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A Multidisciplinary Approach to the Evaluation of Air Quality and Thermo-Hygrometric Conditions for the Conservation of Heritage Manuscripts and Printed Materials in Historic Buildings: A Case Study of the Sala del Dottorato of the University of Perugia as a Model for Heritage Preservation and Occupants' Comfort

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Abstract: The Sala del Dottorato (Hall of Graduates) is a magnificent library in the University of Perugia which plays the double role of providing optimal conservation of valuable books and manuscripts while also hosting important events. This double role is closely connected to contrasting indoor microclimatic conditions. This paper presents the results of a multidisciplinary study, begun in 2019, which investigates optimal conditions for the conservation of volumes by monitoring thermo-hygrometric and air quality parameters. The study describes the current conditions of the Hall (in terms of air temperature, relative humidity and concentration of CO_2), highlighting critical aspects, defining strategies for their mitigation and control, and outlining future developments. Improvement measures relate to the installation of a permanent monitoring system with alarm settings and data storage, technical interventions on the windows, and the restoration of several volumes. The paper shows the importance of monitoring as an instrument of control in real time and provides guidelines for management to be implemented according to indoor microclimatic conditions.

Keywords: cultural heritage; conservation; monitoring; historic library

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1. Introduction

Indoor microclimatic conditions play a key role in the conservation and maintenance of heritage volumes, and their control is necessary in order to limit the processes of damage and subsequent restoration work while also increasing their patrimonial value [1–6]. Library collections consist of a wide range of hygroscopic organic materials (paper, leather, parchment, cloth), which are climate-sensitive and vulnerable to the process of deterioration. This natural process can be accelerated by the environment housing the collections, depending on many factors: indoor temperature, relative humidity (RH), pollutant concentrations, lighting, etc. The principal risks affecting the durability of library collections include mechanical, chemical, and biological mechanisms, as well as photodeterioration. Several recent studies have investigated microclimate data collected in libraries, evaluating various standards and guidelines for heritage conservation and using various methods for assessing deterioration risks [7–9].

Italian technical regulations and guidelines concerning cultural heritage conservation, such as UNI 10829:1999 and D.M. 10.05.2001 [10,11], list optimal and acceptable ranges for temperature and relative humidity, as well as establishing guidelines and methods for measuring indoor temperature and relative humidity values; however, in some cases, when an artefact has acclimatized to specific historical climate conditions over the years, it is advisable to maintain these conditions rather than introduce standard ones [12]. In addition, unsuitable handling of books is frequently responsible for the accumulation of wear and tear on paper, thus reducing the durability of the collections. Moreover, since library materials can shrink/swell as they lose/gain moisture, fluctuations in temperature and relative humidity can be studied as mechanical stressors potentially inducing dimensional changes in library objects [13]. This phenomenon is particularly relevant in historical buildings, especially those not equipped with HVAC (Heating, Ventilation and Air Conditioning) systems or whose envelope is characterized by massive walls with vast hygrothermal inertia. In this case, the indoor microclimate is particularly influenced by the topographic site, the orientation of the walls, the location of the openings and construction materials [14]. Furthermore, for all materials, indoor microclimates should be continually controlled to reduce or eliminate the risk of biological attack by fungi, bacteria, or other parasites. Not only does temperature have a significant effect, but relative humidity can also influence the speed of many deterioration mechanisms of a chemical, physical and biological nature. In fact, biological damage (entomological and microbial), as well as foxing (biological or chemical components), also depend on relative humidity and temperature, which can favour infections and infestations, in addition to deformations, stiffening, ink offset and dehydration. Where the degradation of books and documents in libraries and archives is caused by physical–chemical and biological factors, conservation involves a preventive examination of environmental conditions and a methodology of intervention providing for biological sampling followed by laboratory analyses. A treatment plan may involve disinfection and cleaning by methods suitable for conservation; in fact, when the habitat becomes favourable to pests, microorganisms, insects, or small animals, accurate and frequent cleaning becomes essential. Several works analyse the contribution of architectural features and construction materials to passive climate control [15–17]. Normally, the features of the buildings that house the collections behave as a filter of the external climate, buffering the external weather fluctuations [18].

However, the purpose of libraries is not only to guarantee the conservation of books but also to be comfortably accessed by guests and the public. Both these aims have relevant connections with indoor microclimate conditions, but they are based on different principles: for cultural heritage, well-being means that the item is safe and that its natural aging proceeds at a very slow rate; instead, for people, well-being may be reached within certain temperature and relative humidity ranges, depending on the seasons and personal conditions. To make the microclimate of historical buildings more comfortable for people, HVAC systems are often installed (mainly with radiators or fan coils that control only indoor temperatures). All these systems are used intermittently and are located in specific areas, continually generating microclimate perturbations. For the purpose of conservation, the climate needs to be constant, but for people, it needs to be mild. These factors create a complex situation in which it is necessary to compromise between human comfort and conservation requirements and the need to contain costs [19].

Sahin C. D. et al., in their study of Necip Paşa Library in Turkey [20], highlight passive solutions: regarding the HVAC system, higher priority should be given to not disturbing the environmental conditions to which the volumes have acclimatized over time. Instead, in their research, Corgnati S. and Filippi M. focus their attention on the importance of long-term monitoring to prevent the deterioration of works of art and verify the capacity of HVAC systems to maintain desired thermo-hygrometric values within operating conditions [21]. The authors, in these cases, agree on giving priority to conservation needs.

Another important aspect to be considered in microclimate analysis, both for conservation purposes and for human comfort, is indoor air quality in terms of pollutant concentration. One of the most relevant is carbon dioxide (CO_2) concentration, whose monitoring is important for two reasons. First, for air quality, because high values make the environment unhealthy. Second, for book conservation, as high values may contribute to making the environment unacceptable, especially when relative humidity is high. For this reason, in libraries and museums, the presence of people can be considered an additional microclimate alteration factor (increase in temperature, hygrometric degree, and pollutants) [16,22]. In fact, it is necessary to assess the fluctuations of this indoor air pollutant in relation to human presence so that human well-being can be guaranteed without altering the indoor microclimate for conservation purposes. This is an important aspect, and its control is generally delegated to a mechanical ventilation system, but when this cannot be installed, air exchange may take place through natural ventilation systems such as manual window openings (irregularly made by library staff).

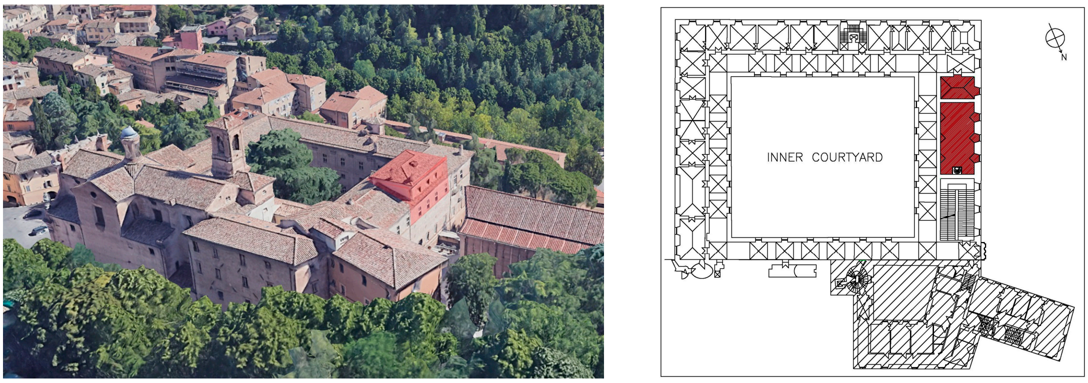
This is the context in which this paper investigates a multidisciplinary approach to the study of the conservation environment of valuable books housed in historical buildings. The study originates from the need for librarians to investigate the suitability of indoor environments for conservation. In fact, some damage has already been detected on the volumes, such as the darkening and discoloration of many ribs and paper dissolution, which is also responsible for the accumulation of dust on shelves. Adopting a multidisciplinary approach means involving different professional figures (librarians, engineers, architects, restorers) in order to define guidelines for librarians, in which conservation requirements are combined with the need for human comfort. This approach is based on a suitable analysis methodology for libraries in historical buildings in order to study retrofitting strategies and to define zero-cost interventions, such as a protocol for curators to manage manually opening windows and solar shading closing.

The case study concerns the “Sala del Dottorato” (Hall of Graduates), located on the first floor of Palazzo Murena, a historical building that is the seat of the University of Perugia, Italy. The Hall hosts more than 10,000 volumes of historical and artistic value. Although it houses a great number of books, the Hall cannot be considered a “standard” library because consultation is permitted only by reservation, as in all historical and conservation libraries. Because of its charming atmosphere, it is sometimes also used by the University for ceremonial purposes and meetings involving significant numbers of people. For these reasons, the Hall has multiple functions (a place for the conservation of heritage books, a reading room for research activities, and a place of representation for events of different types and duration), which make its management very complex.

