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Use of International Adaptive Thermal Comfort Models as a Strategy for Adjusting the Museum Environments of the Mudejar Pavilion, Seville

Inmaculada Gallego-Maya [1] and Carlos Rubio-Bellido [2,*]

[1] International Doctoral School, University Institute of Architecture and Construction Sciences, University of Seville, 41012 Seville, Spain
[2] Department of Building Construction II, University of Seville, 41012 Seville, Spain
* Correspondence: carlosrubio@us.es

Abstract: Adaptive thermal comfort models are increasingly utilized to condition thermal environments by considering occupants' adaptability. The most widely recognized models internationally are the ASHRAE 55-2020 and UNE-EN 16798-1:2020 standards, primarily applied in residential and office buildings. However, their use in heritage buildings such as museums has been very limited. These environments present unique challenges that complicate the implementation of conventional energy-saving methodologies due to restrictions on interventions in the buildings to safeguard their historical value. Therefore, it is essential to develop research that evaluates the applicability of these standards as an alternative strategy to the specific conditions of museums in heritage buildings in Spain. This study aims to explore the application of the international adaptive thermal comfort models of the ASHRAE 55-2020 and UNE-EN 16798-1:2020 standards in parallel with the preventive conservation conditions of the collections established by the UNE-EN 15757:2011 standard. The aim is to evaluate new strategies for environmental reconditioning to improve visitor comfort while ensuring the conservation of the collections in the exhibition spaces of the Museum of Popular Arts and Customs, housed in a 1914 building known as the Mudejar Pavilion in Seville. Field monitoring was conducted to assess the thermal environment and visitor comfort. The results revealed that the monitored environmental conditions of the exhibition spaces of the Mudejar Pavilion, in accordance with ASHRAE 55-2020 standards, showed high effectiveness in ensuring thermal comfort for visitors, achieving comfort 99% of the time annually, with an acceptability of 80%. High suitability for the conservation of collections was also observed, with optimal conditions achieved 87% of the time. However, under the standards of UNE-EN 15757:2011 for a Category III expectation level, comfort was only achieved 70% of the year, while stability of conservation conditions was achieved 88% of the time. Finally, the implementation of specific correction guidelines is proposed to achieve the acceptability limits of greater energy efficiency.

Keywords: thermal comfort; adaptative model; museum; conservation; heritage building

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Citation: Gallego-Maya, I.; Rubio-Bellido, C. Use of International Adaptive Thermal Comfort Models as a Strategy for Adjusting the Museum Environments of the Mudejar Pavilion, Seville. *Energies* **2024**, *17*, 5480. https://doi.org/10.3390/en17215480

Academic Editor: Boris Igor Palella

Received: 4 October 2024
Revised: 26 October 2024
Accepted: 29 October 2024
Published: 1 November 2024

1. Introduction

Heritage buildings used as museums face various challenges to their energy conditioning. These include the environmental preservation conditions of museum collections, which must be balanced with visitor comfort, and the limitations found in the conventional methodologies to meet current energy standards. Any intervention in these buildings must respect their historical and architectural value, which limits the options available to improve their energy efficiency (EE) without compromising their integrity.

1.1. Limiting the Use of Conventional Methodologies

The strategies of conventional methodologies are aimed at reducing energy consumption [1]. The Energy Efficiency European Directive 2010/31/UE introduced the concept of Nearly Zero Energy Buildings (nZEB), which aims to design high energy performance buildings that use mainly renewable energy sources.

In 1979, the first Spanish regulation related to saving energy and EE in buildings was developed. It was NBE CT-79, the old basic standard that required minimum levels of thermal insulation for thermal envelope elements and buildings. Subsequent updates included the appearance of the Spanish Technical Building Code (CTE in Spanish) in 2006, with the introduction of HE0 in 2013, adjustments to European standards in 2019, and the incorporation of electromobility in 2022.

The importance of the temporary line of the evolution of the standard regarding saving energy in Spain shows the need for intervention, particularly regarding energy rehabilitation measurements, in view of the large number of buildings that persist to date that were built prior to the date of entry into force of the first minimum requirements for thermal insulation of the envelope of NBE CT-79.

Heritage buildings are included in this category, as they are architecturally and culturally important, but they lack modern technologies and regulations.

Most of these buildings are included in the Spanish Historical Heritage, so there is rigorous regulation in relation to their conservation and restoration to protect them. Moreover, the most common practice to preserve the architectural historical heritage is to turn these buildings into museums, where the range of intervention is even less strict than in contemporary buildings for that purpose, such as the Acropolis Museum in Athens, Greece, as an example of the use of the most advanced technology in terms of EE, or some examples in Spain such as the Guggenheim Museum Bilbao, which has been adopting new sustainability measures to reduce its energy consumption.

However, it is not only the difficulty of establishing conservation conditions for museum collections or the limitations of interventions to condition the architectural historical heritage that limit the use of conventional methodologies. The energy performance of nZEB buildings is widely shown in the scientific literature. Likewise, member countries of northern Europe have easily adapted this concept to their building technological processes by adapting existing methodologies, such as Passive House standards [2]. However, in the member countries of the south of Europe, climate conditions lead to a high overheating risk in summer, thus limiting their use [3]. Thus, the potential to achieve energy goals in countries with mild climates may be based on a change in paradigm: to change the current methodology to implement nZEB buildings considering other influential parameters, such as climate, socioeconomic, and cultural conditions [4].

1.2. Alternative Methodologies: Adaptive Thermal Comfort Models

Various adaptive thermal comfort (ATC) models have recently been used as an alternative strategy for controlling the thermal environment [5,6]. These models are based on occupants' capacity to adapt bidirectionally to the environment through changes such as clothing insulation (lcl) or physical activity level (M) until the expected comfort condition is reached. In short, to ensure their comfort conditions are met, individuals act to control their environment. Their presence and actions, impacted by many physical variables, determine the balance between the individual and environment [7].

The most used international standards are ASHRAE 55-2020 [5] and UNE-EN 16798-1:2020 [6], which were particularly developed for residential building [8–18] and office [19–21] environments, to which the scientific literature pays greater attention since these models are specifically developed for this field.

The integration of ATC models in buildings significantly affects energy consumption [22], but few research studies have analyzed the influence of the adaptive theory of temporary occupancy spaces for heritage buildings for museum use.

1.3. Literature Reviews

There is very extensive literature on EE for heritage buildings in Italy [23–29] and Spain [30–33], but international research applying thermal comfort models for heritage buildings dedicated to museum use is limited [34–37], and even more limited are models based on the use of adaptive theory [38]. A study by Y. H. Yau and his research team [37] took as a case study the National Museum of Malaysia, where they evaluated the thermal environment and the comfort of the occupants, obtaining 78% of visitors in comfort through the ASHRAE 55 heat balance model, which did not to meet the standards. A.K. Mishra and his research team [36] focused on the Hermitage Museum in Amsterdam, where they evaluated the subjective thermal perception of visitors through surveys and monitoring using ASHRAE, establishing a temporal transition of between 20 min. and 30 min. of stay in the museum, where the thermal perception of visitors evolved towards a preference for warmer temperatures inside. The research of J. Ferdyn-Grygierek [35] investigated the indoor environmental quality in a Polish museum and its effect on heating and cooling demands. The results showed that maintaining mechanical control of a constant temperature of 20 °C in winter can reduce heating demand by 5–16%, while in summer, keeping the temperature below 24 °C required additional cooling. In contrast, Kramer et al. [39] demonstrated substantial energy savings up to 63% in a museum in the Netherlands using dynamic climate control for both temperature and relative humidity, which allowed for varying temperature within the entire comfort range. More recent research, such as that by [40], analyzed fifty case studies in different climates, evaluating factors that affect energy efficiency and natural lighting in museums—some of which were historical in nature. The results indicated that mass and envelope design techniques were the most effective for optimizing energy consumption in museums, but they did not analyze the impact of these techniques on conservation or thermal comfort. Finally, Rich Kramer and his research team [38] used ATC models to simulate control of the indoor thermal environment in exhibition halls; they evaluated the conservation quality of the collection and studied the energy behaviours after using these thermal comfort models in simulated indoor climates. To reduce the energy consumption of the state-of-the-art H'ART Museum in Amsterdam, the Netherlands, the ATC model of ASHRAE 55 was implemented in various adjustment strategies. The conclusion was that the building's energy use could be reduced up to 82%, thus showing an optimal intervention strategy leading to a savings of 77%, significantly improving visitors' thermal comfort as well as indoor environmental conservation conditions.

Considering the Spanish context, Antonio Molina and his research team [41] analyzed the application of Fanger's thermal balance theory through monitoring instruments and questionnaire surveys related to the effect of thermal perception on the preservation of artworks exhibited in the History Museum in Valencia and on visitors' thermal comfort. The results of this study showed the limitations of Fanger's model when applied to this type of building, stressing the need for more studies related to this field.

In recent years, the literature on EE and thermal comfort in heritage buildings or museums has experienced remarkable growth [42–47]. However, the application of ATC models in museums located in heritage buildings has remained an underexplored niche. This study is situated at the intersection of these fields, offering a significant contribution with a particular focus: the application of ATC models by providing empirical data on their effectiveness in a specific context and challenging the predominant conventional methodologies. Furthermore, it was carried out using a dual approach underlining the importance of balancing human comfort with preventive conservation of cultural heritage, attempting to contribute to the achievement of sustainability and EE objectives in heritage buildings.

