Article

Hygrothermal simulation of a historic library: a framework to assess the impact of tourism

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Abstract

A single paragraph of about 200 words maximum. For research articles, abstracts should give a pertinent overview of the work. We strongly encourage authors to use the following style of structured abstracts, but without headings: (1) Background: place the question addressed in a broad context and highlight the purpose of the study; (2) Methods: describe briefly the main methods or treatments applied; (3) Results: summarize the article's main findings; (4) Conclusions: indicate the main conclusions or interpretations. The abstract should be an objective representation of the article, it must not contain results which are not presented and substantiated in the main text and should not exaggerate the main conclusions.

Keywords: keyword 1; keyword 2; keyword 3 (List three to ten pertinent keywords specific to the article; yet reasonably common within the subject discipline.)

1. Introduction

Furthermore, integrated monitoring and simulation strategies have become indispensable tools for understanding the hygrothermal dynamics of these spaces [1]. Environmental monitoring campaigns provide essential data on indoor levels, seasonal variations, and responses to the outdoor climatic conditions.

To complement empirical data, numerical simulation tools such as hygrothermal modelling have proven valuable in predicting indoor environmental behaviour under various scenarios, aiding decision-making processes related to conservation strategies [2]. Despite their potential, the use of simulation in heritage contexts remains limited, with most applications focused on energy performance in modern buildings [3].

The further exploration of such approaches in the current work offers practitioners an evidence-based methodology to navigate complex environmental assessments to enhance the conservation of organic materials. Accordingly, the present chapter contributes to the field by focusing on three core objectives: *(i)* survey the applicable standards and guidelines related to the preventive conservation of cultural heritage under hygrothermal stress; *(ii)* conduct in situ monitoring of temperature and humidity conditions in selected case studies; and *(iii)* employ dynamic simulation tools to assess hygrothermal behaviour under different scenarios. The goal is to characterise the indoor climate conditions in heritage buildings, evaluate the potential risks to collections, and support more informed and sustainable conservation decisions.

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2. Methodology

2.1. Monitoring

The hygrothermal environment in both case studies was monitored over six years (2018 to 2023) using Onset HOBO UX100-003 hygrometers. These devices recorded *TEMP* and *RH* at 10-minute intervals. Twelve devices operated in the library with operating ranges between -20 °C and 70 °C for *TEMP* and 15 % and 95 % for *RH*, with accuracies of ± 0.21 °C and ± 3.5 %, respectively. The spatial distribution of the sensors throughout the main case study is presented in Fig.1. The percentage of missing data for each location during the six years is given in Fig. **??**.

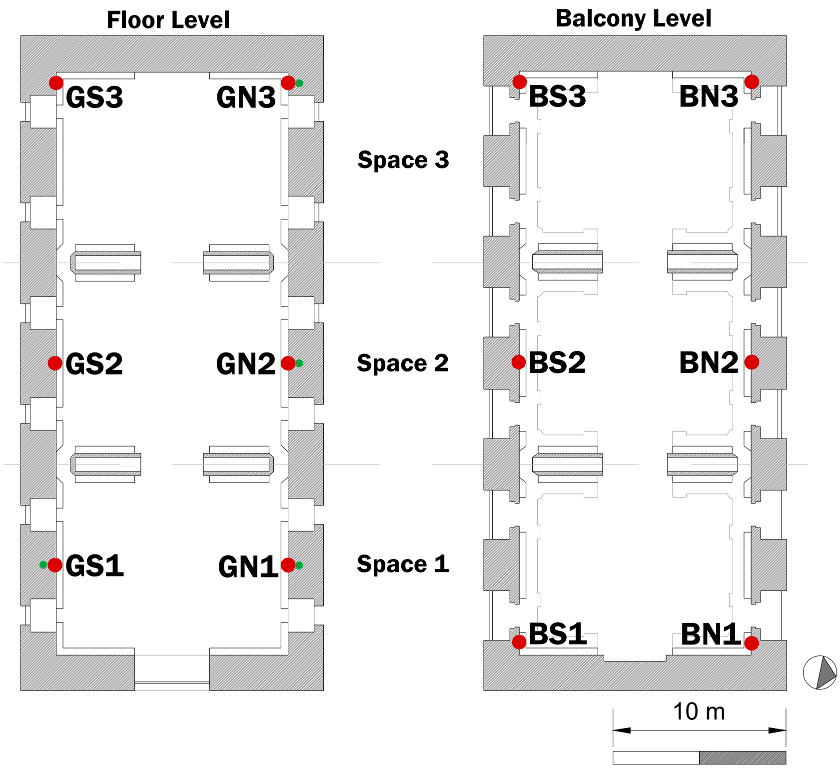


Figure 1. Floor plans of Joanina Library with the distribution of equipment. The red circles represent the thermo-hygrometers, and the green ones the devices measuring both conditions inside books.