2. Material and Methods

2.1. Case Study

The Sala del Dottorato is located on the first floor of Palazzo Murena, the main seat of the University of Perugia since 1810. It was built by the architects Carlo Murena and Luigi Vanvitelli in 1739 and was originally a male monastery belonging to the Olivetan Order. The building is located in the historic centre of the city, next to the University’s “Aula Magna” (Auditorium). As can be seen from Figure 1, the urban context offers limited exposure to wind, due to surrounding buildings and trees. The Sala del Dottorato has a magnificently decorated arched ceiling and a collection of rare and ancient volumes known as the “Fondo Antico”. Originally, it was the library of the monastery, then it became the first library of the University. From the Sixties and up to a few years ago, the Hall was used for the discussion of Doctorate theses (hence the name “Dottorato”), while nowadays it is used only occasionally, for important events. The main hall is preceded by a smaller atrium that is characterized by a long inner balcony with a balustrade (mezzanine) in marbled wood, accessible by ladder. The main hall is characterized by massive walls, and it is equipped with six windows facing west: three on the lower level, which are frequently open in hot weather, and three above the mezzanine wooden bookcase, which stay closed during the year. The heating system consists of four cast iron radiators, one in the atrium and three in the main hall, connected to the central heating of Palazzo Murena. The building is not equipped with a cooling system. Both levels of the room are surrounded by wooden bookcases, which hold about 10,500 rare and ancient books belonging to the University, printed from the 15th to the 19th century. The oldest are 27 incunabula, volumes printed from movable type before 1501. The most antique is an edition of St. Augustine's De Civitate Dei, printed in Rome in 1470 by C. Sweynheym and A. Pannartz, the first printers to bring a press from Germany to Italy [6]. The collection is composed of a series of organic materials such as paper, tissue, animal hair and adhesive substances, which may alter and perish over time.



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

Figure 1. Palazzo Murena from Google Earth, north side (**a**) and plan view of the first floor (**b**). The Sala del Dottorato is highlighted in red in both images.

Most of the books have been kept in the Hall since 1810, except for the period after the earthquake of 1997 that damaged the building and, in particular, the Hall. On this occasion, all the books were temporarily moved to other libraries and book depositories. Given that a great number of rare and ancient books are preserved, consultation and visits are permitted only by reservation. The primary function of the Hall is therefore to conserve the books, but in some cases, it is also used for representative purposes. Many conservation problems related to the books were detected by the librarians (Table 1). For this reason, microclimatic monitoring was necessary along with the intervention of restorers to assess the causes and risks of damage and assess actions to mitigate these conditions.

Table 1. Main conservation problems of the books preserved in the Hall.

Examples of Books	Main Conservation Problems *
	Darkening and discoloration of the ribs of many volumes located on the opposite side of the windows on the mezzanine level.
	Paper dissolution, with many book bindings completely uncovered; material dissolution is also responsible for the accumulation of dust on paper.

* Most relevant damage, visible to the naked eye.

2.2. Methodology

The activities, based on the literature addressing the issue of microclimate risk, can be summarized in the following flow chart (Figure 2).

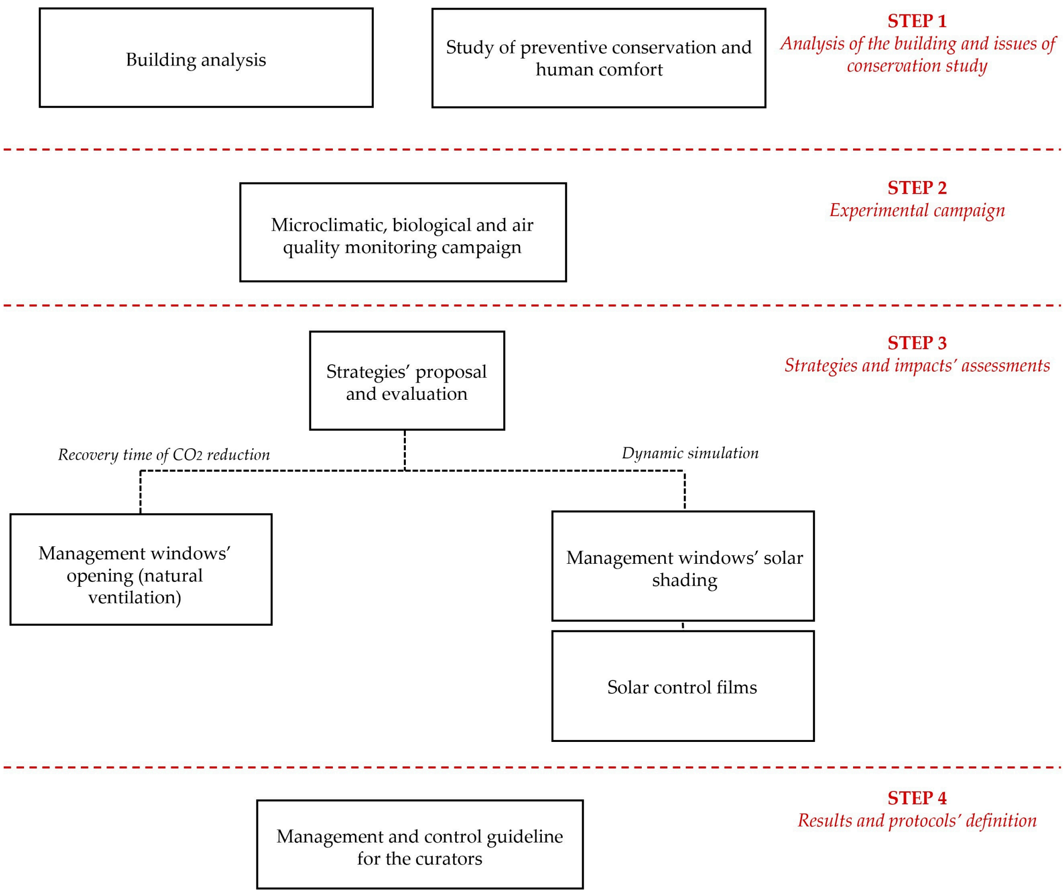


Figure 2. Flow chart of the research methodology.

The steps can be seen as guidelines:

- *Analysis of the building envelope and HVAC system*, in order to understand the relationship between the variation of indoor and outdoor microclimate conditions; this concerns the study of the thermal performance of the materials composing the building envelope and the characteristics of the HVAC system;
- *Study of issues concerning preventive conservation and human comfort.* This concerns the study of the principal standards and guidelines set out to determine acceptable ranges of parameters used for the purpose of conservation and recommended values for human comfort;
- *Microclimatic, indoor air quality, and biological monitoring*; these activities seem disjointed but integrate each other. The thermo-hygrometric parameters and indoor air quality monitoring are needed to establish indoor environmental conditions. The biological monitoring is necessary to reduce or eliminate the risk of biological attack by fungi, bacteria, mould or other parasites that may lurk in the wooden bookshelves. This type of monitoring is linked to microclimatic monitoring because the association of dampness with mild-to-moderate temperatures and dust deposits creates a favourable habitat on all materials;
- *Strategies assessments and dynamic simulation*, to improve conservation conditions and human comfort in the hall. Additionally, thanks to virtual calibrated modelling of the building, strategies regarding the envelope, the HVAC or the lighting systems are simulated in order to evaluate their impact and help library staff make decisions.

All these aspects are described in the present study, in order to define some passive techniques and control strategies: the former aimed at minimizing potential damage to objects caused by the conservation environment, the latter, instead, aimed at minimizing the fluctuations of indoor environmental parameters and reducing the impact of interaction with external agents (window openings, visitor crowding or irregular heating).

2.2.1. Building Analysis

The analysis of the building envelope, the HVAC and lighting systems and the dimensional description of the rooms is of fundamental importance [23]. The thermal envelope is made up of three classes of components: opaque components (walls, floors, ceilings and roof), windows, and internal solar shading devices. Each of these categories must be described utilising appropriate performance indicators defined by current laws and regulations [23,24]. Opaque components can be defined through indicators of steady-state and dynamic conditions, such as thermal transmittance and periodic thermal transmittance. Windows can be defined using thermal and light transmittance as well as the solar factor. Vapour condensation risk, which depends on the distribution of layers and thermal resistance in the wall (or the window), air temperature, relative humidity of the room, HVAC system performance and the number of people present, must also be verified.

Palazzo Murena is a building with massive walls made up of masonry rubble (almost one meter thick); part of the roof was renovated following the earthquake in 1997. The upper floor of the Sala del Dottorato is adjacent to an attic (unheated), while the lower one is adjacent to offices. The windows have wooden frames. The three on the lower level have double glazing, internal drapes and shutters, while the three above the mezzanine wooden bookcase (always closed) are single glazed with no shading device. When the hall is not occupied, the shutters of the lower windows and the drapes are partially closed. Table 2 describes the thermophysical properties of the principal opaque and transparent envelope components (external walls, upper floor and windows), as defined by inspections and information gathered from documentation on historical construction materials and techniques, in order to understand the relationship between the variation of indoor and outdoor microclimate conditions [23,25].

Table 2. Thermal properties of the building envelope.

Building Component	Materials	U * (W/m^{2}K)	Yie ** (W/m^{2}K)	g *** [-]	t_v **** [-]
External wall	Internal plaster, rubble masonry, brick external cladding	1.281	0.02	-	-
Upper floor (main hall)	Concrete floor slab	1.087	0.77	-	-
Lower-level windows	Wood frame, double glazing	3.282	-	0.80	0.82
Mezzanine-level windows	Wood frame, single glazing	5.855	-	0.88	0.90

* Thermal transmittance; ** Periodic thermal transmittance; *** Solar factor; **** Light transmittance.

The heating system consists of four cast iron radiators, one in the atrium and three in the main hall (with a total heating power of about 6 kW), connected to the central heating of the building, and operating in the daytime for about eight hours from Monday to Friday. The building does not have a cooling system. The geometric and construction details of the Hall, defined by inspection, are shown in Table 3. The Hall and atrium are lit by crystal chandeliers with fluorescent light bulbs (two located in the Hall and one in the atrium) only during opening hours.

