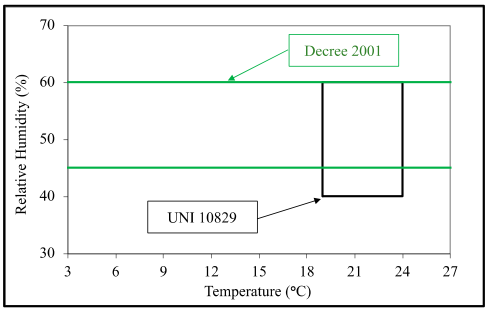
(**b**)



(**c**)



(**d**)



(**e**)

Figure 1. Comparison of the limits of temperature and relative humidity of the indoor microclimate proposed by the Italian Standard 10829 and the Decree of 2001. The comparisons refer to five groups of materials frequently exhibited in museums. (**a**) Furs, feathers, stuffed animals, and birds; (**b**) painting on canvas, oil painting on cloth and canvas, tempera, and gouaches; (**c**) polychromatic wood carvings, painted wood, paintings on wood, icons, wood pendulum-clocks, and wood musical instruments; (**d**) Murals and frescoes; and (**e**) mineralogical collections, marbles, and stones.

Table 2. Suggested values for the prevention of microbiological damage of some relevant artworks according to Italian regulations.

Materials		**Decree of 10 May 2001 [43]**				**UNI 10829 Standard [39]**			
		rh_0 (%)	**Δrh_x (%)**	**θ_0 (°C)**	**$\Delta\theta_x$ (°C)**	**rh_0 (%)**	**Δrh_x (%)**	**θ_0 (°C)**	**$\Delta\theta_x$ (°C)**
Paintings	on canvas	40–55	6	19–24	1.5	40–55	6	19–24	1.5
	on wood	50–60	2	19–24	1.5	50–60	4	19–24	1.5
Wood		50–60	2	19–24	1.5	45–60	4	19–24	1.5
	archeological	50–60	2	19–24	1.5				
	wet	-	-	<4	-	sat.	-	<4	-

Table 2. *Cont.*

Materials		**Decree of 10 May 2001 [43]**				**UNI 10829 Standard [39]**			
		rh_0 (%)	**Δrh_x (%)**	**θ_0 (°C)**	**$\Delta\theta_x$ (°C)**	**rh_0 (%)**	**Δrh_x (%)**	**θ_0 (°C)**	**$\Delta\theta_x$ (°C)**
Paper		40–55	6	18–22	1.5	40–55	6	18–22	1.5
	pastels, watercolors	<65	-	<10	-	45–60	2	19–24	1.5
	books, manuscripts	45–55	5	<21	3	50–60	5	13–18	-
	graphical material	45–55	5	<21	3				
Leathers, hides, parchments		40–55	5	4–10	1.5	45–55	6	19–24	1.5
Tissues	cellulosic	30–50	6	19–24	1.5	30–50	6	19–24	1.5
	proteinic	50–55	-	19–24	1.5				
Ethnographic collections		20–35	5	15–23	2	45–60	6	19–24	1.5
Stable materials		35–65	-	30	-				

Table 3 reports the critical values of air temperature and relative humidity for some specific types of artworks (unstable, affected by corrosion, or wet), as indicated in the Decree of 10 May 2001 [43].

Table 3. Critical values of air temperature and relative humidity for some specific artworks [43].

Handcrafts	**Relative Humidity (%)**	**Air Temperature (°C)**
Archaeological bronzes with chloride corrosions	<42	-
Archaeological irons with chloride corrosions	<20	-
Unstable glasses	40–45	-
Wet wood	100	<4

A comparison of the values reported in Tables 1 and 3 (where only fixed values are reported) and Table 2 (which also includes the variation ranges) shows small differences overall, except for ethnographic collections, whose prevention from microbiological damage requires lower air temperatures.

2.2. Lighting Parameters

Light is a critical element in museums because it influences the visual presentation quality of artworks. However, either artificial or natural lights contain spectral components that can pose a risk to cultural artifacts [46]. Consequently, technical standards are deeply concerned with these museum features. Once again, the Italian regulations appear to be among the most detailed documents regarding this aspect. Specifically, the following lighting parameters are those considered by the Italian standard UNI 10829 [39] for optimal conservation: E_{max} maximum limit of luminance (lx), UV_{max} ultraviolet radiation maximum value (μW/lm), LO_{max} yearly dose of light (lx h/y). Table 4 shows the values given in the standard for each of the above-indicated parameters in the case of steady-state indoor climate conditions relative to the most relevant artwork materials, i.e., those found most frequently (and usually in the greatest number) within museums.

Moreover, the Decree 2001 [43] provides some guidance on the requirements for both optimal conservation and fruition of artworks. In this case, the uniformity of the illuminance (referring to a plane surface) should be guaranteed by considering the following:

$$E_{min}/E_{mean} > 0.5 \quad (1)$$

$$E_{max}/E_{min} < 5 \quad (2)$$

where E_{min}, E_{mean}, and E_{max} are the minimum, mean, and maximum values of luminance, respectively, in the considered environment. These criteria are valid except for paintings on wooden boards, for which it is recommended that the ratio among maximum and minimum values of the luminance should be the following:

$$E_{max}/E_{min} < 2 \quad (3)$$

Table 4. Recommended values for optimal conservation of some relevant artworks [39].

Artworks Materials	E_{max} (lx)	LO_{max} (Mlx h/y)	UV_{max} (μW/lm)
Paper, papier-mâché, paper artwork, tissue-paper, wallpaper, stamp collections, manuscripts, papyri, printings, cellulose materials	50	0.2	75
Fabric, veils, drapery, carpets, fabric tapestry, arras, silk, costumes, dresses, religious vestments, natural fibre materials, sisal, juta	50	0.2	75
Ethnographic collections, masks, leather, leather clothes	50	0.2	75
Painting on canvas, oil painting on cloth and canvas, tempera, gouaches	150	0.5	75
Books of great value, leather-bound books, leather bindings, parchment, miniatures	50	0.2	75
Polychromatic wood carvings, painted wood, paintings on wood, icons, wood pendulum-clocks, wood musical instruments	50	0.2	75
Unpainted wood carvings, wickerwork, wood or bark panels	150	0.5	75
Stone mosaics, stones, rocks, ore, meteorites (not porous), fossils and stone collections	N.R.	-	-
Stable (porous) stones, rocks, minerals, meteorites	N.R.	-	-
Murals, frescoes (detached)	N.R.	-	-

It is important to highlight that such reference values also correspond to the recommended lighting parameters in museums concerning the visual comfort of visitors. Regarding the "energy exposure", consideration must be given to the ultraviolet (UV) component of light and the overall radiance. Table 5 outlines the recommended values for the UV component linked to lighting flux, the maximum total radiance value, and energy density for three distinct levels of photosensitivity based on the annual supported light exposure [43].