2. Methodology

The flowchart in Figure 1 illustrates the methodological process used in the study to assess adaptive thermal comfort in the Mudejar Pavilion in Seville. The process begins with the diagnosis of environmental conditions, assessing the factors present in the exhibition spaces. Then, Adaptive Thermal Comfort (ATC) models are applied to assess their impact on the thermal comfort of visitors. Subsequently, an analysis of the impact of the ATC models on the preventive conservation of the museum's collections is carried out. Finally, a revision proposal is developed suggesting adjustments and improvements based on the results obtained to optimize both the thermal comfort of visitors and the preventive conservation conditions in the museum.

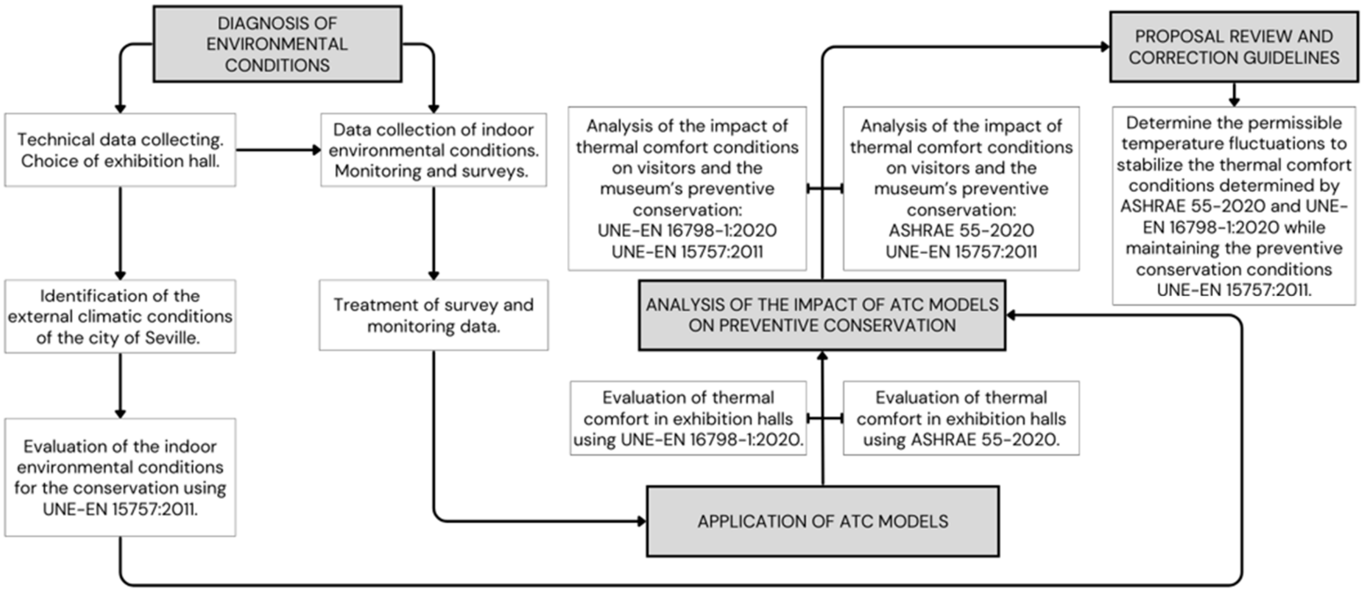


Figure 1. Flowchart of the methodological process.

2.1. Seville, Spain: Climatic Conditions

Köppen–Geiger's classification according to the monthly mean values of rain and temperature in the city of Seville corresponded to the Csa climate. The climate is mild, with an average temperature in the coldest month between 0 °C and 18 °C. Summers are very dry and hot, with less than one-third of the rainfall of the wettest month, and the average temperature in the hottest month is greater than 22 °C. In fact, the temperature in summer frequently exceeds 35 °C maximum, with very little rainfall, making it the driest season of the year with an average RH of 39%. In autumn, temperatures begin to drop, with maximums between 25–30 °C in September and 15–20 °C in November, and rainfall increases progressively, especially in November, as well as RH, rising to 69%. In winter, temperatures are mild, with maximums around 15 °C and minimums around 5 °C, and rainfall is more frequent. Being the rainiest season of the year, winter has the highest RH of the annual period, reaching values close to 75%. During spring, temperatures are mild, with maximums between 20–25 °C, with moderate rainfall that decreases towards the end of the season, lowering the HR to an average of 60%.

2.2. The Museum: Description of the Case Study

The Mudejar Pavilion is one of the three buildings of the architectural historical site located in the America Square of the María Luisa Park in Seville, Spain. The other two are the Provincial Archaeological Museum and the Royal Pavilion. The Mudejar Pavilion is among the most famous sites in the city, so it is one of the Sevillian buildings with the greatest sociocultural impact. Likewise, local and international visitors are interested in its aesthetics (see Figure 2).

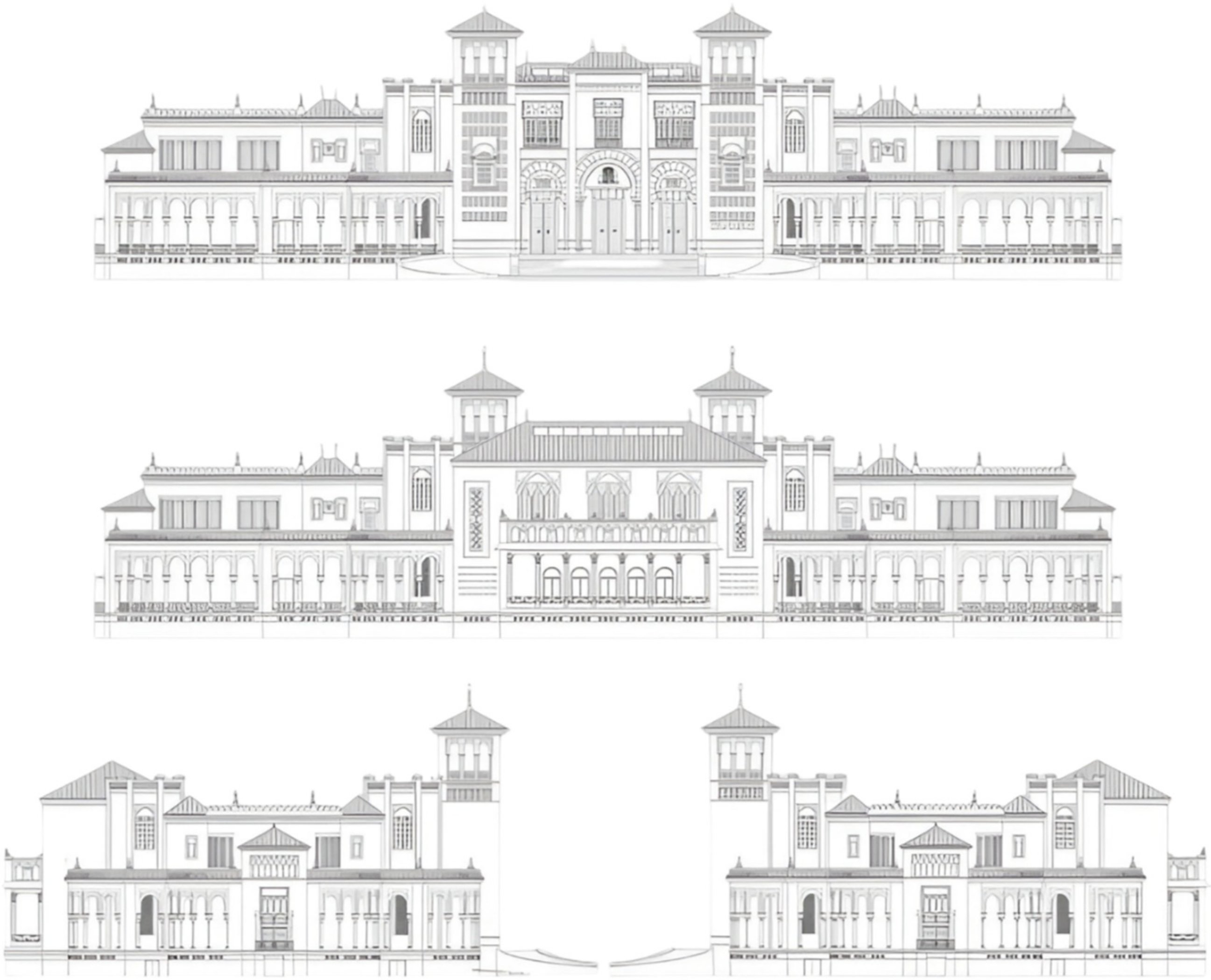


Figure 2. Frontal and posterior elevations and lateral section of the Mudejar Pavilion, which is the headquarters of the MACP SE. Adaptation and dimensioning based on plans [48].

This building was designed by the architect Aníbal González Álvarez-Osorio in 1913 as the headquarters of the Palace of Industries, Manufactures and Decorative Arts during the Ibero-American Exhibition in 1929. The building had many uses until 1972, when it became the headquarters of the MACP SE.

The building is approximately 8000 m^2, distributed in a basement floor at approximately -3.00 m and three floors above ground level with a summit at +22.50 m (see Figure 3). It has four exhibition rooms: three are on the first floor, one of which was not evaluated due to a scheduled intervention there during the data acquisition period, and the basement, with most of this exhibition space being itinerant. This study refers to these halls as Exhibition Hall 1, Exhibition Hall 2, and Basement Tour.

