

Microclimate in historic buildings: the role of in-field monitoring in the design of retrofit interventions

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Abstract. Buildings of historical and architectural value face strict preservation regulations that often hinder energy retrofitting, despite their poor energy performance and low comfort levels. Experimental in-field monitoring campaigns are a useful tool, as they allow the identification of site-specific non-invasive retrofit strategies that combine heritage conservation with energy efficiency, sustainability, and comfort. Understanding the microclimatic phenomena's impact on buildings is a pivotal step in choosing effective retrofit solutions, since these parameters can influence the construction hygrothermal behaviour, affecting the overall performance. In this scenario, Villa Farnesina in Rome was monitored to analyse the indoor and outdoor microclimate. The collected data allowed for evaluating: (i) boundary conditions and their correlations with indoor parameters; (ii) the impact of building's characteristics, internal thermal loads, and building management practices; and (iii) the occupants' comfort. Results revealed temperature increases up to 1.8°C due to envelope characteristics and orientations, reductions up to 1.3°C for passive cooling effects and increases up to 2.3 °C from internal thermal loads. Summer comfort was critical with PMV up to 1.8 and PPD up to 70%. This study confirms monitoring campaigns as crucial for supporting suitable retrofit strategies design in historic contexts, enabling the assessment of local phenomena affecting buildings' performance.

1 Introduction

Historic buildings, commonly defined as buildings older than 70 years, represent a significant portion of the cultural heritage and architectural landscape of both Italy and Europe. More specifically, buildings of historical and testimonial value are defined as those buildings constructed before 1945 or even after, representing an integral part of a historically formed urban or rural context, contributing to the preservation of identity, and being an expression of the historical and cultural stratification of the territory [1]. Today, however, these structures face increasingly complex challenges linked to climate change, including the

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Urban Heat Island (UHI) effect, and the resulting need to safeguard comfort, internal and external environmental microclimate, as well as improve overall energy efficiency [2,3].

Reconciling the environmental performance with the protection of the listed buildings is a significant challenge for professionals in the conservation sector, especially in contexts like Italy, where approximately 46.5% of the building stock is more than seventy years old [4]. Furthermore, these buildings, often subject to strict structural, architectural, and regulatory constraints, are generally characterized by the presence of antiquated systems, the lack of management systems, and poor internal comfort [1].

Therefore, energy and environmental retrofit of historic buildings represents an opportunity to promote the long-term sustainability of the built heritage, as it can significantly contribute to reducing the environmental impact and operating costs of the building-system, without compromising the functionality and comfort of the spaces, in line with the European decarbonization objectives of the construction sector, responsible for 40% of energy consumption and 36% of greenhouse gas emissions globally [5]. Interventions on these buildings must be designed to respect their history and cultural identity, avoiding overly invasive solutions that would compromise their integrity, as well as excessively conservative approaches that would be ineffective from an energy and environmental perspective [6]. In addition to these challenges, further critical issues exist, such as a fragmented regulatory framework, the imposed regulatory constraints, and the high costs of intervention, which further complicate the path to sustainable transformation of existing buildings. Moreover, not all modern retrofitting techniques are suitable for historical buildings [7]. Therefore, when considering retrofitting options, the compatibility with heritage should be rigorously assessed [7,8].

In this context, the adoption of innovative technologies and non-invasive solutions, which do not compromise the historical and cultural value of these artifacts, becomes essential to ensure a balance between conservation and innovation. However, creating a database of passive solutions applicable to the historic context is not sufficient. It is crucial to develop an adaptive methodology capable of understanding the uniqueness of each different application context, using its specificities as input data for the definition of the most adequate retrofit solutions tailored to the specific building.

From this perspective, monitoring can be a useful tool. Field monitoring campaigns and measurements leads to obtain much precise data [9], thus being able to understand the actual behaviour of buildings [10].

This article presents the analysis of the first phase of an innovative methodological approach aimed at identifying customized, ad hoc retrofit strategies that respect the historical and architectural characteristics of the built asset. In this contribution are analyzed and discussed the results of a summer monitoring campaign of a case study identified as a "pilot", i.e., the Villa Farnesina complex in Rome, used for the validation of the methodology proposed.

2 Methodology

2.1 Site description

Built in the 16th century at the behest of Agostino Chigi by Baldassarre Peruzzi, the Villa Farnesina in Rome is one of the most notable creations of the Italian Renaissance [11]. The building, property of the "Accademia Nazionale dei Lincei", is also a museum, currently open to the public and hosting temporary exhibitions.

The Villa is characterized by a U-shaped plan, developed on 5 levels plus one underground floor (see F.1). Two levels, i.e., the raised ground floor and the first floor, are

partially opened to the public (see F.1a and b) hosting, along with the prestigious frescoes, also temporary exhibitions. On the other hand, the underground floor, the first and second mezzanines, and the Altana levels are accessible only to the Villa's staff.