Table 3. Geometric data of the Sala del Dottorato (main hall and atrium).

Parameter	Main Hall	Atrium
External surface * (S) (m^2)	122	25
External volume (V) (m^3)	830	170
Ratio S/V (m^{-1})	0.15	0.15
Window surface (S_w) (m^2)	9.5	1.9
Net floor surface (A_f) (m^2)	96	31
Ratio S_w/A_f (-)	0.10	0.06
Ratio S_w/S (-)	0.08	0.08

* This does not include surfaces leading to adjacent rooms but only the walls bordering the outside.

2.2.2. Study of Preventive Conservation and Human Comfort

Microclimatic monitoring inside libraries can contribute to the prevention of damage caused by inadequate thermo-hygrometric conditions [19], and if it is suitably projected it can suggest the most suitable strategies for improving internal climatic conditions. Moreover, acceptable ranges for microclimatic control in heritage buildings intended for conservation are often more restrictive than those established for human comfort [23]. In this study, attention was paid to thermo-hygrometric parameters (indoor air temperature and relative humidity) with regard to conservation, which is the first purpose of the Hall. Human comfort was also taken into account in relation to indoor air quality in terms of carbon dioxide (CO_2) concentration.

As regards air temperature and relative humidity, UNI standard 10586 recommends a temperature range of 14–20 °C and a relative humidity of 50–60% for book depositories, with seasonal oscillations of 2 °C and 5%. For book consultation spaces, the recommended temperature is 18–23 °C and a relative humidity of 50–65% [26]. UNI standard 10829 suggests values included in the 13–18 °C range for paper objects and 19–24 °C for parchment, with relative humidity between 50% and 60% for paper materials and 45–55% for leather and parchment. The UNI 10829 establishes a maximum daily amplitude of 1.5 °C and 6% RH [10]. Based on these standards, the scientific literature has defined a synthetic "performance index" (PI) that identifies the percentage of time in which the measured parameter lies within the required ranges [27,28]. Considering the different materials which compose the book collection and their optimal ranges as suggested by the standards, the librarians considered the widest range for temperature and relative humidity to be "acceptable" (Table 4).

Table 4. Reference values considered by librarians to be acceptable for the conservation of organic materials housed in the "Sala del Dottorato".

Parameter	Range	Daily Amplitude
Air temperature (T) (°C)	14–22	<1.5
Relative humidity (RH) (%)	40–60	<6

These intervals are to be understood as terms of optimal reference. Modest deviations may be permitted with the caveat of avoiding sudden deviations, daily variations or cyclical day-night variations. The achievement and persistence of thermo-hygrometric values that deviate from the optimal range for a single object (from a material point of view) can produce sudden and long-term damage. Short-term variations/fluctuations are even capable of inducing irreversible changes. These ranges are very different from those provided for human comfort. Comfort charts suggesting various ranges are reported in technical handbooks: 20–24 °C in winter and 23–26 °C in summer, with relative humidity within 30–70% in all seasons. However, thermal comfort is determined by individual thermal balance, which is variable and subjective. For this reason, priority is given to conservation purposes, assuming that people can adapt to indoor conditions through their personal behaviours. This is a reasonable assumption because the duration of the main events in the Hall is limited, varying from half an hour to about two hours.

As regards CO_2 concentration, monitoring is important for two reasons: first, for human comfort when the hall is occupied, and second for the optimal conservation of the volumes. In fact, human presence can be considered an additional alteration factor of the microclimate of historical libraries (increase in temperature, hygrometric degree, and pollutants). Therefore, it is important to assess the fluctuations of this indoor air pollutant in relation to the degree of occupation of the hall, in order to define guidelines for determining a maximum number of visitors and the intervals at which windows should be opened to guarantee human comfort without altering the conservation microclimate. Standards for indoor comfort are determined by threshold limits of carbon dioxide concentration, which are presented in Table 5 [29].

Table 5. Classification of CO_2 levels [29].

CO_2 Concentration Level [ppm]	Evaluation
<1000	Acceptable values
>1000 and <2000	High values (stuffiness)
>2000	Unacceptable values (poor ventilation)

High CO_2 concentration levels may be a danger for book conservation, especially if associated with high values of relative humidity, because of carbonate formation [19].

2.2.3. Microclimatic, Indoor Air Quality, and Biological Monitoring

Following the procedure for measurement of microclimatic parameters as suggested by UNI 10829:1999, a preliminary survey [6] was carried out using portable devices (Tinytag Plus 2-TGU-4500, Gemini Data Loggers Ltd., West Sussex, UK) for measuring indoor air temperature and relative humidity [30]. This preliminary monitoring campaign took place for about a year, between 2019 and 2020, in which sensors were installed at different points of the Hall for different periods, with a recording setting of 10 min. The aim of this monitoring campaign was to characterize the indoor microclimate of the Hall, moving the sensors to different points to evaluate both horizontal differences (different points at the same level) and vertical differences (between the two levels of the room, floor level and mezzanine), in the conditions corresponding to the normal management of the environment.

Based on the results obtained in this first phase, the continuous monitoring positions were properly identified by taking into account the fruition needs of the environments and the operating requirements of the instruments (avoiding contact with local disturbances affecting their proper functioning, such as proximity to heat sources and direct light), as well as the geometric characteristics of the environment. At the beginning of 2021, in fact, a new set of dataloggers was installed (datalogger Wi-Fi Testo) at the specific points of the main hall selected for the preliminary study, as shown in Figure 3 [31]. More attention was paid to the side opposite the windows, where two sensors were placed on the two levels of the hall [32], along the same vertical (bookcase "K"). This continuum monitoring concerned not only the thermo-hygrometric parameters but also lighting and air quality. Obviously, the new sensors had specific requirements for the Hall as regards wireless radio connectivity; in fact, thanks to the wireless system, the recorded parameters were stored in the Cloud for over a year and were available online, on any device (computer, smartphone, tablet). Another important action was setting the acceptability ranges (according to the librarians) of the measured parameters and the relative alarms that, in real time, warn by message or email. In addition, all sensors were equipped with covers suiting the context of the Hall.

For a clearer comprehension of the results of this study, each measuring point will be identified with the letter of the bookcase where the logger is situated, and a number corresponding to the level of the Hall (0 for the floor level and 1 for the mezzanine-level). Figure 3 shows the sensors' positions in the Hall. Obviously, the chosen points are representative of the critical part of the Hall (the side opposite the windows) and not of the entire Hall's conditions. For this reason, more dataloggers should be installed at different points, compatibly with the wireless radio connectivity of the Hall.

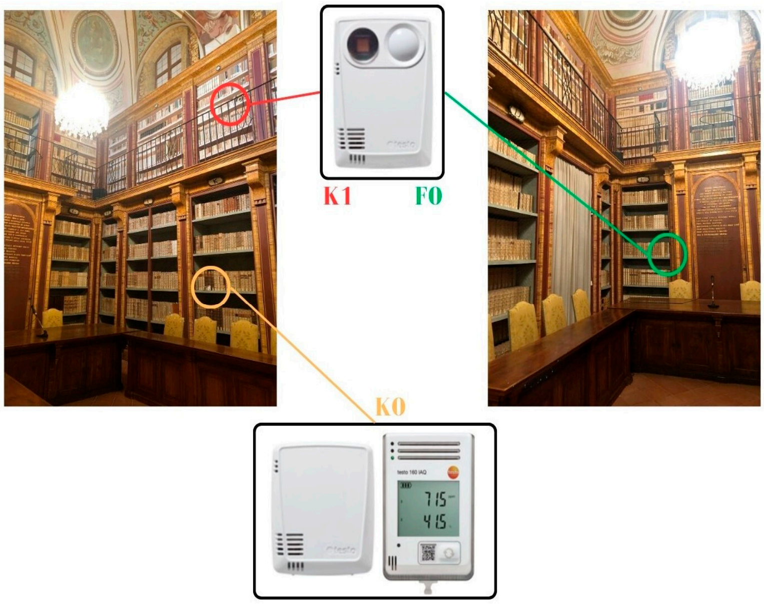


Figure 3. Instruments and their installation in the new monitoring system.

The recording interval was set at 15 min for each sensor. The sensors and their measured parameters are presented in Table 6.

Table 6. Monitoring features (from the technical data sheets).