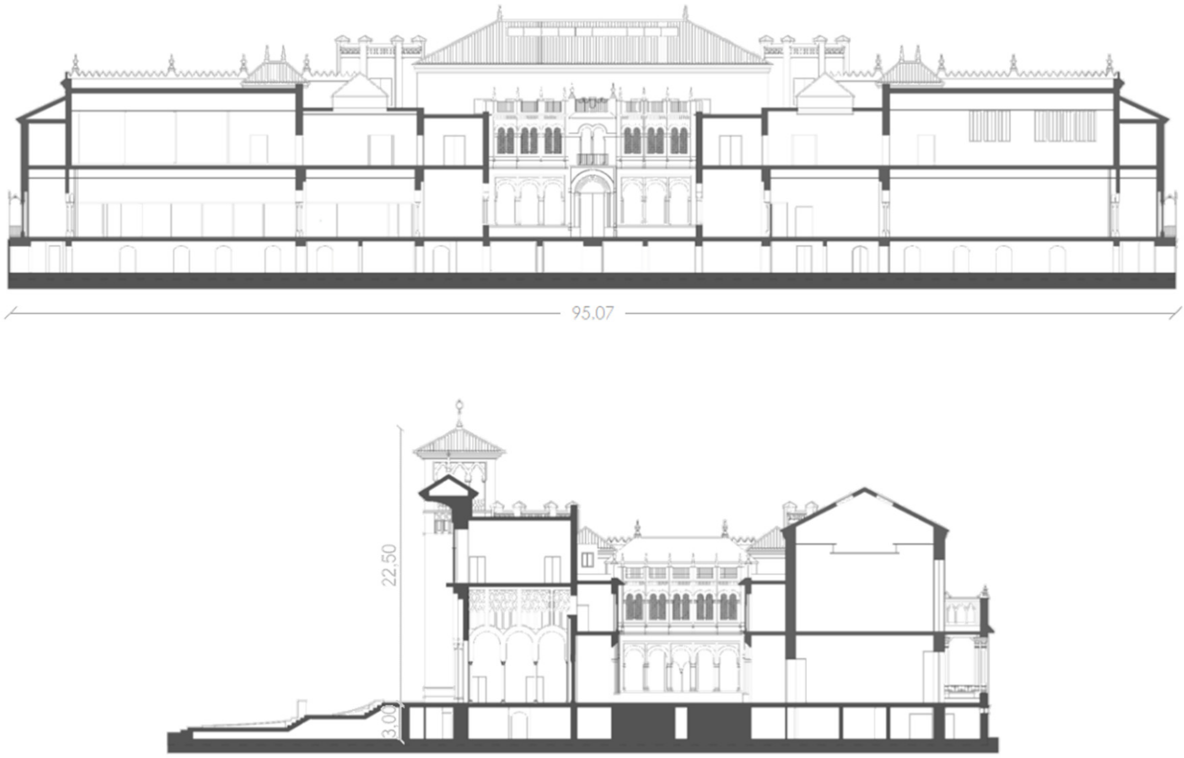


Figure 3. Transversal and longitudinal section of the Mudejar Pavilion, headquarters of the MACP SE. Adaptation and dimensioning based on plans [48].

2.3. Data Acquisition

The monitoring period took place between 2 July 2019 and 14 June 2020.

Temperature (T) and relative humidity (RH) of the outdoor climate were obtained from the records of the State Meteorological Agency (AEMET in Spanish) that were measured by the weather station of San Pablo (Seville) at an altitude of 34 metres above sea level and around ten kilometres away from the location of the building.

The indoor climate assessment was carried out by placing three HOBO U12-U13 sensors in Exhibition Hall 1, Exhibition Hall 2, and Basement Tour. The HOBO U12 sensor is a combined data logger that monitored the T and RH variables of the museum spaces.

In Exhibition Hall 1, the sensor was in the centre of the main exhibition hall (red dot 1 in Figure 4). The equipment was strategically attached to a museum exhibition structure located in the centre of the room at a height of approximately 2.00 m from the floor and another 2.00 m from the ceiling of the room. In Exhibition Hall 2, the sensor was positioned very close to the centre of the hall, above the central structure holding the glass panels that make up the various cubicles that protect the collections in the room (red dot 2 in Figure 4). The approximate height of the sensor position was 2.00 m above the floor and 2.00 m from the ceiling of the room. In the Basement Tour, the sensor (red dot 3 in Figure 5) was positioned in one of the central spaces of the route where the flow of visitors entering and leaving the exhibition converged during the tour of the floor. The sensor was placed on a space-dividing structure at a free height of approximately 2.00 m; as it was a below-ground space, the free distance to the ceiling was considerably reduced compared to the rest of the spaces in the museum.

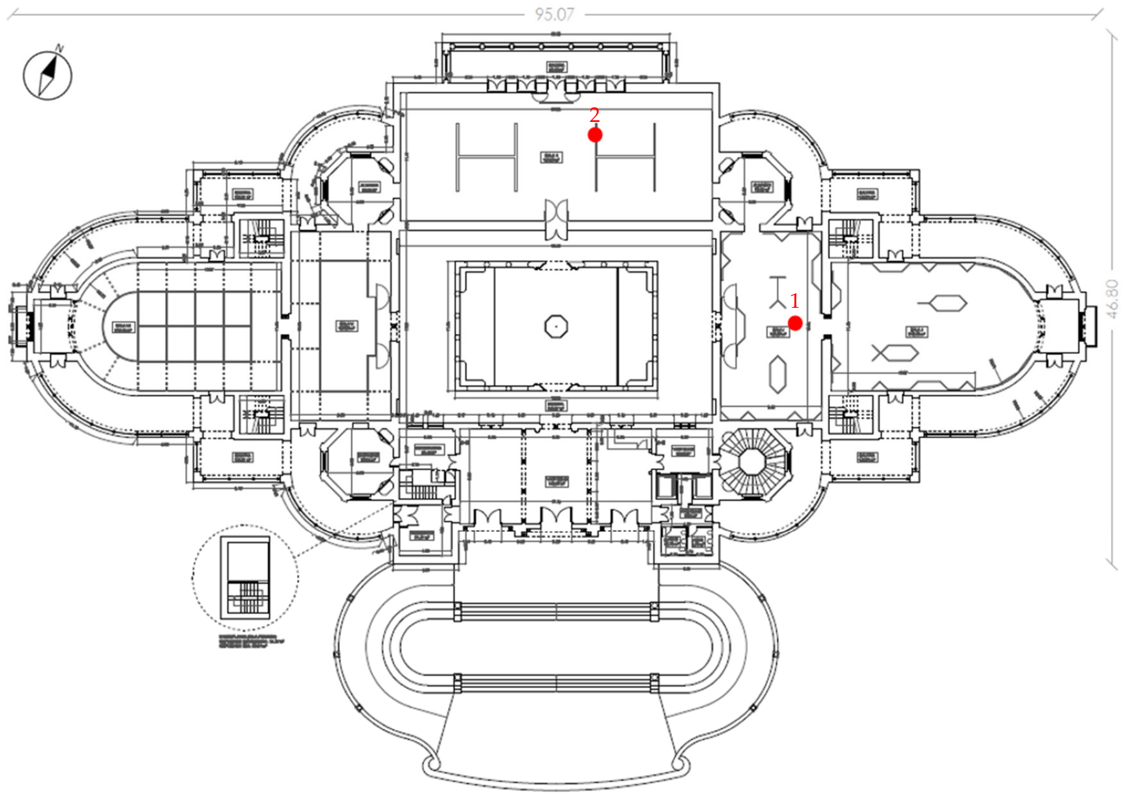


Figure 4. Positioning of monitoring equipment on first floor of the MACP SE. Adaptation and dimensioning based on plans.

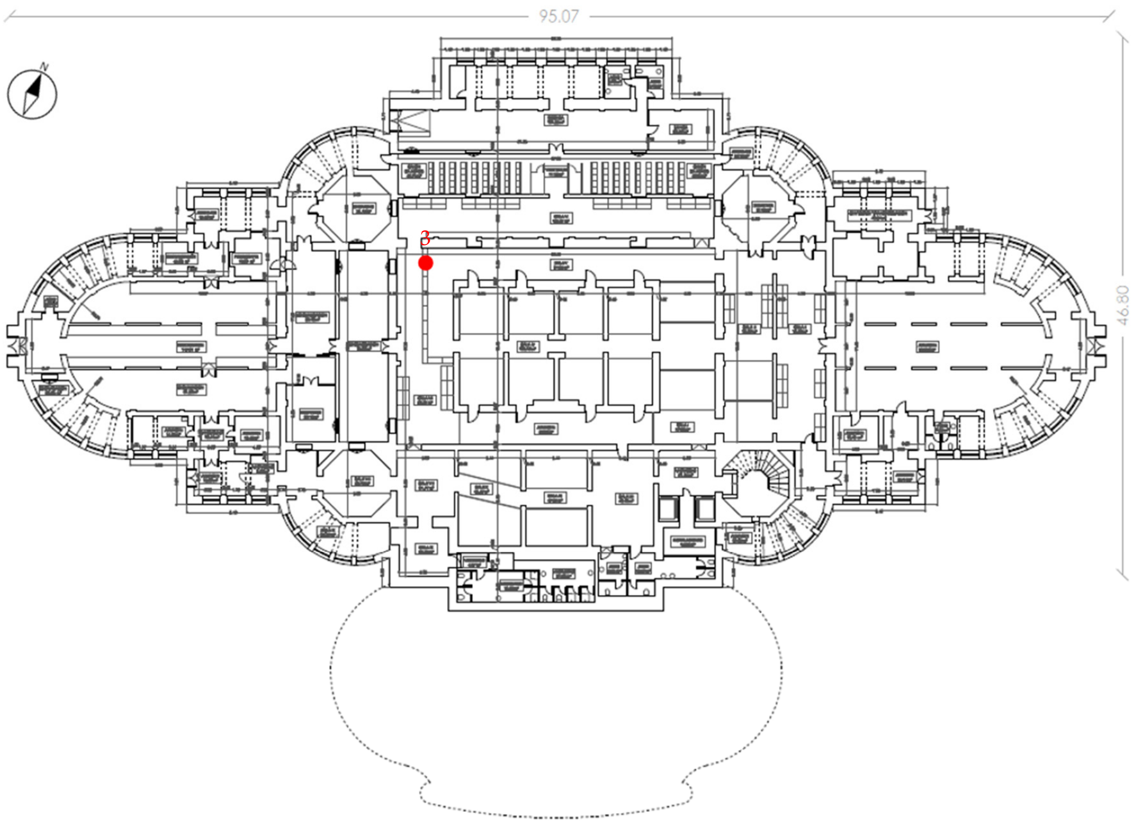


Figure 5. Positioning of monitoring equipment in basement of the MACP SE. Adaptation and dimensioning based on plans.