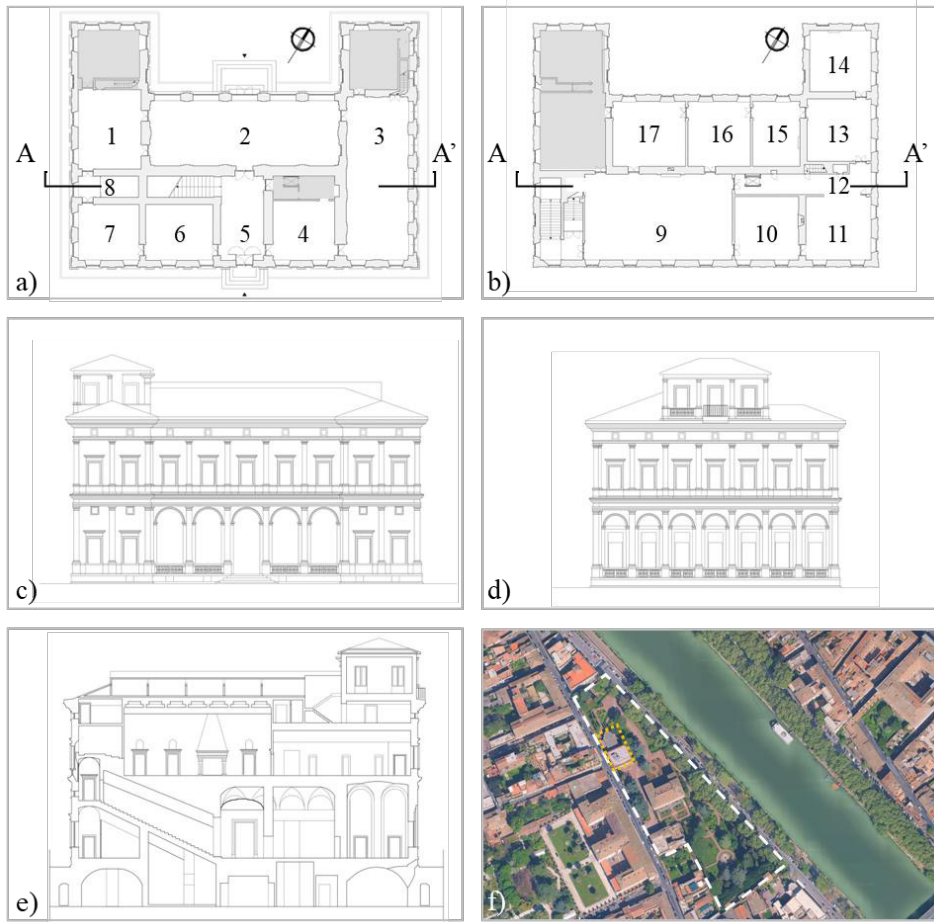


Fig. 1 a) Raised ground floor plan: 1. Hall of the Freize, 2. Loggia of Cupid and Psyche, 3. Loggia of Galatea, 4. Museum hall n.1, 5. Atrium, 6. Bookshop, 7. Museum hall n. 2, 8. Pompeian Room. The grey areas are closed to the public; b) First floor plan: 9. Hall of the Perspectives, 10. Wedding Hall, 11. museum hall n. 3, 12. Gallery of Grottesque, 13, museum hall n. 4, 14. museum hall n.5, 15. museum hall n.6, 16. museum hall n.7, and 17. museum hall n. 8. The grey areas are closed to the public; c) NNW façade; d) NNE façade; e) cross section AA', f) Aerial view of Villa Farnesina complex, identified with dashed perimeter; in yellow the Auditorium building.

The entrance to the Villa is positioned on the NNW oriented façade, corresponding to the Loggia of Cupid and Psyche which, along with the adjacent Loggia of Galatea, hosts impressive frescoes by Raffaello Sanzio. The two loggias, originally open, are nowadays closed with a single glazing envelope with metal frame (Cupid and Psyche Loggia) and an opaque envelope characterized by the presence of five and three openings, ubicated respectively, on the NNE and SSE façades (Loggia of Galatea). Other notable frescoes appear in the Atrium, used as the museum exit, in the Pompeian Room and in the Hall of the Freize, situated on the ground floor, and in the Hall of Perspectives, the Wedding Hall, and in the Grottesque Gallery, located on the first floor. Finally, the Villa appears to be surrounded by a Renaissance garden.

Moreover, the opaque envelope is made of mixed masonry (bricks for the bearing walls and tuff rocks for non-bearing ones), finished with an outer and inner lime-plaster layers. The Villa present single-glass windows with the original wooden frame. In addition, the glazed part of the mezzanines openings is made of leaded glass, composed by rectangular parts.