Instrument	Measured Parameters	Measuring Range	Accuracy	Position
Testo 160 IAQ + Testo 160 E (external probe)	Air temperature (°C) Relative humidity (%) Air pressure (mbar) CO_2 concentration (ppm) Illuminance (lux) Cumulative illuminance (luxh) UV radiation (mW/m^2)	−10 ÷ +50 °C 0 ÷ 100% 600 ÷ 1100 mbar 0 ÷ 5000 ppm 0 ÷ 20,000 lux calculated 0 ÷ 10,000 mW/m^2	±0.5 °C ±2% ±3 mbar ±50 ppm ±3 lux / ±5 mW/m^2	Bookcase "K0"
Testo 160 THL	Air temperature (°C) Relative humidity (%) Illuminance (lux) Cumulative illuminance (luxh) UV radiation (mW/m^2)	−10 ÷ +50 °C 0 ÷ 100% 0 ÷ 20,000 lux / 0 ÷ 10,000 mW/m^2	±0.5 °C ±2% ±3 lux / ±5 mW/m^2	Bookcases "F0" and "K1"

The thermo-hygrometric data recorded by the sensors were post-processed in order to characterize and investigate indoor conditions; in particular, temperature and relative humidity were evaluated using the temporal profile, the minimum, medium and maximum values and the daily gradients for the measured points of the hall (K0 and K1). At the same time, a Performance Index (PI) was calculated both for temperature and relative humidity. In addition, a comparative analysis was carried out with the Sebera's isoperm diagram of the cellulose of books kept in bookcases K0 and K1. This type of diagram was calculated using temperature and relative humidity (measured every 15 min from May 2021 to May 2022) as inputs. It represents, for cellulose molecules, a set of curves of equal durability, called isoperms, making reference to the reaction rate at T = 20 °C and RH = 50%, which will set the baseline with a value of 1. The isoperms are lines of constant durability and their value represents a lifetime multiplier: isoperm 10 means that the climate conditions (temperature and relative humidity) that correspond to the line will increase the lifetime of the cellulose by a factor of 10, in comparison with isoperm 0.1 and the others on the right of line 1. In fact, the area to the right of isoperm 1 year represents conditions for a shorter life of cellulose molecules, compared to the reference. On the contrary, the microclimate on the left of this line will extend the lifetime as indicated by the multipliers on the side of each line [19]. Similarly, indoor air quality was also examined in terms of CO_2 concentration. Based on the data observations, an empirical method was followed to understand when to open windows during the most crowded events. Data observations showed that many institutional meetings took place in winter and, when these involved a great number of people, the CO_2 values increased and exceeded the limit value of 1000 ppm. During this type of event, the windows were kept closed until the end of the event for intervals varying from a few minutes to one hour. Based on this information, the most relevant events were analysed, and a method was established to evaluate the variations that would have been obtained if the windows had been opened. This method involved only natural ventilation obtained by opening the windows for human comfort and it was based on the CO_2 readings on the wi-fi sensor's display in real time. This aspect shows the importance of the continuum monitoring system.

As already expressed, for all materials, the indoor microclimate should be continually controlled also in order to reduce or eliminate the risk of biological attack by fungi, bacteria, or other parasites.

For this reason, in February 2021, a group of restorers was involved in the project with the task of dusting the volumes preserved in the Sala del Dottorato and reporting a list of restoration priorities for each one, linked to the presence of traces of medium/serious entomological or microbiological attacks. An annual entomological monitoring was therefore set up (from May 2021 to May 2022), placing insect traps on the windows and in other places in the hall [33,34]. The aim of this type of action was to verify, on a monthly basis, the presence or absence of woodworms or other types of insect pests, since traces of them had been discovered in some bookcases of the Hall and in rooms adjacent to the floor. Due to the presence of the traps on the windows, the shutters and curtains were kept open for the entire period of monitoring (Figure 4).

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

Figure 4. Volume dusting (**a**) and setting of insect traps on the windows (**b**).

2.2.4. Strategies and Impact Assessments

Based on the yearly microclimatic analysis concerning thermo-hygrometric parameters and indoor air quality (CO_2 concentration), some strategies were defined and assessed. Some critical issues were taken into account in planning the strategies, such as economic and structural factors, linked to the conformation of the Hall, making the study very complex (very high, decorated arched ceilings and the presence of the bookcases on the mezzanine level narrowing the passage for people). A simulated model was also used as an instrument to evaluate the effectiveness of some of them in order to help the decisions made by the librarians.

The strategies considered in this work concern mainly management and passive actions aimed at reducing and mitigating risk conditions, in particular the optimal management of the existing shutters and opening windows for natural ventilation; finally, the installation of solar control films on the windows was investigated. Management actions specifically involving the librarians adopt a curative method, providing for direct actions such as stabilization, consolidation, and disinfestation of the cultural property, and also the correct handling and consultation of books. In addition, great importance was given in this study to the control of the number of visitors during events, their duration and the management of the natural ventilation given by opening the windows.

Management of the solar shading (shutters) was important for defining guidelines and good practices for the librarians in order to obtain a balance between thermal comfort (reduction of thermal gains) and visual comfort (reduction of natural daylight). The installation of solar films, instead, referred to envelope intervention (windows): this was a more complex strategy than the others, because it was also linked to structural, aesthetic (technical feasibility of their installation) and economic aspects. No other passive actions were considered for this case study, because of the presence of some important limits, mainly related to the fact that the entire building is heritage listed. This means that strategies which involve the envelope (such as the walls' insulation) cannot be carried out.

Both these strategies were defined, simulated and assessed with a dynamic calibrated thermal model evaluated by means of EnergyPlus v.8.7 in order to predict hourly indoor temperature in the Hall [35]. To create the model, in addition to the thermophysical properties of the building envelope, thermal loads and HVAC system characteristics were set: as internal gains, human occupancy (5.5 m^2/person), lights (2 W/m^2) and office equipment (5 W/m^2) for all zones used as offices (first and ground floor, except for the hall and atrium) were considered. The presence of occupants in these zones was set from 7 a.m. to 6 p.m. for each workday; the heating period was instead from 15 October to 15 April, as established by Italian law for this climatic zone. Set-point temperature of room air, based on occupancy schedules, was assumed equal to 20 °C for all zones [36,37]. The hall was simulated in the conditions of "non-occupancy", with the shutters partially closed. A weather file [23] was created based on the data collected from a weather station (dry bulb temperature, relative humidity, wind speed, solar radiation), which is located on the roof of a university building about 1 km away from the investigated building.

To validate the energy model, a calibration process was followed: this was an important phase, to allow a reliable simulation model to be created for the purpose of analysing indoor climate to support preventive conservation [38–41]. The energy model was calibrated to consider only the hall zone: the quality of the model was assessed adopting indoor temperature as the calibration control variable [42,43]. In particular, hourly values of indoor air temperature collected during the preliminary monitoring campaign were compared with simulated values (the simulated trend referred to the Hall's average trend and for the validation phase it was compared with the average trend of the two levels measured during the preliminary monitoring campaign). This was performed using three indices: mean bias error (MBE), coefficient of variation of root mean square error (Cv(RMSE)) and Pearson's index (r). The first two indices are suggested by ASHRAE Guideline 14-2002 [44], while the third one (r) is a typical statistical coefficient of linear correlation between the two variables of simulated and measured data [45]. In this study, the Cv(RMSE) index, the normalized mean bias error (NMBE) and the determination coefficient (R^2), that is the square of Pearson's index (r), were considered. The model was considered to be calibrated when the mentioned indices matched the values reported in the literature [44]. During the iterative simulation phase, the model was optimized, varying the values attributed to the infiltration air change rate and the air mixing between adjacent zones, which were regarded as the uncertain parameters mostly influencing simulation results [23]. In Table 7, for the Sala del Dottorato, annual values of the NMBE, Cv(RMSE), and R^2 indices are reported for the model configuration that presents the best annual value.

Table 7. Annual values of the indices for the main hall compared with acceptable threshold values.

Zone	NMBE [%]	Cv(RMSE) [%]	R^2 [-]
Sala del Dottorato (main hall)	1.96	7	0.95
Acceptable values	$-10 \leq$ NMBE $\leq +10$	$\leq$30	$\geq$0.75

The interventions were first simulated individually and then combined. In particular, the installation of solar control films was simulated for the windows of the mezzanine level, modifying the properties of the glass: the solar factor was assumed equal to 0.22 and the light transmittance equal to 0.20. In all cases, the effectiveness of the different strategies was evaluated utilizing the indoor temperature trend variation (°C) over one year.

In order to propose management actions for natural ventilation, the evaluation of the effects of opening the windows during events (in terms of CO_2 concentration), an empirical method was carried out. The most representative events were chosen in terms of the number of people, duration and season to highlight the most critical conditions.

For each event, the following elements were recorded and calculated:

- *Duration*, the duration interval (min);
- *N. people*, the number of people inside the Hall during the meeting;
- *Initial CO_2 level*, the CO_2 level at the beginning of the event (ppm), which represents the background level (measured by the sensor);
- *Final CO_2 level*, the CO_2 level at the end of the event (ppm), which is the maximum value reached (measured by the sensors);
- $v_{increase}$, the growth speed of CO_2 during the event with closed windows (ppm/min);
- *Window opening*, in terms of the interval before the event (min);
- *CO_2 level after opening windows*, the CO_2 level reached with opened windows (ppm);
- $v_{decrease}$ *with open windows*, the degrowth speed when the windows were opened (ppm/min);
- *Recovery time of the initial CO_2 level with closed windows*, the time taken to return to the initial CO_2 level after closing the windows (hours);
- $v_{decrease}$ *with closed windows*, the degrowth speed to return to the initial CO_2 level with closed windows (ppm/min).

The dataset was used to define a protocol for opening the windows considering that the curators could open all the windows for air exchange before the end of the event. The aim of the study is to identify a correct value of the CO_2 concentration, as a limit to open the windows for air exchange. Eventually, the best value (as a compromise in terms of people, duration and external conditions) is estimated and it is defined as a limit before the onset of bad conditions (values greater than 1000 ppm), beyond which the curators could open all the windows. So, once this value is fixed, for each meeting analysed, the *Estimated final CO_2 level* was calculated, which represents the estimated final CO_2 level which could have been reached if the windows had been opened at the CO_2 limit; these values were calculated based on the degrowth speed of CO_2 (when the windows were open) and the window opening interval during the event (from the time at which the CO_2 level reached the limit until the end). To estimate the last parameter (estimated final CO_2 level), the reduction of CO_2 obtained if the windows were opened during the event was calculated once the limit value was reached, according to the equation:

$$\text{Reduction of } CO_2 = v_{\text{decrease with open windows}} \times \text{time}_{\text{remaining}} \tag{1}$$

The time shown in the equation ($\text{time}_{\text{remaining}}$) represents the interval between the time at which the windows should have been opened and the end of the meeting (expressed in minutes). The estimated final CO_2 level was then calculated as the difference between the real CO_2 level measured at the meeting's end and the reduction described above.

