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# Thermal Behavior of a Historic Building Housing Books Across Past and Future Climate Scenarios

**Gianluca Cadelano [1,*], Alessandro Bortolin [1], Antonio della Valle [1], Giovanni Ferrarini [2], Paola Cattaneo [3], Fabio Peron [4] and Giuseppe Emmi [4]**

[1] Institute of Atmospheric Sciences and Climate, National Research Council of Italy, 35127 Padua, PD, Italy; alessandro.bortolin@cnr.it (A.B.); antonio.dellavalle@cnr.it (A.d.V.)
[2] Construction Technologies Institute, National Research Council of Italy, 35127 Padua, PD, Italy; giovanni.ferrarini@cnr.it
[3] Studio Architettura Paola Cattaneo, 35121 Padua, PD, Italy; info@pcastudio.net
[4] Department of Architecture and Arts, University IUAV of Venice, 30135 Venice, VE, Italy; fperon@iuav.it (F.P.); giuseppe.emmi@iuav.it (G.E.)
* Correspondence: gianluca.cadelano@cnr.it

**Abstract:** Climate change poses significant challenges for the renovation of historic buildings, requiring a careful balance between preservation and energy efficiency, particularly considering the forecasted rise in temperatures. This study focuses on a medieval building undergoing renovation, examining thermal behaviors based on future climate settings, with particular attention to the rooms housing a book collection. Books require controlled microclimatic conditions that must be ensured for their preservation; hence, the energy use for air conditioning control must be considered during the renovation planning phase. Through on-site monitoring of the thermophysical properties of the building envelope and indoor microclimate, along with energy model software simulations, both historic climate and global warming scenarios were evaluated for their potential impact on thermal behavior and consequently on energy consumption. This study aims at contributing to the long-term sustainability and resilience of historic buildings, as well as proposing best practices for planning interventions involving sensitive cultural heritage materials, considering the effects of climate change in the renovation process. The results show strategies to address the climatic changes through a methodology optimizing renovation interventions. The sizing of air conditioning systems coupled with a less stringent microclimate control mitigates energy requirements, in line with the sustainable management approach.

**Keywords:** energy efficiency; libraries management; historical building; thermal comfort; cultural heritage conservation; indoor microclimate; historical climate; energy simulations



**Citation:** Cadelano, G.; Bortolin, A.; della Valle, A.; Ferrarini, G.; Cattaneo, P.; Peron, F.; Emmi, G. Thermal Behavior of a Historic Building Housing Books Across Past and Future Climate Scenarios. *Heritage* **2024**, *7*, 6916–6937. https://doi.org/10.3390/heritage7120320

Academic Editor: Lola Kotova

Received: 31 October 2024
Revised: 3 December 2024
Accepted: 5 December 2024
Published: 7 December 2024



## 1. Introduction

The renovation of historic buildings presents a unique set of challenges, especially when it comes to balancing energy efficiency with preservation [1]. As these structures often hold significant cultural heritage value, it is crucial to maintain their architectural integrity while upgrading them to meet modern standards of comfort and sustainability. These challenges are further intensified by the increasing impacts of climate change, which demand innovative approaches to both conservation and energy management [2].

With the advent of more efficient and adaptable technologies, it has become increasingly feasible to retrofit historic buildings for energy efficiency [3–5]. Recent approaches to improving energy efficiency in historic buildings while preserving their architectural integrity include the integration of discreet renewable energy systems such as photovoltaic panels, which can be installed in a way that does not compromise the building's aesthetics. Additionally, low-impact solutions like ground source heat pumps can be employed, as these systems can be integrated without disrupting the building's existing infrastructure or appearance. Other strategies may involve high-performance insulation materials that blend with the original structure or advanced energy management systems that optimize heating, cooling, and lighting without visible modifications to the building exterior or interior. In this context, energy modeling has become a key tool during the design and optimization stages of these interventions. However, modeling historic buildings is inherently more complex than modeling modern structures. For contemporary buildings, the building envelope and its properties are well-documented, with detailed information readily available in manuals and databases. In contrast, historic buildings have a unique and layered history that must be carefully reconstructed to understand the stratigraphy of their building envelope. Over time, the original materials in these structures often degrade, potentially altering their thermophysical properties. Thermophysical properties are the physical properties of materials that describe their behavior, such as their response to temperature changes, and are essential for accurately simulating a building's performance in model simulations. This adds a level of complexity to the modeling process, requiring additional effort, such as direct on-site measurements of these characteristics. Despite these challenges, the process is both manageable and feasible. This framework of assessing the current energy performance of historical buildings finalized to facilitate the design of interventions can be extended far beyond current applications. By incorporating data from both historical climates and projected future scenarios, the energy modeling tool makes it possible to explore a building's energy performance across different temporal contexts. Historical climatology provides valuable insights into how buildings functioned in the past under varying environmental conditions. By accurately adapting historical climate data—such as temperature and humidity records—computational models can simulate the resulting indoor conditions (e.g., indoor air temperature) that a building would have experienced decades or even centuries ago [6]. This retrospective analysis is not only academically significant but also provides a crucial baseline for understanding the evolution of a building's energy needs over time and the indoor environmental conditions in which housed materials and artifacts have been preserved up to the present day. Notably, it is only with the widespread adoption of climate control systems—largely absent in the past—that increasingly frequent preservation issues have emerged [7]. Looking forward, the impacts of global warming introduce additional variables that must be factored into renovation planning. Climate models offer various future scenarios, predicting changes in temperature, humidity, and other factors that will influence the energy consumption of a building in the next years. By integrating these scenarios into building energy models, planners can anticipate future climate challenges and design interventions that ensure both the resilience and efficiency of the heating and cooling system over its expected lifespan. This approach is particularly relevant for historic buildings that house sensitive materials, such as book collections or other microclimate-sensitive items, which require specific thermo-hygrometric conditions for preservation, as well as the maintenance of a suitable living environment for occupants. Microclimate describes the unique set of indoor conditions, such as temperature, humidity, and airflow, within a specific space, like a room, which can affect the materials inside and the perceived comfort by people. By simulating various climate scenarios—both past and future—energy demand modeling can help in designing climate control systems that are both efficient and protective of these valuable materials. In order to effectively use historical and future climate data as inputs for energy modeling, it is essential that these data are accurately represented and adapted to the specific context of the building. This requires a rigorous process of data validation and adaptation, ensuring that the simulations are reliable and physically sound. In this study, this methodology has been applied to a medieval building currently undergoing renovation, with a particular focus on the rooms that house a significant book collection. By leveraging on-site monitoring data, coupled with energy modeling software, three different climate scenarios—historical, current, and future— have been analyzed with regard to the impact on the energy demand of the building and indoor thermo-hygrometric conditions. The ultimate objective has been to propose a framework for renovation that not only preserves the building's historical character but also ensures its long-term sustainability in the face of evolving environmental challenges.

## 2. Materials and Methods

### *2.1. Overall Methodology*

By utilizing historical climatology data from the literature, monitoring, and modeling, alongside information about building materials and geometry, energy modeling software was employed to generate three distinct climate scenarios—historical, current, and future. These scenarios were analyzed in relation to thermal comfort standards. Subsequently, a different indoor microclimate was hypothesized to improve the conservation conditions for the housed book collection, which involves the use of air conditioning. The air-conditioned environment was then evaluated in terms of its impact on thermal comfort for occupants and the energy requirements for heating and cooling. The energy demand of a building is closely linked to the effort required by the HVAC systems (Heating, Ventilation, and Air Conditioning) to maintain specific indoor conditions. This effort is influenced by both the characteristics of the HVAC systems and the properties of the building envelope. However, a critical factor is the difference between the desired indoor environment and the external climate. Indeed, when the desired indoor conditions, such as air temperature ($T_{air}$) and relative humidity (RH) for comfort and the preservation of books and other sensitive items, are kept constant, the key variable affecting energy demand is the outdoor climate. As outdoor temperatures rise, which is a trend associated with ongoing climate change, the HVAC systems must work harder to achieve and maintain the indoor conditions. Consequently, the energy demand due to cooling is expected to increase proportionally with the rise in external temperatures. The analysis was conducted using building energy modeling, with three distinct simulations performed (Table 1), each reflecting different outdoor climate conditions.

**Table 1.** Description of the three modeled scenarios.

| Modeled Scenario | Reference Year Span | Building Characteristics | Indoor Climatization | Outdoor Conditions |
|---|---|---|---|---|
| Past (pre-climate change) | 1951–1960 | - | No heating/ no cooling | Reconstructed from historical climate series |
| Present (recent years) | 2009–2018 | minor updates to fixtures and lighting | No heating/ no cooling | Actual climate data |
| Future forecast | 2031–2040 | major updates to fixtures and lighting | No heating/ no cooling | Data projection based on literature |

Minor upgrades to the building's lighting and windows were made to better represent technological advancements over time. By excluding HVAC systems from the simulations, the gap between the ideal indoor conditions (consistently maintained across all scenarios) and the naturally occurring conditions was identified, outlining the potential workload for a future HVAC system. Lastly, the indoor thermo-hygrometric conditions, designed primarily for conservation, were evaluated for occupant thermal comfort.