The Villa is not equipped with a cooling system, although several portable air-coolers were positioned in the museum halls 11, 13, 14, 15, and 17 during the summer period. Regarding the winter heating necessity, the Villa is equipped with several radiators, positioned in the atrium, the bookshop, and in the museum halls 1, 3, 4, 6, and 8. Moreover, the Loggias of Cupid and Psyche and of Galatea are provided with an all-air heating system.

The building is open to the public from Monday to Saturday between 9:00 and 14:00. During the monitored period, the mean daily visitors' presence was 95 people (from July to September of 2025). More in detail, September was the most crowded month, with a mean daily presence of 130 visitors. In addition, around 10 staff members operate in the Villa.

2.2 Methods

The objective of the work was to identify the best retrofit options for guaranteeing the thermal comfort conditions for the Villa's users, improving the sustainability of the building complex.

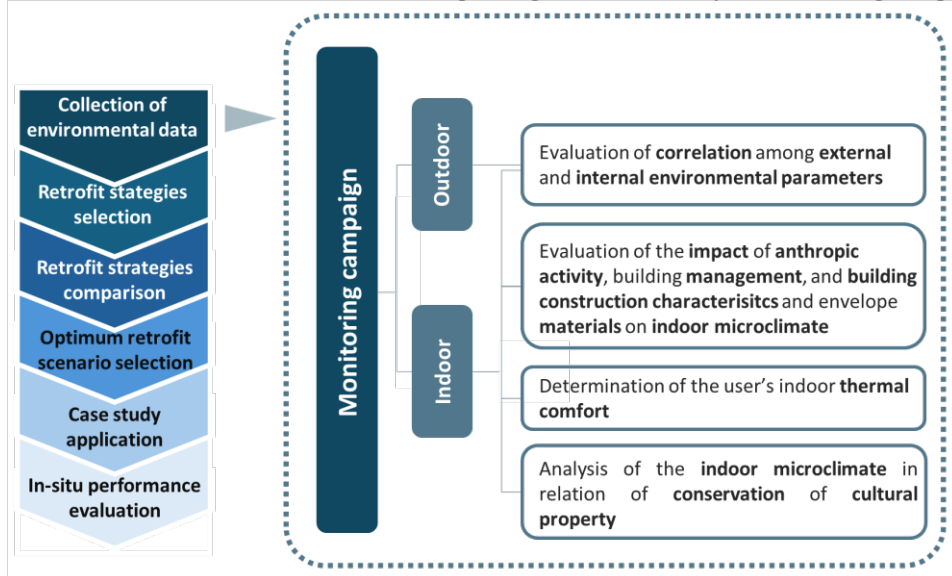


Fig. 2 Applied methodology workflow.

To pursue this objective, a multi-step methodology was developed (see F.2) aimed at selecting the optimum retrofit strategy for the specific case study object of evaluation, and to assess the effectiveness of the selected intervention. In this contribution, the first step of the proposed methodology, i.e., the collection and analysis of the environmental data and their outcomes is discussed in detail.

The applied experimental method consisted of a in-field microclimate continuous monitoring campaign aimed at registering environmental parameters both inside and outside the case study. The monitoring was carried out during the summer period, starting from 21st July to 21st September 2025, according to the building schedule and operations. It must be noted that the campaign is still ongoing, to acquire data regarding the other seasons.

The results of the experimental monitoring campaign were then post-processed and analysed to assess the building indoor microclimate and outdoor environmental conditions in the proximity by considering:

- the impact of site-specific outdoor boundary conditions (e.g., outdoor pavements, greenery, river proximity, urban fabric density);
- the effect of indoor forcings (i.e., building management and operations, visitors' occupational rates, thermal load of electronic equipment and devices, and lighting systems);
- the influence of the building construction, envelope materials and characteristics of the different thermal zones (e.g., orientation, glazed/opaque envelope, rooms elevation).

Moreover, this analysis allowed to determine:

- the correlation between indoor and outdoor local microclimate parameters;
- the indoor environmental conditions in different areas of the building;
- the indoor comfort conditions of the users, evaluated through the application of ISO 7730:2025 [12] prescriptions.

This led to a comprehensive view of the overall performance of the building, foundational to defining the liabilities and strengths pivotal to the selection of proper retrofit measures compatible with all the constraints related to buildings with high cultural and historical value.

The monitoring campaign was carried out using various instruments: two portable indoor and outdoor microclimate stations, and 16 miniaturized thermohygrometers (see F.3). The specific collected environmental parameters are reported in Table 1, including details about the used equipment and its accuracy.

Table 1 List and characteristics of the used sensors.