The sensor ranges were between −20 °C and 70 °C for T and between 5% and 95% for RH, with an accuracy of ±0.4 °C to monitor temperatures in the range between 0 °C and 50 °C and ±2.5% from 10 to 90% regarding RH. Likewise, the standard uncertainty was ±5% for the upper and lower limits of RH. To determine the validation prior to the placement of the equipment, monitoring was carried out with all the equipment in the same space for a period of 10 min, and it was found that the average error margin was ± 0.3 °C. This margin is considered low and was therefore ignored when obtaining the results. The instruments were programmed with a recording sequence of 10 min during the monitoring process at the museum. Readings from the equipment were taken quarterly using a laptop on-site at the museum, obtaining a total of 397.831 T+RH records for this study. Data were prepared for analysis using HOBOware software version 3.7.23.

Considering the diversity of the city's tourists, it was considered a challenge to obtain as much information as possible on the profile of visitors to this museum during the monitoring period. Forms were provided in four languages: Spanish, English, French, and German. A total of 482 forms were collected, identifying the following most relevant biases: 65% of visitors identified themselves as feminine, 35% as masculine, and 0.7% did not specify that aspect. The average age of the visitors that completed the form was 32, with Q1 at 21 and Q3 at 42 years old. Remarkable cultural diversity was on display, with visitors coming from multiple continents. Europe was widely represented, with Spain accounting for 44% of visitors, followed by France and Italy. America also had a significant presence, with the United States and Canada leading the way. Asia, although less represented, included countries such as China and Japan. Africa and Oceania were also present, with countries such as Algeria, Morocco, Australia, and New Zealand. In addition, 7% of visitors came from other unspecified countries, which could further underline the global diversity of the museum's visitors.

2.4. Conservation Conditions: UNE-EN 15757:2011

The seasonal cycle of RH was obtained by calculating for each reading the central moving average (MA), which corresponds to the arithmetic mean of all the readings of RH taken for 30 days, constituted by the 15 previous days and the 15 posterior days to the date when the mean value was calculated. For this reason, the first 15 days and the last 15 days of sampling were excluded as there were not enough data for the calculation.

$$MA_{ongoing} = (RH_{ongoing} + RH_{ongoing} - 1 + [\ldots] + RH_{ongoing} - 360 + RH_{ongoing} + 1 + [\ldots] + RH_{ongoing} + 360)/721 \quad (1)$$

The upper and lower limits were determined by the percentiles 7° and 93° of the fluctuations recorded during the monitoring. Thus, 14% of the fluctuations with the greatest risk were excluded by applying cuts to the crests and valleys of the relative humidity, limiting very wet or dry environments.

2.5. Thermal Comfort

Comfort in moderated thermal environments can be assessed according to two theories:

- The adaptive theory [49,50].
- The thermal balance theory [7].

Both models are based on mathematical models to estimate and predict the appropriate conditions under which people should be to obtain the expected thermal comfort.

There are other thermal comfort models, such as static thermal comfort models, where minimum and maximum setpoint temperatures are similar, regardless of the user and climate conditions. As for temporary occupancy spaces, their environmental quality should not be assessed according to static comfort requirements because users are going to use their ability to adapt to the environment.

Fanger developed the first thermal balance model. He proposed a method where the thermal sensation of people in an arbitrary climate can be predicted, considering as variables the air temperature (°C), the relative humidity (%), the mean radiant temperature (°C), and the air speed (m/s) as environmental factors and level of metabolic activity (M) as well as clothing insulation (lcl) as physiological factors. When these factors have been estimated or measured, the overall thermal sensation of the body can be predicted by calculating the Predicted Mean Vote (PMV). The second indicator, Predicted Percentage of Dissatisfied (PPD), provides information on the percentage of people who are uncomfortable in a given environment.

On the other hand, the adaptive thermal comfort models agree that there are six factors that should be considered when defining thermal comfort conditions: metabolic activity, relative humidity, air speed, clothing insulation, air temperature, and radiant temperature. The adaptive theory is based on occupants' capacity to adapt bidirectionally to the environment through changes, such as lcl or M, to reach the comfort condition expected. In short, individuals act by controlling the environment to satisfy their comfort condition needs, which is especially relevant in buildings with limited environmental control systems.

The UNE-EN 167981-1 standard for indoor environmental input parameters for the design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics establishes four indoor comfort classifications related to occupants' level of expectation, as well as other factors that condition comfort perception and building age:

- Category I: High. High level of expectation; this is recommended for spaces occupied by individuals with special requirements, such as people with disabilities, sick people, children, or the elderly.
- Category II: Medium. Normal level of expectation; this should be used for new and renovated buildings.
- Category III: Moderate. Acceptable and moderate level of expectation; this can be used in existing buildings
- Category IV: Low. Values not included in the criteria from the previous categories. This category should only be accepted during a limited period of the year. There is no health risk, but comfort could be reduced.

The comfort ranges adjusted to the requirements of each category were between the upper and lower limits according to Equations (2)–(7). As days go by from the day considered, temperature loses its influence in the assessment of visitors' comfort conditions, so an exponential sequence of the previous 7 days was established regarding prevailing mean outdoor air temperature θ_{rm} through Equation (8). θ_{ed-1} is the average external temperature of the previous day per day considered, θ_{ed-2} is the average external daily temperature of the day before day θ_{ed-1} and successive. α was considered the recommended value, at 0.8.

$$\text{Upper limit of the comfort zone Category I: } 0.33 \times \theta_{mr} + 18.8 + 2 \quad (2)$$

$$\text{Lower limit of the comfort zone Category I: } 0.33 \times \theta_{mr} + 18.8 - 3 \quad (3)$$

$$\text{Upper limit of the comfort zone Category II: } 0.33 \times \theta_{rm} + 18.8 + 3 \quad (4)$$

$$\text{Lower limit of the comfort zone Category II: } 0.33 \times \theta_{rm} + 18.8 - 4 \quad (5)$$

$$\text{Upper limit of the comfort zone Category III: } 0.33 \times \theta_{rm} + 18.8 + 4 \quad (6)$$

$$\text{Lower limit of the comfort zone Category III: } 0.33 \times \theta_{rm} + 18.8 - 5 \quad (7)$$

$$\Theta_{rm} = (1 - \alpha) \cdot \{\Theta_{ed-1} + \alpha\, \Theta_{ed-2} + \alpha^2\, \Theta_{ed-3+}\, \alpha^3\, \Theta_{ed-4} + [\ldots] + \alpha^n\, \Theta_{ed-n}\} \quad (8)$$

Both this model and the following ASHRAE model were developed particularly for office buildings but are applicable to other similar buildings, mainly those used for occupancy with sedentary activities, where occupants can freely adapt to indoor and/or outdoor conditions by controlling their clothing and accessing windows. It is established for both that the metabolic activity of the visitor must be between 1.0 and 1.3 met, air speed < 0.1 m/s, and—where possible—the level of clothing should be adapted between

0.5 and 1.0 clo. The operating temperature was evaluated based on the measurement of air temperature, although this does not provide an assessment as complete or accurate as that obtained with radiant temperature; this limitation is assumed in this research.

The applicability of the UNE-EN standard model is guaranteed for temperatures between 10 °C and 30 °C for upper limits and between 15 °C and 30 °C for lower limits.

In winter, the temperature limits established by the standard for buildings with mechanical air conditioning systems should be applied. In this study the limits of Table 1 apply. This was the application criterion in Exhibition Hall 2:

Table 1. Design values of set temperature in winter for buildings with mechanical control systems. Adapted from Table B.2 [6].

Type of Building/Zone	Category	Set Temperature Minimum for Heating in Winter, °C
Offices and enclosures with similar activities (individual offices, open offices, conference halls, auditoria, coffee shops, restaurants, classrooms, and so on).	I	21
	II	20
	III	19

Indoor air should not be dehumidified to a lower RH or be dehumidified to an RH greater than that of the design values. The limits recommended by UNE-EN 16978-1:2020 are those contemplated in Table 2:

Table 2. Design values of RH recommended in enclosures with humidification or dehumidification systems. Adapted from Table B.16 [6].

Type of Building/Enclosure	Category	RH of Dehumidification Design, %	RH of Humidification Design, %
Enclosures where humidity criteria are established by human occupancy.	I	50	30
	II	60	25
	III	70	20

ASHRAE 55-2020 establishes two thermal comfort ranges or levels according to the percentage of acceptability:

- 90% acceptability. Greater comfort requirement.
- 80% acceptability. Limit of acceptability under typical conditions.