The procedural scheme is visualized in Figure 1. In particular, the following subsections outline the rationale behind the reference indoor conditions imposed during the simulations, describe the building characteristics as input for the energy modeling simulations, and explain the methodologies used to define the three climate scenarios—past, present, and future.

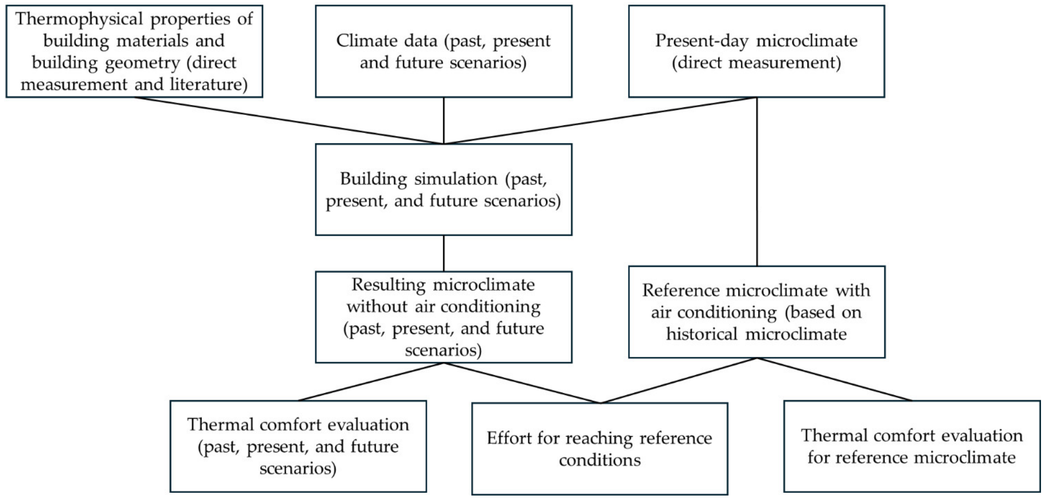
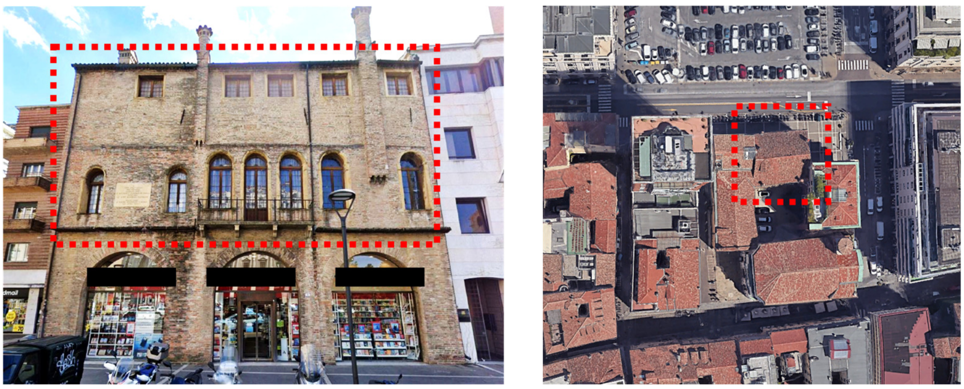



**Figure 1.** The overall procedural flow, outlining each step based on the methodologies presented in the next sections, covering the evaluation of environmental parameters, simulation results, and thermal behavior of the building.

#### 2.1.1. Description of Case Study

The Associazione Gabinetto di Lettura e Società di Incoraggiamento is one of the oldest cultural institutions in Padua (located in the north-east of Italy), established in 1830. Over nearly two centuries, it has amassed a library of more than 60,000 books, and has been a hub for cultural dissemination through a variety of activities, including lectures, conferences, concerts, and exhibitions. The building housing the Gabinetto di Lettura, known as the Casa dell'Angelo, is a remarkable example of Romanesque architecture. The earliest records of the building date back to 1370 when it served as an inn under the name Hospitium Angeli. Located in the historic Santa Lucia district, the Casa dell'Angelo is the only surviving medieval civil structure in the area, having withstood the widespread demolitions of the late 1920s and the subsequent reconstruction in the rationalist style typical of the Fascist era. A picture of the building is reported in Figure 2.



(**a**) (**b**)

**Figure 2.** Images of the building: (**a**) northern façade of Casa dell'Angelo. The building's features have not changed since the 1930s. Nowadays, the ground floor is used for commercial activities, while the first and second floors (red box) host the quarters of Associazione Gabinetto di Lettura e Società di Incoraggiamento. (**b**) Aerial view of the urban context; Casa dell'Angelo building is indicated by the red box.

In the 1950s, after a series of political and administrative changes, the building was granted in perpetuity to the Association with a binding cultural use. The last significant restoration occurred in the early 1930s, transforming the building into the Gabinetto di Lettura's headquarters. However, over time, both the interior and exterior structures of the building have shown signs of significant degradation. The recently accomplished renovation project (2023) focused on restoring and securing the building's north, south, and east façades, marking the first phase of a broader plan to revive this important cultural asset for the city of Padua. Future plans include the renovation of the interior rooms, also including adequate HVAC systems to guarantee the proper condition for the housed library, but also to make possible the envisioned use of the building as a cultural center that will include a range of activities, from exhibitions and concerts to lectures and public events. Ensuring the building can accommodate these functions while preserving its architectural integrity is a central goal of the restoration. Therefore, a key aspect of the renovation is the improvement of the building's energy efficiency, which is critical for both the preservation of the structure and the collection it houses in a sustainable way. The building's historical value imposes strict constraints on the types of interventions that can be made, necessitating careful planning and the use of technologies that are both effective and sympathetic to the building's original materials and design.

#### 2.1.2. Indoor Comfort Conditions for Occupants

The quantitative assessment of comfort was prominently developed by Fanger [8] and later formalized by international standards [9,10]. The Fanger model, that was originally intended for evaluating contemporary indoor spaces, remains the most widely used approach in civil engineering, supporting its selection for this research despite debates on its versatility [11]. The thermal sensation of a human being in an indoor environment is influenced by physical activity and clothing, as well as by microclimate. These parameters allow us to calculate the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD), i.e., the percentage of people who are likely to feel discomfort. PMV is the mean value of comfort on a scale ranging from −3 (cold) to +3 (hot), where 0 is thermal neutrality, which is the optimal condition. Recommended thermal comfort requirements for spaces for human occupancy are commonly considered as satisfactory when the PPD is lower than 10%, which corresponds to the following PMV criteria: $-0.5 < \text{PMV} < +0.5$. In this study, PMV and PPD were calculated according to the standards specified in ISO 7730 [9] for various rooms in Casa dell'Angelo across three different historical periods, both under natural conditions (without heating or cooling systems) and within a controlled microclimate environment. These comfort metrics were influenced by factors like air temperature, relative humidity, surface temperature ($T_r$), and air velocity (v), all of which were obtained from energy simulations and supported by on-site measurements. The average radiant temperature was derived from the energy simulations, specifically calculated from the operative temperature, and the air velocity was set to 0.1 m/s, which was confirmed as realistic based on on-site measurements using an anemometer. Key parameters for the calculations included not only the physical properties of the air, but also the insulating effects of the clothing worn by people and the metabolic rate, which is linked to the level of physical activity being performed. Clothing insulation was modeled as a linear variable of air temperature, realistically changing with the seasons—ranging from light summer clothing like long trousers and short-sleeved shirts (clothing index = 0.61) to heavier winter garments such as long-sleeved shirts and sweaters (clothing index = 1.10). The metabolic rate was set to match typical indoor activities that would take place in Casa dell'Angelo, such as standing or sitting while reading, ensuring the results reflected representative conditions (metabolic rate = 63.8 $W/m^2$).