Such monitoring sensors and their data was used to validate the simulation results within the Noble Floor.

Alongside this campaign, an additional type of device was used, given the limited studies that monitor the hygrothermal conditions directly inside collections. For example, Bülow et al. (2002) monitored the hygrothermal conditions both indoors and directly inside dummy books to identify relationships between collections and their surrounding environment, thereby understanding their buffering capabilities. This approach can be adopted to compare measurements with moving averages calculated for *TEMP* (7 days) and *RH* (30 days) following ASHRAE [5] recommendations. Thus, several paper hygrometers were directly placed inside a dummy book – Fig. 2. The devices model was RH5 from Schaller with an accuracy of ± 0.3 °C and ± 1.5 % for *RH* at 25 °C. Records were stored every 10 minutes.

Given the gradual acquisition and installation of paper hygrometers within the library, the monitored periods of these loggers varied depending on the location. Fig. 1 shows the location of all data loggers inside books (green circles). Considering that the North façade was more exposed to higher *RH*, an effort was made to place devices on this façade in LFP, varying only in their longitudinal placement between Space 1 (closest to the main door),

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

Figure 2. Monitoring devices placed inside books in location GS1.

Space 2 (in the middle space) and Space 3 (furthest from the main door). Tab. 1 presents the specifications of the equipment employed during the monitoring campaign, along with the respective recording periods.

Table 1. Summary of the two tasks regarding the different type of monitoring.

Equipment	Period	Location	Time step
Indoor environment HOBO UX100-003	1st Jan 2018 31st Dec 2023	GN1, GN2, GN3 GS1, GS2, GS3 BN1, BN2, BN3 BS1, BS2, BS3	10 min
Inside books Schaller RH5	17th Jun 2022 16th Jun 2023	$GS1_{IB}$	
	16th Jun 2023 19th Nov 2023	$GN1_{IB}$	
	17th May 2023 16th Oct 2023	$GN2_{IB}$	
	17th May 2023 16th Oct 2023	$GN3_{IB}$	

2.2. Modelling

The building was modelled using EnergyPlus 23.2.0. (started with version 9.2.0, and then updated using IDFVersionUpdater), a dynamic simulation engine developed by the U.S. Department of Energy for the assessment of building energy performance and indoor environmental conditions. The simulation was conducted to evaluate the conservation conditions provided by the indoor environment of the main case study, the Joanina Library.

The building is located in Coimbra, Portugal, where the defined climate zone is *Csb*, as defined by the Köppen-Geiger classification. Two sets of weather files were considered in this work. First, homemade weather files were produced using in-situ measurements for the validation of the simulation model (link [6]). Then, the typical meteorological year

(TMY) weather file for Coimbra, sourced from the U.S. Department of Energy database, was used to study with greater detail the hygrothermal dynamics of the building.

The model represents a total floor area of approximately 2150 m^2, distributed over three floors. The internal spaces were grouped into 56 thermal zones, based on tourism occupancy, orientation, openings, and usage. The building geometry was designed using SketchUp with the Euclid plugin, and then modelled using the IDF Editor provided by EnergyPlus. An effort was made to ensure that all thermal zones have a convex shape. The model is available online on the following link [6].

Although the three floors of the Portuguese library were modelled, the focus of the study remained on the Noble Floor, which was mainly divided into three thermal zones, Spaces 1, 2, and 3, as depicted in the x-ray view of the southern façade in Fig. 3.