The limits of acceptability of the adaptive comfort model ASHRAE are obtained according to the application of Equations (9)–(12).

$$\text{Upper limit of the comfort zone with 90\% acceptability: } 0.31 \times \theta_{rm} + 21.3 \quad (9)$$

$$\text{Lower limit of the comfort zone with 90\% acceptability: } 0.31 \times \theta_{rm} + 14.3 \quad (10)$$

$$\text{Upper limit of the comfort zone with 80\% acceptability: } 0.31 \times \theta_{rm} + 24.08 \quad (11)$$

$$\text{Lower limit of the comfort zone with 80\% acceptability: } 0.31 \times \theta_{rm} + 11.52 \quad (12)$$

The applicability of the standard model is guaranteed for temperatures between 10 °C and 33 °C for upper limits and between 15 °C and 30 °C for lower limits. This standard recommends a value of α = 0.9, but this factor was considered 0.8 as for UNE-EN.

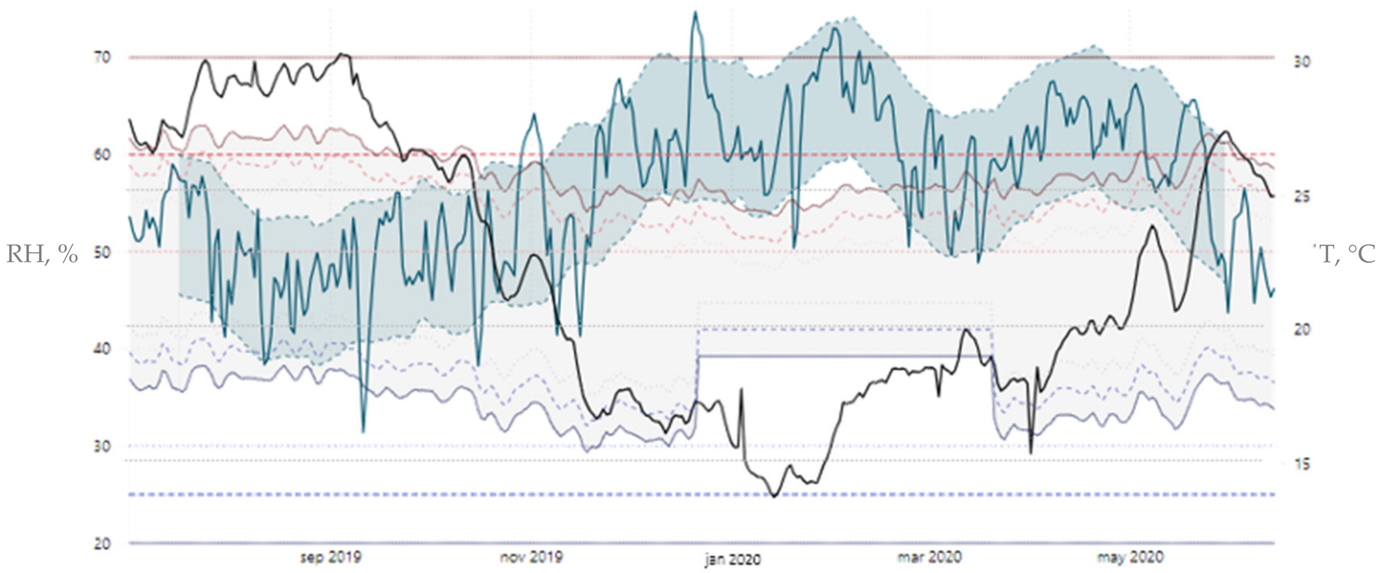
The ASHRAE 55-2020 standard adopts a thermal feeling scale. This scale is designed to compile information on respondents' subjective thermal perception. The descriptions of this scale are completely descriptive, so there is no effective reference to the comfort level. The standard does not accurately define specific considerations for an environment to be considered as acceptable, but the thermal feelings linked to the consigned votes in the three intermediate ratios, i.e., slightly cold, (−1), neutral (0), and slightly hot (+1), have been accepted as levels of satisfaction with the environment within the scientific scope [5,7].

The model to assess thermal comfort through the adaptive theory of ASHRAE 55:2020 does not require limits on humidity.

3. Results

3.1. UNE-EN 16798-1:2020–UNE-EN 15757:2011

The RH reference values of Exhibition Hall 1 (see Figure 6) on the first floor of the MACP SE under the free oscillation condition provided visitors with desirable comfort conditions 97% of the time, according to UNE-EN 16978-1:2020. For 3% of the time—equivalent to 11 days of the assessment period and no more than 4 consecutive days—preventive preservation values exceeded the Category III range. Within the limits of the model that guarantees a comfort condition of 97% of the time, preventive preservation conditions fluctuated outside the range determined by UNE-EN 15757:2011 [51], coinciding with thermal oscillations in the outside climate. This indicated the need to adjust RH, such as increasing the temperature in winter and reducing RH peaks. Nevertheless, ideal preservation conditions for the collections were achieved 88% of the time.



Where:

- Comfort zone for Category III limits, °C
- Preventive conservation zone, %
- Measured indoor air temperature, °C
- Measured relative humidity, %
- Upper limit of the comfort zone Category III, °C
- Upper limit of the comfort zone Category II, °C
- Upper limit of the comfort zone Category I, °C
- Lower limit of the comfort zone Category I, °C
- Lower limit of the comfort zone Category II, °C
- Lower limit of the comfort zone Category III, °C
- Upper limit of RH for preventive conservation, %
- Lower limit of RH for preventive conservation, %

Figure 6. Effect of the comfort conditions set by using the ATC model of UNE-EN 16798-1:2020 and the preventive conservation conditions regulated by UNE-EN 15757:2011 in Exhibition Hall 1.

By incorporating the T assessment, thermal comfort conditions were only achieved 51% of the time, limited by the lower and upper limits of T under severe weather conditions, with discomfort applying 93% of the time in winter and 97% in summer. For the rest of the year, the application of the model provided visitors with the theoretical comfort condition 93% of the time.

RH parameters in Exhibition Hall 2 (see Figure 7) guaranteed a desirable comfort condition 100% of the time, according to UNE-EN 16978-1:2020. According to UNE-EN 15757:2011, the oscillation in RH values indicated stability in the collections of the hall 87% of the time when analyzed from a conservation point of view.

