Potential of Natural Ventilation in Heritage Buildings: A Case Study at the 'Casa Fabiola' Museum in Seville, Spain

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Abstract: Historical heritage buildings often face challenges in maintaining suitable indoor environmental conditions, leading to high energy consumption. Insufficient control of the hygrothermal environment and indoor air quality can have adverse effects on both occupants and the valuable artworks housed within these significant structures. However, some heritage buildings also possess construction features that enable them to effectively withstand local climatic conditions.

This study focuses on the 'Casa Fabiola' Museum in Seville, which houses an art collection donated by Mariano Bellver. The main objective is to characterize the museum's hygrothermal comfort and explore the feasibility of implementing integrated passive measures to assess their impact on the indoor conditions. The study aims to reduce the ecological footprint of historical buildings while preserving their environmental legacy. It also seeks to quantify the energy consumption resulting from the implementation of stricter operational conditions.

Through energy simulations, this research aims to harmonize modern conservation efforts with the building's historical past, ensuring a sustainable and ecologically sensitive approach to the preservation of art and human habitability.

Keywords: Thermal conditions, risk assessment, preventive conservation, energy optimization, heritage buildings

1. Introduction

Historic buildings often show wide variation in indoor humidity levels and weather conditions that can be hazardous to cultural heritage materials. How much additional ventilation and thermal energy is required to ensure safe indoor conditions for cultural heritage when a historic building is exposed to extreme weather conditions or many visitors? What will happen to the hygrothermal behavior of Walls and ceilings if you change the use of a historic basement, for example? How do indoor air conditions and the envelope of buildings in temporary use react to different heating and ventilation strategies? These are some issues of the CLIMATE FOR CULTURE (*Climate for Culture*, 2014) project where it is shown that identifying the precise fluctuations of indoor humidity and humidity profiles in the building envelope is essential for an assessment of risks and noise damage, taking into account the complex hygrothermal interactions between indoor air, use, the furniture and the envelope of the building.

The hygrothermal behavior of components exposed to different climatic parameters is an important aspect of the overall performance of a building (Lucchi, 2016) (Sendra Salas and Navarro Casas, 1991) (*Climate for Culture*, 2014). One of the main innovations of this project is the use of simulation and modeling tools to predict the influence of changing outdoor climate on the microclimate in historic buildings up to 2100 and thus assess the damage of these future microclimates in art collections in various climatic zones. To do this, they use a tool that considers the main hygrothermal effects derived from the sources of humidity inside a room, the entry of moisture from the envelope by capillarity and diffusion, as well as the absorption of steam in response to outdoor climatic conditions. The result is nothing more than future energy demand and the measures needed to improve conditions.

Likewise, in the research of Jiménez Torrecillas et al (Jiménez Torrecillas *et al.*, 2007), it is ratified that lighting can damage or deteriorate the works due to a bad approach of it, so, in the spaces destined to the exhibition use, it is essential to control the factors that make up the interior atmosphere. Therefore, a system is used that adapts to the conditions of the building, without creating invasive spaces, taking into account the conservation of the exhibited goods, as well as the achievement of an appropriate level of comfort for the occupants (Jiménez Torrecillas *et al.*, 2007). This level of indoor comfort can sometimes be very complex to achieve in historic buildings due to the presence of decorated surfaces or high artistic and heritage values that do not allow any intervention on the technical elements (Boarin, 2016). However, Boarin (Boarin, 2016) is responsible for improving indoor air quality through ventilation, indoor air management, the use of low-emission materials and products and the possibility for occupants to control comfort conditions.

This last aspect is of great importance because the activity inside buildings generates microclimatic instability and indoor pollutants (Lucchi, 2016). Something that endangers the use of buildings considering the current COVID-19 crisis. Therefore, according to Manuel Duarte et al (Pinheiro and Luís, 2020), a critical exploratory evaluation is necessary, to allow measures that help reduce the transmission of this virus. Their measurements include: thermal sensors, new HVAC filters and new HVAC systems (Pinheiro and Luís, 2020) (with linear flow extractions and increased humidity control) with possible mixed modes. It also proposes contactless digital solutions and other IT solutions, such as new networks and communication systems that would not damage the building, one-way pedestrian paths and complementary wastewater monitoring and treatment measures (Pinheiro and Luís, 2020).