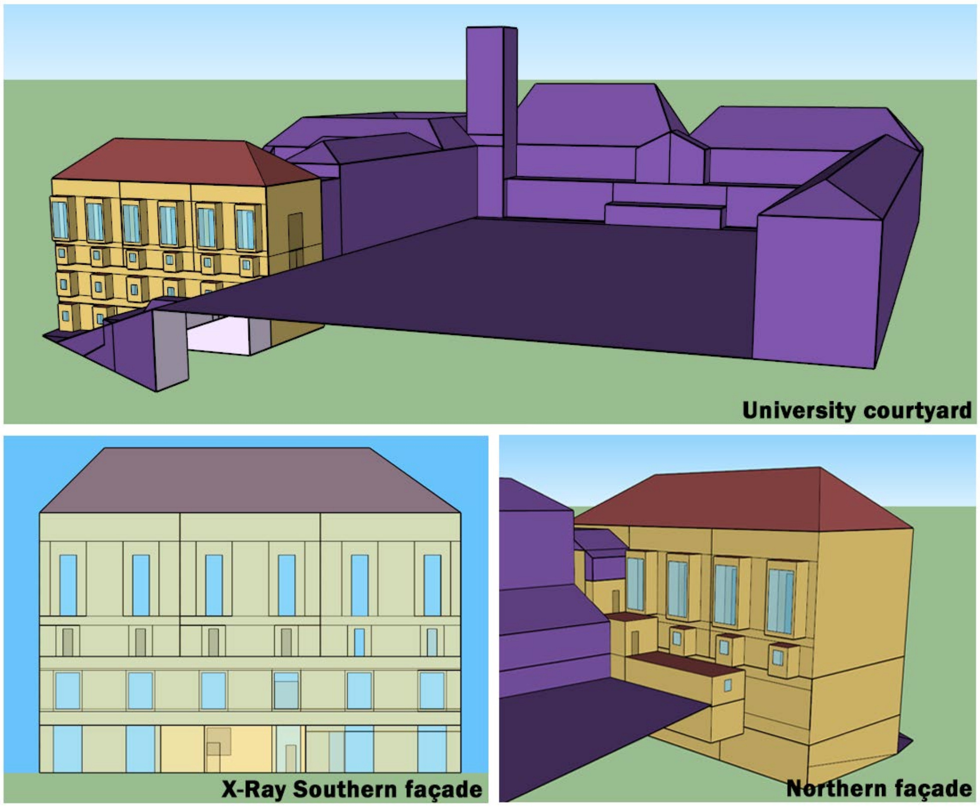


Figure 3. 3D model representation. Note: the view of the southern façade has the thermal zones of the reading offices hidden.

The archaeological research team of the University of Coimbra was contacted regarding the building envelope. However, the lack of information regarding the envelope assemblies of the historic building was limiting. Accordingly, the building envelope changed from century to century depending on the floor. Thus, the only documented research found indicated assumptions about the construction elements of the building envelope [7], which was adopted for the current work. The constructions, composed of different materials, are defined in Tab. 2, where the thermal properties for the main envelope elements are provided. The materials' database consulted was based on the Portuguese national construction practices (ITE50 [8]).

Table 2. Building envelope construction and respective thermal properties.

Element	Description (Outside to inside)	***U-Value*** [a] W.m^{-2}.K^{-1}
Opaque exterior		
External roof	Clay tile, 3 cm Wood, 4 cm	2.11
External wall	Mortar, 2 cm Limestone, 50 cm Half-timbered, 100 cm Limestone, 50 cm Mortar, 2 cm	0.49
External floor	Limestone, 50 cm	1.93
External door	Wood, 10 cm	1.16
Opaque interior		
Wood ceiling [b]	Wood, 4 cm Mortar, 2 cm	1.76
Internal wall	Mortar, 2 cm Limestone, 15 cm Mortar, 2 cm	2.67
Internal ceiling and floor	Mortar, 2 cm Limestone, 50 cm Mortar, 2 cm	1.59
Internal door	Wood, 4 cm	1.90
Fenestration		
External fenestration (windows)	Simple glass, 0.4 cm	6.01
Internal fenestration (diffusers)	Curtains, 0.1 cm	3.19
Internal wall	Mortar, 2 cm Limestone, 15 cm Mortar, 2 cm	2.67
Internal Mass		
Carpet	Carpet, 2 cm	3.00 [c]
Bookshelves	Wood, 10 cm Air gap, 10 cm Wood, 4 cm	0.75 [c]