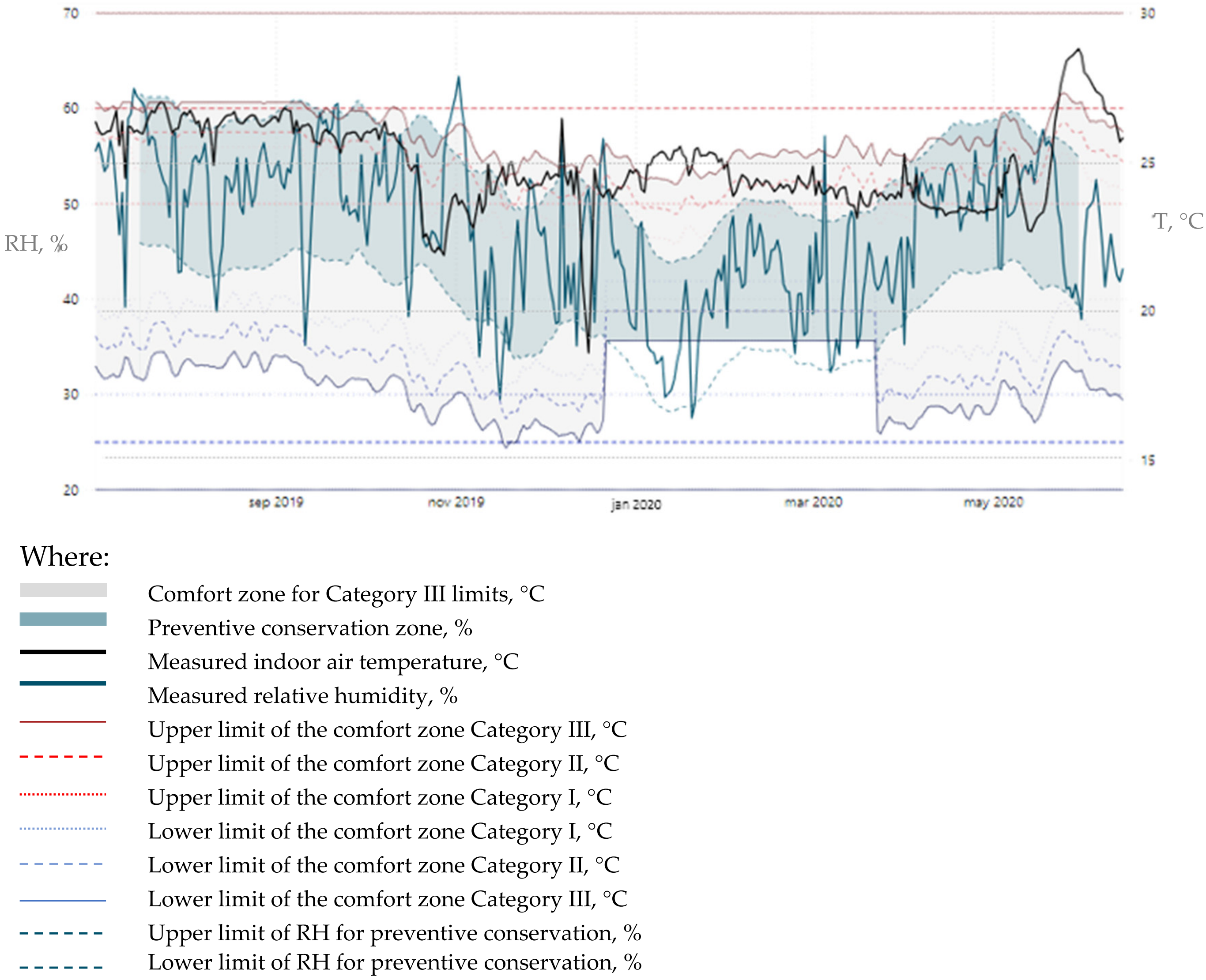


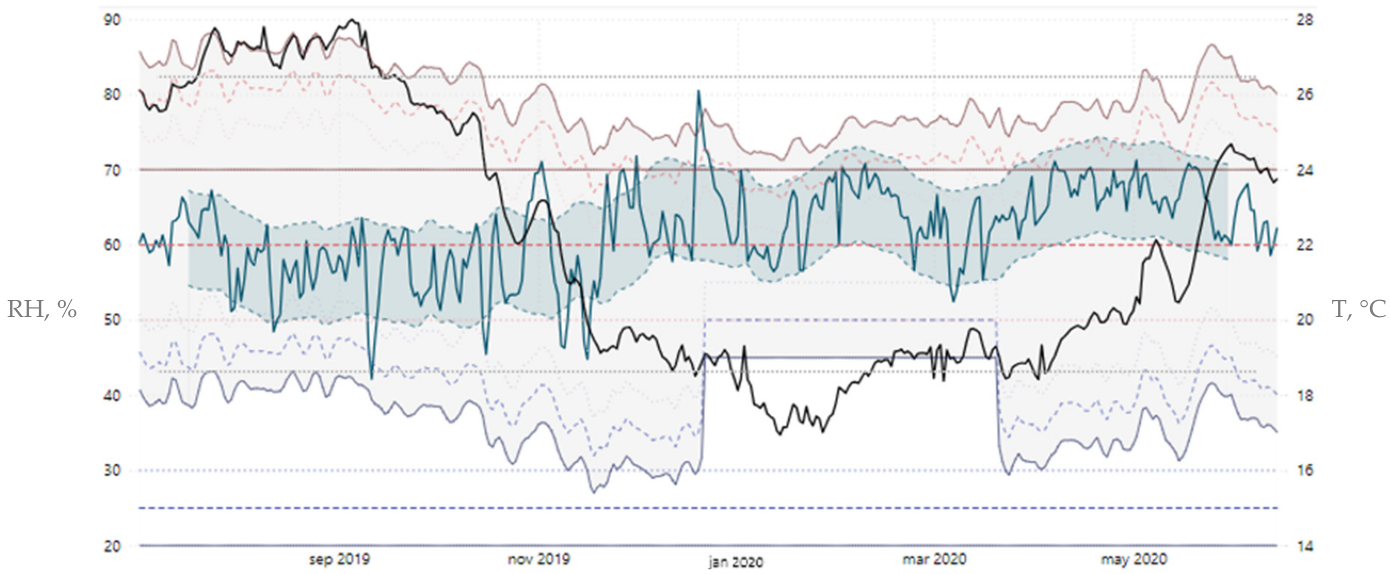
Figure 7. Effect of the comfort conditions set by using the ATC model of UNE-EN 16798-1:2020 and the preventive conservation conditions regulated by UNE-EN 15757:2011 in Exhibition Hall 2.

The use of the adaptive thermal comfort model of UNE-EN 16978-1:2020 as an evaluation methodology in Exhibition Hall 2 of the MACP SE established visitors' thermal comfort conditions were met 85% of the time, coinciding with 87% for preventive conservation values of UNE-EN 15757:2011.

In this hall, visitors' comfort was guaranteed 69% of the time in winter. In summer, comfort was guaranteed 99% of the time and conservation 87%. In autumn and spring, these percentages were 86% for comfort and 83% for conservation.

The theoretical basis of the UNE-EN and ASHRAE adaptive thermal comfort models, as a strategy to condition thermal environments considering the occupants' ability to adapt to the environment, applied to Exhibition Hall 2 under environmental control conditions through mechanical systems, suggests not making assumptions about the use of the standard. This is because perpetual control of the air conditioning systems in the pavilion would restrict the visitors' ability to adapt through lcl levels. This pavilion could potentially improve energy savings if free fluctuation of the thermal environment were allowed and a mixed regulation system was implemented when maximum limits were reached.

For the Tour Basement floor (see Figure 8), greater RH parameters as well as the greatest micro-climate stability of RH values and T were obtained in comparison with the same free oscillation condition of the exhibition halls on the first floor of the building.



Where:

- Comfort zone for Category III limits, °C
- Preventive conservation zone, %
- Measured indoor air temperature, °C
- Measured relative humidity, %
- Upper limit of the comfort zone Category III, °C
- Upper limit of the comfort zone Category II, °C
- Upper limit of the comfort zone Category I, °C
- Lower limit of the comfort zone Category I, °C
- Lower limit of the comfort zone Category II, °C
- Lower limit of the comfort zone Category III, °C
- Upper limit of RH for preventive conservation, %
- Lower limit of RH for preventive conservation, %

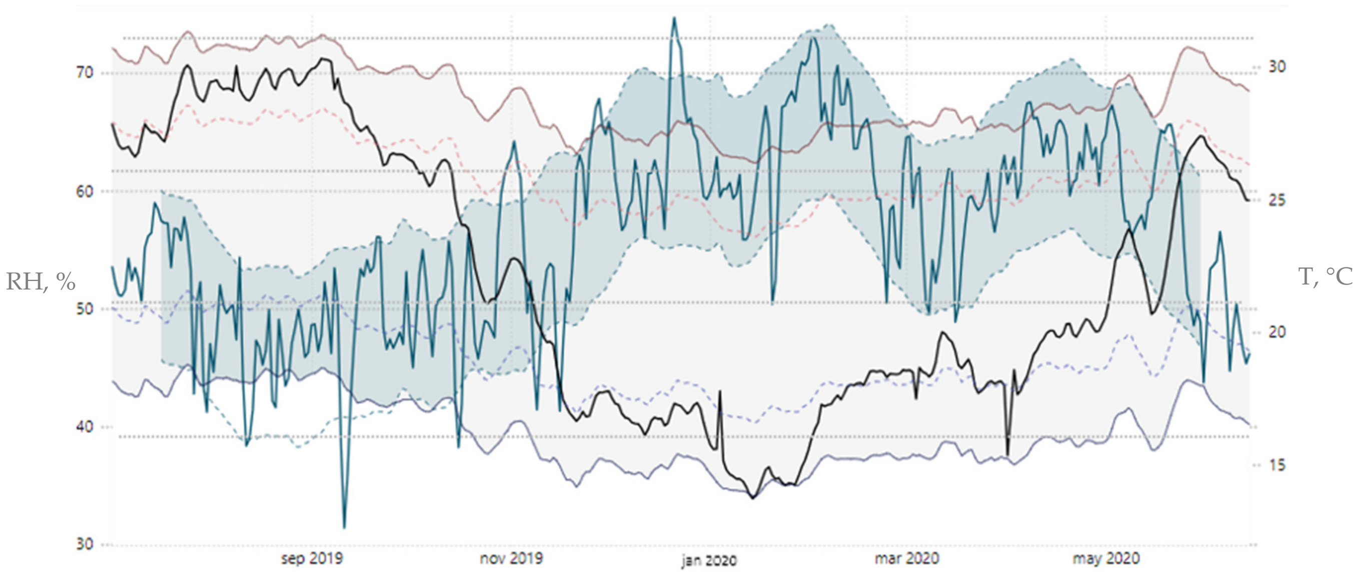
Figure 8. Effect of the comfort conditions set by using the ATC model of UNE-EN 16798-1:2020 and the preventive conservation conditions regulated by UNE-EN 15757:2011 in the Tour Basement.

The adaptive thermal comfort model of UNE-EN 16978-1:2020 achieved comfort conditions 73% of the time. However, the achievement of comfort conditions was reduced to 35% of the time in winter, whereas it increased by 59% in summer. On the other hand, optimal preventive conservation percentages were reduced from 95% to 87% of the time.

As in Exhibition Hall 1, isolated correction guidelines for RH should be implemented, such as the adjustment to the lower limit of T for Category III allowed by the standard, thus increasing the temperature in winter and reducing RH.

3.2. ASHRAE 55-2020–UNE-EN 15757:2011

The use of the adaptive thermal comfort model set by ASHRAE 55-2020 in Exhibition Hall 1 of the MACP SE, together with the preventive conservation values of UNE-EN 15757:2011, led to the following results (see Figure 9): under cold climate conditions, the greatest percentage of time spent at the appropriate preventive conservation conditions in the hall was obtained, reaching 94 and 98% for thermal comfort with an acceptability of 80%. For spring, summer, and autumn, the standard considers that the existing environmental conditions would ensure that visitors in Exhibition Hall 1 are under thermal comfort conditions with 80% acceptability. Conservation conditions would vary from being achieved 85% of the time in summer to 84% in spring and autumn.



