

Review

Up-To-Date Challenges for the Conservation, Rehabilitation and Energy Retrofitting of Higher Education Cultural Heritage Buildings

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Abstract: In higher-education world heritage sites, the conservation and energy retrofitting of heritage buildings (HBs) is an important vector for their development, competitiveness and welfare. To guarantee their ongoing use, these buildings must be adapted to face current and emerging societal challenges: (i) the conservation of cultural heritage and the maintenance of their original characteristics and identity; (ii) the transformation of heritage sites into tourist centers that energize the local economy, generating revenue and jobs; (iii) the adaptation of the buildings to new uses and functions that demand energy retrofitting strategies to satisfy today's standards of thermal comfort, indoor environmental quality (IEQ) and energy efficiency; (iv) tackling impacts of climate change, particularly global warming and extreme weather events; and finally, (v) the implementation of strategies to mitigate the impact of a growing number of tourists. The combined implications of these challenges require a comprehensive approach with interrelated measures strongly reliant on the use of technology and innovation. This work aims to discuss how higher-education cultural HBs can be rethought to serve these expectations. Moreover, a multidisciplinary intervention framework is provided to discuss how HBs can respond to the challenges and risks of rehabilitation, energy retrofitting, climate change and increasing tourism.

Keywords: heritage buildings; higher-education world heritage sites; retrofitting; energy efficiency; indoor environmental quality; multidisciplinary approach; in situ measurement; building simulation



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1. Introduction

Currently, the debate on climate change, fossil fuels depletion and energy security highlights the need for a more sustainable built environment [1]. As stated by Roque et al. [2], the improvement of the thermal performance and energy efficiency of historic building stock has the potential to revitalize these buildings and reduce their operational energy costs. In higher-education world heritage sites, like the Alta area of the University of Coimbra [3] or the city of Ferrara [4], heritage buildings (HBs) have been cyclically adapted (or readjusted) for new uses over time. This cycle is part of the history of these buildings that must be preserved. However, to guarantee their use in the future, these buildings must also be adapted (adaptive reuse), repaired, rehabilitated and/or retrofitted to face current societal challenges and user expectations regarding thermal comfort and energy efficiency [5], as seen in the “new heritage” 20th-century architecture pieces, of the Urbino University Colleges, designed by architect Giancarlo de Carlo [6]. By definition, rehabilitation is the act of restoring a building to its original state; repair aims to bring back the architectural and functional shapes of the building so that all activities can resume; and energy retrofitting is the act of adding new features, materials, technologies and/or active systems that had not earlier been used in order to improve the thermal and energy performance of the building, improve indoor environmental quality (IEQ), save energy and reduce environmental emissions.

In literature, the following challenges have been addressed to bring HBs to the 21st century, as shown in Figure 1: (i) the adaptation of HBs to new uses and functions demands energy retrofitting strategies to satisfy today's thermal comfort, IEQ and energy efficiency requirements; (ii) the conservation of cultural heritage and the maintenance of the original characteristics and identity of HBs must be preserved in any retrofitting intervention; (iii) the transformation of heritage centers into tourist centers that energize the local economy, generating revenue and jobs, is a great opportunity to simultaneously draw conservation funded plans; (iv) the growing number of people visiting HBs, namely tourists, must be considered in order to mitigate adverse impacts of visitors in the heritage buildings' structure and IEQ, as well in museum collections and/or libraries hosted in these buildings (notwithstanding the current COVID-19 pandemic that has reduced touristic increase through 2020 [7,8]); (v) future climate change scenarios must be addressed, namely global warming and extreme weather events. Additionally, the worldwide trend of existing regulations typically includes exceptions for the energy retrofitting of HBs due to its difficulty, which has its pros and cons. Considering all these challenges, this paper aims to answer—or at least bring up discussion—on the following research question: “How can higher-education HBs located in heritage sites respond to the challenges and risks of rehabilitation, energy retrofitting, climate change and increasing tourism?”