3. Results and Discussion

3.1. Microclimatic and Biological Monitoring

3.1.1. Indoor Air Temperature and Relative Humidity

The dataset available from the wireless sensor system was processed over one year, from May 2021 (normal operation of sensors) to May 2022 (although monitoring continues), considering only the K0 and K1 positions (side opposite the windows) as representative, respectively, of the lower and mezzanine levels. The temporal profiles of temperature and relative humidity, minimum, medium and maximum values of temperature and relative humidity, daily gradients of temperature (ΔT_{24}) and relative humidity (ΔRH_{24}) of these two points were analysed.

As regards indoor air temperature, Figure 5 shows an annual trend: from May the temperature increases and in the warm seasons the mezzanine's values are higher than the floor-level ones, due to the direct solar radiation coming through the windows, while in the cold seasons conditions are the opposite because of the heating system.

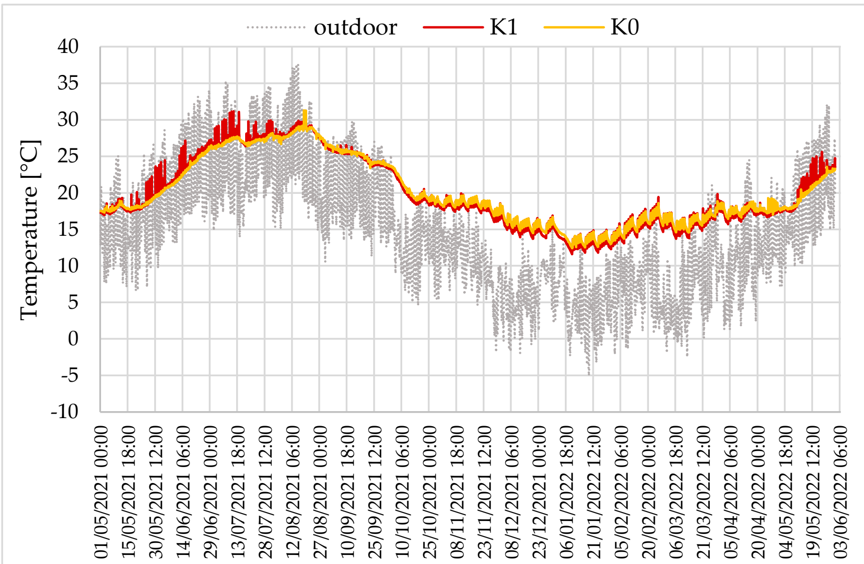
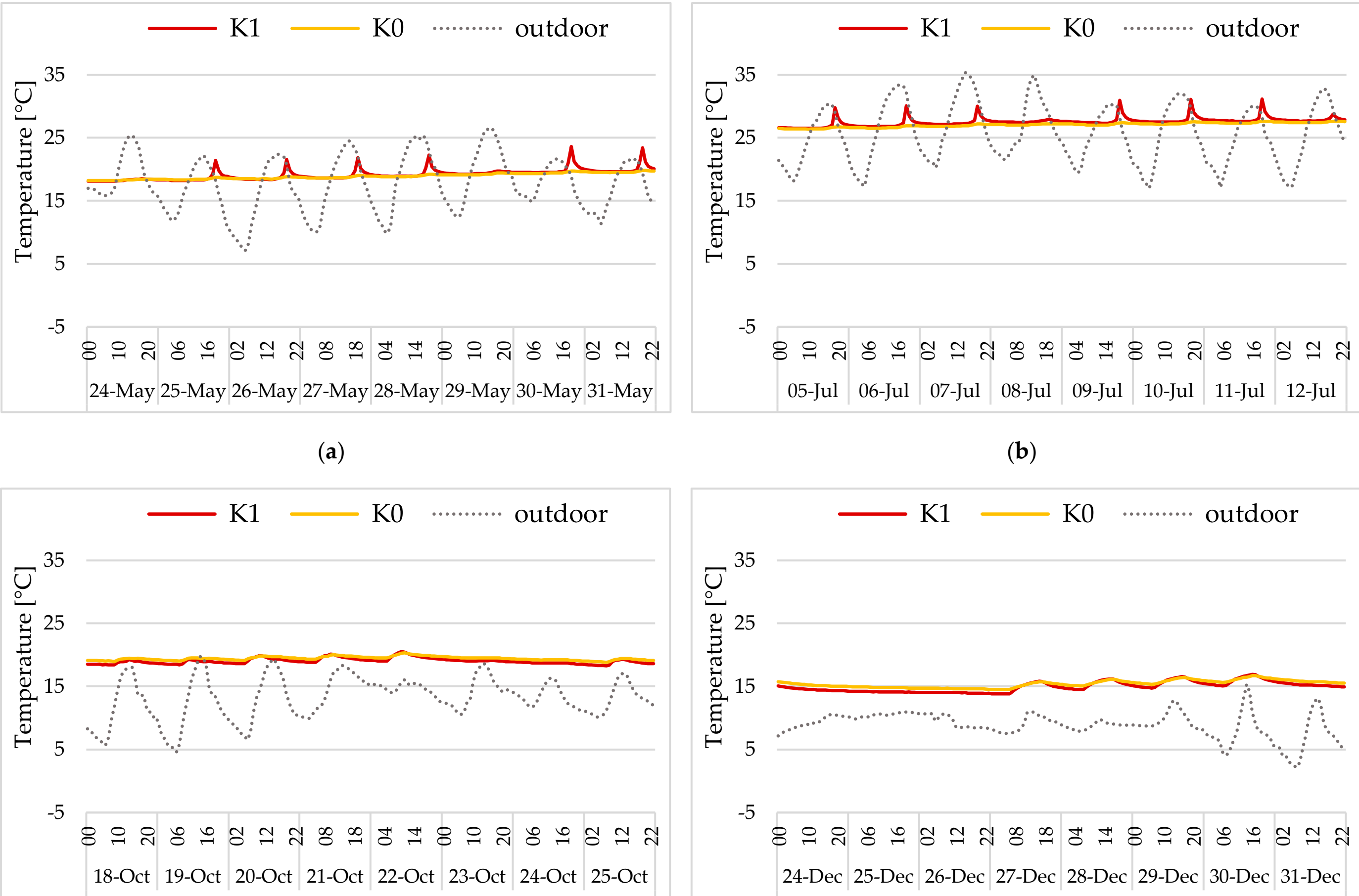


Figure 5. Indoor and outdoor temperature, annual trend (hourly averaged data).

Figure 6 shows the weekly trends of specific months, representative of the seasons: May, July, October and December.

In Spring (a), the thermal inertia of the thick walls keeps the indoor temperature lower than outside; the temperature values are similar at both levels, even if on the mezzanine the effect of solar radiation in the afternoon (from 18:30 to 19:00), with peaks of over 3 °C difference, is already evident.

In Summer (b), the effect of solar radiation is stronger and at this time, temperatures tend to be warmer, more than 25 °C, and thermal layering stratifies the air, also due to the effect of the solar gains from the upper windows. The increase on the mezzanine level has high peaks from 18:30 to 19:30.



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

Figure 6. Weekly indoor and outdoor temperature trends during Spring (**a**), Summer (**b**), Autumn (**c**) and Winter (**d**).

In Autumn (c), the heat accumulated during the warm months makes the internal temperature higher than the average daily temperatures. In the selected week, on workdays the heating was already turned on, with evident differences from the weekend, when it was turned off. In this period, because of the effect of heating, the floor level was warmer than the mezzanine level (by about 1 °C).

In December (d), even when the heating system was on, the temperature did not reach 20 °C: this was a positive condition for the conservation of the volumes but not for people. Conditions worsened during the Christmas break when the heating system was off for several consecutive days and temperatures dropped as low as 14 °C.

Table 8 shows the maximum, average and minimum indoor temperature values, divided into representative seasonal periods in which times of heating are highlighted; in addition to these parameters, the table also shows daily temperature variations, maximum and average.

As described above, the winter season is critical because of the daily temperature variation caused by the radiators: when the heating system is off (at night, on the weekend and holidays) the temperature drops below 14 °C. It then rises when the heating is on (especially on the floor level where this effect is greater). There is a slight vertical temperature gradient between the two levels of the room: during the summer season, the side opposite the windows of the balcony is warmer because of the sunlight, especially in the late afternoon, while in the winter months, the inertia of the walls maintains the lower level warmer than the balcony. When the heating is on, the temperature tends to stratify at the upper level.

Table 8. Analysis of the monitoring campaign data (indoor air temperature).

