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Integration of structural performance and human-centric comfort monitoring in historical building information modeling

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ABSTRACT

The integration and processing of monitoring data in Historical Building Information Modeling (HBIM) can aid the design, restoration, and maintenance activities of historic buildings through the conscious assessment and potential improvement of their performance. In this regard, this paper presents a new methodology for performing structural performance and human-centric environmental comfort monitoring of historic buildings within the HBIM environment. A new Python-based software application, named H2BIM, developed by the authors to fully implement the proposed approach in Revit, i.e. the BIM design authoring platform by Autodesk, is also developed and implemented for the first time in this paper. The effectiveness of the novel methodology and developed software is demonstrated through an application case study involving a recently renewed historic building located in the countryside of Perugia, Italy, and subjected to various monitoring activities within the framework of GEOFIT Horizon 2020 Project. Obtained results highlight the multidisciplinarity and high interoperability of the new approach, whose employment via the developed software led to a comprehensive assessment of the building during its operating conditions.

1. Introduction

The international building heritage, especially in Europe, comprises a large number of historic buildings such as churches, castles, and palaces, of immeasurable cultural value. Considering their construction period, which took place before 1960 for 38% of the structures included within the European building stock and between 1961 and 1990 for another 45%, historic buildings often demand for refurbishment interventions aimed at restoring/improving their structural integrity [1], energy efficiency [2], and indoor microclimate conditions to ensure a safe and comfortable living of their occupants. Evaluating the health state and thermal comfort during the service life of the building is, therefore, a task of the utmost importance for decision-makers since it can help new design and lead to the prompt scheduling of targeted restoration and maintenance interventions. For this purpose, tailored monitoring systems can be employed as a source of knowledge on the performance history of a building. In particular, vibration-based monitoring systems can be adopted to globally assess the structural performance of historic buildings [3–5], while microclimate monitoring stations are implemented to gather information on indoor environmental conditions for the comfort of the occupants [6] and for better predicting their behaviour in terms of energy needs [53], but also for the preservation of historic buildings and their community content [7]. To date, the design process of refurbishment interventions is increasingly often managed through the use of software tools for Building Information Modeling (BIM), a holistic approach integrating different design aspects in a common digital environment with a high grade of uniformity, which in the case of application to historical structures takes the specific name of Historical Building Information Modeling (HBIM) [8]. HBIM methodology is generally applied to interventions on historic buildings. The aim of the process is to expand the potential of the BIM paradigm. Currà et al. [9] affirmed that the information given by an HBIM model consists of the representation of the built object allowing the evaluation of the actual correspondence to the state of the art and the value of different levels of performance. This kind of information can be useful to identify the knowledge gap in historic buildings and to propose a theoretical method for built heritage [10], as stated by Garcìa--Valldecabres et al. The cooperation of multiple disciplines within the

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same design and analysis process is a characterizing factor of the BIM methodology as well as of the HBIM, which tools can be used as a comprehensive data set of information about all disciplines [11]. Consequently, different technical aspects can be involved into the HBIM paradigm as shown by the work of Dore et al. [12] who performed a structural and conservation analysis to measure the impact of war damage, and Khodeir et al. [11] who on the other hand, exploited the integrating HBIM tools within a case of a sustainable retrofitting intervention of heritage buildings in Egypt. In this context, the need to embed information and data from different monitoring systems within the HBIM framework to achieve an integrated and conscious design of the restoration and maintenance activities is of pivotal importance [13].