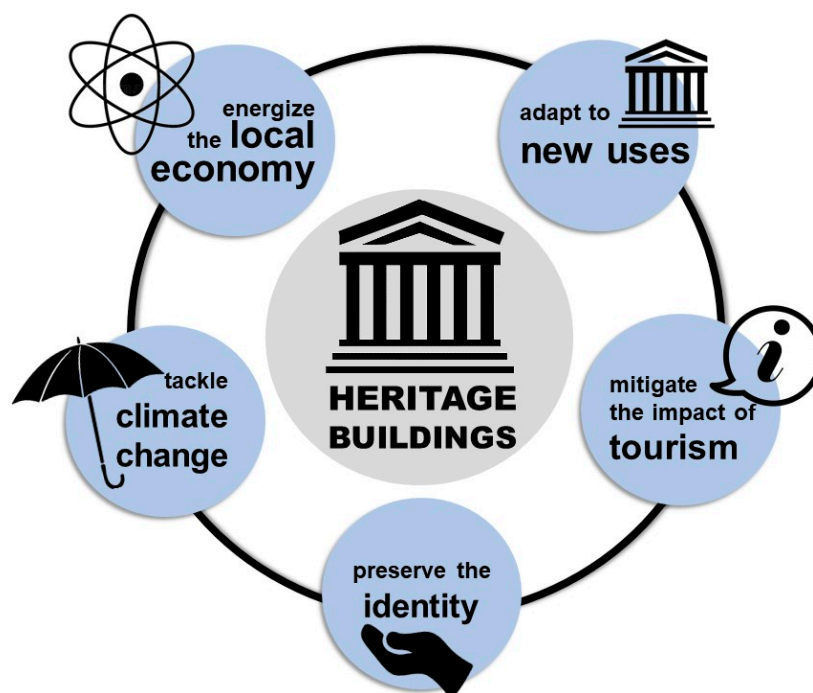


Figure 1. 21st-century challenges for heritage buildings.

Soares et al. [9] have highlighted the importance of the improvement of energy efficiency and the environmental performance of systems, the development of new technologies, increasing the use of renewable energy sources, the promotion of holistic and multidisciplinary studies [10] and the implementation of sustainable oriented policies at different scales. To draw a sustainable multidisciplinary intervention framework for higher-education HBs, several areas of expertise have to be taken into account. For instance: (i) energy audits, building and systems monitoring assessment and energy efficiency planning [6]; (ii) cultural heritage and preventive conservation analysis, including control of IEQ parameters, safeguarding of collections from a preventive conservation perspective and proposing non-invasive measures aimed at mitigating the potential risks of the effects of increasing numbers of visitors [11]; (iii) the development and/or use of non-invasive in situ monitoring to measure the thermal and hygrothermal performance of historic con-

struction elements [12]; (iv) using innovative materials and construction solutions while maintaining the identity of heritage constructions [13]; (v) using more efficient active systems to guarantee thermal comfort and IEQ [14]; (vi) the implementation of solutions and systems based on renewable energy sources [15]; (vii) building information modeling, design and the incorporation of energy efficiency concerns in the design of intervention plans [16,17]; (viii) dynamic simulation of energy in HBs and prediction of the energy performance of buildings in future climate change scenarios, including different tourism scenarios and future climatic data [15,18].

Improving a HB for the future is the best way to promote its heritage sustainability. To address this problem, the main purpose of this work is to report the importance of wider multidisciplinary frameworks, conscious rehabilitation and energy retrofitting strategies to support decision makers. This work also aims to contribute to the discussion of the importance of the conservation of higher-education cultural HBs. Built heritage problems cannot be faced as simple conservation problems, but rather as integrated and living parts of the built environment with the ability to adapt to new functions, needs and requirements, as well as living parts of the activities of higher-education institutions and the academic community. In other words, the conservation of this tangible heritage should be able to guarantee and promote its previous intangible and unique values and ‘experimental experience’, and contribute to the sustainability of higher-education world heritage sites.

2. The Importance of Multidisciplinary Methodologies Converted into Virtual Libraries

Within this context, the words of Garner and Mann, “Design for the built environment is probably the most multidisciplinary practice in all of the design professions” [19], gain an even greater meaning.