	Heating System	1 May 2021 31 August 2021 OFF	1 September 2021 17 October 2021 OFF	18 October 2021 15 April 2022 ON	16 April 2022 31 May 2022 OFF
Bookcase K0	T_{max} (°C)	33.9	27.1	31.6	23.6
	T_{ave} (°C)	24.1	24.0	19.9	19.3
	T_{min} (°C)	17.3	19.1	11.6	17.0
	ΔT_{24max} (°C)	5.5	1.4	3.8	3.8
	ΔT_{24ave} (°C)	0.5	0.5	0.7	0.9
Bookcase K1	T_{max} (°C)	33.2	26.6	31.4	27.1
	T_{ave} (°C)	24.3	23.7	19.7	19.3
	T_{min} (°C)	16.9	18.5	10.8	16.6
	ΔT_{24max} (°C)	6.1	1.6	6.1	6.1
	ΔT_{24ave} (°C)	1.7	0.6	1.2	1.8

The same type of analysis was carried out for relative humidity; this parameter also presents a historical yearly trend which is shown in Figure 7. During the cold season, the relative humidity values of the mezzanine level are higher than the lower level, in accordance with the temperature trend. However, the values of both levels are inside the recommended range for the entire annual period. A weekly analysis was carried out for the representative periods of the seasons.

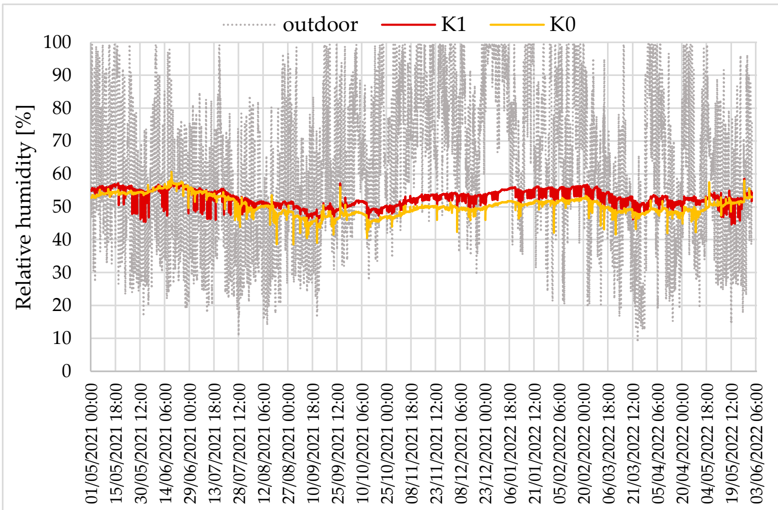


Figure 7. Indoor and outdoor relative humidity, annual trend (hourly averaged data).

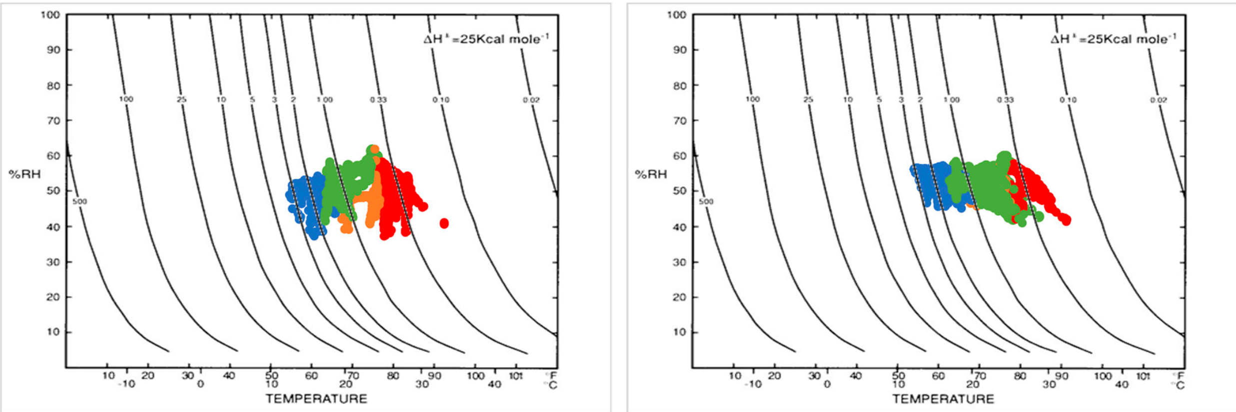
In general terms, relative humidity values did not exceed the suggested maximum value (60%) and daily fluctuations were limited, as reported in Table 9. During summer, the trends on both levels were similar, while in winter the floor level presented lower values, owing to heating by the radiators.

Finally, a comparative analysis of indoor air temperature and relative humidity was carried out: Figure 8 shows a Sebera's isoperm diagram of the cellulose of books kept in bookcases K0 and K1, calculated using temperature and relative humidity values of an annual period (from May 2021 to May 2022).

To facilitate comprehension of the graph, the temperature and relative humidity readings are coloured to highlight the seasons: blue dots for Winter (the interval in which the heating is on, from 15 October to 15 April), green dots for Spring, red dots for Summer and orange ones for Autumn. For both positions, the most negative period corresponds to the warm seasons, in particular the entire summer season and half of the autumn and spring readings.

Table 9. Analysis of the monitoring campaign data (indoor relative humidity).

	Heating	1 May 2021 31 August 2021 OFF	1 September 2021 17 October 2021 OFF	18 October 2021 15 April 2022 ON	16 April 2022 31 May 2022 OFF
Bookcase K0	UR_{max} (%)	61.3	61.5	62.0	58.4
	UR_{ave} (%)	52.9	46.6	51.6	50.2
	UR_{min} (%)	38.1	37.2	30.9	41.4
	ΔUR_{24max} (%)	11.9	15.0	13.9	8.7
	ΔUR_{24ave} (%)	1.8	2.7	1.8	2.5
Bookcase K1	UR_{max} (%)	59.5	57.4	64.2	59.3
	UR_{ave} (%)	53.9	49.5	54.5	52.3
	UR_{min} (%)	41.3	42.0	32.9	40.9
	ΔUR_{24max} (%)	14.2	8.4	9.1	11.9
	ΔUR_{24ave} (%)	3.9	1.7	2.3	3.8



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

Figure 8. Lifetime multiplier of the cellulose molecule of books kept in K0 (**a**) and K1 (**b**).

This type of diagram is specific for cellulose, but the books kept in these bookcases may also be composed of other organic materials, not only paper. However, the graph represents a useful instrument for simultaneously analysing the temperature and relative humidity of the environment that hosts the books.

To complete the analysis, performance indices (PI) for temperature and relative humidity were calculated: four levels were established according to the acceptability ranges of these two parameters (Table 4). The percentage of time during which the parameters fell within the recommended values for the annual period examined was calculated [14]. The results are shown in Table 10.

Table 10. Performance indices (PI) for the comparative analysis of indoor air temperature and relative humidity.

Level	Description	PI [%] K0	PI [%] K1
1	T and RH within recommended ranges	62.7	59.8
2	Only RH within recommended ranges	37.2	40.2
3	Only T within recommended ranges	0.0	0.0
4	T and RH outside recommended ranges	0.1	0.0

Figure 9 shows, in graphic form, the results of this analysis: in the monitoring period (from May 2021 to May 2022), more than 50% of the measured data of both positions were within level one (the acceptable range for temperature and relative humidity), but a large percentage of both positions, about 40%, registered temperatures outside the recommended range. This phenomenon occurred especially in Summer when indoor temperatures were too high, particularly on the side of the mezzanine level opposite the windows, which received direct solar radiation, increasing temperature. This consequently raised questions linked to the acceleration of the rate of degradation which can occur when high temperatures are maintained for a long period.

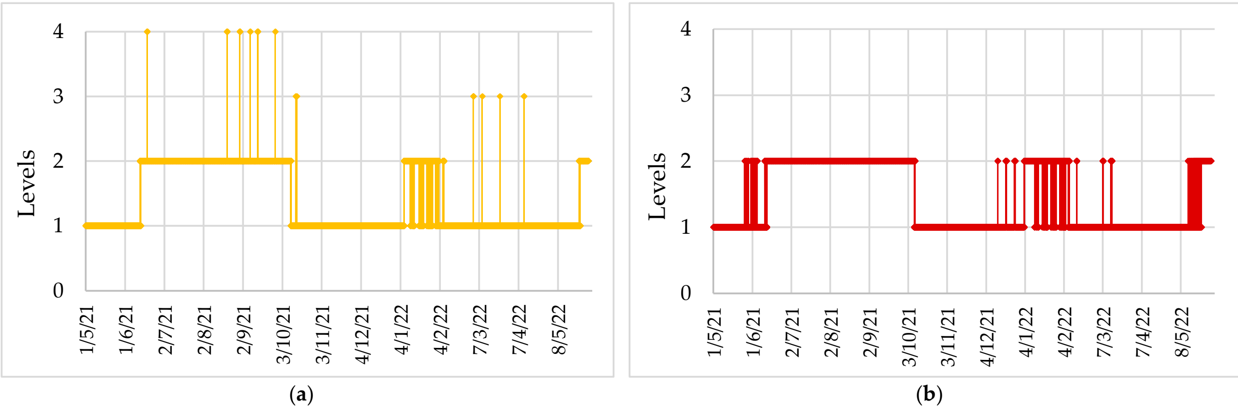


Figure 9. Comparative data analysis for indoor air temperature and relative humidity on the floor level (**a**) and the mezzanine (**b**).