Therefore, it is necessary to carry out sustainable and cost-effective interventions by reducing energy and operating costs, improving building performance, without compromising human safety and comfort, aiming to ensure that cultural heritage is duly included in the response to the COVID-19 crisis (NOSTRA, 2020), as well as in long-term recovery plans (Next Generation EU) (NOSTRA, 2020).

It has been proven that the effects of thermohygrometric parameters generate mechanical, chemical and biological degradation in objects of historical value (Sahin *et al.*, 2017) since the relationship of humidity and the panels of these works change their properties, affecting their resistance, stability and permanence. It is shown that cyclical changes in humidity cause variations and generate harmful impacts on the panels, even causing an environment in favor of mold germination (Bülow, Colston and Watt, 2002).

In all these effects of the quality of the indoor environment, the fundamental role of building infiltrations comes into play. Hermeticity is the fundamental parameter that drives infiltration throughout the space as a result of air passing through cracks, leaks or other unintended openings in the building envelope (Sahin *et al.*, 2017) (Sherman and WR Chan, 2006). Therefore, it is essential to control the tightness in buildings that do not have HVAC systems, to control short fluctuations of T and HR, within the permitted limits (Sahin *et al.*, 2017) (Luciani *et al.*, 2013).

Chapter 21 of ASHRAE (ASHRAE, 2007) introduces control classes to assess the potential for mechanical, chemical, and biological degradation in library, museum, or art gallery collections. It verifies that the collections must be at the established points (T between 15 and 25 ºC, HR 50%), if the indoor climate meets the requirements indicated in any kind of control, the objects are assumed as preserved against major and minor risks of degradation.

This building is part of the historical buildings owned by the City Council of Seville

The City Council of Seville has a total of 85 heritage buildings, dating from the 13th to the 20th centuries, which are being included in a larger-scale project. From this initial sample, the most representative ones were statistically selected from generated subgroups. In this case, the study has focused on Casa Fabiola, the current museum that houses the Mariano Bellver Art Collection.

This project aims to characterize the environmental and energy conditions of a case study, the Casa Fabiola Museum, to study the conservation potential that some historical buildings represent compared to the construction of new buildings as a way to valorize historical buildings through the reduction of their ecological footprint. Envelope improvements are introduced to assess if there are significant changes in their hygrothermal conditions, as well as to evaluate the energy consumption associated with the incorporation of HVAC systems.

2. Case study: Casa Fabiola

La Casa Fabiola is a prominent historic building located in the neighborhood of San Bartolomé, in the district of Casco Antiguo in Seville, Andalusia, Spain. Built in the 15^{th} century, it exhibits a unique combination of architectural styles that reflect Gothic and Renaissance influences. The construction of Casa Fabiola has a total built area of 1,915 m^2, with over 1,600 m^2 being functional space. It is distributed across three floors and is characterized by prominent elements such as ceramic tiling, polychrome wooden coffered ceilings, decorative paintings, stuccos, and 18th-century hydraulic floors (*La Casa Fabiola y el Museo Bellver*, 2018) (IAPH, 2022).

On the ground floor, numerous offices are situated around the courtyard, while the first floor houses the most noble rooms, such as the former ballroom, which features large windows facing the street. The second floor accommodates additional multi-purpose rooms and offices.

Throughout the years, Casa Fabiola has undergone continuous renovations in the 16^{th}, 17^{th}, 18^{th}, and 20^{th} centuries. In 1970, a restoration was carried out to adapt the building into a House-Museum. The most recent intervention took place in 2019 due to its deficient state of conservation, with identified issues in the galleries and empty vaults on the ground floor, as well as damages to the ceramic coverings caused by human factors. The building also faced a wood-boring insect infestation that threatened the wooden carpentry. The museum reopened its doors in May 2023.

Casa Fabiola houses the 'Mariano Bellver Art Donation', a collection donated by art collector Mariano Bellver in 2007. The collection comprises 943 art pieces, including 364 paintings, 38 wooden sculptures, 19 marble sculptures, 156 ceramic and porcelain pieces, 87 goldsmithing pieces, and 105 furniture pieces. The collection notably features paintings from the 19th century and the first half of the 20th century, with a significant presence of Sevillian artists such as Esquivel, Barrón, Grosso, Villegas, Jiménez Aranda, García Ramos, Gonzalo Bilbao, Rico Cejudo, Cabral Bejarano, Sánchez Perrier, and García Rodríguez, among others (Ruesga, 2017)(Junta de Andalucía, 2020).