Instrument	Sensors	Accuracy	Measured/calculated parameter
Thermo-hygrometer	- 10K NTC Thermistor - Capacitive	- $\pm 0.6^{\circ}\text{C}$ - $\pm 3.0\%$	- Air temperature [$^{\circ}\text{C}$] - Relative humidity [%]
Indoor station	- Capacitive - Pt 100 - Hot wire anemometer - Pt 100 - Photodiode	- $\pm 1.0\%$ - $\pm 0.15\text{ K}$ - $\pm 0.06\text{ m/s}$ - $\pm 0.15\text{ K}$ - $\pm 3\%$	- Relative humidity [%] - Air temperature [$^{\circ}\text{C}$] - Air speed [m/s] - Globe temperature [$^{\circ}\text{C}$] - Illuminance [lx] - Mean radiant temperature [$^{\circ}\text{C}$]
Outdoor station	- Capacitive - Diode voltage	- 3% - $\pm 0.3^{\circ}\text{C}$	- Relative humidity [%] - Air temperature [$^{\circ}\text{C}$]

In order to carry out the campaign, the thermohygrometers were positioned in different halls of the museum (ground and first floor) to continuously record the air temperature and relative humidity. The indoor microclimatic station was used to characterize 6 halls, three located on the ground floor (the Loggia of Cupid and Psyche, the Loggia of Galatea, and the Hall of the Freize), and three on the first floor (the Hall of the Perspectives, the Wedding Hall, and the museum hall n. 7, facing the NNW Façade). The indoor station position was varied weekly throughout the entirety of the observation period. The placement of the indoor station and the thermohygrometers was conditioned by the necessity of guaranteeing the complete fruition of the exhibition space for the visitors. Finally, the outdoor station was used to collect data from different spaces of the garden.

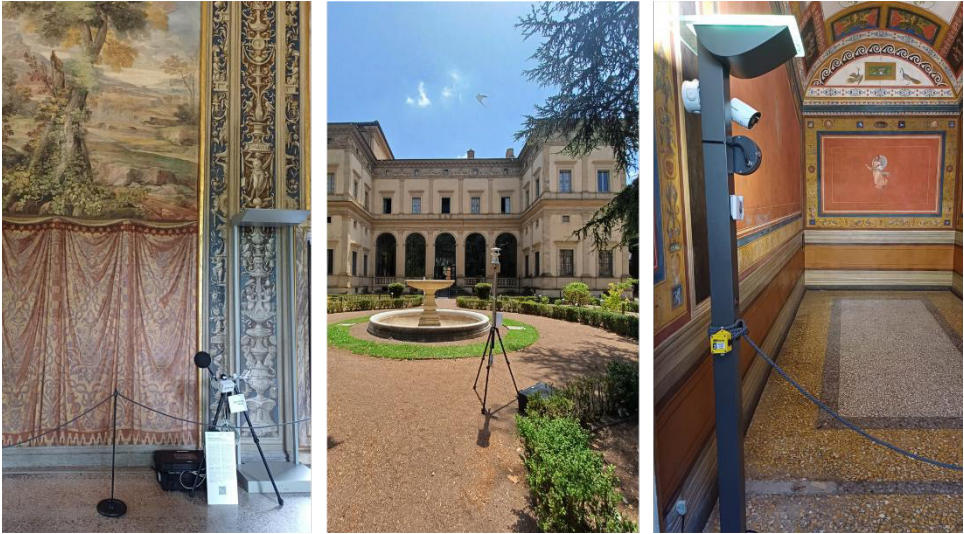


Fig. 3 Placement of the environmental sensors. Left: indoor station in the Loggia of Galatea; centre: outdoor station positioned in the garden in front of the NNW entrance; right: thermohygrometer in the Pompeian Room.

3 Results and discussion

3.1 Outdoor microclimate boundary conditions: correlations with indoor environmental parameters

The comparison of outdoor and indoor air temperatures are reported in Figure 4.

The higher correlation was observed in the ground floor rooms (see F.4a, F.4b, and F.4c). Conversely, the first floor had lower correlation values, especially for the museum halls facing NNW and NNE (see F.4d, F.4e, and F.4f), characterized by a correlation ranging from non-existent to weak. It has to be noted that there are several factors potentially affecting the correlation between the indoor and outdoor environmental parameters, and specifically the air temperature inside these specific halls: (i) the windows and the blinds of the said rooms were kept closed or ajar during the entire summer period; (ii) portable air conditioner machines were installed inside these rooms; (iii) higher thermal loads were experimented due to the presence in two of the said rooms of light screens, and (iv) higher visitors stationing levels in museum hall n. 7 caused by the presence of several virtual reality exhibition stations.