Where:

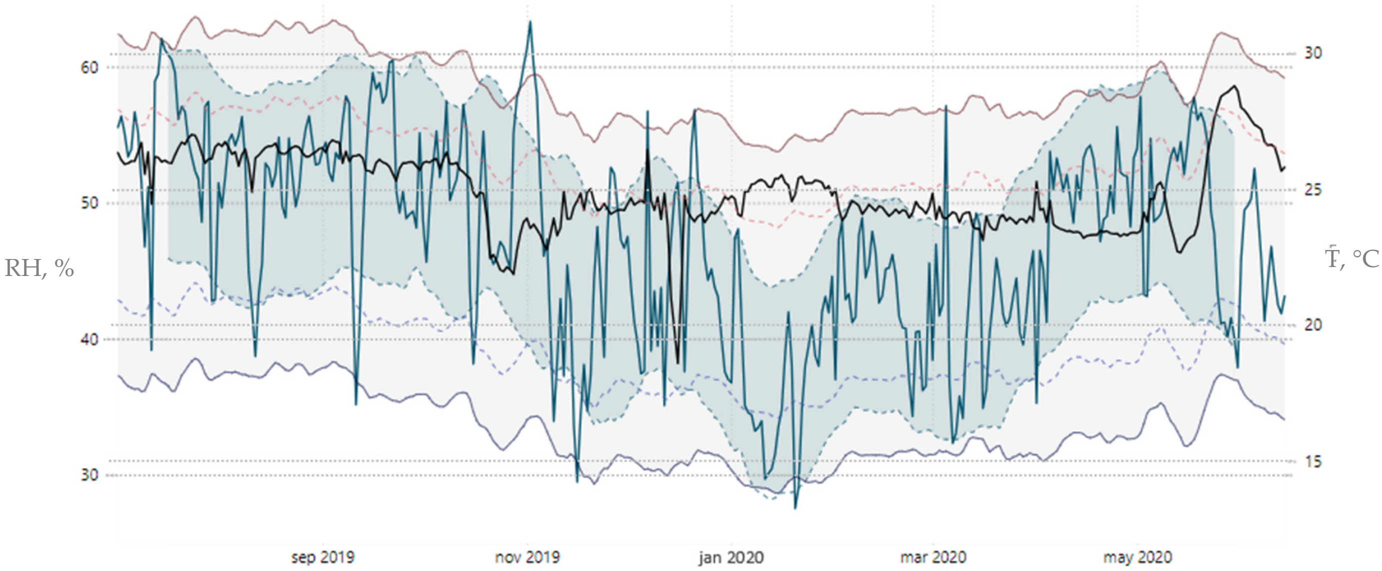
- Comfort zone for Category III limits, °C
- Preventive conservation zone, %
- Measured indoor air temperature, °C
- Measured relative humidity, %
- Upper limit of the comfort zone Category III, °C
- Upper limit of the comfort zone Category II, °C
- Upper limit of the comfort zone Category I, °C
- Lower limit of the comfort zone Category I, °C
- Lower limit of the comfort zone Category II, °C
- Lower limit of the comfort zone Category III, °C
- Upper limit of RH for preventive conservation, %
- Lower limit of RH for preventive conservation, %

Figure 9. Effect of the comfort conditions set by using the ATC model of ASHRAE 55:2020 and the preventive conservation conditions regulated by UNE-EN 15757:2011 in Exhibition Hall 1.

The climate conditions of Exhibition Hall 2 (see Figure 10) guaranteed visitors' thermal comfort conditions and preventive conservation 87% of the time.

Acceptable temperature parameters were always achieved around 90% of the time, whereas achievement of conservation conditions was higher in winter (93%) and lower in summer (87%) and the rest of the year (83%).

Finally, the same time percentages as in Exhibition Hall 2 (see Figure 11) were obtained in the Tour Basement, that is, 100% of the time for comfort (within the acceptability limit of 80%) and 87% of the time for preventive conservation. However, conservation conditions varied when they were analyzed seasonally, with reduced comfort times in spring (75%) and autumn (69%) using the adaptive thermal comfort model in ASHRAE 55-2020.



Where:

- Comfort zone for Category III limits, °C
- Preventive conservation zone, %
- Measured indoor air temperature, °C
- Measured relative humidity, %
- Upper limit of the comfort zone Category III, °C
- Upper limit of the comfort zone Category II, °C
- Upper limit of the comfort zone Category I, °C
- Lower limit of the comfort zone Category I, °C
- Lower limit of the comfort zone Category II, °C
- Lower limit of the comfort zone Category III, °C
- Upper limit of RH for preventive conservation, %
- Lower limit of RH for preventive conservation, %

Figure 10. Effect of the comfort conditions set by using the ATC model of ASHRAE 55:2020 and the preventive conservation conditions regulated by UNE-EN 15757:2011 in Exhibition Hall 2.

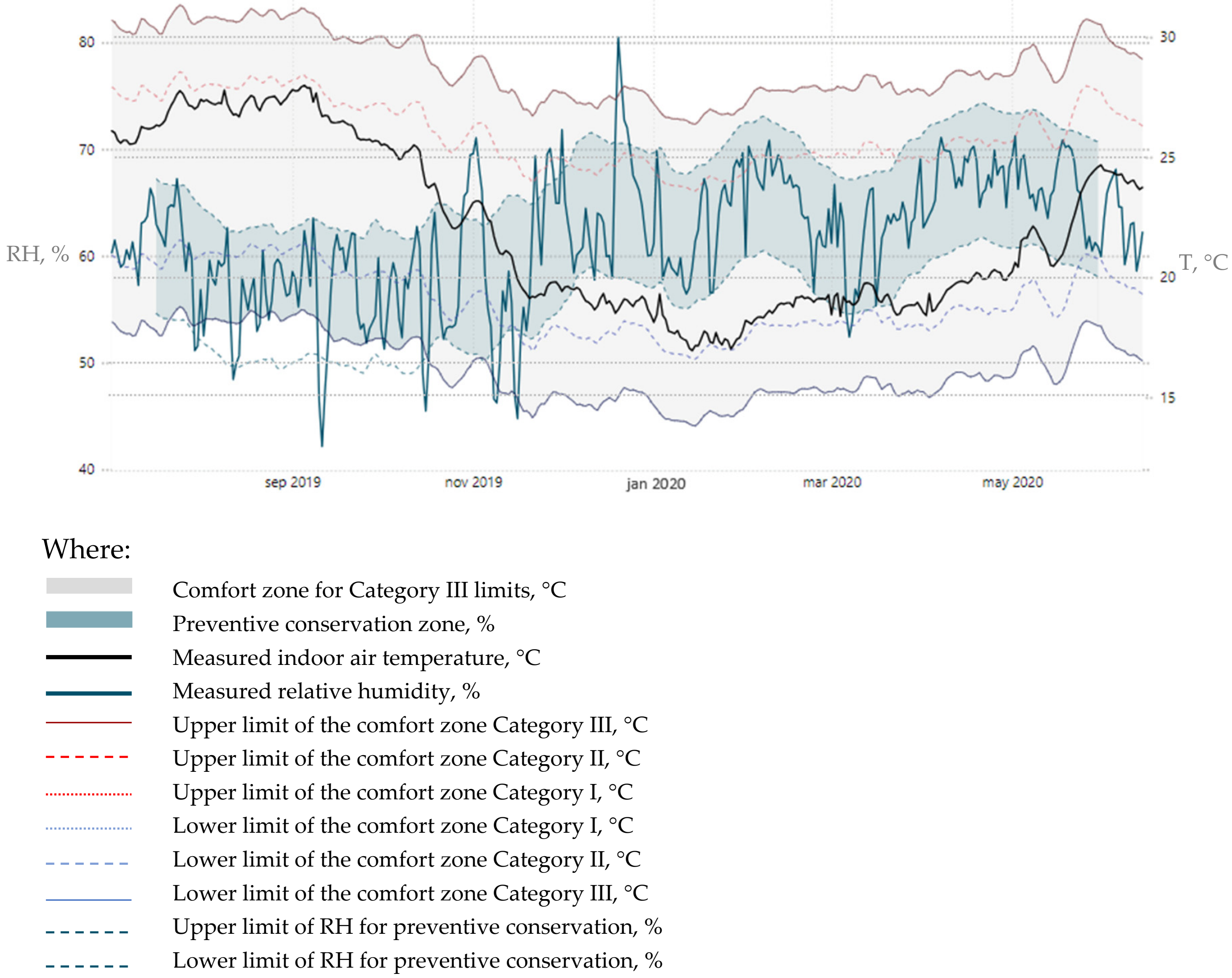


Figure 11. Effect of the comfort conditions set by using the ATC model of ASHRAE 55:2020 and the preventive conservation regulated by UNE-EN 15757:2011 in the Tour Basement.

3.3. Setpoint Strategy

The technical resources for stabilizing the environmental conditions of this study at the levels required by the international standards ASHRAE55-2020 and UNE-EN 16798-1:2020 for the evaluation of thermal comfort and conservation of the MACP SE collections can be oriented towards the fluctuation of the interior temperatures of the exhibition rooms. This involves correcting values outside the range towards the limits of acceptability of greater EE. When temperatures exceed the limits, mechanical conditioning systems could be activated in a limited manner to ensure that the temperature remains within the range, as an alternative to the set points of traditional methodologies.

In the Table 3, an optimal seasonal average T and RH are proposed with small differences between both standards. The largest differences in T are observed between winter and summer, where ASHRAE tends to recommend slightly lower temperatures in winter and slightly higher in summer. Relative humidity recommendations are very consistent between both standards.

Table 3. Optimal average T for seasonal periods to meet thermal comfort conditions of visitors using the ATC models of the international standards ASHRAE 55-2020 and UNE-EN 16798-1:2020 and optimal average RH of the preventive conservation conditions in the MACP SE exhibition halls.