#### 2.1.3. Indoor Conditions for the Conservation of Books and Cultural Heritage

Microclimate control is essential not only for ensuring human comfort but, more importantly, for the preservation of both movable and immovable cultural heritage [12,13]. In this regard, books are stored on wooden shelves, which, along with other wooden furniture such as tables and chairs, essentially represent the main type of objects. Each material within the housed collections must be preserved within specific environmental ranges, which often differ from the ranges required for human comfort, making HVAC system management challenging [14,15]. In the case of many libraries, including the one presented in this study, the vastness of the collections or their regular use for public consultation makes microclimate control through air-conditioned showcases impractical. Therefore, curators often struggle to find a balance between ensuring both comfort for occupants and preservation of the materials, leading to excessive and sometimes unjustified energy consumption. In addition to balancing energy use, it is crucial that preservation measures do not compromise accessibility. Books and other cultural objects must remain available for consultation, which means climate control systems must protect the collections while also accommodating the presence of readers and researchers, without destabilizing the fragile environmental conditions necessary for preservation. Among the various factors that affect preservation, air temperature and relative humidity are the most critical. Higher temperatures and humidity levels accelerate chemical reactions in organic materials, while fluctuations in these parameters can cause mechanical stresses that lead to material damage. For this reason, maintaining stable conditions is often more important than achieving ideal, but inconsistent, levels of these parameters. Moreover, no single temperature or humidity range is appropriate for all materials found in books, which are often composed of paper, leather, metal, and vellum. Each material requires distinct conditions to minimize deterioration [16]. Depending on the source (e.g., International Centre for the Study of the Preservation and Restoration of Cultural Property—ICCROM, Canadian Conservation Institute—CCI and Institut Français de Restauration des Œuvres d'Arts—IFROA, Italian Ministry of Culture- MiC, formerly MiBAC [17]), as reported in the literature [18], the suggested reference ranges for temperature and humidity for the conservation of materials constituting books may vary. According to The International Federation of Library Associations and Institutions (IFLA) [19], paper generally remains stable at low temperatures and relative humidity levels between 30 and 40%, while leather and vellum usually need at least 50% relative humidity to prevent desiccation and cracking. The European standard UNI EN 15757 [20] outlines the recommended levels of temperature and relative humidity to minimize damage to hygroscopic organic materials caused by physical climate conditions. The challenge, then, lies in balancing the differing needs of these materials within a single collection. Maintaining low temperatures is typically essential to prevent chemical degradation, but overly low humidity may lead to embrittlement in some materials. These factors must be carefully considered to avoid exacerbating degradation, particularly when the conditions under which the artifact was originally created, or to which it has been exposed over time—the "historical microclimate"—may differ significantly from modern preservation standards. The "historical microclimate", distinct from the "historical climate" discussed in the following Section 2.3, refers to the specific microclimatic conditions in which an artifact has been preserved throughout its existence. In cases where the indoor microclimate and artifact were not initially compatible, the artifact may have adapted, potentially undergoing irreversible changes such as the formation of cracks. If the historical microclimate is unknown, it should be monitored for at least a full year [21]. When an artifact is relocated or the environment is altered (e.g., due to heating), the item adjusts to these new conditions. However, even if the new conditions align with established best practices, they may introduce new degradation processes if they differ from the historical climate. A microclimate monitoring campaign has therefore been conducted in the rooms that, after restoration, will be used for the storage of books and for various cultural activities of the association, specifically, in spaces that are being considered for the installation of climate control systems. Indoor conditions were collected using stand-alone data loggers (Onset HOBO, U12 series) with the following characteristics:

Temperature Sensor:

- Range: −20 °C to 70 °C
- Accuracy: ±0.35 °C from 0° C to 50 °C
- Resolution: 0.03 °C at 25 °C
- Drift: <0.1 °C per year

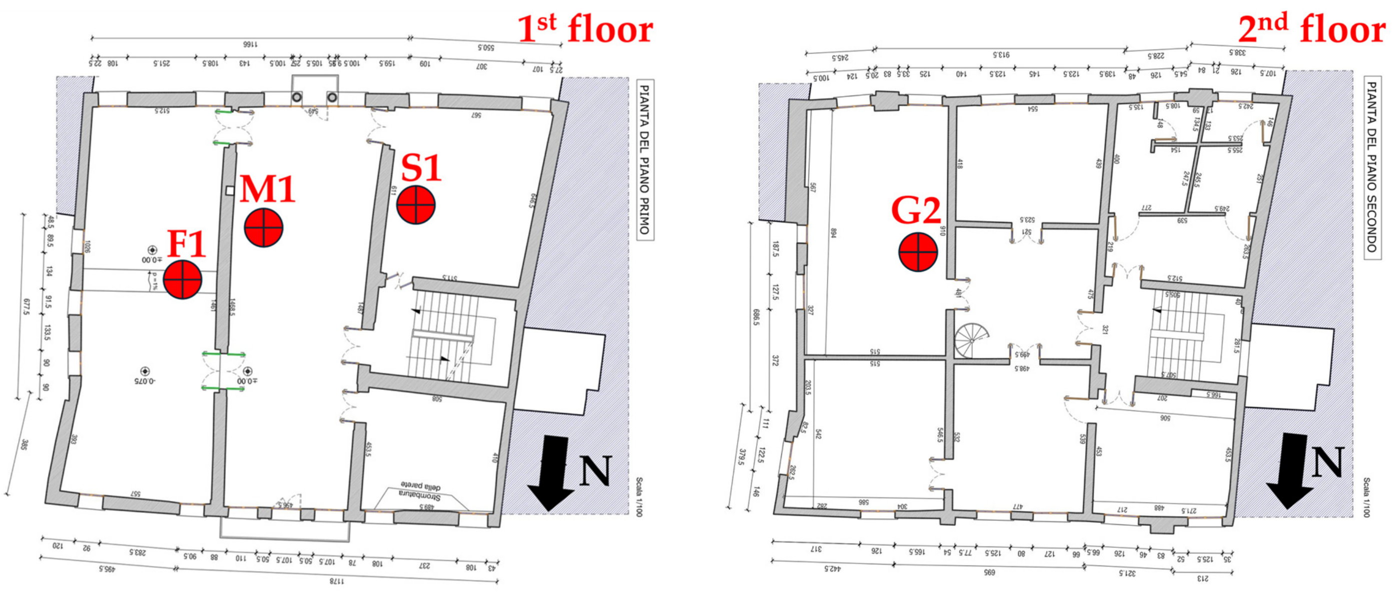
Relative Humidity Sensor:

- Range: 5% to 95% (non-condensing)
- Accuracy: ±2.5% from 10% to 90% RH (maximum of ±3.5% at 25 °C); below 10% and above 90% ± 5% typical
- Resolution: 0.05% RH
- Drift: <1% per year (typical)

These loggers were placed in different rooms of the building, as outlined in the table below, to continuously record air temperature and relative humidity at 15-min intervals over the monitoring period. The following Table 2 lists the rooms analyzed within Casa dell'Angelo, along with their corresponding IDs, floor locations, and the specific air parameters measured. The locations of the dataloggers in the floor plan are shown in Figure 3.

**Table 2.** Overview of the analyzed rooms within Casa dell'Angelo, including their respective IDs, floors, and measured air parameters, which encompass temperature and relative humidity.

| Room | ID | Floor | Measured Air Parameter |
|---|---|---|---|
| Fireplace room | F1 | 1 | Temperature, relative humidity |
| Secretary room | S1 | 1 | Temperature, relative humidity |
| Main room | M1 | 1 | Temperature, relative humidity |
| Gaming room | G2 | 2 | Temperature, relative humidity |




(a) (b)

**Figure 3.** Layouts of the building: (**a**) first-floor plan, (**b**) second-floor plan. The rooms of interest are marked with codes corresponding to those listed in Table 2. Red markers indicate the monitored positions, placed at heights between 1.5 and 2 m above the floor level.

Currently, all these rooms are used to house books and paper materials for consultation, with the secretary's office standing out due to its role as a storage area, where volumes are stored on open shelving units. Recorded data refer to the building in its current state, which has remained unchanged over the last few decades. There are no active heating or cooling systems, nor any humidity control. The only internal thermal loads come from the sporadic presence of people and limited use of light bulbs. Regarding external thermal loads, aside from solar radiation and the external climate, it is important to note the presence of a shop on the ground floor, which is a conditioned environment. As shown in Figure 4, relative humidity values at times exceed the presumed safe conditions for conservation. Additionally, notable daily fluctuations could pose risks to the preservation of items. Similarly, the temperature values often exceed the recommended limits outlined in the technical literature [16–20], particularly during extreme cold and warm seasons. The same concern about daily fluctuations noted for humidity also applies to air temperature.

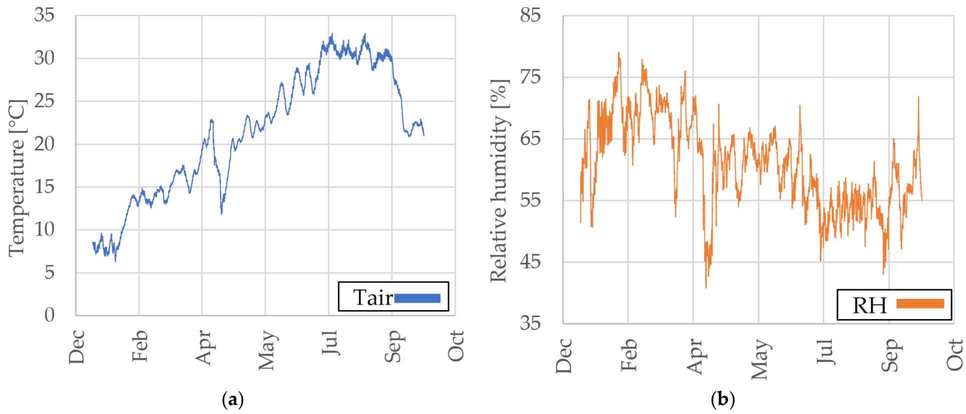



**Figure 4.** The graphs show the air temperature Tair, in blue (**a**) and relative humidity RH, in orange (**b**) data collected in the secretary room on the 1st floor over several months of monitoring. These graphs are examples of the raw output from the monitoring system. The data time resolution directly corresponds to the recording interval, i.e., 15 min without any averaging.