Finally, the most relevant aspects concerning thermo-hygrometric parameters can be summarized as follows:

- During the summer, the temperature reaches high values, approximately 29 °C; this condition can accelerate the rate of paper degradation processes, as previous studies have highlighted the correlation between high temperatures and book embrittlement;
- In the mezzanine, on the opposite side of the windows, there are daily temperature peaks due to direct sunlight;
- In winter, the effect of heating by radiators is noticeable, causing daily temperature fluctuations (daily and weekly switching on/off of the heating);
- Regarding relative humidity, this parameter does not exceed the suggested maximum value (60%), and its fluctuations are limited.

3.1.2. Biological and Entomological Aspects

Studies and analyses made by restorers show that many volumes (over a thousand) have suffered entomological damage. Of the 190 volumes damaged by microbiological attacks (moulds and active bacteria), 103 books were mildly affected and 87 seriously damaged. These were first isolated, then treated and repaired by the restorers.

To find the origin of the moulds and bacteria, other specific monitoring campaigns were carried out by measuring the surface temperature, relative humidity and the dew point temperature of the walls behind the bookcases at the critical points identified by the restorers. The aim was to investigate these points of the hall in terms of problems related to mould, surface condensation, or water seepage from the walls, highlighting the importance of monitoring as an instrument of integration with other studies concerning conservation. The campaigns were carried out in two different two-week periods: March 2021 (Spring) and December 2021 (during the Christmas holidays when the heating was off). The results obtained exclude links between the presence of cold walls or problems linked to high RH values and the activation of moulds and bacteria.

With regard to the monitoring points in Figure 10, it must be specified that in this case the letters refer to the bookcases and the numbers to the shelves. As shown in the figure, following the restorers' indications, the monitoring campaign also involved the atrium, where the wooden bookcases differ from the others in the hall in that they are closed by glass panes without ventilation, therefore resembling showcases.

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

Figure 10. Monitored points on the floor level of the hall and in the atrium. Letters refer to the bookcases and numbers to the shelves (**a**), and examples of installed sensors (**b**).

The results obtained showed that there was no correlation between the moulds found on many volumes and contemporary environmental conditions; their origin may have been linked to storage in a book depository while the hall was being restored after the earthquake, where conditions in terms of relative humidity and the presence of books damaged by moulds and bacteria were at their worst.

Entomological monitoring using insect traps detected several specimens that were identified by experts as originating from wooden furniture, also located outside the room and in the adjacent areas (Figure 11).

Figure 11. Insect specimens found in the traps. Dusting mitigated and, in some cases, also removed the causes of the proliferation of insects and fungal spores. However, considering that the furniture of the hall is wooden (and partially damaged), it cannot be excluded that under favourable conditions and without periodic disinfection, new insect outbreaks may occur (such as parasite eggs or larvae).

3.2. Strategies Assessment for Indoor Air Quality and Natural Ventilation

An empirical method was followed to assess the effect of opening the windows during events involving a great number of people. This assessment allowed library staff to define a strategy of opening the windows according to the number of people and the duration of the event. This simplified method included opening all the windows (the estimated CO_2 reduction levels were calculated taking into account the opening of all three windows of the hall). Aspects linked to energy saving (loss of heat) and human thermal comfort during the cold season (discomfort due to the open windows) were also considered [46–49]. A preliminary solution to this problem would be to open only one window, decreasing the speed of degrowth of the CO_2 trend by a third. Figure 12 shows the CO_2 trend during selected institutional events in winter (with the heating on), in relation to indoor temperature and relative humidity.

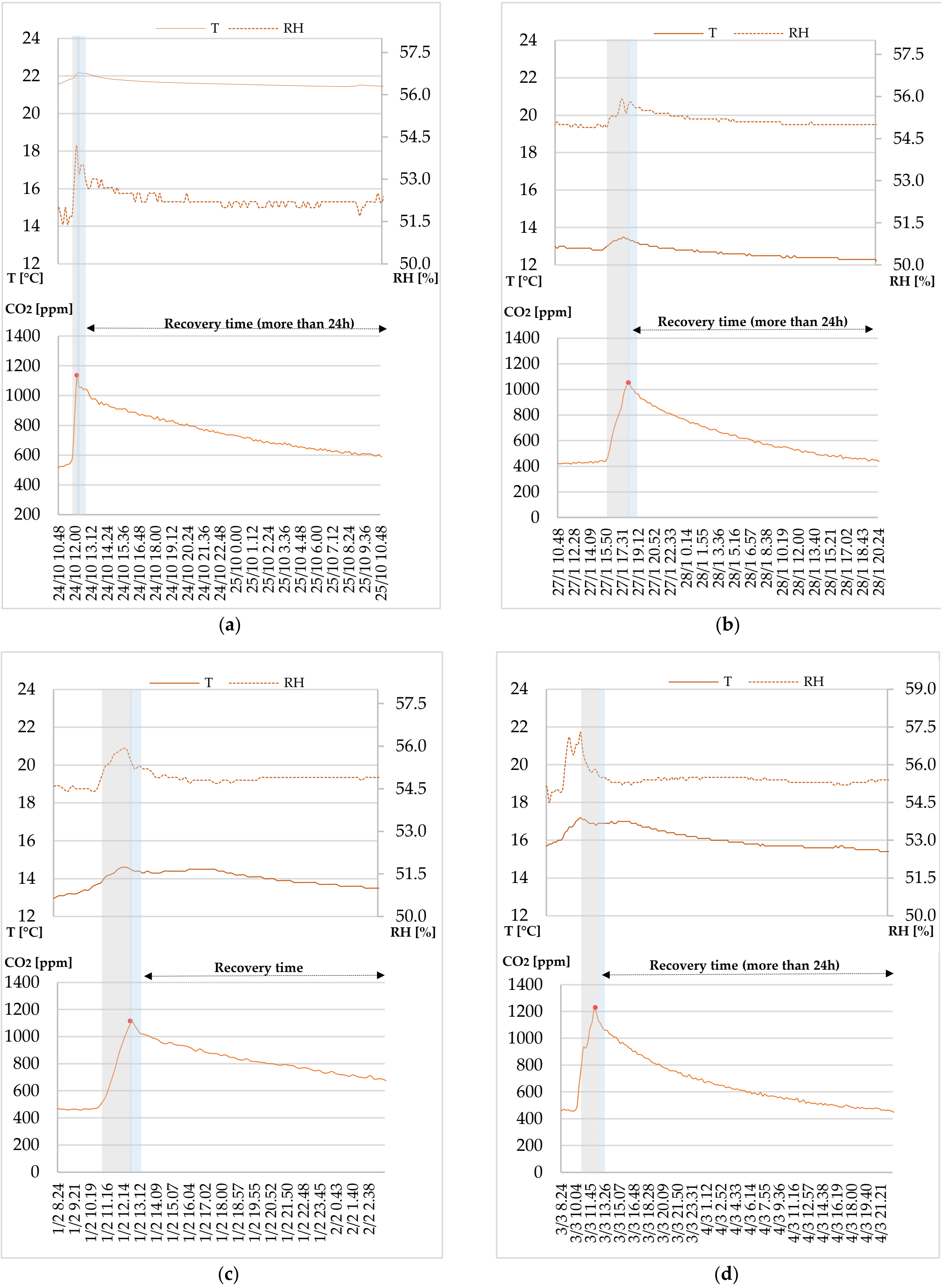


Figure 12. CO_2, indoor temperature and relative humidity trends during analysed events: October event (**a**), January event (**b**), February event (**c**) and March event (**d**).

The coloured areas identify the duration of the events (grey area) and the interval for which the windows were opened (blue area), while the red dot indicates the CO_2 peak reached during the event, and the black line represents the recovery time needed to return to the initial level of CO_2. The T and RH increases are limited, both depending on the number of people present and the use of technical equipment such as lighting, projectors or computers.

The CO_2 trend shows that during the events, especially with large audiences, the CO_2 trend increases very rapidly; similarly, it decreases very rapidly when the windows are opened. The decrease is very slow once the windows are closed and, in some cases, the recovery time to return to the initial level of CO_2 is more than 24 h.

From the analysis of the monitoring, it emerged that the limit value before the bad conditions is estimated at 900 ppm. It represents the best value to impose as a CO_2 concentration limit during the events with a great number of people and a significant duration. In fact, as can be seen in Table 11, the final CO_2 level, estimated by Equation (1) for each event, never exceeds the critical value of 1000 ppm.

Table 11. Features of chosen events.

	Meetings			
	(a) October	(b) January	(c) February	(d) March
Duration (min)	60	150	120	135
No. of people (-)	70	15	15	30
Initial CO_2 level (ppm)	547	437	474	460
Final CO_2 level (ppm)	1058	1056	1108	1220
$v_{increase}$ (ppm/min)	9	4	5	6
Window opening (min)	90	15	30	15
CO_2 level after opening windows (ppm)	956	1016	1024	1187
$v_{decrease}$ with open windows (ppm/min)	1	3	3	2
Time of recovery of the initial CO_2 level (hrs)	40	26	24	33
$v_{decrease}$ with closed windows (ppm/min)	0.2	0.4	0.3	0.4
Estimated final CO_2 (ppm)	879 (−17%)	799 (−24%)	790 (−29%)	775 (−36%)

Table 11 shows the level of CO_2 concentration reached at the end of the events and the estimated level with open windows.

As can be observed from the data contained in the table, with the windows open until the end of the event, the final CO_2 concentration would have been 20–30% lower than the real values measured. However, degrowth speeds with closed windows do not vary significantly when presences vary, and they are more than five times lower than when the windows are open. This empirical method shows, once again, the importance of continuous monitoring thanks to which staff can decide whether or not to open the windows according to the reading of the CO_2 level recorded by the sensor (when the level exceeds 900 ppm).