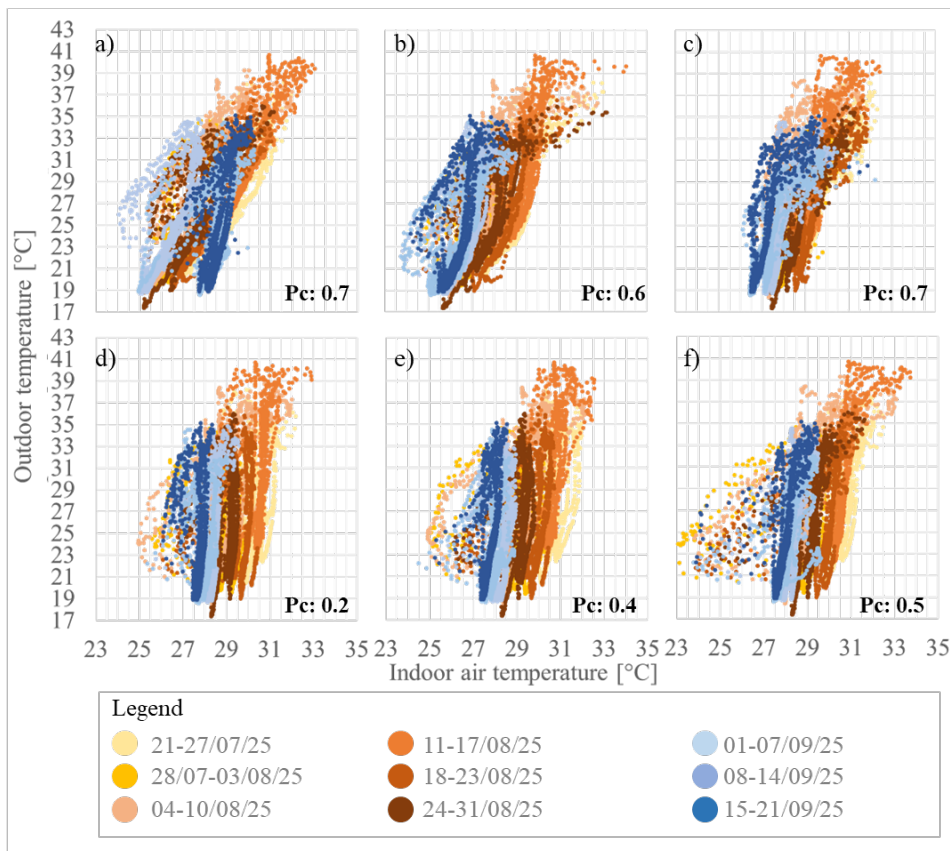


Fig. 4 Correlation between outdoor and indoor air temperatures and Pearson's coefficient (PC) evaluated for: a) Cupid and Psyche Loggia, b) Atrium; c) Pompeian Room; d) museum hall n.4; e) museum hall n. 5; f) museum hall n. 7.

Conversely, from the comparison between the relative humidity measured outside and inside the Villa, a higher linear correlation was registered, with the Pearson's coefficient varying from moderate to strong, as shown in Figure 5.

Specifically, higher correlation values were registered for the rooms with a higher Window-to-Wall Ratio (WWR), like the Loggia of Cupid and Psyche (see F.5a). As noted for the air temperature, also in this case, lower correlation was registered for museum halls facing NNW and NNE (see F.5e and F.5f).

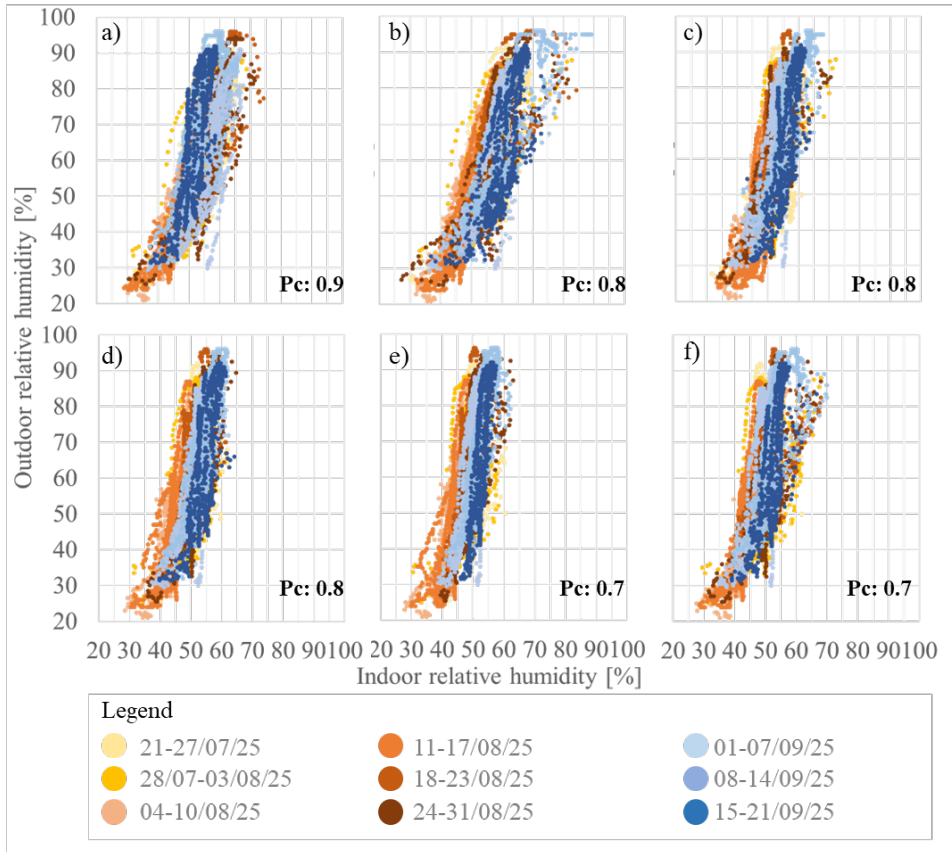


Fig. 5 Correlation between outdoor and indoor relative humidity and Pearson's coefficient (PC) evaluated for: a) Cupid and Psyche Loggia, b) Atrium; c) Pompeian Room; d) museum hall n.4; e) museum hall n. 5; f) museum hall n. 7.