Despite these uncontrolled historical microclimate conditions, the furniture and items within the building have maintained a good state of conservation. Table 3 summarizes the key values collected during the monitoring campaign.

**Table 3.** Seasonal variations in air temperature and relative humidity for different rooms within Casa dell'Angelo, highlighting minimum, maximum, and average values for both temperature and relative humidity across the monitored period. The months from December to February are labeled as the cold season, while those from June to August are labeled as the warm season. DF represents the daily fluctuations, expressed as the maximum deviations from the 7-day averaged values.

| Room ID | Season | Min $T_{air}$ [°C] | Max $T_{air}$ [°C] | DF $T_{air}$ [°C] | Average $T_{air}$ [°C] | Min RH [%] | Max RH [%] | DF RH [%] |
|---|---|---|---|---|---|---|---|---|
| F1 | Cold | 7.9 | 16.2 | 1.3 | 12.2 | 43.7 | 76.2 | 9.3 |
| S1 | Cold | 7.0 | 15.7 | 1.8 | 11.5 | 48.3 | 71.8 | 15.0 |
| M1 | Cold | 6.3 | 14.8 | 1.2 | 10.7 | 50.7 | 79.1 | 7.9 |
| G2 | Cold | 5.2 | 17.1 | 3.5 | 10.5 | 54.1 | 79.6 | 8.9 |
| F1 | Warm | 22.9 | 32.8 | 1.5 | 28.7 | 42.4 | 69.4 | 6.9 |
| S1 | Warm | 22.6 | 32.4 | 2.0 | 28.5 | 43.6 | 69.4 | 13.1 |
| M1 | Warm | 22.4 | 32.9 | 1.7 | 28.8 | 43.1 | 70.5 | 6.4 |
| G2 | Warm | 22.1 | 34.2 | 1.4 | 29.4 | 41.1 | 69.7 | 6.2 |
| F1 | Mid | 13.7 | 24.0 | 2.6 | 19.3 | 39.0 | 74.9 | 7.8 |
| S1 | Mid | 13.6 | 23.5 | 4.0 | 18.8 | 46.2 | 71.2 | 13.6 |
| M1 | Mid | 11.8 | 23.7 | 1.6 | 18.3 | 40.8 | 76.4 | 9.9 |
| G2 | Mid | 12.2 | 24.9 | 2.1 | 18.2 | 42.0 | 78.7 | 10.1 |

This on-site data collection not only provided insights into the actual pre-renovation microclimate but was also instrumental in defining the historical microclimate, serving as real benchmark values for testing and fine-tuning the computational simulations [22] described in the following sections.

#### 2.1.4. Determining Reference Values

The principles that have been considered in dealing with the conservation of books align with both international standards regarding the optimal storage conditions for archive and library materials [23], and provide guidance on environmental control for cultural property [24]. The IFLA also offers detailed guidelines on preserving library collections [19] that have been taken into account in the analysis. Determining accurate absolute value limits for cultural heritage objects solely based on the literature is challenging and potentially risky due to their variety and complexity. Therefore, careful interpretation of environmental guidelines is essential, and includes the following:

- Evaluating the current condition of the artifacts;
- Analyzing the microclimatic, lighting, and air quality conditions of their current environment;
- Assessing the same conditions for their future storage or display environment;
- Forming an overall judgment on the relationship between the state of conservation and the environment;
- Understanding how the artifact interacts with its environment.

In accordance with these principles and the analysis of historical microclimates, basic reference values for indoor air temperature and relative humidity have been adopted for the purposes of this study. The reference values were selected based on the collected data and adjusted throughout the year to account for seasonal variations. The reference values are not fixed but are modulated, calculated to vary sinusoidally over the course of a year (with one period corresponding to one year). The sinusoidal function was designed to reach its maximum value at the lowest temperature measured during the summer and its minimum value at the highest temperature recorded during the winter. For example, in room F1, this results in an annual maximum variation ranging between 16.2 °C (for heating) and 22.9 °C (for cooling). This approach maintains temperatures within the range of the highest recorded lows and the lowest recorded highs (as shown in Table 3), pivoting on the average values, thereby reducing, but not entirely eliminating, seasonal fluctuations. Daily or hourly variations, as well as other high-frequency fluctuations, were minimized. While these conditions mostly align with the literature recommendations for absolute temperature, a compromise was made for relative humidity, which is generally maintained at a higher level. These reference values were applied ideally and consistently across all simulated scenarios to evaluate the impact of changing external climate conditions on the building's energy demand, comfort, and preservation capabilities.

### *2.2. Building Model and Envelope Stratigraphy*

Various techniques are utilized to assess the thermophysical properties of building envelopes, including external walls, roofs, and glazed surfaces. This information has been crucial for accurately calculating [25–28] a building's total energy demand, indoor microclimate conditions, and thermal loads by means of TRNSYS 17, a commercial specialized software [29]. Energy model software is a tool commonly used to simulate and analyze the energy performance of buildings, helping to optimize energy use, heating, cooling, and overall efficiency. The simulation tool employed in this study is specifically designed for dynamic energy simulations. It particularly accounts for the thermal capacity of building components, a critical factor in characterizing the thermal behavior of historic buildings. For calibration purposes, information from on-site measurements of the walls was used as a reference to define their properties. Traditional methods often rely on database information regarding the thermophysical properties of materials, which is generally effective for modern structures. However, this approach can be less reliable for historic buildings, where structural discontinuities resulting from multiple construction phases complicate such assessments. The thermal properties of the building envelope often change over time primarily in response to variations in water content within the masonry, which can stem from various sources, such as moisture infiltration, capillary rise, or leaks. This moisture can significantly affect the thermal properties of materials such as bricks and mortars, leading to altered thermal performance [30]. Additionally, structural modifications made to a building over the centuries, such as the application of plaster layers or more impactful interventions like layered walls, contribute to changes in the envelope's stratigraphy, which in turn affect its overall thermal properties. The case study presented focuses on a building that has retained its original construction without significant modifications. Its well-documented history and comprehensive records facilitate an accurate evaluation of its stratigraphy and thermophysical properties, leading to a precise estimation of the thermal characteristics of the envelope. However, to enhance the accuracy of this assessment, on-site measurements (using *Thermozig* device) according to the standards outlined in ISO 9869 [31] were conducted to determine the thermal transmittance value of the outer walls. The building was therefore modeled in 3D (Figure 5) and divided into distinct floors and internal environments corresponding to specific rooms, in addition to the attic and ground floor, the latter currently occupied by a shop. In particular, the ground floor indoor air temperature was considered between 20 and 26 °C during the heating and cooling period, respectively.

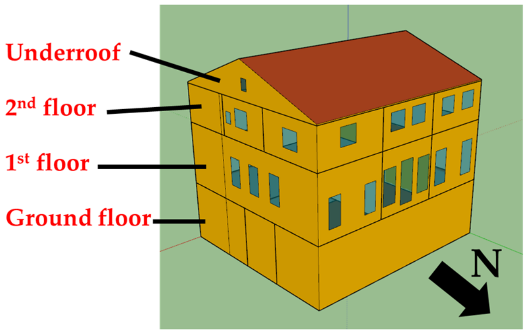



**Figure 5.** Simplified 3D model of Casa dell'Angelo used in the energy simulations, viewed from the northeast. The main façade faces north. The building is modeled with four stories, including the underroof and ground floor, as well as the 1st and 2nd floors where the rooms studied in this research are located. In these floors, the internal space is subdivided by internal partition walls to reflect the actual layout.

The focus of the simulations is on the rooms belonging to the Gabinetto di Lettura association, located on the first and second floors, that have been preliminarily selected by the organization as eligible rooms to host the books. Other rooms and service areas, such as stairwells and restrooms, were also modeled, but are excluded from the discussion of the results, as they will not house valuable collections or books. The modeling parameters include technical specifications of the building elements, reported in following Tables 4–7.

Internal loads included in the simulations, apart from the occupancy of one person per room from 8 a.m. to 8 p.m., primarily stem from lighting. The model accounts for three distinct historical periods: past, present, and future. Throughout all three scenarios, the building's stratigraphy and overall model remained consistent, while technological upgrades were implemented for the windows and lighting systems:

- Past (Pre-Climate Change: 1951–1960): characterized by single-glazed windows with low-performance frames and incandescent bulbs lighting.
- Present (2009–2018): featuring upgraded double-glazed windows and fluorescent lighting.
- Future (2031–2040): anticipating further advancements with triple-glazed windows and energy-efficient LED lighting.

In each of the three simulated scenarios, the ventilation rate was maintained equal to 0.5 air changes per hour. To assess external contributions, solar radiation load in relation to the building's geographical exposure has been considered. However, other outdoor conditions varied across scenarios, with each simulated period using a different set of climate parameters, as detailed in the next section.