Nowadays, the development of multi- and interdisciplinary rehabilitation and energy retrofitting methodologies being converted into online open-access libraries should be seen as an important tool to foster sustainable worldwide intervention in higher-education cultural HBs, as the information can be made available for a larger audience, including both practitioners and academics. In ref. [20], authors proposed a new 8-phase protocol aimed at supporting the adoption of HBIM (historic building information modeling) in heritage intervention, named BIMlegacy, which goes slightly beyond existing life-cycle management methods such as the RIBA Outline Plan of Work [21].

Additionally, the methodologies developed for specific case studies can be extrapolated more easily to other cases. These libraries should consider the following features: (i) they should provide detailed building models with virtual scenes, validated simulation models, performance reports on several evaluation dimensions (e.g., thermal/hygrothermal performance of the envelope, energy performance of the systems, thermal comfort parameters, IEQ, etc.); (ii) they should engage the general public, practitioners, architects, engineers, decision-makers and academia—as the higher-education sector holds important functions in educating the next generation of professionals for a sustainable culture [22]—and provide education activities; (iii) they should contribute to the life extension of HBs and the promotion of their cultural and patrimonial values by openly disseminating their cultural heritage via online library and design strategy reports. These libraries should also comply with the UN 2030 Agenda goals as they will promote sustainable consumption of energy and resources, and they will contribute to combating the impacts of climate change. By exploring the sustainability of tourism [23] and developing an open dissemination program, these approaches also hold an inclusive and socially sustainable character.

In order to develop a multidisciplinary rehabilitation and energy retrofitting methodology converted into a library with virtual models (as proposed in [24] towards the creation of a sustainable and interactive archiving platform in Qatar; as exemplified in Figure 2), the following objectives are typically defined:

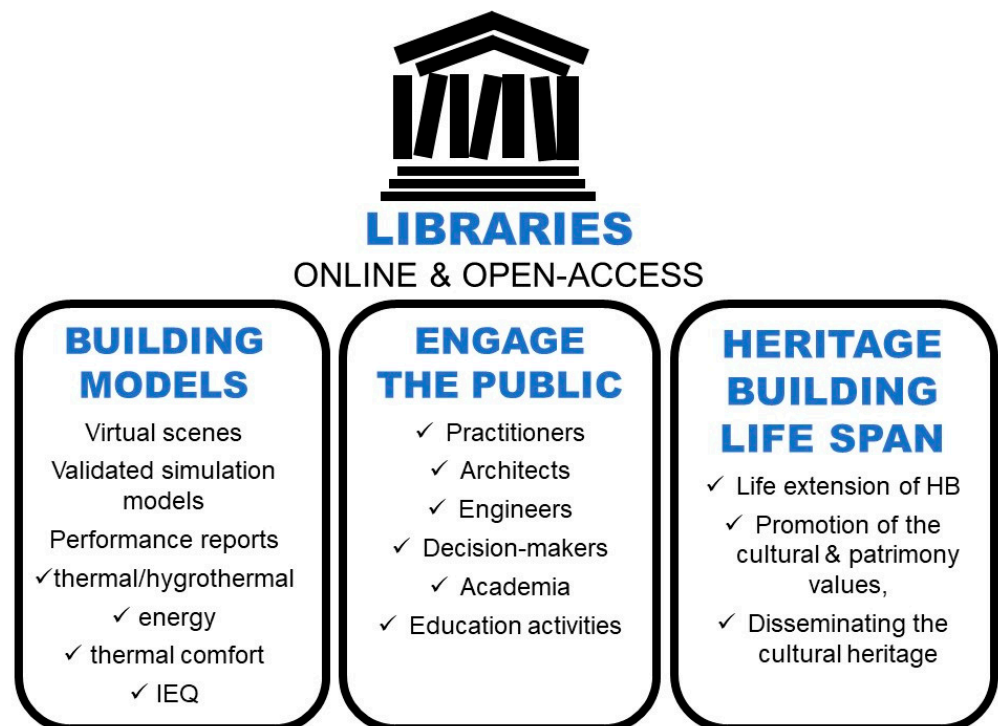


Figure 2. Historic buildings libraries with virtual models addressed objectives.