Table 5. Maximum limits of total radiance and UV components [43].

Photosensitivity Class	Supported Light Dose LO_{max} (Mlx h/y)	E_{max} (lx)	UV_x (μW/lm)	Maximum Radiance (μW/cm^2)	Energy Density within the 400–4000 nm Range (W/m^2)
Medium	0.5	150	75	1.2	10
High	0.15	50	75	0.4	3
Very high	0.05	50	10	0.05	1

In order to choose suitable lighting for artwork exposition, the CEN/TS 16163 standard [47] provides suggestions and procedures to best illuminate artworks and, at the same time, gives some information about the damage that lighting can cause to them. Regarding the last consideration, this standard recalls the classification reported by CIE 157:2004 [48] about different light sensibility categories of artworks:

- Irresponsive: object unsensible to light (e.g., the majority of metals, stones, glasses, ceramics, enamels, minerals);
- Low responsivity: an object with a light sensibility to light (e.g., the majority of oil and tempera paintings, frescoes, unpainted leathers and woods, horn ivory, bones, lacquers, and plastics);

- Medium responsivity: an object with a moderate sensibility to light (e.g., the majority of fabrics, pastels, watercolors, manuscripts, prints, drawings, miniatures, paintings in distemper media, wallpapers, natural history objects);
- High responsivity: an object with a high sensibility to light (e.g., silk, newspaper, fugitive dyes, most graphical arts, photographic documents).

Accordingly, the standard provides illuminance (lux) and maximum annual light exposure (lux hours per year) limits for such different categories of materials are listed in Table 6.

Table 6. Maximum annual light exposure (lux hours per year) and illuminance (lux) limits according to the CEN/TS 16163 standard [47].

Category	E_{max} (lx)	LO_{max} (Mlx h/y)	Annual Exposure Time (h)
Irresponsive	-	-	-
Low responsivity	200	0.600	3000
Medium responsivity	50	0.150	3000
High responsivity	50	0.015	300

The CEN/TS 16163 standard suggests for UV_{max} a limit the value of 75 μW/lm (as also reported in the previous Table 4). As for the E_{max} suggested thresholds, it should be considered that 50 lux is the minimum level of light required to discern the colors and details of a displayed object. Moreover, as can be observed, the values reported in Table 6 are much more similar to those reported in Table 5.

2.3. Indoor Air Quality Parameters

In spite of the extensive research on indoor air characteristics in museums and buildings dedicated to conserving and exhibiting cultural artifacts, the current status of technical standards remains uncertain. An absolute list of suggested values for indoor microclimate parameters is still unavailable. This poses a significant challenge for technicians tasked with monitoring and controlling museum air quality using mechanical systems or natural conditions.

Below, Table 7 presents a compilation of data showing the maximum admissible values for key pollutants in museums, sourced from existing regulations, standards, and literature.

Table 7. Maximum limits of gaseous pollutants in museums derived from the available regulations, standards, and literature.

Source	SO_2 (μg/m^3)	O_3 (μg/m^3)	NO_2 (μg/m^3)	Particulate Matter
[49]	2.5	25	5	-
[50]	<1 (SO_x)	<25	<5 (NO_x)	<75 μg/m^3
[22]	<1.0	<2	<5	Adoption of the best available technology
[25]	<10	2	<10	-
[51]	1	5	5	-
[52]	<1	2.5	<5	Percentage of removal > 95% for PM with diameter > 2 μm
[53]	<12.5–25	<10–20	<10–20 (NO_x)	Percentage of removal > 95%
[54]	<10 (Sox)	2	<10 (NO_x)	-
[55]	≤1 μg/m^3	≤2 μg/m^3	≤4.7 μg/m^3	Percentage of removal > 95%
[56,57]	<1.0	<2	<5	<75 μg/m^3
[58]	≤2 μg/m^3	≤2 μg/m^3	≤2 μg/m^3 (for NO_x)	≤50 μg/m^3

The carbon dioxide concentration is not included here because it primarily serves as an indicator of indoor air freshness; indeed, CO_2 is not considered a pollutant.

The standard EN 15759-2 [59] provides some consideration for controlling pollution levels within heritage buildings, specifically addressing ventilation control. Essentially, it serves as a guideline for managing ventilation systems to enhance the conservation condition of buildings that house artwork collections or that are heritage buildings themselves.

3. Indoor Requisites of Museums for People's Comfort and Health Safety

According to the above-reported literature, handbooks, and standards, people's comfort in museum buildings mainly attains to four aspects that are common to all enclosed spaces, that is, thermal, visual, air quality, and acoustics [60]. However, in this paper, only the first three aspects will be examined, considering the aim of comparing requirements for both human comfort and artwork preservation. Acoustics, indeed, have no direct impact on the preservation conditions of cultural artifacts. However, it is important to recognize that ensuring a comfortable environment necessitates appropriate control of the acoustic characteristics of museum spaces, where episodes of noise annoyance could depend on both outdoor conditions (and on the insulation properties of building envelopes) and noise emissions released by the climatization systems.

3.1. Thermal Comfort Parameters

Regarding the thermal comfort of people, a relevant difference in the approach used for the conservation and proper display of artworks can be immediately noted. In fact, as noted earlier, the thermal performance evaluation criterion suggested for artwork conservation is based on ideal ranges of air temperature and relative humidity, as well as on their variation within a period of 24 h. On the other hand, the assessment of thermal environmental performance for people's comfort should be based on the two thermal comfort indices described in the international standard ISO 7730 [40], namely, PMV and PPD, which take into account air temperature, relative humidity, velocity and mean radiant temperature as environmental parameters, and metabolism (activity level) and thermal clothing insulation as subjective parameters. This consideration is also made by the European standard EN 16798-1 and by ANSI/ASHRAE Standard 55 [41,61].

However, when the design of HVAC equipment for the thermal comfort of people is involved, the parameters taken into account by the aforementioned standards are operative temperature and relative humidity, where operative temperature is defined as follows:

$$t_o = (h_r \cdot t_r + h_c \cdot t_a)/(h_r + h_c) \quad (4)$$

where t_r is the average radiant temperature, which represents the weighted average of the surface temperatures of all surfaces "seen" by the human body, while h_c and h_r are the convective and radiative coefficients that consider heat exchanges between the human body and the surrounding closed environment. Anyway, for the sake of simplicity, the air temperature and mean surface temperature are considered to be at least equal.

According to the ISO 7730 and EN 16798-1 standards, the optimal design ranges of values of operative temperature for buildings of Category II (to which museums may be assimilated) are those outlined in Table 8.