**Table 4.** External wall parameters.

| | Thickness [m] | Density [kg/m$^3$] | Heat Capacity [kJ/(kg·K)] | Thermal Conductivity [W/(m·K)] | Thermal Resistance [m$^2$·K/W] | Thermal Transmittance [W/(m$^2$·K)] |
|---|---|---|---|---|---|---|
| Indoor | | - | - | - | - | 1.464 |
| Internal plaster | 0.03 | 1400 | 0.84 | 0.700 | 0.043 | |
| Brick wall | 0.375 | 1800 | 0.84 | 0.798 | 0.470 | |
| External | - | - | - | - | 0.040 | |

**Table 5.** Boundary/Adjacent Wall parameters.

| | Thickness [m] | Density [kg/m$^3$] | Heat Capacity [kJ/(kg·K)] | Thermal Conductivity [W/(m·K)] | Thermal Resistance [m$^2$·K/W] | Thermal Transmittance [W/(m$^2$·K)] |
|---|---|---|---|---|---|---|
| Indoor | - | - | - | - | 0.130 | 1.226 |
| Internal Plaster | 0.03 | 1400 | 0.84 | 0.700 | 0.043 | |
| Brick Wall | 0.375 | 1800 | 0.84 | 0.798 | 0.470 | |
| Internal Plaster | 0.03 | 1400 | 0.84 | 0.700 | 0.043 | |
| Indoor | - | - | - | - | 0.130 | |

**Table 6.** External Roof parameters.

| | Thickness [m] | Density [kg/m$^3$] | Heat Capacity [kJ/(kg·K)] | Thermal Conductivity [W/(m·K)] | Thermal Resistance [m$^2$·K/W] | Thermal Transmittance [W/(m$^2$·K)] |
|---|---|---|---|---|---|---|
| Indoor | - | - | - | - | 0.100 | 1.531 |
| Wood | 0.02 | 450 | 1.4 | 0.120 | 0.167 | |
| Air | 0.18 | - | - | - | 0.180 | |
| Wood | 0.02 | 450 | 1.4 | 0.120 | 0.167 | |
| External | - | - | - | - | 0.040 | |

**Table 7.** Intermediate Floor parameters.

| | Thickness [m] | Density [kg/m$^3$] | Heat Capacity [kJ/(kg·K)] | Thermal Conductivity [W/(m·K)] | Thermal Resistance [m$^2$·K/W] | Thermal Transmittance [W/(m$^2$·K)] |
|---|---|---|---|---|---|---|
| Indoor | - | - | - | - | 0.170 | 1.277 |
| Wood | 0.03 | 710 | 1.4 | 0.180 | 0.167 | |
| Air | 0.18 | - | - | - | 0.180 | |
| Wood | 0.03 | 710 | 1.4 | 0.180 | 0.167 | |
| Indoor | - | - | - | - | 0.100 | |

### *2.3. Climate Dataset for Past, Present, and Future*

The building simulation software needs outdoor temperature and relative humidity at hourly resolution, but only for the present scenario are these data available. For the past and future scenarios, the time resolution has been improved as described as follows.

#### 2.3.1. Past (Pre-Climate Change) Dataset

The decision to use the 1950s as the historical reference period for the past climate dataset is grounded in the significant changes that occurred in the medieval Santa Lucia district just before this time. Moreover, during that period, the Associazione Gabinetto di Lettura already took over the building, establishing continuity with its current use. This timeframe is particularly valuable for our study as it represents a period before the widespread implementation of climate control systems and the onset of global warming. Since the building and its surroundings have remained relatively unchanged since the 1930s, it offers a stable historical context for comparing the building's performance under various climate scenarios analyzed in this study. This stability eliminates the potential impact of significant changes in adjacent buildings or other architectural factors on our results. The past climate dataset has been made using the data of the weather station of the Padua Airport (Meteorological Service of the Italian Air Force), about 2.5 km south-east of the Casa dell'Angelo. (Padua Airport weather station coordinates are Latitude: 45.3953 and Longitude: 11.8483) The station recorded air temperature and dew point temperature every three hours, but not relative humidity, and its data are available for the period 1951–1990, when it was closed. In this work, 1951–1960 data have been used. The relative humidity used in the building simulation software has been calculated from air and dew point temperatures, using Equation (1) [13]:

$$RH = 10^{7.5 \cdot \left(\frac{T_d}{237.3+T_d} - \frac{T}{237.3+T}\right)} \cdot 100 \quad (1)$$

where $RH$ is the relative humidity, $T_d$ and $T$ are the dew point and air temperatures, respectively. Then $T$ and $RH$ data have been linearly interpolated to obtain an hourly dataset from the three-hours original data. Finally, data have been averaged to have an hourly dataset of a year.

#### 2.3.2. Present (Recent Years) Dataset

The present dataset has been obtained using the data of the Botanical Garden weather station (Regional Environmental Protection Agency of Veneto), 1.2 km south from the Casa dell'Angelo (Botanical Garden station coordinates are Latitude: 45.3993 and Longitude: 11.8805). Temperature and relative humidity measurements have been available at hour resolution since October 1993. In this work, 2009–2018 data have been used, because in 2019, the station was relocated [32]. A year dataset has been calculated by averaging the hourly data of the chosen period.

#### 2.3.3. Future Forecast Dataset

The future temperature and relative humidity datasets have been taken by the Met Office Global Coupled Model GC3 (0.23 × 0.35 degree) part of CMIP6 [33]. The simulation was run from 2015 to 2050. Maximum and minimum daily temperature and relative humidity have been taken for the years 2030–2039. Since hourly data are required by the building simulation software, the following procedure has been applied to generate hourly temperature and relative humidity values. The CIBSE algorithm has been applied to calculate hourly temperature [33]. This method needs only the daily maximum and minimum temperatures ($T_{max}$ and $T_{min}$), since it allocates times when maximum and minimum temperature occur in the day and uses two sinusoidal curves to fit the data. Time for $T_{min}$ is near sunrise, while for $T_{max}$, 2 p.m. has been chosen [34]. Hourly temperatures *T(t)* are calculated using Equation (2):

$$T(t) = f_1 \cdot T_{min} + f_2 \cdot T_{max} \quad (2)$$

where t is the time expressed in hour, $f_1$ and $f_2$ are factors calculated using sinusoidal interpolations depending on the minimum and maximum temperature times ($t_{min}$ and $t_{max}$) as follows (3):

For $t < t_{min}$

$$f_1 = \frac{cos\left(\frac{\pi(t_{min}-t)}{24} + t_{min} - t_{max}\right) + 1}{2} \quad (3)$$

For $t_{min} < t < t_{max}$

$$f_1 = \frac{\cos\left(\frac{\pi(t-t_{min})}{t_{max}} - t_{min}\right) + 1}{2}$$

For $t > t_{max}$

$$f_1 = \frac{\cos\left(\frac{\pi(24+t_{min}-t)}{24} + t_{min} - t_{max}\right) + 1}{2}$$

Hourly relative humidity has been calculated using Equation (4) [35]:

$$RH(t) = RH_{max} + \frac{T(t) - T_{min}}{T_{max} - T_{min}}(RH_{min} - RH_{max}) \quad (4)$$

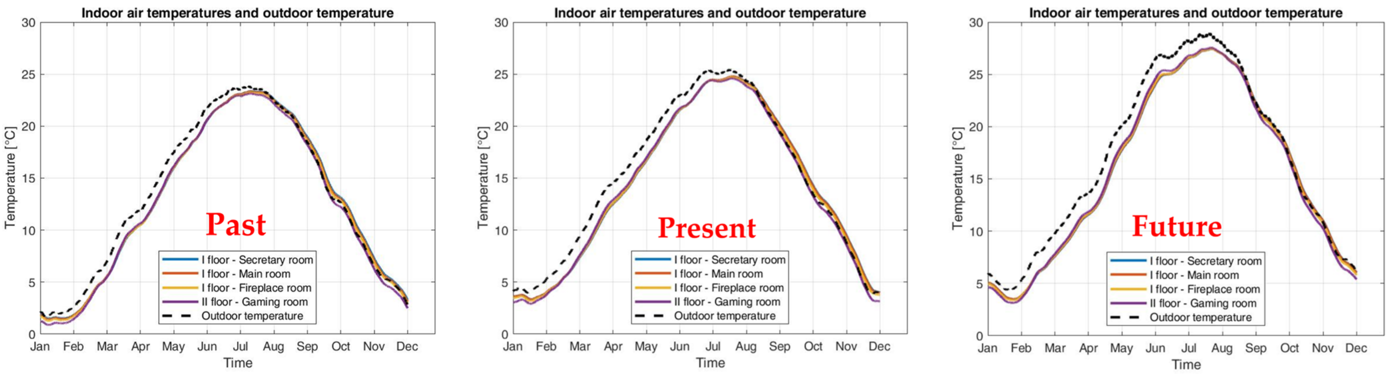
where *T(t)* is the hourly temperature calculated above, $RH_{min}$ and $RH_{max}$ are the minimum and maximum daily relative humidity of the model. Hourly temperature and relative humidity, calculated as above, have been averaged over a ten-year period to have an hourly dataset of a year. Before the calculation of hourly temperature, model $T_{\max}$ and $T_{\min}$ were compared with the station data over the period 2015–2018. The model predicted a temperature lower than the values measured by the local weather station: the average values of the two datasets over the common period differ from each other by about 1.7 °C, which has been added to the model data to be consistent with measured ones.