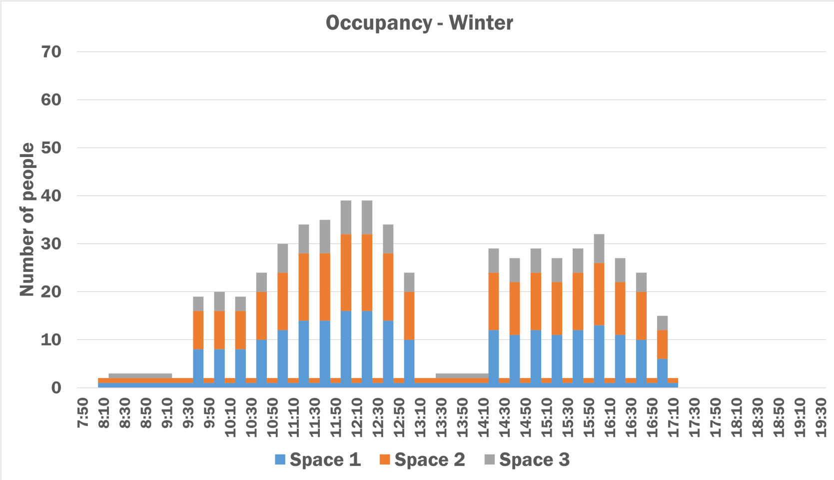
[a] Includes superficial resistances (with film).
[b] Between Noble Floor and the attic on the roof.
[c] No film was considered for internal mass elements.

Due to uncertainty around the envelope solutions, thermal bridges were not initially modelled. The validation of the model indicated whether *U-Value* was correct or if global correction factors were necessary to account for thermal bridges.

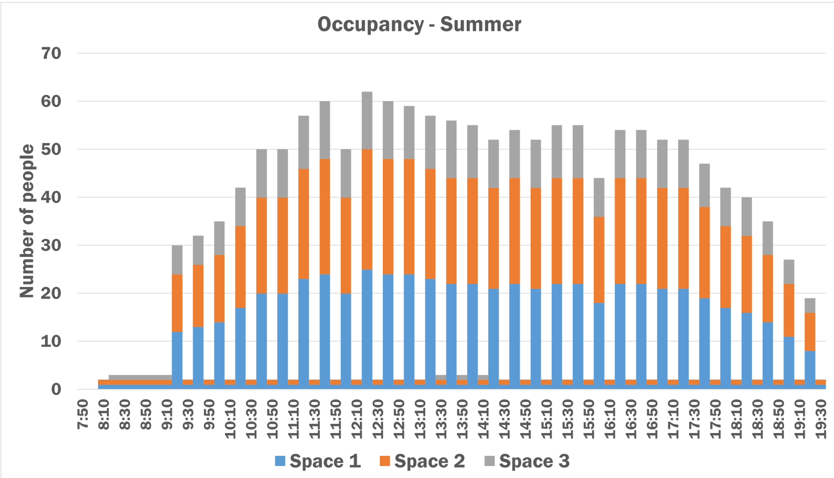
To complement the information provided in Tab. 2, the optical properties of fenestration elements are discussed: windows have a *SHGC* equal to 0.84 and a T_{vis} of 0.89; and internal diffusers have a *SHGC* equal to 0.47 and a T_{vis} of 0.60.

In terms of operational schedules for occupants, tourism schedules for 2018 and 2019 were based on the tourism data provided by the Rectory, which were used to estimate average values for each visit slot in the Noble Floor of Joanina Library, reflecting seasonal variations – as shown in Fig. 4. The occupancy levels in the Intermediate Floor were equal to the sum of the occupancy in all spaces of the Noble Floor.

The occupancy load was modelled in terms of percentage with regard to a maximum occupancy of 70 people. To evaluate the thermal comfort of the occupants, a metabolic rate of 1.4 met (people walking corresponding to a heat load rounding 144 W) was considered,



(**a**) Occupancy during the Winter.



(**b**) Occupancy during the Summer.

Figure 4. Information about occupancy schedules in the Noble Floor.

the indoor air velocity was equal to 0.1 m.s^{-1}, and the clothing insulation was equal to 1.3 clo (Winter) and 0.5 clo (Summer).

Along with the occupancy schedules, times when doors open were equally modelled to include the movement of air between different thermal zones.

In terms of operational schedules for lighting, they were turned on from 08h00 to 11h00 and 15h00 to 17h00 (Winter) or 19h00 (Summer). In each space, an installed capacity of 800 W of compact fluorescent lamps was considered as internal gain.

Infiltration rates were set according to the concept of *ACH* with a calibration work based on a parametric analysis that varied *ACH* from 0.25 h^{-1} to 0.55 h^{-1}.