Table 8. Values of the operative temperature for the thermal acceptability for slightly active persons (M = 1.2 met), at 50% relative humidity, for PPD equal to 10% (when −0.5 < PMV < 0.5).

Season	Clothing Level (clo)	ISO 7730 [40]		EN 16798-1 [61]	
		Optimum Value (°C)	Acceptable Range (°C)	Optimum Value (°C)	Acceptable Range (°C)
Winter	1	22.0	20.0–24.0	22.0	20.0–24.0
Summer	0.5	24.5	23.0–26.0	24.5	23.0–26.0

The ISO 7730 and EN 16798-1 standards provide design criteria for four different categories of buildings: in the present work, we referred to Category II (to which museums may be assimilated) for which the indoor parameters determine that at most 10% of occupants declare to be dissatisfied with the indoor environment in relation to their thermal comfort conditions (PPD < 10%, corresponding to PMV index values in the range of −0.5 and 0.5). Accordingly, for the EN 16798-1 standard, the considered ranges of operative temperature are those indicated for calculating cooling and heating energy on an hourly basis in the Category II of the indoor environment, with relative humidity varying between 40% and 60%, as suggested by ASHRAE [42] for "general museums, art galleries, libraries and archives", and operative temperature coincident with air temperature (i.e., equal to the average radiant temperature). Specifically, (as represented in Figure 2) during the winter season (heating conditions), the values of operative temperature vary between 19.5 °C and 24.1 °C for 40% of air relative humidity and between 19.0 °C and 23.5 °C for 60% of air relative humidity. Meanwhile, in the summer season (cooling conditions), the values of the operative temperature vary between 23.2 °C and 26.6 °C for 40% of air relative humidity and between 22.8 °C and 26.1 °C for 60% of air relative humidity.

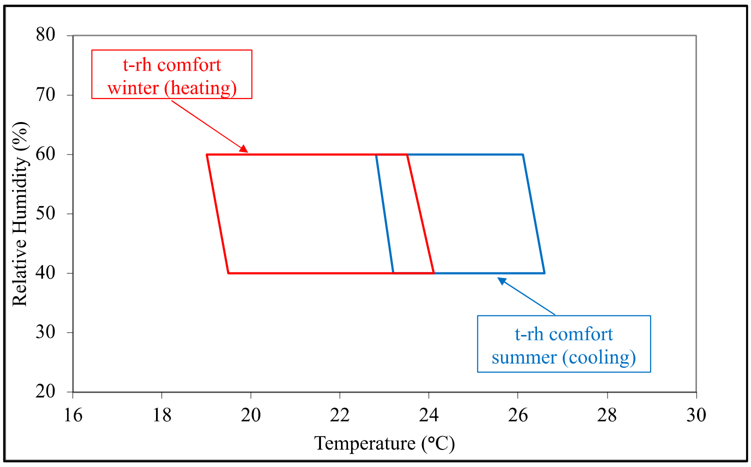


Figure 2. Comparison of the comfort limit values of temperature and relative humidity in the indoor microclimate according to the ISO 7730 and EN 16798-1 standards for winter and summer seasons.

Table 9 contains the limit for the temperature parameters defining local discomfort, as recommended by ISO 7730 [40] and EN 16798-1 [61].

Table 9. Default criteria for local thermal discomfort parameters for the designing of HVAC systems in buildings belonging to Category II according to ISO 7730 [40] and EN 16798-1 [61].

Parameters Characterizing the Local Discomfort	Limits
Draught, DR	DR < 20%
Vertical air temperature difference between head and feet, Δt_a	$\Delta t_a < 3$ K
Radiant temperature asymmetry with warm ceiling, Δt_{pr}	$\Delta t_{pr} < 5$ K
Radiant temperature asymmetry with cool wall, Δt_{pr}	$\Delta t_{pr} < 10$ K
Radiant temperature asymmetry with cool ceiling, Δt_{pr}	$\Delta t_{pr} < 14$ K
Radiant temperature asymmetry with warm wall, Δt_{pr}	$\Delta t_{pr} < 23$ K
Floor surface temperature, t_f	19 °C < t_f < 29 °C

As for indoor air relative humidity, which constitutes the second parameter of the couple t_o-rh, it must be noted that people's thermal comfort is only weakly affected by this parameter [41]. Anyway, the EN 16798-1 standard [61] provides recommended design values of 60% and 25% for dehumidification and humidification, respectively (with the further suggestion of limiting the absolute humidity to 12 g/kg).

3.2. Visual Comfort Parameters

The topic of visual comfort has been addressed by various literature studies, standards, and regulations. The reviewed literature indicates some optimal values of lighting parameters, in particular, the European standard CEN/TS 16163 [47] provides some suggestions for selecting suitable lighting for indoor exhibitions and suggests lighting values of 50 lux, which is the minimum value to discern details of artworks. However, it should be considered that the relation between luminance and visual acuity varies as a person's age increases. As a matter of fact, on average, to achieve the same levels of visual comfort and acuity over an object and/or task, a 75-year-old person needs about two times the luminance level compared to a 25-year-old person [62]. Additionally, the EN 12464-1 European standard recommends that "lighting characteristics are determined by the exhibition requisites" [63] in the case of museums.

However, so far, the basics of ergonomic visual design [64] have been considered in a similar way to that related to the design of indoor work systems' lighting features. Indeed, in order to determine some quantitative indications for museums' visual parameters, it has usually been decided to assign to such buildings the high-level criteria suggested for workplaces [63,65] that relate to a visible task and ensure good visual comfort. In line with such indications, For artificial lighting, it is recommended to maintain a minimum illuminance of 500 lux on a horizontal working plane, with illuminance uniformity higher or equal to 0.8. While for view purposes in daylight, the EN 17037 standard [66] suggests a minimum value of 500 lux for at least 50% of the plane reference area (generally working area, 0.85 m above the floor) and at the same time a minimum value of 300 lux for at least 95% of the plane reference area and for at least 50% of the time of daylight hours with reference to vertical or inclined daylight openings (i.e., windows) in order to obtain a medium level of recommendation. Anyway, several studies conclude that the use of daylight is inappropriate in buildings not specifically designed to host museums but used as such (as is the case in Italy for many historic buildings used as museums) because it might harm and damage artifacts [30,42].

3.3. Indoor Air Quality Parameters

The issue of indoor air quality in buildings is typically addressed with a dual focus: guaranteeing the comfort and health of individuals who live and work indoors. Globally, there are numerous standards, recommendations, and handbooks that specify ventilation rate values capable of achieving these objectives in indoor spaces.