Several research studies addressing the inclusion of monitoring systems in BIM have been published over the last few years. Specifically, with regard to Structural Health Monitoring (SHM) systems, Park et al. [14] developed a plug-in program allowing the visualization of monitoring data directly via the BIM model of a pedestrian steel bridge equipped with different types of sensors such as strain-gauges, accelerometers, and tilt-meters. Delgado et al. [15] proposed a methodology to model SHM systems on BIM models by also presenting its implementation for the managing and visualization of strain measurements acquired from a set of fiber-optic sensors installed on pre-tensioned concrete beams of a bridge. That approach was subsequently improved by including the automatic generations of parametric BIM models of structural monitoring systems and by enabling the visualization of the monitoring data in a 3D dynamic and interactive environment [16]. Boddupalli et al. [17] developed a visualization tool for BIM software aimed at facilitating decision making on maintenance and rehabilitation of large structures using long-term SHM data. Singh et al. [18] proposed a web-based approach allowing vibration-based system identification within the BIM framework. On that basis, the authors also developed an effective management and visualization tool for bridge maintenance. Deng et al. [19] proposed a visual safety warning method for SHM of bridges encompassing data acquisition and storage, output analysis, and early warning information recording and sharing. Considering the integration of indoor microclimate monitoring systems in BIM, Chen et al. [20] implemented an ontology engineering approach to prototype the relationship among monitored data from sensor networks and indoor thermal and acoustic comfort of the occupants. Penna et al. [21] integrated the indoor comfort data collected in a residential building into its BIM model to the purpose of improving the visualization of the data and the management of the building energy system. Similarly, Kazado et al. [22] developed different approaches for the integration of monitoring systems and sensors in BIM models to allow the visualization of real-time and historical data. They demonstrated how this approach can improve the efficiency of facility management by providing monitored data to property managers, owners, and occupants during the lifecycle of the building. A step forward was made by Xie et al. [23], who developed a tool supported by augmented reality technologies to automatically detect environmental anomalies and faults and, therefore, assist facility managers in the control of the thermal comfort of the occupants. In this framework, Valinejadshoubi et al. [24] suggested a solution based on BIM and Internet of Things (IoT) to provide a sensor-based alert system integrated into the building BIM model for the control and the visualization of thermal comfort conditions. The proposed system was demonstrated to be effective in transmitting alarms to the facility manager when required. A similar approach was implemented by Desogus et al. [25] in the development of a platform for the joint visualization of energy and indoor environmental conditions in buildings. Low-cost IoT sensors and the BIM process were combined to provide a useful tool for facility managers. Literature shows that a fundamental role is played by buildings' occupants. As underlined by Berg et al. [26], improving energy performance in historic buildings requires a deliberate balance between societal and climate goals for energy efficiency and building conservation. This kind of user-centered approach was carried on by Lucchi et al. [27], who focused the attention on the importance of User-Centered Design-Driven approaches to enhance the historic public social housing, by applying the methodology to a didactic experience for a deep refurbishment and revitalization of the San Siro neighborhood located in Milan (Italy). Similarly, Egusquiza et al. [28] provided an operative approach to the urban conservation of historic urban environments through the enhancement of their energy performance based on living labs operating as inclusive multi-agent discussion arenas with a long-term vision, where multi-criteria co-creation processes were implemented to select conservation-friendly solutions based on local materials including criteria such as operational energy, impact on heritage values, quality of life, socio-economic development and easy logistics. On this trend, Pioppi et al. [29] pointed out the importance of integration of the cited approaches with the modern sensor systems, presenting a method for microclimate investigation and outdoor thermal comfort evaluation at pedestrian level, by coupling experimental monitoring and cluster analysis with the aim of finding data driven techniques to mitigate local community problems such as Urban Heat Island [54], and to enhance potential energy community scale performance.

In light of the above-presented literature review, a lack of approaches capable of evaluating historic buildings on the basis of monitoring data from multi-domain monitoring systems can be noted. In this regard, this paper proposes a new methodology aiming at defining a multi-domain HBIM environment to evaluate in a simple, reliable, and user-friendly system the structural performance of historic buildings and human-centric comfort. In particular, this latter assessment is to be intended as the analysis of comfort conditions that places the vibration and thermal perception of the building occupants at the same level of the functional data related to the structural performance of the building. Hereinafter, such an inclusive approach is first conceptually explained, then implemented in HBIM by means of a new multidisciplinary application software developed by the authors. The effectiveness of the proposed methodology is finally demonstrated through an application case study of a recently renewed historic building included in the medieval complex of Sant'Apollinare Fortress in Perugia. The organization of the paper is as follows: Section 2 introduces the proposed methodology for structural performance and human-centric comfort monitoring in HBIM, and the case study. Section 3 presents the application software and its employment for the assessment of the case study building, while Section 4 reports final comments and remarks.

2. Methodology

This section outlines the methodology proposed to perform structural performance and human-centric comfort monitoring in the HBIM framework. After an overall description of the new approach, the case study is presented by providing a detailed description of the historic building being assessed, its HBIM model, and the performed monitoring activities.