This work includes analyses of hygrothermal behavior and evaluations of HVAC systems to assess the results of the restoration carried out.

Figure 1. Central Courtyard. (Fernando Alda Photography).

Table 1. Collection of spatial and constructive characterization data of Casa Fabiola

CASA FABIOLA	
Assignment to the Department of the City Council/Assignment	Institute of Culture and Arts of Seville
Chronology	**XV-XIX**
Localization	**C/Fabiola 5**
Orientation Facade (N)	**45º**
Typology	**Residential**
BIC	**NO**
Degree of Protection	**B**
Historical Use	**Residential**
Current Use	**Cultural**
Specific use Actuality	**Exhibitions**
Morphological characteristics (number of plants/shape)	**Groud floor+2**
Height (m)	**13.45**
Volume (m^3)	**6002**
Constructed area (m^2)	**1915**
Facade area (m^2)	**246**
Constructive Characteristics	**Brick factory walls thickness of 65-90cm** Sloping roofs of wooden beams and covered by tiles

Figure 2. Type floor plan of Casa Fabiola

3. Methodology

When it comes to a museum located in a historic building, there are particular challenges in terms of conservation and environmental comfort. These buildings often have unique architectural features such as stone walls, high ceilings, old windows, and limited ventilation systems. These characteristics can create challenging environmental conditions, including temperature and humidity fluctuations, which can have a negative impact on artworks, especially paintings.

Adapting and aligning the public with the environmental comfort conditions involves educating visitors about the importance of maintaining a suitable environment for the preservation of artworks. It includes avoiding behaviors that can cause abrupt changes in temperature or humidity in the exhibition rooms.

Furthermore, it is essential to have an efficient environmental management system in the museum. This entails constant monitoring of environmental conditions such as temperature, humidity, and air quality to ensure they remain within optimal ranges for the preservation of artworks. Heating, ventilation, and air conditioning (HVAC) systems must be carefully designed and implemented to prevent extreme fluctuations and provide a stable and controlled environment.

The methodology followed includes the following phases:

- Characterization of environmental conditions
- Simulations of the model in free evolution before and after the intervention
- Inclusion of an HVAC system for studying its energy consumption.

3.1. Energy Modelling

Energy performance calculations were conducted using Design Builder software v 4.5.0.148, which is based on the EnergyPlusTM methodology developed by the United States Department of Energy and recognized by the International Energy Agency. A dynamic nodal calculus simulation of the building was performed to assess the energy demands for each housing unit. The models used in the study were calibrated and validated during the Efficacia project, which involved a monitoring campaign of energy consumption and inhabitants' behavior in control dwellings over an 18-month period (León A L et al. 2010).

Simulations were carried out for the original conditions and for each proposed intervention solution to determine the improvements in energy demand for the building retrofit. Each housing unit in the model was treated as a separate space to be climate controlled. The simulations followed the official protocol for conditions of use and operation in Spain for alternative energy simulation programs.

The hourly thermal evolution of the operative temperature was analyzed to identify peak temperature occurrences in different types of housing units. The analysis included typical days for each season. The thermal evolution of indoor and outdoor temperature was examined along with an adaptive comfort temperature band, which serves as a simplified approximation to thermal comfort, given its subjective and complex nature.
Typical climate for Seville is defined as a EPW file.

For the definition of the activity and typical schedule a standard profile for Libraries and Museums is selected.

3.1.1. Free running model

An analysis of the different parameters is carried out with the building in free running evolution, where the operation of the building in its current state can be observed.

The following parameters have been considered: relative humidity (%), indoor air temperature (ºC), radiation (ºC) and operating temperature of space (ºC).

3.1.2. Enhanced Free running model -Passive retrofit.

The study of incorporating improvements, both passive and mechanical, considering the current use of the building, is carried out.

Firstly, the incorporation of thermal insulation in the roof has been implemented, starting with solutions that would have a lesser impact on the historical image of the building, as well as its interior microclimate. This improvement has been analyzed during the free evolution of the building to compare it with the initial state and quantify the improvements in hygrothermal comfort through temperature ranges.

3.1.3. Mechanical environmental control model

A comprehensive HVAC system is incorporated to cope with the environmental control of the complex. The mechanical systems will adjust to ASHRAE and national standard to maintain indoor ambient inside visitors and workers comfort range, as well as the values set by ASHRAE for museums as previously described.