The recently released standard EN 16798 [61] proposes three methods for the determination of criteria for the indoor air quality and ventilation rates in buildings: Method-1 is based on the perceived air quality by the occupants; Method-2 is based on the calculation of the ventilation rates by means of the mass balance among the indoor polluting substances and their outdoor concentrations; and Method-3 suggests the minimum pre-defined ventilation rates for both meeting acceptable air quality perceived by people and their health safety. However, whatever method the designer chooses, the minimum airflow rate should be higher than 4 l/s per person. Based on these considerations, Method-1 is particularly suggested for persons non-adapted to the indoor climate (e.g., entering an indoor space after have being subjected to outdoor air for a certain period), as is likely the case for visitors of museums.

The standard EN 16798 [61] also provides the limit values of indoor concentrations for some pollutant substances considered harmful to persons, taking into account the World Health Organization (WHO) indoor air quality (IAQ) guidelines [67,68] (Table 10).

Moreover, from a social perspective, the recent COVID-19 pandemic, which has affected (and is still affecting) the entire planet, has led to people's need to feel more secure, although new restrictive requirements have not been introduced yet. Hence, specific attention to the types of air conditioning systems and to the techniques and procedures for monitoring and controlling indoor air quality must be ensured. Accordingly, a strong increase in room air exchange is rightly regarded as a fundamental tool for enabling a reduction in viral concentration in indoor environments [69,70]. At the same time, to avoid an increase in energy consumption, such drastic enhancement of ventilation must be accompanied by the introduction of heat recovery systems on exhaust air that are significantly improved over the current ones.

Table 10. Limit concentrations to guarantee IAQ for people according to the standard EN 16789 [61].

Pollutant Substance	Limit Value
Carbon monoxide	7 mg/m^3 (24 h mean)
Formaldehyde	0.1 mg/m^3 (30 min mean)
Nephthalene	100 µg/m^3 (annual mean)
Nitrogen dioxides (NO_2)	20 µg/m^3 (annual mean)
Radon	100 Bq/m^3
Tetrachloroethylene	250 µg/m^3 (annual mean)
Sulphur dioxides	20 µg/m^3 (24 h mean)
Ozone	0.1 mg/m^3 (8 h mean)
Particulate matter ($PM_{2\cdot5}$)	25 µg/m^3 (24 h mean)
Particulate matter (PM_{10})	50 µg/m^3 (24 h mean)

4. Results and Discussion: Simultaneously Fulfilling Requisites for Artwork Conservation and People's Comfort and Safety

In this section, the requisites for artwork conservation and people's comfort will be compared to discuss possible compatibilities, constraints, and criteria to be used when deciding whether and what types of artworks to display within the same environment, also considering the presence of people; this analysis will be carried out in reference to the three previously introduced aspects: thermo-hygrometric, lighting, and indoor air quality.

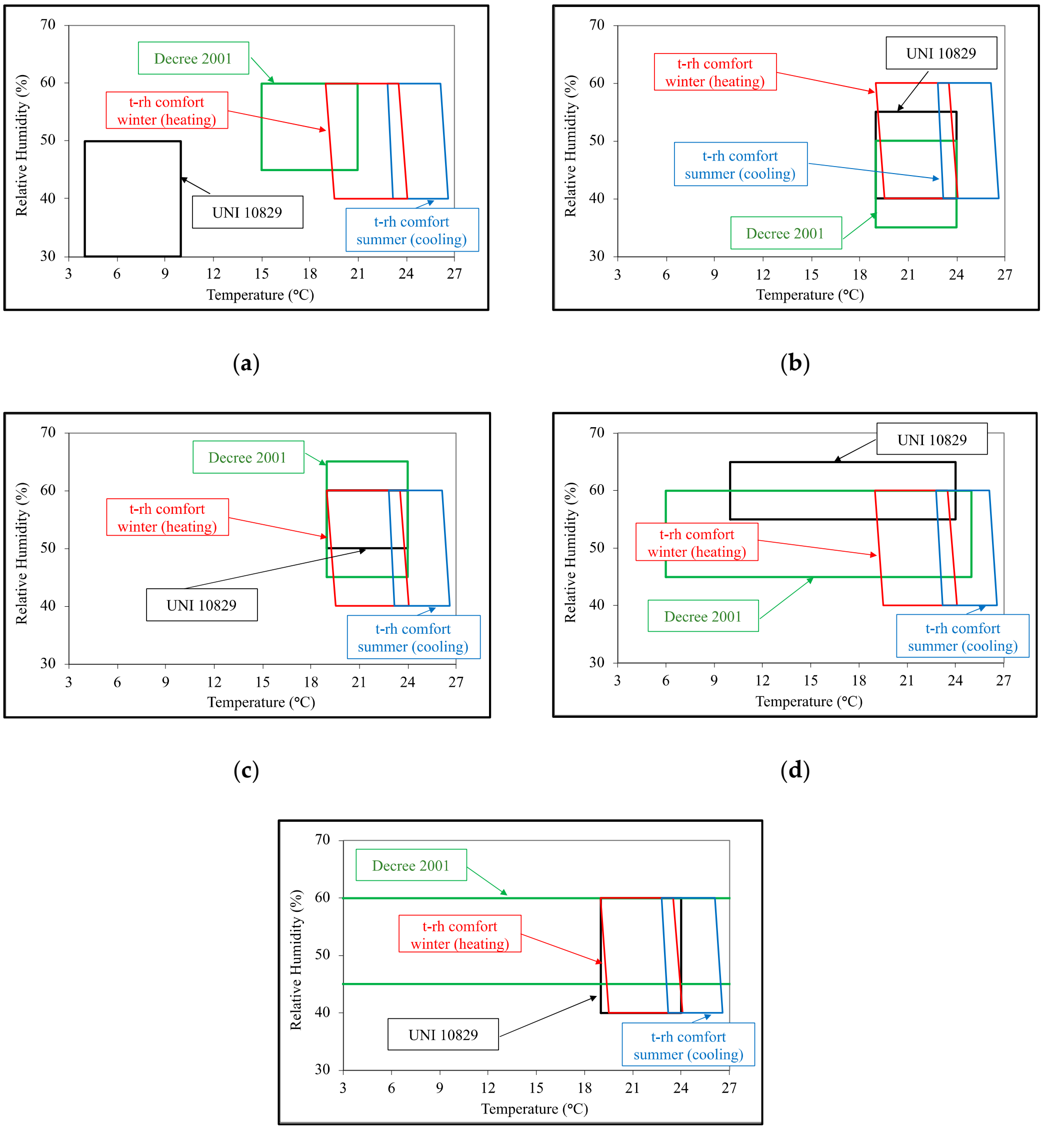
In addition, an example will be given based on a real case that can be considered as representative of the conditions of several Italian museums, namely, those housed within historic buildings where different kinds of artworks are usually exposed within common halls.