3.2 Analysis of the indoor environmental conditions

The analysis of the indoor environmental conditions, and specifically of the air temperature registered throughout the summer, was developed to assess the impact on the said parameter of:

- building characteristics, such as envelope construction layers, passive cooling design choices, room positioning in plan, and with respect to the floor level;
- thermal loads and building management solutions, e.g., anthropic presence, electric devices and lighting systems, windows and blinds opening/closing.

Specifically, in this section, the analysis performed on the data collected during the hottest summer week is reported.

The comparison between the two Loggias, characterized by the same dimensions and the same height, highlights that in the Loggia of Cupid and Psyche, characterized by a higher Window-to-Wall Ratio with respect to the one of the Loggia of Galatea (0.7 vs 0.1), the air temperature showed a greater dependence on the external temperature. Moreover, a higher daily fluctuation in the average temperature (3.9°C vs. 2.3°C) was observed in the Loggia of Cupid and Psyche (see F.6a).

The data registered in the Atrium and in the bookshop, two museum halls with the same exposure (SSE) both positioned on the ground floor were compared. This highlighted that

the Atrium, characterized by the presence of passive cooling elements (i.e. cross ventilation), showed a lower average temperature (-0.8°C) and a greater daily temperature fluctuation (3.2°C vs. 2.2°C) than the bookshop (see F.6b).

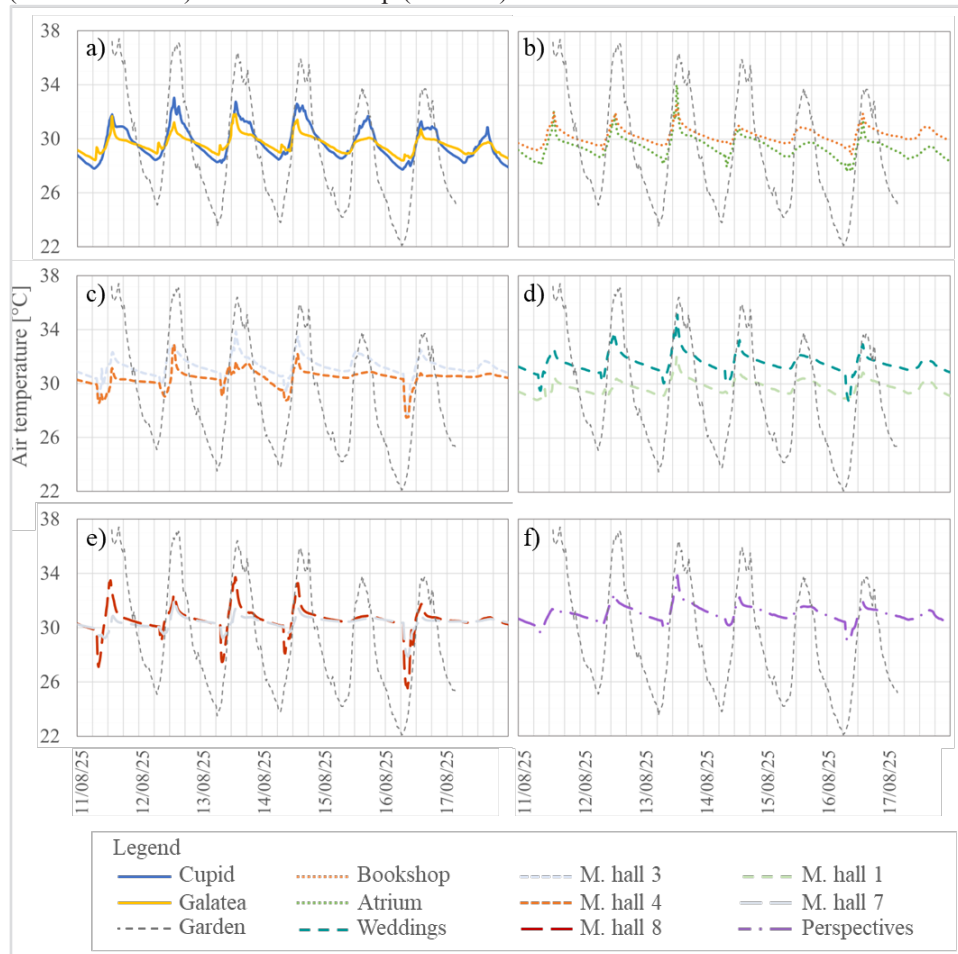


Fig. 6 Air temperature measured during the hottest summer week (11-17/08/25) in: a) Cupid and Psyche Loggia and Galatea Loggia; b) Atrium and bookshop; c) museum hall n. 3 and n.4; d) museum hall n. 1 and Wedding Hall; e) museum hall n. 6 and n. 7; f) Hall of Perspectives.