In a situation of not-strict-conservation needs, thus assuming the benefits from the inertia and the shelter capacity, indoor air temperatures could be set in an annual interval of 15 to 25 °C and air relative humidity around 50% +/-10%. The aim of such system is to avoid extreme conditions and to shave thermal peaks, assuring slow evolutions against fast changes.

However, this previous scenario presents difficulties in ensuring the comfort of poorly adapted visitors, as well as a conflict with occupational health and safety regulations. This situation draws the high energy intensity scenario considered for the assessment.

The set assume a typical compliance with HVAC figures with temperatures in ranges of 21 to 25 °C and relative humidity in ranges of 40-60%.

4. Results and Analysis

4.1. Passive control (free running scenario)

To analyze the results of the building in free running, it has been carried out, first, the study of the parameters applying the ASHRAE Standard 55 (ASHRAE, 2017) that aims to establish the acceptable thermal conditions for the occupants of the buildings, according to a set of factors associated with the interior environment (temperature, thermal radiation, humidity and air velocity), as well as the occupants themselves (activity level and clothing).

This adaptive approach assumes no mechanical control on the environment.

It defines two ranges of operating comfort temperatures for average monthly temperatures ranging from 10 to 33.5°C. For the first range, limit operating temperatures result from adding 3.5°C to comfort temperatures, assuming an acceptability percentage of 80% (proportion of people who would theoretically feel comfortable). For the second range, limit temperatures result from adding 2.5°C to comfort temperatures, resulting in a 90% acceptability percentage. This range is designed for situations where a stricter level of thermal comfort would be desirable.

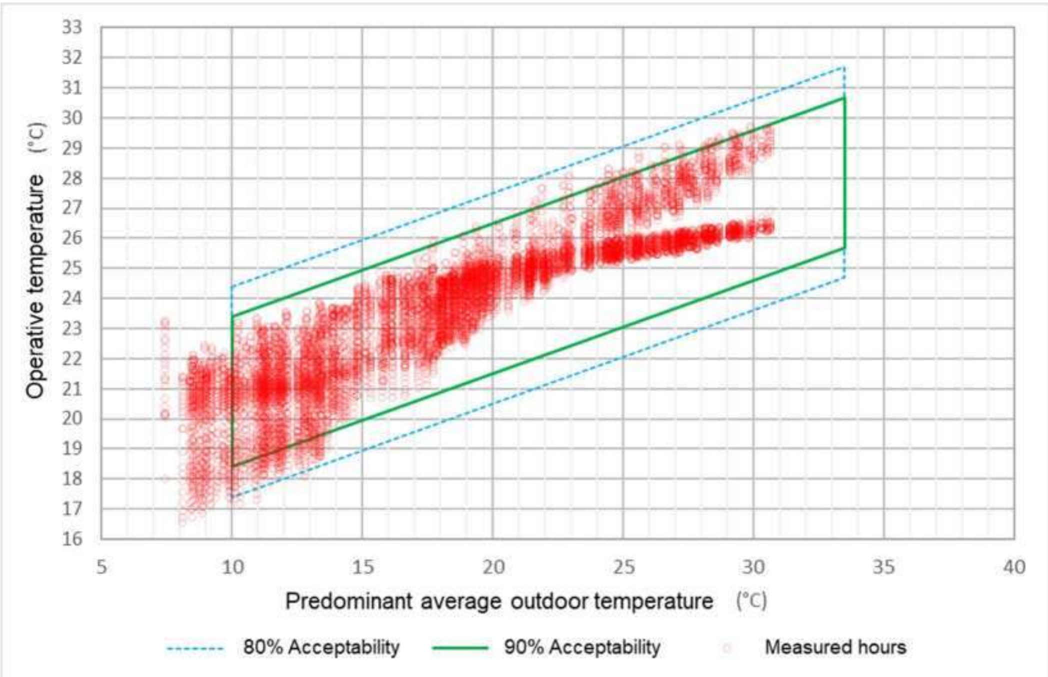


Figure 3. Adaptative Comfort Range

Table 3. Adaptative comfort results according to ASHRAE 55-207 standard

Invalid measured hours	**720 h**	
Valid measured hours	**8040 h**	
Total measured hours	**8760 h**	
Hours within 90% acceptability	**7763**	**96.55%**
Hours out of 90% acceptability	**277**	**3.45%**
Hours within 90% acceptability: HEAT	**63**	**0.78%**
Hours out of 90% acceptability: COLD	**214**	**2.66%**
Hours within 80% acceptability	**8032**	**99.90%**
Hours out of 80% acceptability	**8**	**0.10%**
Hours within 80% acceptability: HEAT	**0**	**0.00%**
Hours out of 80% acceptability: COLD	**8**	**0.10%**