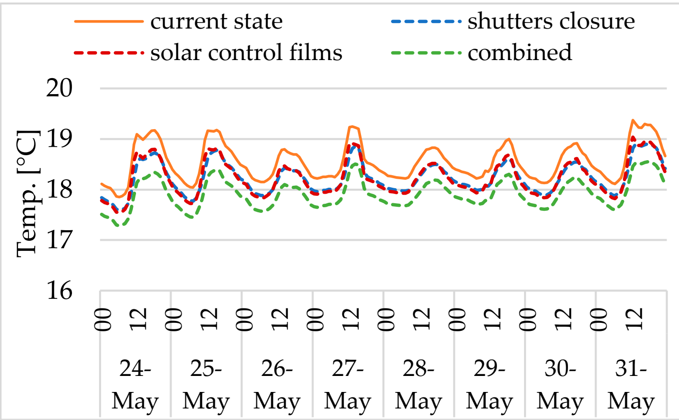
3.3. Strategies Assessment for Solar Shading Management and Solar Control Film Installation

The strategies simulated with the thermal model of the building, did not involve the HVAC (heating system) and the envelope (walls or roof) because the entire building is heritage listed, which excludes this type of intervention. For these reasons, the strategies referred only to the solar shading of the windows of the hall, in particular the control of existing solar shadings of the lower windows (internal shutters) and the addition of solar control films for all the windows. For a better comprehension of the results, each strategy is defined as follows:

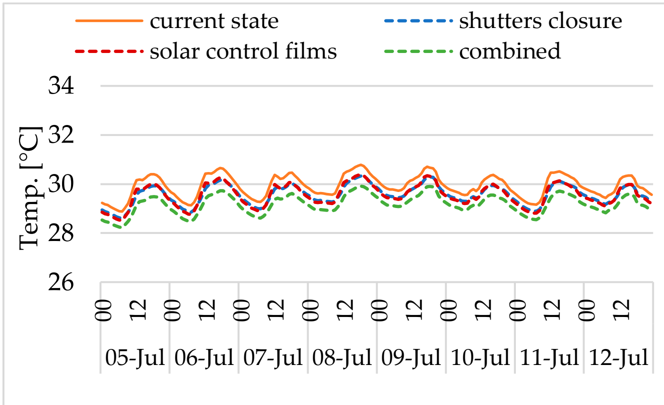
- *Current state*: simulation of the actual conditions of the hall (non-occupancy);
- *Shutter closure*: simulation of total closure of the shutters on the lower windows;
- *Solar control films*: simulation of the installation of films on the windows on the mezzanine level;

- *Combined*: simulation of combined strategies.

The results of the simulations in terms of temperature trend calculated on a daily average showed trends very similar to each other, but in warmer periods the effects of the strategies are more evident. For this reason, attention was focused on some weeks in spring and summer that were considered typical, calculating temperature trends on an hourly basis (Figure 13).



(**a**)



(**b**)

Figure 13. Effects of the strategies applied to the hall in a typical spring (**a**) and summer week (**b**).

As can be seen from the graphs in Figure 13, the temperature trends of the separate strategies involving the complete closure of the shutters and the installation of solar control films are completely comparable in terms of average indoor temperature: in both seasons, the decrease is about 0.5 °C. However, the local effect could be different because the solar films should allow a significant reduction of solar radiation on the mezzanine level (in front of the windows). Instead, if the two strategies are considered together, temperature values are about 1 °C lower than actual trends. Finally, the simulations demonstrated that the chosen strategies chosen did not guarantee relevant effects in terms of a decrease in temperature trend, but their contribution is undoubtedly appreciable in mitigating solar radiation and its effects in terms of illuminance.

3.4. Protocol Definition for the Curators

The results of the studies concerning the indoor microclimate of the hall show that high temperatures during the warm seasons are unsuitable both for the conservation of the volumes and for human comfort. The most reassuring fact is that the relative humidity never exceeds 60% in the hottest months. The main problem is the absence of an air conditioning system, which would allow a stable indoor microclimate all year round and reduce some risky conditions. Further problems are represented by unsuitable winter conditions, such as day and night temperature fluctuations, due to intermittent heating. In addition, after a long period of heating shutdown (such as the Christmas holidays), the environment becomes very cold, and this aspect is worsened by the fact that during events, the only way to exchange the air is by opening the windows. In this context, the installation of Wi-Fi sensors appears to be an important instrument for passive and zero-cost strategies aimed at reducing the risk of damage during management of the hall due to the exclusion of intervention on the HVAC and the envelope because the entire building is heritage listed.

Therefore, a protocol for curators was defined by using alarms set in the wireless sensors that can help to understand precisely when to do it (Figure 14).

The first strategy is related to the management of the windows' shutters of the lower level, in terms of indoor temperature. Even if this strategy has a low impact on temperature trend, it is better to set an alarm on temperature data (T > 20 °C) to close the shutters when this value is exceeded. From the dataset recorded over the years, this condition mainly occurs during the period from May to October. The second one, instead, is related to the management of natural ventilation, which is obtained by the opening of the windows during events. Also in this case, it is fundamental to set the alarm in terms of CO_2 concentration, based on the individuated limit value (900 ppm), which permits the curators to open the windows when the CO_2 concentration exceeds the critical value during events without impacting people's comfort.

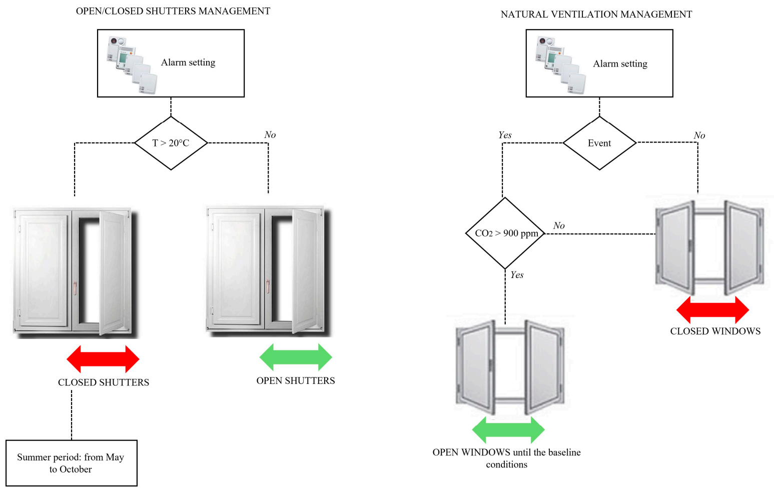


Figure 14. Protocol for the curators for the management of the windows' shutters and natural ventilation during events.

4. Conclusions

Studies concerning libraries in historical buildings underline the priority of microclimate monitoring for evaluating critical issues in the conservation of artworks and the planning of future retrofitting or management strategies.

This paper, in fact, illustrates the results of a methodological approach in which measured thermo-hygrometric parameters were analysed not only to investigate the environment in terms of human comfort and conservation requirements, but also to study biological and entomological issues and to provide a basis for restoration activities.

Given the complexity of the case study, the aim of the research was to define a guideline for library staff based on an innovative monitoring system, in terms of effective strategies for risk reduction. The method was based on a multidisciplinary approach, which involved different professional figures and various areas of investigation: indoor microclimate monitoring, biological and entomological studies, and building simulations aimed at evaluating the impact of the strategies.

The study showed that the intermittent operation of the heating system in winter caused temperature oscillations between day and night. The problem was the opposite in summer: without an air conditioning system, temperature values were too high, especially on the mezzanine level, due to the solar radiation through the windows which had no system of shading control. The worst season was during the warmer months when temperatures were outside the ranges recommended by conservators. This aspect was also confirmed by restorers, with high temperatures being identified as the main cause of damage to the books (darkening and discoloration of the ribs of many volumes and paper dissolution), while relative humidity resulted in values inside the acceptable range for all seasons.

Analysis of the building highlighted the limits of the HVAC system, but being a listed building, any retrofitting strategies would have to be suitably designed and approved. For this reason, thanks to a calibrated thermal model of the building, some passive strategies with a low impact in terms of implementation and economic commitment were simulated at a preliminary stage. The first of these concerned the total closure of the internal shutters when the hall was not occupied. The second concerned the installation of solar control films on the windows. Each strategy was simulated individually and then combined. The effects in terms of temperature variations were very low, especially when a single strategy was adopted. When they were combined, in the warm seasons, the temperature decreased by about 1 °C. These strategies are, however, recommended for mitigating illuminance levels, even if this was not part of the study.

Thanks to the new Wi-Fi sensor system, which also measured the CO_2 concentration (with recordings available online and in real time), it was also possible to propose window opening strategies for natural ventilation and obtaining air exchange during crowded events. In fact, this was the only way of guaranteeing human comfort in terms of air quality and in relation to external conditions, without a mechanical ventilation system. Thanks to the analysis of CO_2 concentration data registered during some relevant events, it was possible to estimate the benefits obtained from opening the windows before the CO_2 reached high values. Obviously, this empirical method was based only on CO_2 concentration, without considering anything in terms of energy saving or thermal comfort.

Future developments concern the study of an MVHR system (Mechanical Ventilation Heat Recovery System), capable of providing good indoor air quality and mitigating unsuitable conditions in warmer seasons while contemporaneously protecting the artistic, structural and historical characteristics of the hall.

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