- Characterization and planning of the monitoring of the energy systems performance, activities and occupancy, including: (i) 3D laser scanning of the building and HBIM; (ii) planning in situ measurements to characterize the thermophysical properties of the building envelope and design energy retrofit solutions (U -value and hygrothermal monitoring), as suggested in various reports of European projects (see refs. [25,26]) or field studies (see ref. [27]); (iii) market survey/invitation to participation of companies/manufacturers of construction materials and solutions;
- In situ monitoring of energy consumption and IEQ, e.g., indoor air quality (IAQ) parameters, thermal comfort (assessed objectively and subjectively), lighting sampling and in situ monitoring/testing of energy retrofit solutions;
- Detailed digital models of the building and its surroundings via BIM; dynamic simulation modeling of the energy in HBs; hygrothermal simulation modeling, and validation of the models (with the surveyed monitored data); complementary, lighting simulation tools shall also be used;
- Performance analysis of IEQ, energy and hygrothermal parameters;
- Report of conscious and informed intervention strategies, followed by the implementation of a digital library of the building with virtual models.

In short, the HB shall be surveyed and monitored, and models shall be developed as an information repository. Afterwards, dynamic simulation models can be validated with onsite measurements. The models can then be used to assess and evaluate potential intervention strategies considering future scenarios (e.g., climate change extreme events such as higher temperatures).

In more detail, the proposed methodology starts with a thorough analysis and characterization of the HB to gather data on the construction system, building pathologies, building geometry and surroundings, energy consumption, activities and occupancy of the building. In this phase, the virtual BIM structure with geographic survey data (collected using laser scanning and photogrammetry, as suggested in ref. [28]) can be created. This will then be used as a digital and georeferenced repository of the information collected during the survey of all existing data (e.g., mapping the sensors location, harvesting more precise and correlated data, facilitating data storage). In parallel, energy retrofiting

solutions can be carefully planned, and in situ experiments can be carried out (e.g., to evaluate the thermal resistance of the building envelope, as well as to monitor the hygrothermal performance of historic elements). The performance of such solutions can be monitored through remote sensing technology designed for the hygrothermal assessment of historic walls in a conservation-compatible mode [29]. These initial steps of the methodology should be done in agreement with the most recent 'Guidelines on energy efficiency of cultural heritage' [30], current practices/research activities [31,32] and other codes/protocols/examples addressing this matter [33].

Then, energy consumption patterns (including lighting, heating, cooling and other appliances) shall also be monitored. This way, these data can be used to validate models built in dynamic building energy simulation programs (e.g., EnergyPlus). These are important approaches since a building's effective construction type is likely not known with sufficient detail a priori.

After the models are created and validated, the energy performance of the building can be assessed for different scenarios, including the construction pathologies; the energy consumption (and hot-water production, if possible) and the IEQ performance. The effect of climate change can also be predicted by using morphed weather data for future projections (2050 and 2080) according to the Intergovernmental Panel on Climate Change's data report from the UN [34]. Constraints and requirements that may restrict intervention and design strategies should also be reported.

Finally, multidisciplinary intervention methodologies can be defined. These strategies will address construction pathologies, ensuring structural integrity (or even improving it) and improving buildings' energy performance; they can also propose passive design measures and/or eventually suggest air-conditioning systems or other active systems to improve the energy efficiency of the HB. The reports, HBIM and simulation models should be made freely available online (Figure 2).

3. The Importance of In Situ Characterization and Planning

In situ diagnosis and characterization of the current status of the building stock is vital for drawing any intervention strategy. As the building envelope plays an important role in terms of energy consumption, tests and field data are imperative to measure the building's actual behavior, especially in HBs, since the building's envelope properties are often unknown. In fact, energy auditors often use assumptions and simplifications to predict it. However, as reported by Roque et al. [2], wrong estimations or excessive simplifications may have a severe impact on a thermal behavior assessment and consequently on the effectiveness of any retrofitting measures. The in situ assessment of the thermal resistance of both the external and internal envelopes of HBs is one of the most relevant parameters for the characterization of building elements and is vital for the simulation of different aspects of the whole building, and for considering alternative retrofit strategies and climate change scenarios. In parallel, objective and subjective IEQ surveys are important to assess both the conservation conditions of the exhibited items and the comfort of the users/visitors, and to assess the need of reducing their impact. Finally, the combination of these two reports can be used to draw an intervention approach and mitigation strategies against climate change.