Alongside the main model, an alternative simulation was conducted to account for the natural ventilation of the historic library and assess the impact of having different visiting itineraries. Door and window opening schedules were also defined to include an approach that accounts for the movement of air between different thermal zones. This was conducted using the airflow network (AFN) model available in EnergyPlus to evaluate the ventilation promoted by opening the main door for the tourists' exit and its impact on the conservation conditions of the indoor environment.

Six simulations were carried out from 2018 to 2023 (4 years with tourism and 2 without). The data from these four years was used to validate the model. Then, the study of additional measures to improve the indoor environment was conducted by simulating the building for a full calendar year, using the EPW file corresponding to the building's location. The simulation time step was set to 5 min, and surface heat balance convergence limits were maintained at EnergyPlus defaults. Outputs were printed hourly throughout one year of simulation.

Some simplifications were made during the modelling process: *(i)* internal zoning was simplified to reflect functional use rather than exact room boundaries; *(ii)* no detailed modelling of occupant behavior was included beyond schedule-based assumptions constant for all days of the week, including weekends; and *(iii)* default values were assumed for the multi-zone airflow approaches regarding wind pressure coefficients, cracks properties, and air mass flows coefficient for openings. While these assumptions may have introduced some uncertainty, the validation of the model demonstrates the consistency of results, which aligns with the study's scope.

The validation becomes, then, an essential milestone in the conservation methodology proposed in this work. Thus, it was important to carefully understand and analyse the best approaches to validate a dynamic model. A thorough review on simulation in heritage buildings was made by Huerto-Cardenas et al. (2020), who concluded that microclimatic parameters (such as *TEMP*, *RH*, or others) are usually more used for validation of simulation models than energy-related variables (thermal loads or energy consumption). The absence of climate control systems and the difficulties in measuring their energy consumption justify the focus on the environmental conditions. Within the microclimatic sphere, the same study [9] concluded that *TEMP* stands as the most frequent for validating a model, especially for comfort assessment studies. Furthermore, dynamic simulation models often do not take into account the hygrometric behaviour of environments [9], especially when the research does not intend to investigate possible problems concerning conservation of collections. However, when conservation matters, which is the primary focus of the present doctoral work, additional humidity-related variables (*e.g.*, *RH*, or others) should be considered. Therefore, for the purpose of modelling the hygrothermal environment in heritage buildings, both *TEMP* and *RH* were considered in this study for the adequate validation of simulation models. Consequently, one keeps questioning how to carry out the validation of simulation models concerning the hygrothermal environment in this type of building.

Considering that the most used existing standards (*e.g.*, ASHRAE Guideline 14) deal with model validation based on energy-related parameters, Huerto-Cardenas et al. (2020) identified the most suitable recommended thresholds for validation using microclimatic parameters, which were proposed in two levels – the results are summarised in Tab. **??**.

Tab. **??** summarises the results found in literature [9], which has some metrics that go beyond the typical approach of validation. When working for preservation of collections in heritage buildings, some authors included analyses of frequency of residuals (F_i) and the differences in terms of daily fluctuations between measurements and predictions (Q_v).

F_i focuses on evaluating differences between measured and simulated values (deviation) and verifying the percentage of them that remain below an acceptable threshold [10]. This metric offers a more informative assessment than traditional statistical indices, as it emphasises the distribution of deviations and forces that 95 % of deviations should be lower than the proposed thresholds presented in Tab. **??**.

Kilian (2013) proposed a validation method for preventive conservation models based on assessing the risk of degradation from microclimatic fluctuations. Considering the relevant impact of *RH* and its fluctuations in the preventive conservation assessment, the same author introduced the Prediction rate (Q_v), which compares the number of days with *RH* fluctuations exceeding a critical threshold between simulated and measured data to evaluate a model's predictive accuracy. Q_v is expressed by Eq. 1.

$$Q_v = \frac{N_s}{N_m} \quad (1)$$

Here, *Ns* and *Nm* are counters of the number of times when the simulated and measured daily *RH* cycles exceed a certain daily fluctuation threshold, which should depend on specific thresholds recommended by conservation norms (*e.g.*, UNI 10829 [12]). The recommended thresholds for Q_v to validate prediction results are presented in Tab. **??**.