4.1. Thermo-Hygrometric Characteristics

The evaluation of optimal indoor parameters presented in Section 2.1 starts from the assumption that in each room only homogeneous artworks are exhibited. However, in many cases of museums, various artworks of different kinds could be housed in the same room, which, in general, requires different indoor thermo-hygrometric parameters. Moreover, the presence of people, other than being an additional element relative to the maintenance of comfort conditions, constitutes an environmental disturbance that could contribute to the degradation process of the artwork. These conditions impose a more accurate evaluation of the limits of temperature and relative humidity of indoor air, in search of common areas within which the control of indoor environment parameters should be exercised.

Referring to what was shown in Section 2.1, Figure 3, reported below, shows the conditions for which the limits of the four groups of artworks most frequently exhibited in museums are overlaid with values for people's comfort.

The evident differences shown in Figure 3 point out how the definition of optimal conditions based on the air temperature and relative humidity limits reported in current regulations and standards concerning both the exposure of artworks and people's comfort is a complex and quite controversial issue. This circumstance is also due to the still not precise knowledge of (i) the degradation mechanisms over time of the different materials of which artworks are composed and (ii) the effect that the aggressiveness of indoor air exerts on them. All this, obviously, poses very challenging commitments to facilities and museum designers, also because the responsibility of managing air temperature and relative humidity should be accomplished and checked independently (and sometimes even locally) in each room of a museum.



(**e**)

Figure 3. Comparison of the limit values of air temperature and relative humidity of the indoor microclimate for artworks conservation/preservation (Italian Standard 10829 and Decree of 2001) with those for people's comfort (ISO 7730 and EN 16798-1 standards). The comparisons refer to five groups of materials frequently exhibited in museums: (**a**) Furs, feathers, stuffed animals, and birds; (**b**) painting on canvas, oil painting on cloth and canvas, tempera, and gouaches; (**c**) polychromatic wood carvings, painted wood, paintings on wood, icons, wood pendulum-clocks, and wood musical instruments; (**d**) murals and frescoes; and (**e**) mineralogical collections, marbles, and stones.

In this regard, to take into account both the thermo-hygrometric characteristics per se and their effect on the possible causes and/or substances that can damage artworks, it would be more appropriate to use some of the general metrics that have been introduced in the last few years. Indeed, in the literature, there are various works regarding indicators of the quality of environmental conditions for the conservation of artworks, such as IPI preservation metrics [71], NICHE [72], IMQ [20], EMC [12,21,73], and so on, whose aim is to use a unique value for evaluating the environmental conditions for conservation of a specific artwork or a group of specific artworks. Accordingly, as previously reported in Section 3.1, a better assessment of indoor thermal performance for the comfort of people should be based on the PMV and PPD thermal comfort indexes [40] rather than on fixed values of temperature and humidity.

In addition, the latest update of the ASHRAE regulation [42] and the EN 15757 standard [37] on the preservation of artworks suggest that the "thermo-hygrometric history" to which the works have been subjected over the years should be taken into account primarily, rather than referring exclusively to set limits, since it is actually the modification in temperature and humidity that would most affect the health of the artworks. As for the people, an aspect to consider concerns the fact that in exhibition spaces, people are supposed to occupy the same position for a moderately long period of time (e.g., in front of a painting). This means that, also in this case apart from (above cited) conditions for the total and theoretical thermal comfort, it is important to investigate the reasons for local thermal discomfort, that is, more or less sudden variations in temperature and humidity characteristics.

Nevertheless, when evaluating the air temperature and relative humidity requisites for both people's comfort and artwork preservation, the second aspect should be accomplished first, as this represents the priority in museums. In fact, artworks cannot "defend" themselves, while people can still adjust their comfort level through clothing. In this regard, guidance could be given to museum users (both workers and visitors).

Anyway, it should be underlined that a correct evaluation of thermal conditions could obviously also affect the energy consumption for the climatization of museum buildings. An incorrect evaluation could, indeed, lead to an over- and/or under-estimation of the size of the HVAC system, since the rooms could be considered in a non-optimal zone for periods longer and/or shorter than the actual ones.

4.2. Lighting and Visual Comfort

In reference to what was reported in Sections 2.2 and 3.2, it is evident how the values that ensure a good/optimal visual task to people diverge significantly from the safety limits for the artworks within museums, making appropriate visual comfort a delicate aspect to consider. In fact, according to the regulations cited above, the maximum limits for the preservation of artworks are often even lower than the minimum limits to guarantee optimal levels of visual comfort/acuity for people. The need for adequate illumination clashes with the imperative to preserve artworks (particularly in terms of the UV component), thus necessitating the use of dim lighting controls.

Additionally, what makes the finding of common values for artworks and people benefits more difficult is the fact that suitable thresholds for clear visual parameters have not been firmly established for museum environments. For instance, the indication given by Decree 2001 in reference to the luminance levels seems more linked to the fact that 50 lux is the minimum level of light required by the human eye to discern colors and details of a displayed object than to reasons purely related to the preservation of the artwork [13,43,74].

Conversely, in terms of establishing proper reference values, tentatively precautionary actions should be taken by giving priority to the values for the artwork's optimal conservation and exhibition, particularly due to the possible content of UV radiations that might be released by the lighting fixtures adopted in museums.

4.3. Indoor Air Quality

When contrasting maximum allowable pollutant concentrations for considerations of both human comfort and artwork preservation, it is advisable to adopt the most stringent values during the design and control phases of indoor air quality in museum buildings.

Table 11 presents a first approach of comparison of the maximum allowable [25,52,75,76] concentrations of chemicals in enclosed environments for museums and people's comfort and safety.

Table 11. A comparison of allowable concentrations for IAQ for artworks and people.

Chemical Component	Limits for Museums and Archives	Limits for People
Sulphur oxides (SO_x)	10 μg/m^3	20 μg/m^3 (24 h mean)
Nitrogen oxides (NO_x)	10 μg/m^3	20 μg/m^3 (annual)
Ozone (O_3)	2 μg/m^3	0.1 mg/m^3 (8 h mean)
Particulate matter (PM_{10})	75 μg/m^3	50 μg/m^3 (24 h mean)
Carbon monoxide (CO)	-	7 mg/m^3 (24 h mean)
Formaldehyde (VOC)	N/A *	0.1 mg/m^3 (30 min mean)

* N/A: not available.

As can be observed, for the considered pollutants, other than the case of particulate matter, the most limiting thresholds reported in Table 11 are related to the requirements for displaying and conserving cultural artifacts (first column). Moreover, for carbon monoxide (CO), the criteria for human comfort should also be met since no specific limitations are indicated for museums. Of course, these limits depend on the type of materials of which the artworks are made and should, therefore, be understood as recommended average values. For example, the ASHRAE handbook [77] indicates limits of less than 0.05 ppb for sensitive materials for the ozone, from 0.5 to 5 ppb for general collections, from 1.0 (Canada) to 13 (USA) ppb for the storage of archival documents, and 2.0 ppb for libraries, archives, and museums.