## 3. Results

The results of this study are presented in the following subsections, illustrating the dynamic interplay between indoor microclimate conditions and external temperature variations across the three historical periods considered. This includes an analysis of the energy effort for heating and cooling (humidity control has not been evaluated in the energy effort figure) in the indoor spaces. Furthermore, thermal comfort for occupants was assessed in each simulated scenario under natural conditions, without any HVAC system in action. The findings were then contrasted with the expected comfort levels following the application of the microclimate control strategy outlined in Section 2.1.4.

### 3.1. Comparative Temperature Analysis

Figure 6 displays comparative graphs of averaged internal temperatures in the reference rooms against averaged external temperatures for each historical epoch. A centered 28-day window size running average smoothed the daily peaks and fluctuations, while emphasizing significant low-frequency trends in the graphs. This highlights how internal temperatures have responded to seasonal changes and external climate influences over time.




(**a**) (**b**) (**c**)

**Figure 6.** Comparative graphs illustrating average internal air temperatures in the reference rooms (colored lines) at different times: past (**a**), present (**b**), and future (**c**) against external temperatures for each historical epoch (dotted line). These graphs reveal significant trends, highlighting how internal temperatures have adapted to seasonal changes and external climate influences over time.

During the heating period, the mean indoor temperature seems to be close to the outdoor one. This phenomenon is due to the low values of the sky temperature that occur during the night that increase the radiative infrared heat exchange with the sky. The sky temperature during the night is lower than the air temperature [36].

### 3.2. Thermal Comfort Metrics

Subsequent analysis includes the Predicted Mean Vote and Predicted Percentage of Dissatisfied values for each reference room across the three scenarios without any active microclimate control, as illustrated in Figure 7. The parameters used for the calculation of PMV and PPD are those described in Section 2.1.2 (variable clothing insulation value ranging from 0.61 to 1.10, metabolic rate equal to 63.8 $W/m^2$, air velocity equal to 0.1 m/s). Air temperature, relative humidity, and average radiant temperature are the direct outcomes of the energy simulations.

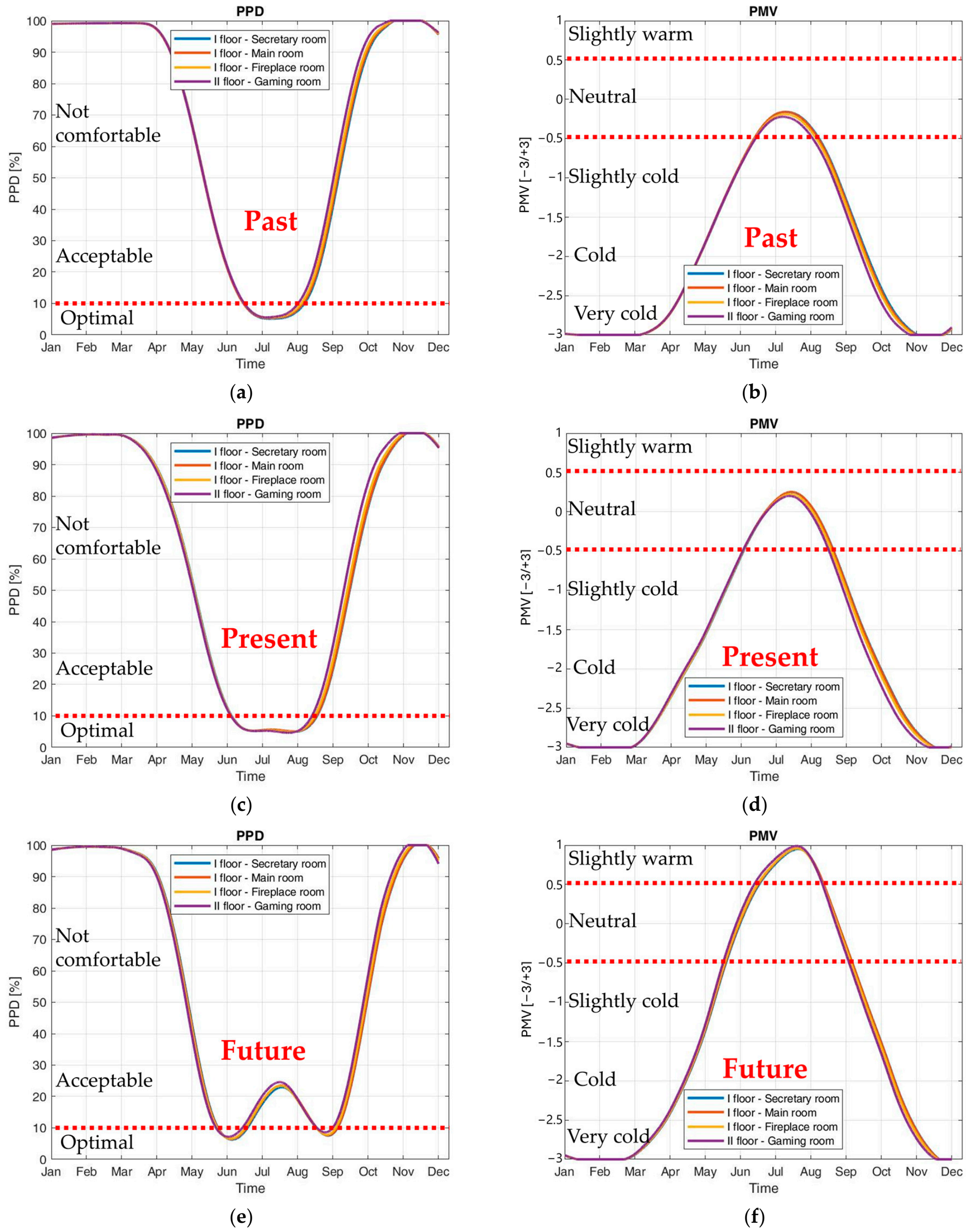
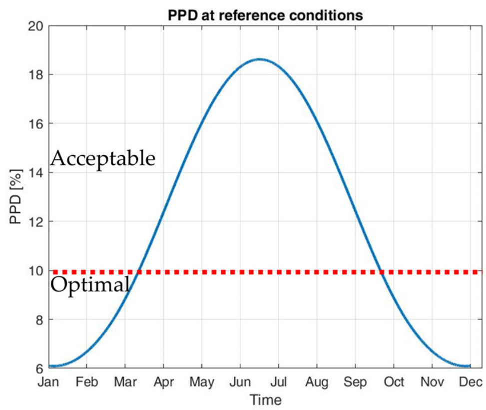
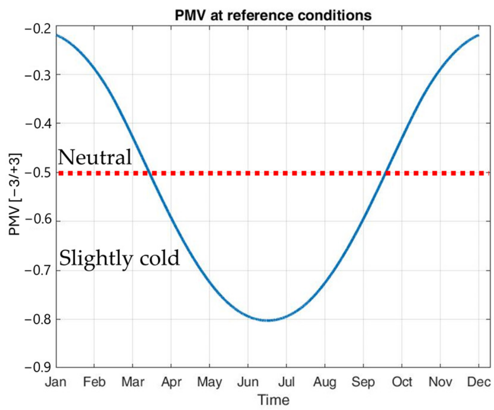



**Figure 7.** Predicted Mean Vote and Predicted Percentage of Dissatisfied values for each reference room across the three historical epochs, under uncontrolled indoor conditions (i.e., without any air conditioning). The analysis is presented in pairs, with PMV and PPD values depicted for each epoch: (**a**,**b**) for the past (pre-climate change), (**c**,**d**) for the present years, and (**e**,**f**) for the future forecast. These figures provide insights into the comfort levels experienced in the reference rooms, illustrating how thermal comfort has evolved over time. Red dotted lines indicate limits, respectively, 10% PPD and ±0.5 PMV, that are commonly used as a boundary for optimal/neutral conditions.