The results obtained according to the criteria of ASHRAE Standard 55 are shown in Figure 3 and Table 3. Overall, favorable results were obtained regarding the passive operation of the building following the developed criteria. The building stays within the established ranges for most of the year, with only a few short periods outside of those ranges. Approximately 96.5% of the time, it falls within the "Hours within 90% acceptability" category.However, the ASHRAE 55 comfort criteria take into account very low and high temperature variations and ranges, and do not take into account relative humidity variations. If compared with the criteria followed in Chapter 21 of ASHRAE (ASHRAE, 2007), where control classes are introduced to assess the potential for degradation in museum collections, highly controlled operating temperatures and relative humidity are taken into account. The summary of these classes is shown in Table 4, which indicates that all objects should be stored at set points (T between 15-25 °C and HR50%) or at the annual historical average value when they are collections of interest. While the indoor climate is expected to differ by brief and seasonal fluctuations, if they do not exceed the values. If the indoor climate satisfies the requirements indicated in any kind of control, the objects can be assumed to be preserved against risks of degradation, otherwise damage could be observed.

Table 4. Summary of indoor climate conditions of ASHRAE Chapter 21 (ASHRAE, 2007)

Type	**Set-point or Annual average**	**Class of control**	**Short Fluctuations**	**Seasonal adjustments in system set point**
General Museums, Art Galleries, Libraries and Archives	**50% RH (or historic anual average for permanent collections) T set between 15 and 25 ºC**	**AA**	**± 5% RH, ± 2 K**	**RH no change; Up 5K, down 5K**
		A		
		A1	**± 5% RH, ± 2 K**	**Up 10% RH, down 10% RH, Up 5K, down 10K**
		A2	**± 10% RH, ± 2 K**	**No RH change, up 5k, down 10K**
		B	**± 10% RH, ± 5 K**	**Ip 10% RH, down 10% RH, Up 10K but not above 30ºC, down as low as necessary to maintain RH control**
		C	**Within 25-75% RH year-round**	
			T rarely over 30ºC, usually below 25ºC	
		D	**Realiably below 75% RH**	

On the other hand, about the health and thermal comfort of the users of the building, encompassing both the working staff of the museum and the visiting users of the same, the fact of reaching extreme temperatures both in hot periods and in the cold ones, it is not considered adequate. Well, temperatures are around 30ºC in summer periods, while in cold periods minimum temperatures of up to 16°C are reached inside. Following the RITE Technical Instruction (RITE, 2007), the interior conditions of space design should have operating temperatures in summer between 23-25°C, with relative humidity between 45-60%, and in winter temperatures between 21-23 °C, as well as humidity between 40-50%.

That is why it has been verified that despite the fact that ASHRAE 55 is more permissive in terms of adaptive comfort ranges, we find ourselves in an apparently favorable situation, based on the use of the building, which is an exhibition area and their corresponding offices, and following what is described in Chapter 21 of ASHRAE for museums as well as what is described in RITE for internal thermal conditions of workers, we would not speak of a favorable situation with regard to the functioning of the building in free evolution.

4.2. Results with improvement systems

Since we came across a building with great historical and patrimonial value, improvement systems were studied that did not imply the loss of identity of the building, nor alter its interior microclimate.

For this we consider appropriate the inclusion of a thermal insulation in the roof of the building, to control the environmental behavior and the higher temperature ranges that occur inside.