In short, the following steps should be considered in the in situ characterization and planning phase (Figure 3):

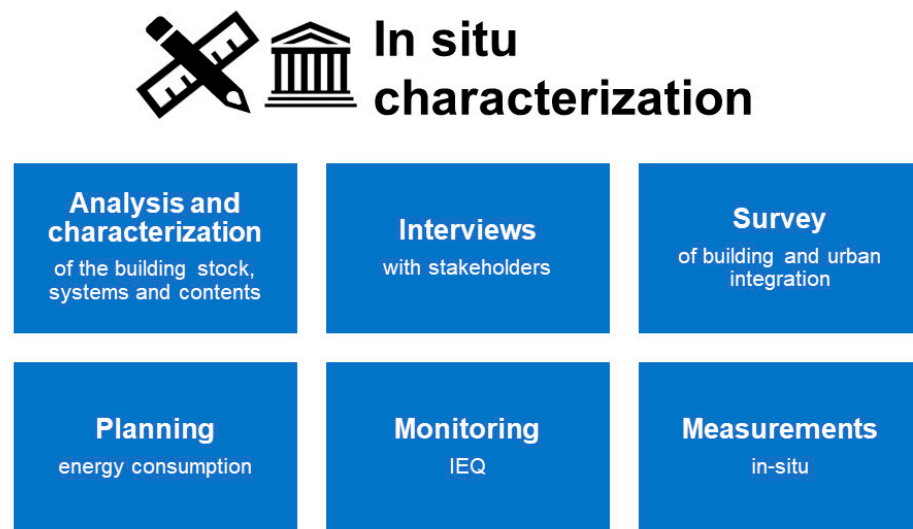


Figure 3. Heritage buildings in situ characterization and planning synthesis.

- Analysis and characterization of the building stock, systems and contents—Here, the whole building should be characterized. This includes information on the building construction and materials, interior spaces' arrangement and function, energy consumption of different systems (air-conditioning, ventilation, lighting and other equipment) and current occupancy in every space. Additionally, construction conservation and indoor environment preservation requirements are identified. This information is used to plan both the building survey and the indoor environmental campaign.
- Interviews with stakeholders—Interviews with the different stakeholders and decision makers can be carried out to assess the expectations of the users and owners of the building. The reported information can also be used in the monitoring campaigns and in the definition of multidisciplinary intervention methodologies.
- Building and urban integration survey—A survey of the constructive elements should be performed, including a technical characterization based on existing documents, bibliography, interviews, figure recording and in situ inspection (including pathologies and thermal bridges, e.g., thermography imaging). These data are required to accurately model and analyze the building's energy performance and will also identify the best strategies for improving it. This step includes 3D laser scanning and initial HBIM modeling.
- Planning energy consumption and IEQ monitoring—This includes the survey of construction typology, type of space activity, number of people and periods of occupancy, energy consumption of systems and operation scheduling, type of HVAC system, etc. This information can be complemented with analysis of energy bills and equipment technical sheets. These data are required to accurately model and analyze the energy performance of the building.
- Planning in situ measurements—Mainly, this step includes the measurement of the U -value of some building envelope elements with non-destructive tests (e.g., the Simple Hot Box—Heat Flow Meter Method (SHB-HFM), based on the procedure described in standard ISO 9869) [35], and hygrothermal monitoring.

4. The Importance of In Situ Building Monitoring

Monitoring energy consumption patterns is vital, and this information is obtained mainly from an energy consumption systems survey, including specific information about equipment operation schedules and power demand that might not have been determined otherwise. In these cases, power meters can be used to measure operation periods and power consumption variability. In addition, the overall energy demand of the building can

be collected from records and utilities bills. These data will be organized and archived to be used for modeling and validation purposes.