These metrics provide crucial insights into occupant thermal comfort, illustrating variations in comfort levels influenced by factors such as insulation due to window types, and internal lighting, but predominantly by the increasing warming effect of outdoor climate across the epochs. Regardless of the simulated scenario, all unconditioned cases are uncomfortable for most of the year, except for part of late spring and early autumn. During these periods, thermal sensation generally ranges from slightly cold (past), neutral (present), to neutral/slightly warm (future), suggesting a future trend where discomfort may further increase during summer due to overheating. In all scenarios, the winter season is extremely uncomfortable, indicating that the effect of climate change does not appear to sufficiently mitigate this discomfort. It should be noted that the reported comfort indexes refer to average daily conditions. Assuming a daytime-focused occupancy schedule, future projections suggest an elevated risk of discomfort due to warmer conditions (i.e., PMV > 1), particularly during midday. As stated before, in many situations, a challenge arises in harmonizing conditions for conservation and comfort simultaneously. Sometimes, it is simply not possible to find an intersection between these very different requirements, making it necessary to implement measures such as climate-controlled showcases to separate the two environments, along with other strategies. The presented case study must consider this aspect, which is particularly relevant due to human activities that will involve the consultation of books for on-site reading, as well as other events such as small musical concerts where occupants are present. Thus, their thermal comfort must be taken into consideration. Given the modulated air temperature and relative humidity reference values used for ideally controlling the indoor microclimate for conservation, as proposed in Section 2.1.4, such conditions have been analyzed quantitatively in terms of thermal comfort by calculating the resulting PPD and PMV parameters, which are illustrated in the following Figure 8. The other parameters for calculating the comfort indices have been determined as presented in Section 2.1.2 (variable clothing insulation value ranging from 0.61 to 1.10, metabolic rate equal to 63.8 W/m$^2$, air velocity equal to 0.1 m/s). The average radiant temperature was estimated based on the behavior observed in the simulations performed, and for the purpose of the calculations in Figure 8, it was assumed to be equal to the air temperature.




(**a**)



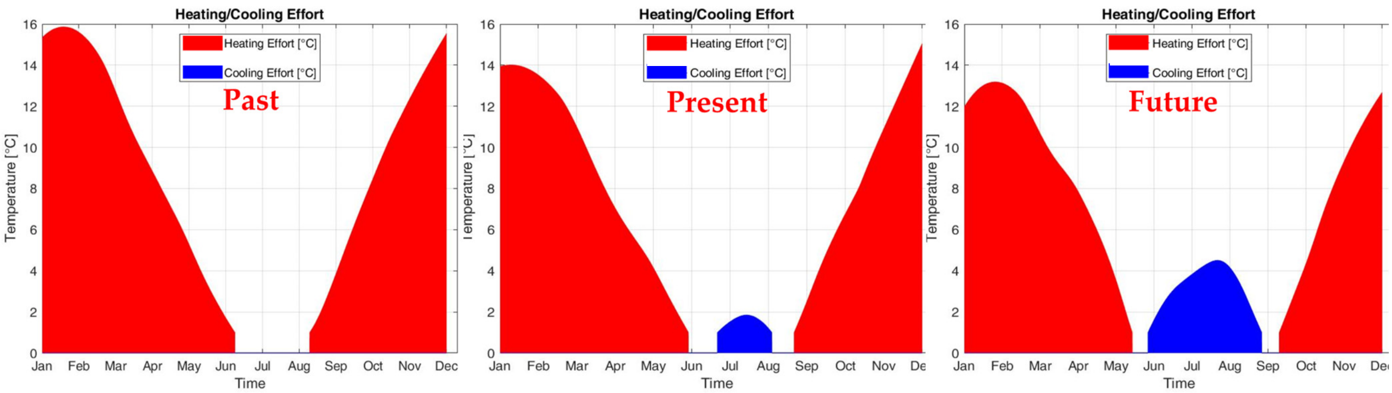

(**b**)

**Figure 8.** Predicted Percentage of Dissatisfied (**a**) and Predicted Mean Vote (**b**) values for the suggested indoor reference conditions based on the historical microclimate data. These figures offer insights into the comfort levels experienced in the rooms, demonstrating how thermal comfort is balanced with conservation needs. Stricter conservation conditions could negatively affect comfort and may even pose a risk to preserving items that have adapted to a specific microclimate. Red dotted lines indicate limits, respectively, 10% PPD and −0.5 PMV, that are commonly used as a boundary for optimal/neutral conditions.

It is clear that the comfort parameters PPD and PMV shown in Figure 8 are significantly better than those resulting from Figure 7. The proposed reference setpoint, designed solely for conservation purposes, also creates a more comfortable thermal environment for occupants. They are estimated to experience adequate comfort throughout the year, with only minor discomfort—specifically, feelings of slightly cold— during summer. This could be seen as a reasonable compromise, as it imposes minimal personal drawbacks while ensuring the preservation of valuable items.

### *3.3. Analysis of Thermal Behavior Under Simulated Indoor Controlled Conditions*

An analysis was conducted to evaluate the extent to which the indoor microclimate meets the selected reference values for the conservation of items. The three scenarios without any active microclimate control were compared to the reference indoor temperatures designed with conservation in mind, which serve as the setpoint for hypothetical heating and cooling systems. This comparison allows for an assessment of the effort required to reach the setpoint, as illustrated in Figure 9. The diagrams present the hourly temperature differences (absolute values) over a simulated year, highlighting both positive and negative deviations from the setpoint using different colors. These differences enable an evaluation of the necessary heating (in red) or cooling (in blue) efforts and the duration throughout the year when such interventions are required.




(**a**) (**b**) (**c**)

**Figure 9.** Comparative graphs illustrating the average climatization effort over time: past (**a**), present (**b**), and future (**c**). The effort (vertical axis) is represented as the difference (absolute values) between the set reference temperature and the temperature that would occur without any air conditioning. This differentiation allows for visualizing the effort required for heating (in red) and cooling (in blue) to maintain the desired indoor temperature. A threshold of ±1 °C has been applied to avoid frequent switch-on and switch-off cycles of the HVAC systems when the air temperature fluctuates around the setpoint.

The data in Table 8 reveal a clear trend in the percentage of yearly time allocated to air conditioning across three distinct scenarios: past (pre-climate change), present (recent years), and future forecast. In particular, yearly heating and cooling time indicate the number of days in which the internal conditions are, respectively, above or below the suggested reference values for conservation. The yearly conditioning time is the sum of these, i.e., the total number of days when the HVAC system would be active to control the temperature. Historically, the reliance on heating was predominant, accounting for a substantial majority of the year, with no recorded need for cooling. This reflects a period characterized by more temperate climate conditions, where indoor environments could be comfortably maintained without artificial cooling. In the present scenario, there is a notable shift, with heating time decreasing and cooling time emerging, such that 50 days of the year are now spent on lowering the indoor air temperature. Looking forward, the future forecast anticipates a further decline in heating time, with cooling time expected to double compared to current levels. This increase indicates that the demand for air conditioning will become more pronounced, contributing to an overall rise in the percentage of time that buildings require active climate control.

**Table 8.** Modeled scenarios showing the percentage of yearly time spent on heating, cooling, and total air conditioning for past (pre-climate change), present (recent years), and future forecast conditions. The data illustrate an increase in cooling demand over time due to climate change, resulting in a higher overall use of air conditioning systems.

| Modeled Scenario | Yearly Heating Time [%] | Yearly Cooling Time [%] | Yearly Air Conditioning Time [%] |
|---|---|---|---|
| Past (pre-climate change) | 81 | 0 | 81 |
| Present (recent years) | 75 | 13 | 88 |
| Future forecast | 64 | 27 | 91 |

### *3.4. Evaluation of Energy Trend over Time*

To further understand the impact of indoor conditions on energy use, the need for heating and cooling has been evaluated for each room across all periods by means of an index. The proposed index is evaluated, calculating the difference between the supposed setpoint indoor temperature and the indoor temperatures obtained by the dynamic simulations. At each timestep, the previous difference is calculated for each room and the resulting values are summarized along with the heating and cooling period. This assessment is necessary for identifying the specific interventions needed to maintain optimal preservation conditions. The results do not evaluate the amount of energy needed but show a whole view of the building's behavior in the three different scenarios. The data presented in Table 9 highlight a significant shift in energy demand related to indoor climate control across three scenarios: past (pre-climate change), present (recent years), and future forecast. In the past, the focus was solely on heating, as there was no need for cooling. However, in the current scenario, heating efforts have decreased while cooling efforts have emerged, indicating a growing necessity for climate control systems to maintain comfort and item preservation in increasingly warmer conditions. Looking ahead, it is anticipated that the demand for cooling will continue to increase, further overshadowing the reduced heating requirements. This trend illustrates that while energy use for heating has diminished, the rising demand for cooling is poised to have a significant impact on overall energy consumption. Consequently, the net energy savings achieved from reduced heating may be entirely offset by the increasing energy requirements for cooling.