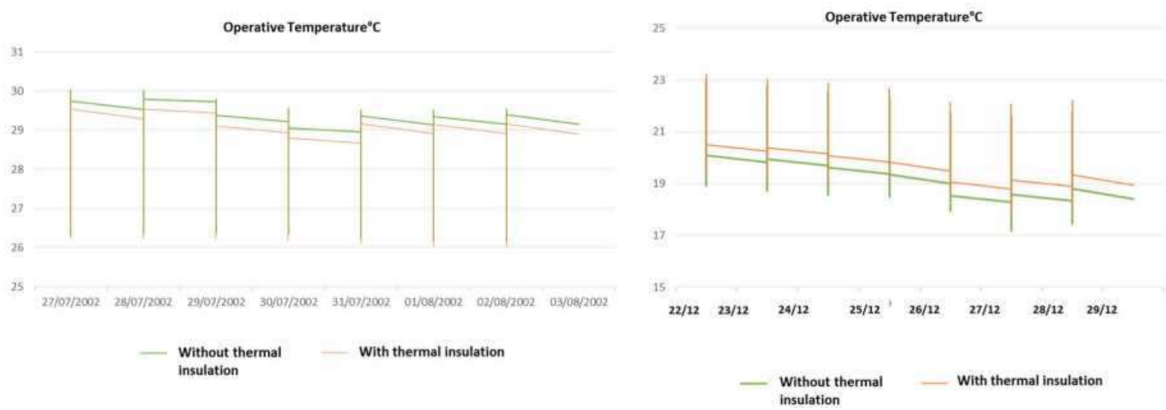
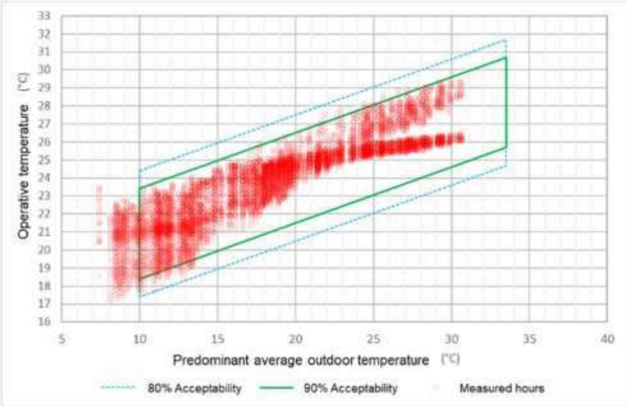


Figure 4. Comparison of temperature range in extreme weeks of summer (left) and winter (right)

In Figure 4, it can be seen how both in the extreme week of summer and in the extreme week of winter, the temperatures have improved in both cases.

More stable temperatures were obtained in winter, which above all do not become as cold as in the case of not having said insulation.



Invalid measured hours	720 h	
Valid measured hours	8040 h	
Total measured hours	8760 h	
Hours within 90% acceptability	7921	98.52%
Hours out of 90% acceptability	119	1.48%
Hours within 90% acceptability: HEAT	31	0.39%
Hours out of 90% acceptability: COLD	88	1.09%
Hours within 80% acceptability	8039	99.99%
Hours out of 80% acceptability	1	0.01%
Hours within 80% acceptability: HEAT	0	0.00%
Hours out of 80% acceptability: COLD	1	0.01%

Figure 5. Adaptative Comfort Range and Adaptative comfort results according to ASHRAE 55-207 standard with thermal insulation

That is why it is shown in Figure 5 and its adjacent table, how it has been possible to increase the number of hours that are within the range of 90% acceptability throughout the year, up to 98.52%, taking into account that this It would be for very demanding categories of spaces, and that could respond to museum spaces that store highly valuable collections, as is the case of Casa Fabiola. It was also connotative to reach 99.99% of hours that are within the range of 80% acceptability, leaving only 1 hour outside this range.

However, they continue to be temperatures that would not meet the most demanding ranges or that would not be the most suitable for exposure, especially the warmer period. Likewise, they would also be ranges that continue to be outside the effective conditions for the development of the work, as well as for the visit of the users. For this reason, the inclusion of an HVAC system was conducted, which would determine what the behavior of the building would be like, and if it could be adjusted to a more constant temperature and relative humidity throughout the year that would meet the requirements pursued.

For this, the incorporation of a VRF direct expansion system has been chosen to air-condition each of the floors of the building where the works are located. Likewise, to solve the ventilation and air treatment requirements, an independent ventilation system is incorporated, made up of an AHU that would be located on the roof of the building and that would oversee providing air at 22°C and 50% RH. An all-air system has been chosen since this would prevent the appearance of humidity, its refrigerant being a gas.

A HVAC system was included as mentioned in the methodology, and the results of the annual consumption for cooling, heating, lighting, and other appliances were obtained. In Figure 6, it can be observed that the annual consumption for cooling and heating to maintain the building at a standard and constant temperature is 58.98 MWh and 10.22 MWh, respectively, with the cooling consumption being 5 times higher than the heating consumption.