In situ monitoring campaigns should also be continuously performed considering the type of use, occupancy schedule, number of users, presence/absence of HVAC systems and outdoor conditions (climate and pollution levels). Assessing thermal comfort (objectively and/or subjectively) during the year can also provide important information in terms of the operation of active or passive systems and the need to improve the current technologies or implement new solutions. In parallel, indoor lighting conditions should be assessed, and the existing luminaires and shading systems should be verified against the surveyed technical plans (Figure 4). This information will be used to validate the simulation models. Besides using the existing equipment to monitor IAQ, some monitoring kits for indoor temperature, relative humidity and CO₂ concentration should be used. Outdoor climate data may be obtained from the nearest meteorological station that openly provides real-time weather information data.

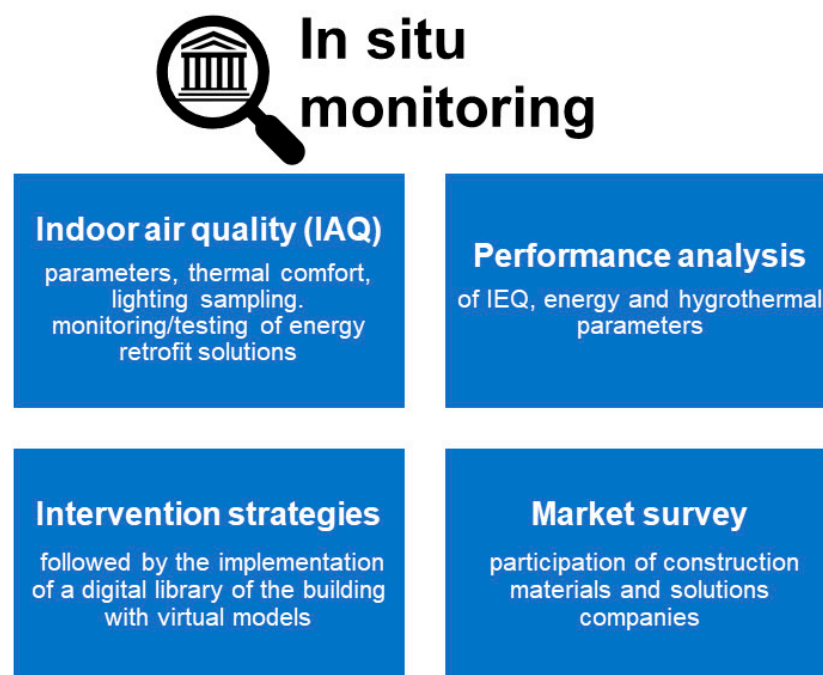


Figure 4. Heritage buildings in situ building monitoring synthesis.

Besides thermography imaging, other noninvasive methods should be used to evaluate the thermal transmittance and behavior of walls, windows and other construction elements, as reviewed by Soares et al. [36]. In parallel, some retrofitting measures can be installed and monitored, accompanied with remote sensing technology applied to the installed sensors, with software control (e.g., email notification to ensure everything is running, hourly backup copy of raw data on local drive, and a daily PDF report produced at midnight on local drive). Web pages can also be considered with summaries of systems and measurement details updated every minute and synchronized with an online web server.

5. The Importance of Building Simulation

HBIM models of the building and its surroundings are built after the automatic data collection (laser scanning) of the geometry and using parametric objects. In the case of HBs, BIM models are often complemented with the use of the Revit platform [37], as in the following Italian studies [38,39].

Later on, the HBIM model can be used in the dynamic simulation of the energy in buildings software to assess the thermal/energy performance of the HB (Figure 5). In ref. [40], the authors highlight the importance of BIM use in existing buildings towards their

renovations. In ref. [17] instead, authors highlight the crucial role that HBIM can have on risk management in the preservation and intervention of heritage buildings in the cultural heritage domain. Often, these models are also complemented/combined with virtual reality (VR) [41,42]. The surroundings of the buildings are typically modeled at a low level of development (LOD) since only the basic geometry will be needed for subsequent tasks related to the simulation models and 3D viewing. The models of the building are developed at a higher level, since they are required for the adequate representation of individual construction systems and elements (including structures, HVAC, etc.). An overall LOD goal of between 200 and 300 is considered sufficient for most elements, as in ref. [20], although detailed modeling requirements will be specified before modeling takes place. Although the models are developed using commercial BIM authoring tools, they can be exported and made available as IFC files (an open access standard for building information).