**Table 9.** Modeled scenarios indicating the yearly heating, cooling, and total air conditioning efforts (indicated in °C, it represents the annual sum of the differences between the air temperature in uncontrolled conditions and the desired air temperature, rounded to the nearest thousand) for past (pre-climate change), present, and future (recent years) forecast conditions. The data reflect a shift in energy requirements, illustrating a decrease in heating effort and a significant increase in cooling effort. Foreseen climate change is expected to be characterized by the rising demand for cooling in the future, potentially leading to no energy savings or even increased energy consumption over time.

| Modeled Scenario | Yearly Heating Effort [°C] | Yearly Cooling Effort [°C] | Yearly Air Conditioning Effort [°C] |
|---|---|---|---|
| Past (pre-climate change) | 67,000 | 0 | 67,000 |
| Present (recent years) | 56,000 | 2000 | 58,000 |
| Future forecast | 48,000 | 8000 | 56,000 |

## 4. Discussion

The analysis of the monitored data reveals that there are no significant differences in the average conditions between the analyzed rooms within the building, particularly concerning air temperature. The minimal air temperature variation observed between the first and second floors can be partially attributed to the influence of the air conditioning system installed in the ground-floor shop. While differences in peak values are present and more pronounced on the second floor, where the most extreme high and low temperatures were recorded during the monitoring campaign on-site, the average temperature difference amongst the rooms remains consistently below 1.7 °C throughout the year. In establishing the indoor setpoints for both air temperature and relative humidity for microclimate control, an approach was adopted that is informed by the historical microclimate to which the items housed in the building have been acclimated over the decades. This strategy has proven beneficial, as it not only helps maintain favorable conservation conditions but also results in a microclimate that experiences fewer high-frequency fluctuations and less pronounced seasonal variations, ensuring that the acclimatized items remain undisturbed. Additionally, by minimizing deviations from the natural conditions that would prevail without any heating or cooling systems, the energy use associated with these systems is somewhat limited, thereby reducing overall energy consumption and associated costs, as well as the environmental emissions linked to energy usage. This approach also significantly enhances thermal comfort for occupants, who benefit from a more stable and pleasant indoor environment. The results of this analysis underscore the necessity of balancing occupant comfort with the conservation requirements of historic structures, a balance that can, in some cases, be achieved with minimal compromise, resulting in only slight but tolerable comfort drawbacks. To ensure that occupant comfort does not compromise the conservation needs of a building, modern approaches often focus on educating occupants and raising awareness about the importance of preservation. These efforts highlight the value of cultural heritage as a shared asset and emphasize the collective responsibility for its protection. By fostering a sense of stewardship, institutions can encourage visitors and users to understand that their comfort, while important, may need to be secondary to the requirements of conservation. For example, users might be asked to tolerate slightly higher or lower indoor temperatures or humidity levels to maintain optimal conditions for preservation. Actually, the proposed microclimate management strategy is based on the principle that indoor thermo-hygrometric parameters must be designed primarily to support the preservation of cultural heritage, with occupant comfort considered as a secondary concern, ensuring it is not significantly compromised. The insights gained from findings of energy use highlight the importance of adaptive strategies and improved energy efficiency measures in building design and climate control systems, particularly as future scenarios suggest a growing demand for cooling solutions. As climate change continues to alter outdoor temperature patterns, leading to warmer indoor environments, the percentage of time allocated to cooling is projected to approach and even exceed 20%. This shift signifies a substantial transformation in energy consumption dynamics, raising critical concerns about the sustainability of energy use in the built environment. The increasing reliance on cooling solutions emphasizes the urgent need to implement energy-efficient technologies and adaptive architectural designs, also facilitated by energy modeling of future climate scenarios, that can effectively respond to the escalating cooling demand driven by climate change. To address the growing cooling demand, it is essential to implement adaptive strategies and energy-efficient technologies that not only account for current needs but also anticipate future requirements. Considering future demand allows for the design of systems that can be effectively integrated during the building renovation, ensuring they can adapt to changing climatic conditions without becoming obsolete and requiring immediate replacement. This approach may include the use of heat pumps, which, when combined with properly sized terminal units, can adjust the balance between summer and winter loads. By accounting for both current and future energy needs, the system can be optimized for efficiency, reducing the need for major adjustments or upgrades in response to evolving climate patterns. This forward-thinking approach enhances the resilience of the building infrastructure, ensuring by adaptation that it remains efficient and effective in meeting energy demands in the long term. Future climate scenarios, including rising and fluctuating temperatures along with changes in humidity levels, could accelerate material degradation, leading to issues such as cracking, warping, and other forms of damage. Increased humidity can also promote the growth of mold, further threatening the integrity of both the building and its contents. The consequent rising demand for energy due to the increased use of HVAC systems poses an additional risk to conservation efforts. Future climate scenarios may heighten the need for energy-intensive cooling systems, particularly in regions facing hotter summers. This could result in increased energy inefficiency and inadequate environmental control, which, coupled with the economic cost of maintaining appropriate conditions, may leave preservation efforts unaddressed.

## 5. Conclusions

The research identifies the following critical points:

- Air conditioning is essential to balance preservation and visitor comfort in the analyzed case study, particularly in response to forecasted climate change impacts.
- Rooms on the 1st and 2nd floors of Casa dell'Angelo are suitable for storage due to stable microclimatic conditions with controlled temperature and humidity.
- Moderate climate control, guided by the "historical microclimate" paradigm, can be considered a methodology to mitigate risks to sensitive materials.
- Combining historical data and future projections has proven to be an interesting methodology to optimize energy use while preserving heritage.

The findings of this study underscore the necessity of strategically air conditioning spaces within historical buildings to effectively balance the preservation of books and furniture with visitors' comfort. Rooms on the 1st and 2nd floors of Casa dell'Angelo emerge as eligible for items storage due to their relatively stable microclimatic conditions that could be met thanks to the implementation of air conditioning to maintain ideal temperature and humidity levels continuously. The analysis indicates that temperature and humidity fluctuations can be effectively managed, making it suitable for housing sensitive materials, and even a not overly impactful microclimate control strategy mitigates the risk of damage from extreme temperatures. One of the main focuses of this work is the use of the historical microclimate as a paradigm for conservation, aiming to replicate the environmental conditions to which materials have already been exposed and adapted over time. Although these conditions may deviate from the fixed values traditionally considered optimal for certain artifacts, they can be advantageous and non-damaging precisely because the materials have already acclimated to them. In contrast, shifting to a microclimate that, on paper, appears more appropriate but is significantly different from the historical one could trigger new deterioration mechanisms. Unfortunately, this has often occurred in the past, with many artifacts—previously stable for centuries—suddenly experiencing accelerated degradation despite being placed in supposedly ideal conditions. For this reason, maintaining mildly controlled conditions based on the historical microclimate will allegedly not harm sensitive materials like book bindings or furniture finishes. Instead, these conditions are likely to sustain the stability that has already been observed in such environments over time.

The potential costs that this approach aims to help mitigate concern, on the one hand, reducing energy demand by managing internal setpoint parameters. This involves maintaining conditions that are primarily acceptable for conservation and secondarily for comfort, while limiting the effort required to bridge the gap between desired indoor temperatures and external conditions. Particular attention is given to avoiding extreme or overly stringent air conditioning strategies, which, due to climate change, could pose significant challenges in the future, especially during summer scenarios. On the other hand, the approach seeks to limit installation costs by supporting long-term planning that anticipates and scales interventions based on future scenarios, preventing systems from becoming obsolete due to changing climatic conditions. In the context of a historical building, these systems should be chosen based on their impact on the architectural and aesthetic features of the structure, as well as potential barriers related to existing installations or insulation characteristics. Such challenges are compounded by regulatory constraints, which often impose strict limitations on alterations to historical buildings, further complicating the implementation of effective and efficient solutions.

Furthermore, this study highlights the critical role of integrating both historical climate data and future projections to optimize energy use in historic buildings. Given their rich cultural heritage and diverse construction materials, these structures demand a careful balance between preservation and energy efficiency. Utilizing historical climate data reveals how these buildings have adapted over time, while future climate scenarios enable planning for resilient and sustainable renovations. Modeling these scenarios through building energy software provided a clearer understanding of the building's past performance and future trends about energy demands. This understanding is crucial for designing HVAC systems that protect sensitive materials while enhancing occupant comfort, all without compromising the historical value of the structure over time. Such long-term benefit leverages the importance of designing interventions that are not solely based on the current conditions and needs of the building but also take into account its future requirements. By anticipating future needs, the installed systems can be better designed and adapted to evolving scenarios, ensuring they remain suitable over time. While it is beyond the scope of this research to endorse or propose specific technical interventions, it is important to emphasize the necessity of evaluating such interventions—whatever they may be—based on future projections. This approach enables more informed decision-making when sizing interventions and ensures that the building will be able to withstand the impacts of climate change, thanks to a more sustainable and resilient planning process. This approach prevents systems from quickly becoming obsolete or requiring replacement due to inadequacy, making the interventions more beneficial in the long run. It enhances their efficiency, adequacy, resilience, and economic sustainability, ultimately leading to more durable and cost-effective solutions.

**Author Contributions:** Conceptualization, G.C. and A.B.; methodology, G.C. and G.E.; software, G.C., G.E. and A.d.V.; validation, G.C., G.E., G.F., F.P. and A.B.; formal analysis G.C., G.E., G.F., F.P. and A.B.; investigation, G.C., G.E., A.d.V. and A.B.; resources, G.C., A.B. and P.C.; data curation, G.C., G.E., A.d.V., G.F. and A.B.; writing—original draft preparation, G.C.; writing—review and editing, G.C., G.E., A.d.V., G.F., F.P., P.C. and A.B.; supervision, G.C.; project administration, G.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Data are available from the corresponding author on reasonable request.

**Acknowledgments:** The authors would like to express their sincere gratitude to Enzo Moi and to the governing board of Associazione Gabinetto di Lettura e Società di Incoraggiamento for their invaluable support throughout the preparation of this study.

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

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