The data collected in the museum halls n. 3 and n. 4, both located on the first floor and characterized by the same volume, were analyzed. It was noted that the room with a NNE exposure (museum hall n. 4) showed a lower average temperature (-0.8°C) and a higher daily temperature fluctuation (3.1°C vs. 2.4°C) than the hall facing SSE (see F.6c).

Examining the temperature registered in two rooms with the same exposure SSE and the same volume, it appeared that they showed similar temperature trends. However, the room on the first floor (Wedding Hall) had a higher average temperature (+1.8°C) than the one on the ground floor (museum hall n.1) (see F.6d).

It was noted that the opening of the Villa and the subsequent activation of electronic devices and lighting systems, and the presence of visitors led to higher maximum temperatures. Specifically, in opening days a higher maximum daily temperature up to +2.3°C was measured. Moreover, throughout the closing days (i.e., Sundays and the 15th of August), the air temperature remained stable (see F.6e).

Finally, it was registered that contextually to the windows opening (around 9:00), occurring after the night closure, the rooms cooled rapidly, with a temperature reduction up to -1.4°C in 30 minutes (see F.6f).

3.3 Occupants' comfort

The occupants' thermal comfort was determined in accordance with the prescriptions of EN ISO 7730:2025 for the hottest and coolest summer weeks and days, considering only the opening hours of the Villa to the public.

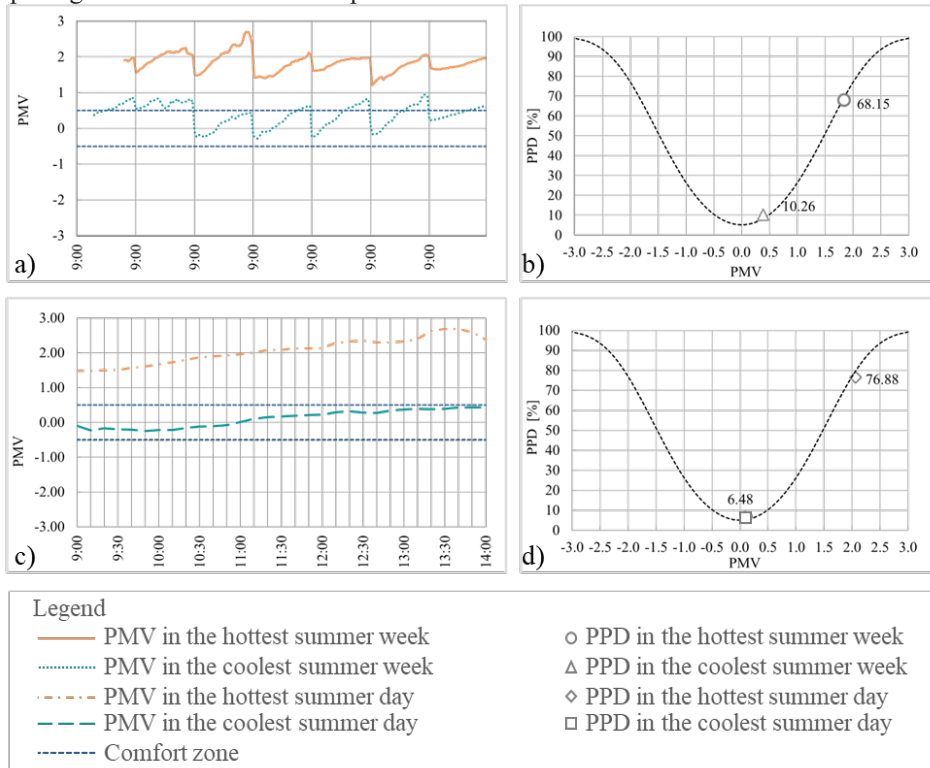


Fig. 7 Occupants' comfort evaluation: a) PMV and b) PPD for the hottest and coolest summer week; c) PMV and d) PPD for the hottest and coolest summer day.

In the hottest summer week, the Predicted Mean Vote (PMV) ranged from "fairly hot" to "hot" (1.8), with a high Predicted Percentage of Dissatisfied (~70%, with a maximum of ~80% on the hottest day, which was the 13th of August 13).

During the coolest summer week, the PMV was 0.1, with a low percentage of dissatisfied (~10%, dropping to ~6% on the coolest day, the 3rd of September). However, it should be noted that even in the coolest week, from 12:00 PM until closing time (14:00), the PMV rose up to ~1.