In the context of cultural heritage conservation, those two metrics can be particularly relevant depending on the type of collections stored in the building, as they enable the inclusion of conservation approaches upon the validation of hygrothermal simulations. However, Q_v was not adopted in the present work, considering the literature review indicates that daily fluctuations have little impact on the degradation of hygroscopic materials.

R should not exceed a maximum value for validation threshold (< 0.5) [9], but it ends up being redundant when R^2 is already assessed. Therefore, *R* was not considered for the validation approach.

In conclusion, according to most of the literature [9], a model is considered validated when a very high share of residuals are within the specified intervals, simulated *RH* fluctuations are similar to the measured ones, and it performs well for general statistical metrics (*RMSE*, R^2, and *IC*).

3. Conclusion

Preserving the hygrothermal environment in museums and heritage buildings demands careful attention to artefact conservation. By integrating standards and guidelines, monitoring tasks, and modelling simulations, institutions can study further strategies to find more balanced solutions that need to find a good compromise among all decay methods of delicate materials. The adoption of these multidisciplinary approaches is critical to ensuring the sustainability of collections and cultural heritage buildings themselves, particularly as climate change and increasing visitor numbers are introducing new challenges in the future.

The present chapter started by surveying state-of-the-art guidelines and damage risk metrics, and proposed a framework to clarify the most adequate assessment tools. Based on available documentation, a need to evaluate the effectiveness of general guidelines against various types of damage-risk models (biological, chemical, and mechanical) was identified. The methodology referred to records of a six-year monitoring campaign of hygrothermal conditions in two case studies. Then, compliances between the guidelines and damage metrics were assessed using confusion matrices, which constituted a novelty in this type of approach. The analysis of compliance between general guidelines and damage risk models yielded several insights. General guidelines effectively addressed fungal and mechanical damage risks. However, they fell short in safeguarding against insect and chemical damage. Among the tested guidelines in these case studies, ASHRAE Class B emerged as a reliable standard for assessing chemical and mechanical risks. At the same time, EN16893 was most effective for mitigating biological damage risks – **RQ1**.

The monitoring campaign combines in-situ records of temperature and relative humidity in the indoor environment and also within collections (hygrometers placed directly inside books). At the same time, modelling was employed to explore further the impact of opening doors and tourism, and estimate the thermal loads – **RQ2**.

This work supported the characterisation of the hygrothermal environment in Joanina Library and the validation of the hygrothermal model of the case study. Measurements demonstrated more thermal dependence on outdoor climate than on relative humidity, which showed weaker correlations. A seasonality of the indoor parameters was identified, with Summer and Winter being the most harmful. The running periods recommended by guidelines to predict the books' response to fluctuations were contested. It was recommended that the historical climate should be calculated using periods of 10 h and 21 days for temperature and relative humidity, respectively, which are different from those recommended. From a decay perspective, collections were more exposed to chemical decay (and some biological) than mechanical decay.

Tourism impact was not noticeable when comparing the historical climate throughout the six years, but increased the hygrothermal parameters during periods of high tourist rates in the Summer. During the Winter, the sensible heat load generated by occupants can help reduce relative humidity. Nonetheless, both the number of visitors and respective metabolic rates are noticed, slightly the natural conditions of the indoor environment – **RQ3**.

When looking for solutions, some passive strategies were contemplated. It was shown that opening the main door promoted the interaction between indoors and outdoors, although it was not proven that there is a negative impact or an improvement in conservation conditions from the analysis of data from devices placed inside books. Similarly, creating an alternative entrance did not significantly improve the indoor conditions. Therefore, six dehumidifiers were installed on the Noble floor to reduce humidity levels. It is recommended that further solutions should be investigated, namely, exploring climate control systems for cooling during the Summer to reduce temperature and relative humidity (chemical and biological risk, insect pests), and heating during the Winter to reduce peaks of relative humidity (biological risk, fungal) – **RQ4**. Besides the technical challenge of incrementally controlling the historical climate to minimise risks, the job becomes even harder when looking for an equilibrium between conservation and energy consumption, especially for the coming years with the problem of climate change.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.", please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

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Acronyms

The following abbreviations are used in this manuscript:

BJUC	Biblioteca Joanina da Universidade de Coimbra
FCT	Fundação para a Ciência e a Tecnologia

Nomenclature

The following variables are used in this manuscript:

TEMP	Air temperature, °C
RH	Air relative humidity, %

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