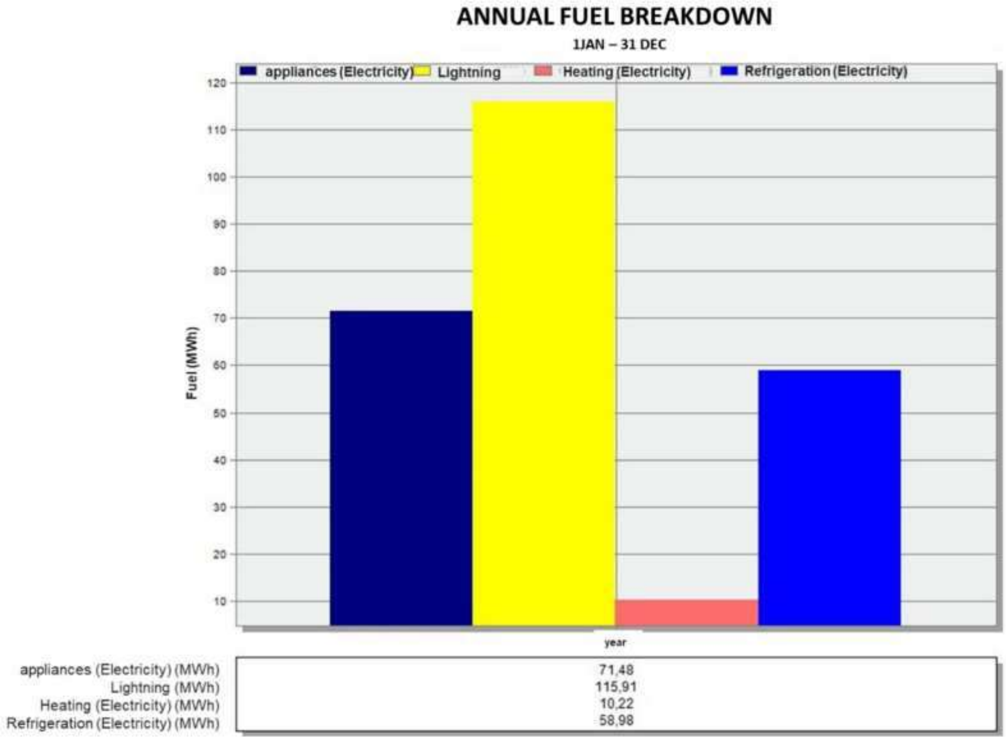


Figure 6. Annual Fuel Breakdown

5. Conclusions

This work is part of a comprehensive and in-depth study being conducted with all historical heritage buildings belonging to the Seville City Council. In this case, our focus has been on Casa Fabiola, the current museum housing the Mariano Bellver Art Collection.

The main objective was to identify the potential of this historical building for its use as a museum. Hence, it was necessary to determine if the building's hygrothermal behavior under natural conditions was sufficient for the preservation of the art collection and the comfort of its occupants. For this purpose, we considered both the parameters of ASHRAE Standard 55 and those indicated in Chapter 21 of ASHRAE and the RITE (Spanish HVAC regulation).

Under the building's current natural conditions, according to ASHRAE Standard 55 parameters, it would be on the optimum side in terms of adaptive comfort. However, certain temperatures reached during the hottest period are considered concerning, and according to ASHRAE Chapter 21, they could influence the degradation of the collection.

Additionally, these temperatures would not be considered comfortable for the building's users and visitors, following Spanish regulations that establish a fixed operating temperature range without considering adaptive comfort. The stability of the building could be explained by its high thermal mass in the building envelope, which acts as a buffer to outdoor temperatures.

Passive solutions, such as adding insulation to the roof, have been considered but have had little influence on improving the average temperature by less than 0.5°C in the building.

Another improvement measure studied was the incorporation of an HVAC system, which proved to be an optimal way to approach the most demanding operating temperature ranges. However, operating the system results in high energy consumption, so this measure may only be activated during extreme moments.

In conclusion, this study reveals the potential of Casa Fabiola as a museum, but it also highlights the need for careful consideration of its hygrothermal conditions and energy consumption to preserve the art collection and ensure the comfort of its occupants and visitors.

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