2.1. General description

The methodology exemplified by the flowchart in Fig. 1 consists of two main phases, named "Data management" and "Data processing", preceded by a preliminary step dedicated to the gathering of monitoring data from the sensors installed on the historic building under assessment, namely measurements of vibrations, air temperature, relative humidity, and CO_2 concentration. The first phase of the proposed approach aims to create in HBIM a digital archive including past and ongoing monitoring activities carried out on the considered building. To this aim, meaningful information relating to the adopted measurement setups, as the typology and positioning of sensors and data acquisition systems within the building, the wiring methods, and the settings considered to perform the measurements, are integrated in the HBIM model reproducing the historic building. Consequently, monitoring data acquired in the preliminary step can be organized according to the

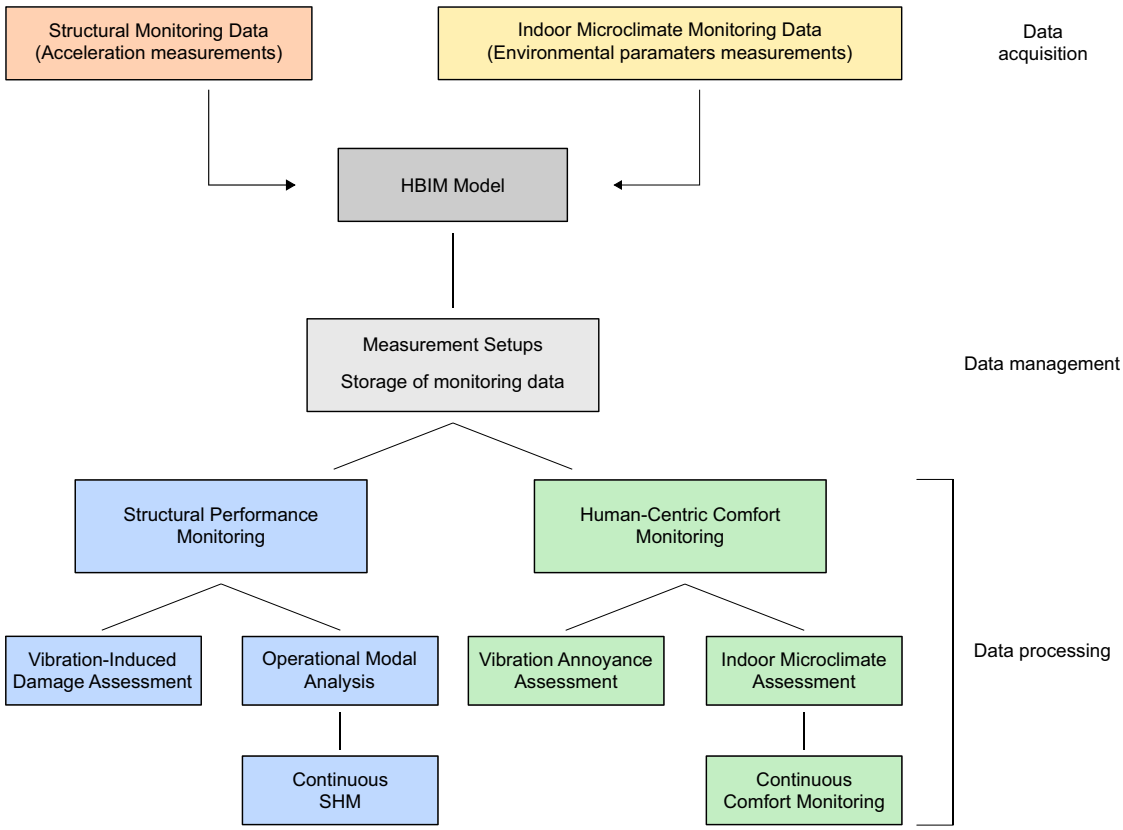

Fig. 1. Flowchart representing the methodology proposed to evaluate the structural performance of historic buildings and the human-centric comfort of their occupants in HBIM.