In summary, when museum buildings are involved, special attention must be given to the design of the HVAC systems to be installed. Ventilation rates are, indeed, intended to guarantee not only adequate thermo-hygrometric conditions, but they should also ensure an appropriate clearness of air, avoiding causing discomfort to people (e.g., draught and noise). Furthermore, the filters of the systems should ensure the effective reduction of hazardous concentrations of chemical components for both artworks and people and take into account the possible risks for people highlighted by recent events related to the pandemic crisis.

4.4. A Real Case Example: The Sicilian Regional Museum

For a better understanding of what has been described and discussed earlier, in this subsection it was decided to report an application example by referring to a real case, namely, the Sicilian Regional Museum sited in Palermo (Italy), where many artifacts of the highest quality can be found displayed mainly within shared rooms. The museum itself (which has been the subject of previous studies by the present authors [12,60,73]) represents an element of the cultural heritage since it is hosted by the historical *Palazzo Abatellis*, a splendid example of Gothic-Catalan architecture built in 1495 by Matteo Carnilivari (Figure 4).

It must be once again underlined that, although the values pertinent to the comfort of people are easy enough to define, making a distinction between winter and summer conditions, the limits for artworks vary significantly based on the materials used in their creation. Consequently, it was decided to evaluate the possible ranges of compatibility and/or incompatibility, for winter and summer conditions, by referring to the simultaneous presence within the same environment of (i) an artwork made of organic material (i.e., considered to be from highly to moderately sensitive to changes in environmental characteristics); (ii) an artwork made of inorganic material (i.e., considered to be from low to not sensitive to changes in environmental characteristics); and (iii) people. Specifically, the artworks considered for the purpose of this example are, as the organic type, an oil on wood-panel painting (the *Virgin Annunciate* by Antonello da Messina, 1475 ca.) and, as the inorganic type, a marble sculpture (the *Bust of Eleanor of Aragon* by Francesco Laurana, 1471 ca.).

Figure 4. Atrium of *Palazzo Abatellis*, Palermo.

To highlight how the combination of the presence of different artworks and visitors in the same room changes their thermo-hygrometric, lighting, and indoor air quality requirements, the following Figures 5–8 show the data relating to the artworks previously mentioned and exhibited at *Palazzo Abatellis*. In particular, three different cases were analyzed: (a) the display of a single low-sensitive (i.e., inorganic) artwork (the *Bust of Eleanor of Aragon*), (b) the co-presence of a low-sensitive and a sensitive artwork (i.e., inorganic and organic, hence the *Bust of Eleanor of Aragon* and the *Virgin Annunciate*) in the same exhibition hall, and (c) the simultaneous presence of these artworks and people.

Figure 6 shows graphically how the indoor parameters change when, in addition to the presence of a single sensitive artwork (the *Virgin Annunciate*), a less sensitive artwork (the *Bust of Eleanor of Aragon*) and the presence of people are added, both in the winter and summer cases. The data reported in Figure 6 allow us to make some interesting considerations, which are reported in the following. Regarding the environmental thermo-hygrometric parameters, the boundary areas (plotted in T-RH graphs) allow the identification of common zones for both winter and summer conditions. It is evident how the extent of such overlapping areas decreases as the sensitivity of the artworks increases, and how this reduction is influenced more by the presence of the people in reference to the considered season (with a worsening during the summer season) rather than by the combination of the different artworks. This circumstance signals to pay particular attention to both choosing the type of artwork to be displayed within the same environment and designing an HVAC system able to consider different needs at the same time.

Concerning the lighting parameters, which are reported in Figure 7, as already discussed in Sections 2.2, 3.2 and 4.2, it is difficult to find common ranges for two main reasons: (i) artwork preservation and visual comfort have very conflicting needs; (ii) different types of artworks have different sensitivities to light exposure; and (iii) people of different ages have different sensitivities to minimum illumination levels. Hence, the suggestion that can be made (which has already been partly implemented by the considered museum) is to provide basic general lighting such that the most restrictive limits related to the most sensitive works are met, and to add spotlights to illuminate less sensitive works more brightly.

As for the indoor air quality (IAQ), looking at Figure 8, it is noticeable how, although under current regulations and standards [39,43] the limits on the preservation of artworks are unique, the guidance given by the ASHRAE [42,77] makes it possible to identify which types of artworks are more sensitive to one type of pollutant than another. In this case, for example, the *Bust of Eleanor of Aragon* (inorganic) is the one most sensitive to particulate matter, while for other substances, the *Virgin Annunciate* (organic) appears to be more susceptible to damage. However, people's health turns out to outweigh artwork preservation only in the case of particulate matter.

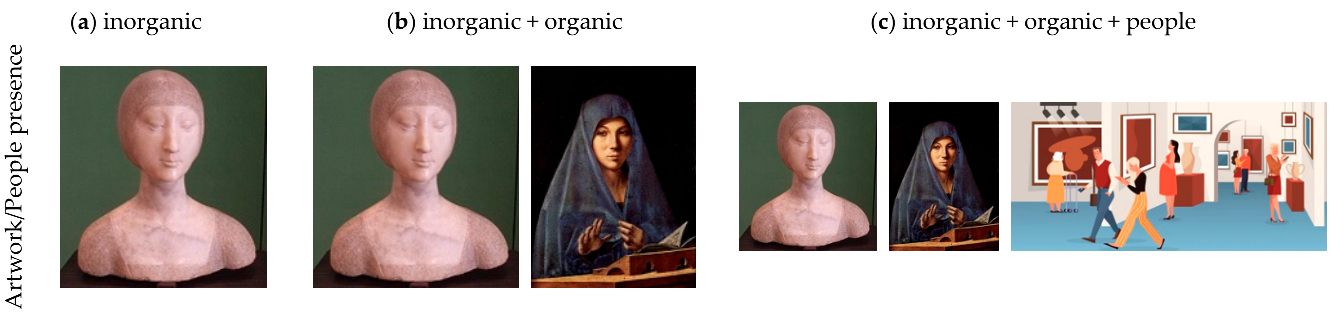


Figure 5. Considered cases for the comparison of the optimal thermo-hygrometric, lighting, and indoor air quality parameters depending on the presence of different kinds of artworks and people in the same hall at the Sicilian Regional Museum (*Palazzo Abatellis*, Palermo).