4 Conclusions

Retrofitting historic buildings has significant potential in reducing carbon emissions and the energy consumption of the construction sector, although it is a complex task, where strong constraints are involved. It is therefore crucial to develop an approach capable of taking into account each building's peculiarities to promote and apply tailor-made strategies capable of

reaching the sustainability and efficiency objectives, while preserving the cultural and historical value of the architectural heritage. Within this framework, this study analysed the summer environmental data collected in Villa Farnesina in Rome, gathered to assess the current condition of the building.

The results, which will be foundational to selecting the appropriate retrofit measures for the case study, showed that:

- indoor temperature showed non-existent to moderate correlation with outdoor temperature, being strongly influenced by internal thermal loads and building management, whereas relative humidity showed moderate to strong correlation with outdoor conditions;
- building characteristics had a significant impact on indoor temperature. As expected, SSE halls and first floor rooms experienced higher temperatures. Moreover, higher WWR and passive cooling design choices increased daily temperature fluctuation;
- thermal loads and building management solutions significantly affected the magnitude of daily temperature peaks;
- occupants' comfort was not reached in the hottest summer week (PMV: ~1.8, PPD: ~70%) and in the late mornings of the coolest week.

The results of the monitoring campaign highlight the urgent need to implement retrofit measures to ensure the occupants' comfort throughout the summer period.

However, the historical constraints of the Villa strongly limit the application of traditional retrofit measures.

Considering the operational framework and taking into account the need to preserve the huge cultural significance of the heritage complex of the Villa, some possible retrofit measures can be designed. For instance, it could be beneficial to replace the current all-air heating system with an HVAC system that also serves air cooling purposes. Moreover, the system could be coupled with a Building Energy Management System (BEMS) and the application of photovoltaic panels on the near Auditorium building roof, to optimize energy consumption and partially provide for the increased energy demand from cooling request, respectively.

Another possibility could be intervening with passive retrofit solutions on the building envelope, specifically on its glazed portion and on the roof, while maintaining the opaque envelope and, therefore, the Villa's aesthetic appearance unaltered. More in detail, several interventions on the windows can be implemented. One option can be the substitution of the single-glazing Loggia of Cupid and Psyche's envelope with a double-glazing envelope with a hidden window frame, to improve the building's energy performance and indoor thermo-hygrometric conditions while simultaneously reducing the aesthetic impact of the intervention. Moreover, the substitution of the remaining single-glazing windows with double-glazing windows, while preserving the original and historical wooden frame, can further contribute to enhancing the building's performance. Moreover, the application of films for passive daytime radiative cooling onto the windows subjected to direct solar radiation can help in reducing passive solar heat gains. With respect to the roof, the tiles can be replaced with high-albedo aged tiles with the same aesthetic appearance of the historical ones, reducing summer overheating.

To assess the actual efficacy of the proposed retrofit options, a future step will be to perform the dynamic energy simulation of the building within different possible scenarios. This will allow to measure the actual impact of each retrofit solution, while highlighting possible synergies useful to identify an "optimum" retrofit scenario. However, limiting the evaluation only to the summer season can create a serious winter imbalance.

Therefore, the next steps of this research will focus on expanding the monitoring campaign to cover all seasons, enabling a complete characterization of the building's microclimatic behaviour throughout the year. This extended dataset will be fundamental for

understanding the dynamic interactions between outdoor conditions, internal thermal loads, and operational strategies.

A key aspect of future work will be the analysis of overall internal heat gains, thermal loads, and operational conditions, which play a strategic role for the management of HVAC systems. These evaluations will allow a precise estimation of actual thermal demands in different zones of the building, supporting the design of tailored solutions that balance energy efficiency, and visitors' comfort.

To achieve this, the research will integrate further in-situ monitoring during fall and winter, dynamic simulations, and real consumption data, creating reliable models that reflect the actual behaviour of the building. This approach ensures consistency between energy efficiency objectives and conservation constraints, providing a solid knowledge base for decision-making. Such integration is essential for the dimensioning and regulation of HVAC systems, as well as for defining control strategies that improve indoor comfort.

Experimental analyses will continue to play a fundamental role in the evaluation of retrofit scenarios. Laboratory investigations on innovative materials will complement the modelling phase, enabling accurate calibration and validation of simulation tools. These activities will also support the assessment of passive and active retrofit measures, including insulation strategies, natural ventilation enhancement, and advanced control systems.

Ultimately, the goal is to develop a data-driven framework for sustainable retrofit interventions in historic buildings, capable of reconciling technical requirements, economic constraints, and cultural values. The methodology will provide predictive insights into the impact of different strategies on energy demand, thermal comfort, and conservation conditions. This integrated approach will serve as a reference for similar heritage contexts, promoting solutions that are both efficient and respectful of historical authenticity.

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