		Winter		Summer		Spring & Autumn	
		T, °C	RH, %	T, °C	RH, %	T, °C	RH, %
UNE-EN 16798-1:2020	Exhibition Hall 1	19.1	62	27.1	50	21.4	57
	Exhibition Hall 2	22.6	40	26.3	53	24.4	48
	Tour Basement	19.0	64	26.8	59	21.5	62
ASHRAE 55-2020	Exhibition Hall 1	16.9	62	28.6	50	21.4	57
	Exhibition Hall 2	24.5	41	26.3	53	24.5	48
	Tour Basement	18.5	64	26.9	59	21.5	62

In Exhibition Hall 1, the winter temperature according to UNE-EN 16798-1:2020 should be 19.1 °C with a RH of 62%, while ASHRAE 55-2020 suggests a lower temperature of 16.9 °C with a similar RH of 62%. The average T of fluctuation of the thermal environment of Exhibition Hall 1 using the American standard attends to a period of two consecutive days in the month of January of the monitored annual period, with an average T deviation of 2.9 °C below the lower limit of the comfort zone, with an acceptability of 80% of the time. In summer, both standards are fairly aligned. Exhibition Hall 2 reflects the reality of the practice of using temperature set points in HVAC systems in accordance with the traditional regulations established. The stabilization of the environmental conditions of this room would respond to an average T fluctuation of −6.2 °C in winter and −9.9 °C in spring and autumn to keep the T within the upper limit of the Category III comfort zone of the UNE-EN 16798-1:2020 standard, being able to deactivate the operation of the room's HVAC equipment at least 15% of the time in one year. For the Tour Basement, the permissible average T of fluctuation in winter is +0.9 °C to reach the lower limit of the Category III comfort zone and −0.2 °C to remain at the upper limit of the comfort zone of said category. Despite presenting such a slight fluctuation temperature, the standard establishes a percentage of comfort time of 35% of the time in winter and 59% of the time in summer. This is because temperatures flow tangentially over upper and lower limits for an extended period.

4. Discussion

The results obtained in the different MACP SE exhibition halls indicate a significant variability in the conditions of thermal comfort evaluated according to the ASHRAE 55-2020, UNE-EN 16798-1:2020, and UNE-EN 15757:2011 standards:

UNE-EN 16798-1:2020–UNE-EN 15757:2011

Exhibition Hall 1: Thermal comfort within the comfort limits of Category III was achieved 51% of the time in the annual period, with a notable reduction in winter, with discomfort occurring 93% of the time, and summer, with discomfort occurring 96% of the time. This suggests that severe weather conditions negatively affect visitors' comfort. The conservation conditions were adequate 88% of the time.

Exhibition Hall 2: Within the comfort limits of Category III, this hall presented better performance, achieving comfort 85% of the time, although with significant seasonal variations of 69% in winter and 99% in summer. The conservation conditions were adequate 87% of the time, with a remarkable stability in the RH and T parameters compared to the other rooms.

Tour Basement: This space achieved comfort within the comfort limits of Category III 73% of the time, with conservation percentages that varied from 95% of the time in winter to 87% in summer.

ASHRAE 55-2020–UNE-EN 15757:2011

Exhibition Hall 1: Thermal comfort was achieved 99% of the time in the annual period, with acceptability set at 80%. Under the cold winter temperatures, the conservation conditions were guaranteed for a higher percentage of time, at 93%.

Exhibition Hall 2 and the Tour Basement: Both rooms achieved comfort 100% of the time, with an acceptability of 80% set by the standard. The conservation conditions were acceptable in both rooms at 87% of the time, with the clarification that Exhibition Hall 2 worked under mechanical control while the Basement Floor Route received free oscillation. It was observed that the conservation conditions proposed by the UNE-EN 15757:2011 standard for the preservation of MAP SE's collections improved as temperatures decreased, presenting a behaviour consistent with the direct influence demonstrated in the scientific literature [52]: a low T favours a high percentage of HR. The lower the T, the more beneficial it is for organic objects because it slows down the speed of chemical reactions, limits biological activity, and prevents materials such as resins or varnishes from losing their integrity and functionality [53].

The acceptable range of comfort and conservation levels can be achieved in the absence of mechanical control systems, as supported by the research of [25]. In this study, appropriate conservation values were achieved without HVAC technology, with a percentage of up to 99% of the time for comfort according to ASHRAE (with an acceptability of 80%) and 87% of time for optimal conservation conditions. However, the implementation of intelligent HVAC systems could allow us to reach the maximum requirement for which adaptive T and RH ranges are proposed.

In Exhibition Hall 2, HVAC equipment could be deactivated for 15% of the year compared to continuous use of these when adjusted with traditional set points. This would allow for more efficient calculation of equipment sizing and would have a potential impact on savings. These results underline the suitability of implementing flexible strategies based on adaptive comfort models, highlighting, for example, research by Kramer et al. [39], which demonstrated savings of up to 63% in a museum in the Netherlands using dynamic climate control for both T and RH, or as already demonstrated in other research [37,38,54–56], allowing for simultaneously improvement of the thermal comfort of visitors and the conservation of collections with a reduction in energy consumption.

On the other hand, ignoring the reference values proposed by UNE-EN15757:2011 for preventive conservation, there is a concomitant link with RH for the dual analysis of comfort and conservation of 97% of the time for the case study. In other words, 97% of the time, the conservation conditions were guaranteed to be in accordance with the thermal comfort evaluation requirements according to UNE-EN15757:2011.

Finally, the average duration of visitors in the museum was 39 min—this result was obtained from the data collected in the form—so this time was significant to establish a relationship between individuals and the environment. Visitors' adaptation capacity to the environment was widely shown by the clothing level, particularly in winter, which is in line with the study by A.K. Mishra et al. [36] at the H'ART Museum in Amsterdam, showing the adaptive capacity of individuals after 20–30 min of stay. It is relevant to add that the average time of the visitors surveyed in the city of Seville is established at 6 days, a reference of great significance that could allow for new research about the acclimatization capacity of individuals to new climatic environments. This could be a strategic resource for the reconditioning of the built park under the theoretical foundation of adaptation to spaces of temporary occupation.

5. Conclusions

This research sought to explore the application of the international adaptive thermal comfort models of the ASHRAE 55-2020 and UNE-EN 16798-1:2020 standards, in parallel with the preventive conservation conditions of collections established by the UNE-EN 15757:201 standard, as a method of evaluating the thermal comfort of individuals in a scenario and under climatic conditions different from those of the theoretical basis. We cannot forget that international standards are developed specifically for residential buildings, with constant occupancies that facilitate modelling, and not for buildings for museum use, with a transient and variable occupancy that presents additional challenges.

The conclusions of the research on the application of international models of ATC in the Mudejar Pavilion of Seville are the following:

- The implementation of the ATC model, which was set by UNE-EN 16798-1:2020 in museum exhibition spaces of the Museum of Popular Arts and Customs of Seville, shows its appropriateness under slightly less hot climate conditions. As temperatures drop, visitors will see an increase in the percentage of comfortable time.
- The adaptive thermal comfort standards set by ASHRAE 55-2020 were better adapted to the proposed environment compared to the European standard. Despite presenting a more reduced climate diversity bias than the European standard, visitors were comfortable most of the time during the period monitored while in the museum exhibition spaces of the Museum of Popular Arts and Customs of Seville.
- Implementing adaptive control strategies could significantly reduce energy consumption. ATC models allow for greater flexibility in managing HVAC systems than current regulations. By allowing controlled fluctuations —T and RH —the use of mechanical HVAC systems can be minimized, activating them only when temperatures exceed the limits.
- The basement is the exhibition space with the greatest microclimatic stability in the museum, ensuring the best thermal comfort conditions for visitors in accordance with both international standards, as well as the best preventive conditions for conservation. For these reasons, it is suggested that the basement of the Mudejar Pavilion could be the most suitable space for the conservation of sensitive objects in the museum.
- This article determines that, due to the fact that the data were collected in a single museum as a case study, and given the cultural diversity of the visitors it receives as well as their ages and physical conditions, further research in other museums would be necessary to reach precise results and conclusions that can be extrapolated to other case studies that use similar methodologies, combining preventive conservation parameters and the thermal comfort of visitors under the same climatic conditions.

As a general conclusion, this study considers that the applicability of ATC models could be validated in the Mudejar Pavilion of Seville, current headquarters of the Museum of Popular Arts and Customs of Seville, demonstrating its effectiveness in improving visitor comfort, preserving museum collections, and offering a significant opportunity to reduce energy consumption, offering an adaptable solution to the unique challenges presented.

6. Limits of Research

In the scope of application of ATC models, this research reinforces the idea that these models, originally designed for residential and office buildings, could be effective in heritage buildings under similar conditions. Adaptive models can ensure comfortable conditions for occupants and the preservation of collections for most of the year in the Pavilion. This could expand the scope of ATC models, validating their use in a variety of architectural and functional contexts, and offering opportunities to reduce energy consumption in buildings with unique architectural and climatic challenges. Finally, in this study, visitor thermal comfort was assessed solely based on air temperature and relative humidity, variables that cannot capture the finer nuances of thermal comfort in MACP SE environments. This hypothesis could alter, on the other hand, the validity of results in spaces with glass walls, but this reliability was assumed because the largest glass surfaces were in the basement of the building, a space with better insulation, without direct exposure to sunlight, and with greater microclimatic stability. Consequently, further research is required to enable more in-depth and comprehensive assessments on thermal comfort.

Author Contributions: Conceptualization, C.R.-B. and I.G.-M.; methodology, C.R.-B. and I.G.-M.; software, C.R.-B.; validation, C.R.-B. and I.G.-M.; formal analysis, I.G.-M.; investigation, I.G.-M.; resources, C.R.-B.; data curation, I.G.-M.; writing—original draft preparation, I.G.-M.; writing—

review and editing, I.G.-M.; visualization, I.G.-M.; supervision, C.R.-B.; project administration, C.R.-B.; funding acquisition, C.R.-B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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