Figure 5. Historic building information modeling (HBIM) digital model premises and outputs.

With the HBIM model of the building and surroundings, a dynamic energy simulation model can be created using, for instance, EnergyPlus from the US Department of Energy. All thermal zones must be modeled to consider all occupancy types and profiles, equipment usage, lighting conditions, hot water consumption, air-conditioning, mechanical and/or natural ventilation, constructive system, shadowing elements and other energy systems.

Through the use of dynamic calculation, the hygrometric simulation of some construction elements can also be carried out. Lighting schemes and daylighting can also have significant energy saving potential in an energy-efficient HB. Therefore, daylight illuminance and its consequences should be modeled in the energy analysis process with the application of simulation software.

The previous simulation models should be validated using the monitored data, seeking an accuracy of 5% and 10%, respectively, for monthly averages and hourly criteria (ASHRAE 140-2011) [43]. The accuracy of the models is essential to adequately analyze the current state of a HB, to evaluate intervention measures, and to determine future impacts from climate change scenarios using morphed weather data.

6. Assessment of the Thermal and Energy Performance of the Building

Data from monitoring campaigns and validated simulation models, as proposed in ref. [38], can be used to carry out a multidimensional analysis considering the building's function, construction pathologies, energy performance and energy consumption patterns, thermal comfort, IEQ analysis, hygrothermal performance of the historic construction elements, etc. Indeed, with the energy consumption data and the validated energy model, a parametric study can be carried out to test different actions and measures to reduce the energy consumption, identify passive design solutions and compare alternative energy systems combined with passive actions (e.g., ventilation strategies, indoor thermal mass, etc.), as planned in ref. [44]. As a building's behavior might change under new climate conditions, future challenges of climate change (e.g., using different climate scenarios) should also be considered, as suggested in ref. [45]. This assessment can compare typical weather files and weather-morphed data simulations using the CCWorldWeatherGen (Univ.

of Southampton, UK) [46], according to the Hadley Centre Coupled Model. At the end, the most capable interventions can be defined, considering the improvement of the solutions in terms of energy consumption, IEQ, thermal comfort, minimizing/avoiding the identified pathologies and risks, etc. Improvement measures are expected to be suggested towards IAQ upgrades and the conservation conditions of exhibited items (e.g., the objects in the museum halls and libraries) through the operation of active systems or the introduction of passive actions. It is also likely that the implementation of new solutions and the improvement of current technologies will be suggested.

7. Conclusions

This paper presented a multidisciplinary intervention framework for the sustainable rehabilitation and energy retrofitting of higher-education cultural HBs. It was concluded that these buildings must be updated to adapt to new uses and functions, meeting the requirements of thermal comfort, IEQ and energy efficiency; the rehabilitation/retrofitting frameworks must respond to the challenges and risks of climate change and increasing tourism; the conservation of cultural heritage and the maintenance of heritage identities have to be guaranteed; all the stakeholders must be involved in the process, including owners, practitioners, engineers, architects and the academic community and other users/visitors; the intervention frameworks must potentiate the reduction of energy consumption and CO₂ emissions; they should also facilitate the use of new construction technologies and more efficient active systems.

This work has also discussed the importance of converting multidisciplinary methodologies into open-access virtual libraries, through the use of technology and innovation as HBIM libraries, to foster sustainable worldwide intervention in higher-education cultural HBs. Finally, it was concluded that the in situ characterization of the building stock, the development of monitoring campaigns during the different phases of the intervention process, the development of validated simulation models to predict the behavior of the HB in different scenarios and, finally, the assessment of the thermal and energy performance of the building (before and after the implementation of the intervention) are important steps to be accomplished during the intervention process.

List of Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
HB	Heritage Buildings
HBIM	Historic Building Information Modeling
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
LOD	Low Level of Development
SHN-HFM	Simple Hot Box—Heat Flow Meter Method
<i>U</i> -value	Thermal transmittance (W/m ² K)
UN	United Nations
VR	Virtual Reality

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