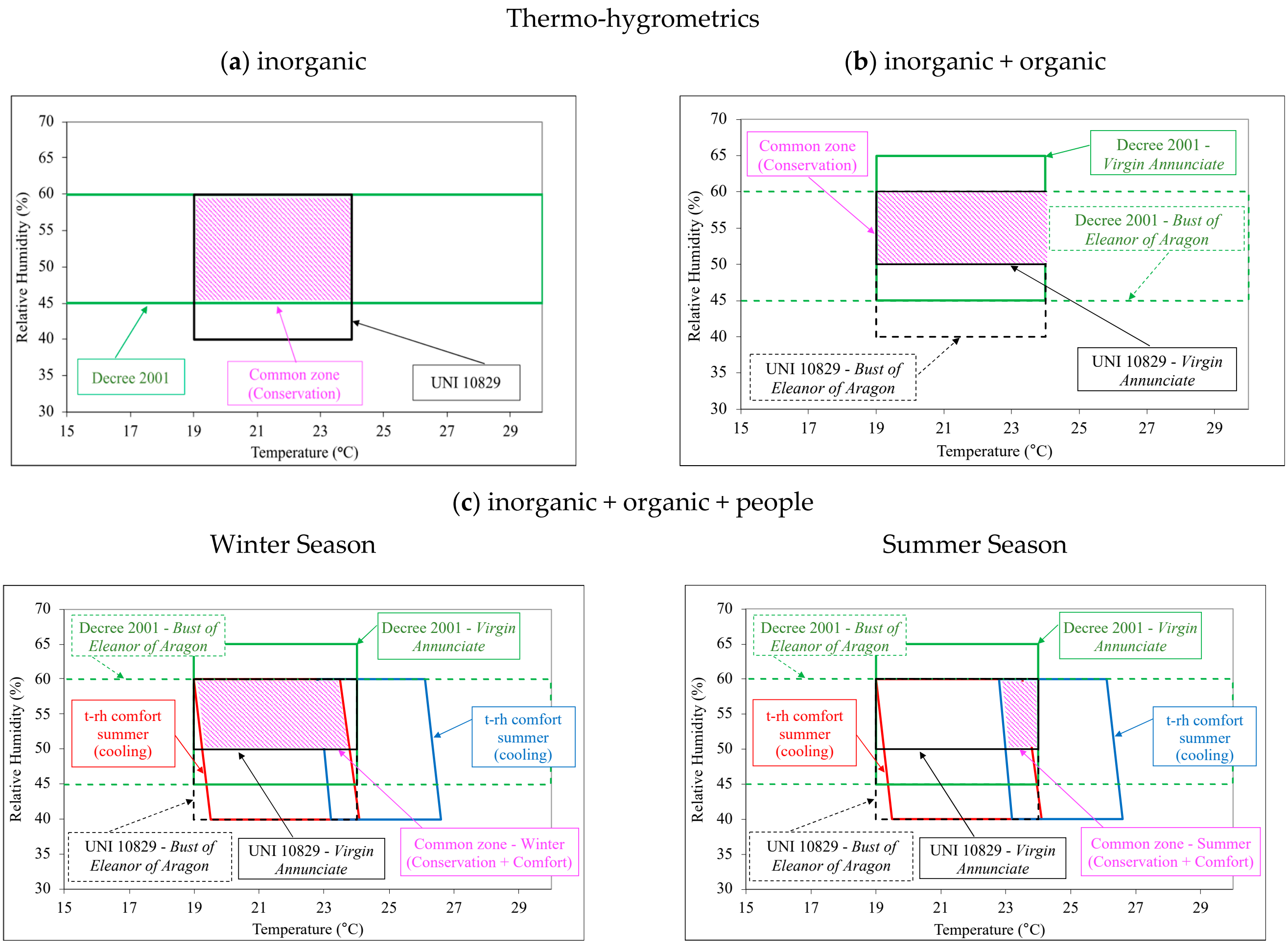


Figure 6. Comparison of the optimal thermo-hygrometric parameters depending on the presence of different kinds of artworks and people in the same hall at the Sicilian Regional Museum. (*Palazzo Abatellis*, Palermo).

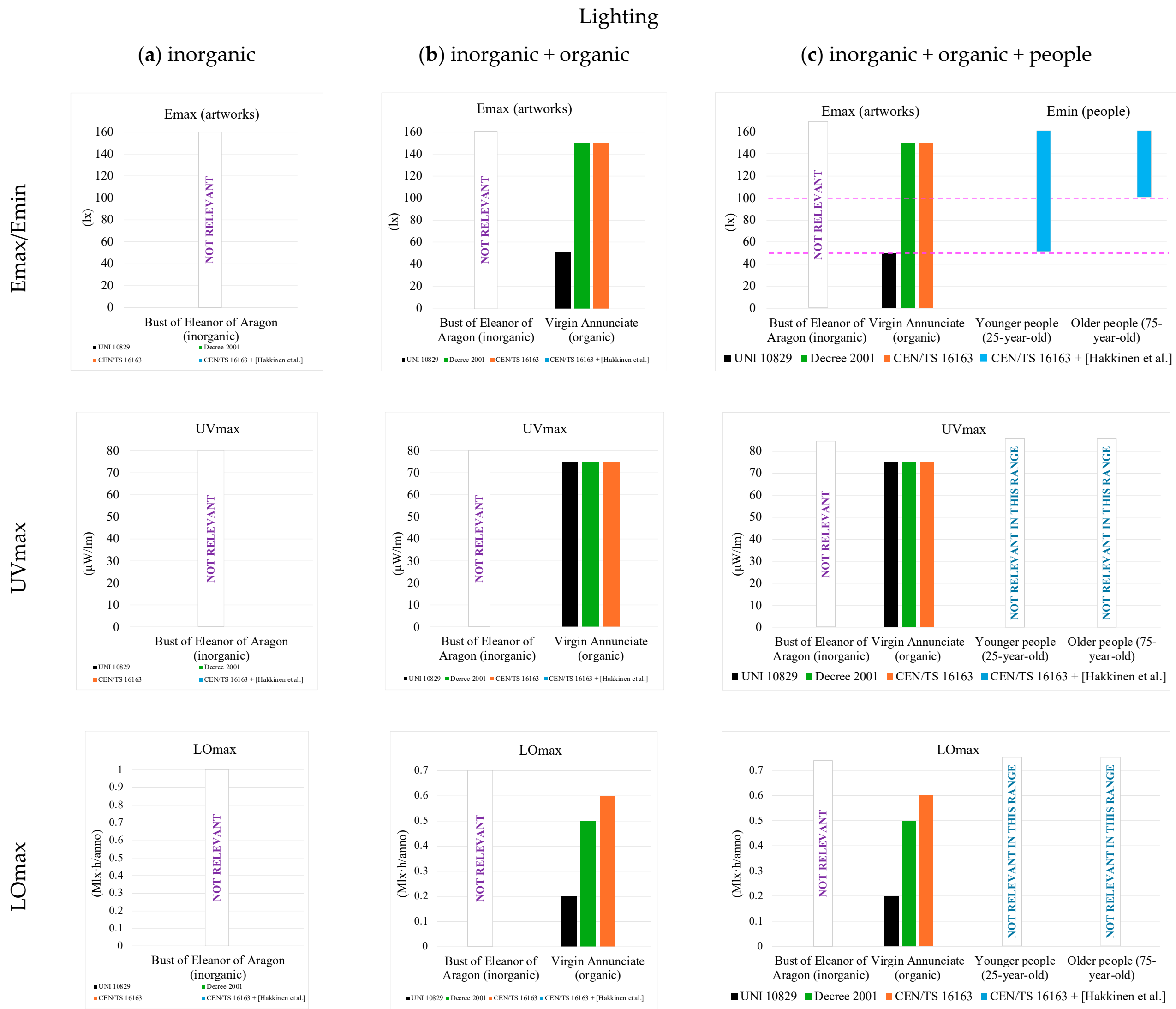


Figure 7. Comparison of the optimal lighting parameters depending on the presence of different kinds of artworks and people in the same hall at the Sicilian Regional Museum (*Palazzo Abatellis*, Palermo).

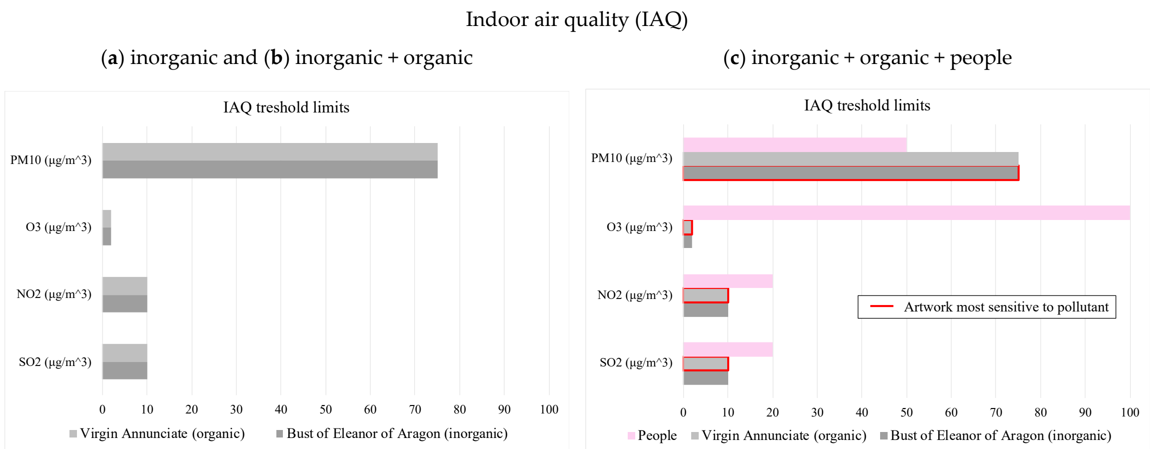


Figure 8. Comparison of the optimal indoor air quality parameters depending on the presence of different kinds of artworks (i.e., conditions (**a**) and (**b**) reported on the left side of the Figure) and people (condition (**c**) reported on the right side of the Figure) in the same hall at the Sicilian Regional Museum. (*Palazzo Abatellis*, Palermo).

5. Conclusions and Future Perspectives

The here presented review/examination of the current up-to-date literature of standards, regulations, and handbooks on museum buildings' indoor parameters started from the consideration regarding the possibility of establishing a useful set of rules/guidelines to follow for proper management of indoor parameters in museums, in order to accomplish the (often conflicting) needs relating to artwork preservation and people's comfort.

The conducted work has emphasized that, although some progress has been made, there is still much to be done regarding the issues addressed. As a matter of fact, the importance of identifying and providing suitable values of indoor (thermo-hygrometric, lighting, and indoor air quality) parameters that can simultaneously meet the requirements for the achievement of comfort conditions for visitors and workers and, especially, those for the adequate display and conservation of the artworks has emerged. To this aim, it has been shown how the consideration of the specific needs of different types of artworks is of fundamental importance for the definition of proper criteria that would consent to implement an optimal control strategy of the indoor environment in museums (particularly those hosted by historical buildings).

Furthermore, based on the considerations made on the real case example, the importance of performing assessments of indoor parameters even in museums already set up, and not only in the initial design phase, has also emerged. Indeed, such analyses would make it possible to (a) verify the suitability of existing HVAC units (for controlling thermo-hygrometric and air quality characteristics) and lighting fixtures; (b) assess whether, in museums inadequately (or even not) equipped with such systems, any corrective intervention is necessary; and (c) possibly rethink the arrangement of artworks in different halls. Of course, in all cases, the role of curators is essential in safeguarding the correct exhibition policy from a scientific and philological point of view [12].

Finally, it should be pointed out that the requisites for artwork conservation and people's comfort and safety discussed in this paper are also closely related to measures focused on enhancing the energy and environmental efficiency of museums (especially in the case of historical buildings [78]). To this aim, future (theoretical and field) research developments of the present authors are directed toward the definition of criteria and smart strategies (e.g., using innovative sensors) based on the following main aspects:

- Improvements/retrofit of the building envelope for correct maintenance of indoor environmental conditions;
- Proper choices/modifications and control of air conditioning (HVAC) systems to avoid unwanted disruptions to the displayed artworks and overall visual experience while, concurrently, ensuring optimal environment conditions both in terms of thermo-hygrometric characteristics and indoor air quality (aggressiveness/dangerousness);
- Suitable selection/change/positioning and checking of lighting equipment to ensure an accurate visual perception and, simultaneously, avoid damage to the artifacts;
- Adequate handling of people's presence, such as access management and behavior suggestions for both workers and visitors, along with a rethinking of current filtration techniques, to minimize the risks associated with both damage to collections and contagion among people (particularly in environments with high crowding indices);
- A possible implementation of a single comprehensive indicator of museum environmental performance instead of a mere checking of the reference values (e.g., by making use of some of the already existent and fragmented indices).

Of course, this new vision of museum design, retrofit, and management must be accompanied by a focus on energy and environmental costs, thus inducing remarkable energy savings and a significant reduction of pollutant releases into the atmosphere, for a better level of consciousness of the natural environment also in tune with the UN Sustainable Development Goals [5] and the EU Climate Agenda 2030 [79]. It is indeed quite evident that these goals, mainly designed for residential and tertiary buildings, are entirely consistent with the requirements for a sustainable fruition and running of museums.

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