corresponding measurement setup reproduced in the HBIM model by allowing their systematic inspection and processing. This last task is accomplished in the second phase of the proposed methodology, leading to the assessment of the structural performance and human-centric comfort in HBIM. Specifically, the structural performance of a historic building is assessed by considering two methods, both based on the processing of acceleration measurements: the first method consists in assessing whether vibrations, produced for instance by particular human activities, such as those generated by a construction site, are of such entity as to induce modifications in the structural performance of the building. To do that, specific Technical Standards defining limit thresholds, the exceeding of which indicates the possible occurrence of structural damages, can be employed [30,31]. The second method, more comprehensively, assesses the structural performance by seeking for changes in the dynamic behavior of the building, with respect to a reference condition, which may present alterations by following the development of structural damages. Several dynamic identification methods can be employed to retrieve the modal features characterizing the dynamic response of the considered structure, such as its natural frequencies and mode shapes, yet the use of the Operational Modal Analysis (OMA) is herein considered due to its applicability in operational conditions and without a known artificial excitation of the structure [32–34]. In light of this, a discrete assessment of the structural performance can be achieved with this second method by periodically carrying out Ambient Vibration Tests (AVTs) on the historic building, while a continuous structural performance monitoring can be pursued through the installation of an appropriate monitoring system allowing the continuous recording of ambient vibrations and the automation of OMA procedures for their processing in a real-time fashion [5,35]. Depending on the case, the two methods described above can be used separately or in a complementary way. The assessment of the human-centric comfort in the building is carried out by taking into account a data fusion approach based on the processing of both acceleration measurements and environmental parameters, e.g. air temperature and relative humidity. In this case, the entity of vibrations is evaluated to investigate their possible influence on the comfort conditions of the occupants of the building. Like before, specific Technical Standards dealing with vibration perception in building occupants can be used to conduct this assessment [36–38]. Similarly, the available microclimate parameters are implemented to assess the achievement of thermal comfort conditions for the occupants, also against outdoor local microclimate conditions. At this first stage, the evaluation is carried out based on the indications of acknowledged specific Technical Standards concerning indoor thermal comfort [39,40]. Nevertheless, the monitored indoor microclimate data could be also used to drive occupant-centric building operation and control by means of their systematic processing. In fact, the continuous human-centric comfort monitoring can be achieved thanks to a monitoring and building management system (BMS) installed in the building and providing real-time data.

2.2. *Case study: the medieval complex of Sant'Apollinare fortress in Perugia, Italy*

The case study building is an ancient stable included in the medieval complex of Sant'Apollinare Fortress in the countryside of Perugia (Fig. 2). Built in the second half of the XIX century, the structure was recently retrofitted according to the current seismic and energy technical standards [41], earning the gold GBC Historic Building (HB) certification [42] for the sustainability of the refurbishment activities. This is the first historic building in the world certified according to the GBC HB protocol. Moreover, during the retrofit it was converted to an office building hosting some working stations and laboratories of CIRIAF, an Italian inter-university research center dealing with green energy and sustainable development. In particular, the basement of the building

Fig. 2. Case study: (a) Overview of the medieval complex of Sant'Apollinare Fortress in Perugia, Italy; (b) Details of the case study building; (c) Main geometrical dimensions of the case study building (in meters).

hosts the scientific laboratory of the research center, while the first and second floors are used as offices. The load-bearing structure of the case study building is composed of sandstone elements bonded with mortar. Burnt clay bricks were used to build the corners of the structure, arches, vaults, pavilion, and lintels. Both the slabs and the roof are made of wood. The North-Est wall of the case study building borders a structure used to dry grains. Furthermore, during the retrofit, the building envelope was improved in terms of thermal-energy performance through a sustainable external insulation made of recycled cork for reaching an overall thermal transmittance of the opaque wall of 0.36 W/m^{2}K with a total thickness of 54 cm and a 10 cm thick cork panel insulation. The same thermal insulation retrofit has dealt with windows system, which now presents a thermal transmittance (averaged between the glad double panel and the wood frame) equal to 1.32 W/m^{2}K. The full description of the building envelope system and stratigraphy, the monitoring and control equipment of the whole HVAC has been already published in the specific paper [8], where also the HBIM procedure has been described with the purpose to combine energy retrofit design and architectural preservation. Here key details are also reported for the sake of clarity as below. The building was indeed equipped with a gas boiler and under-floor heating panels and mechanical ventilation to ensure thermal comfort in winter and the proper air changes yearly. No cooling system was operating due to the expected minor energy need in the cooling season, with the observed occupancy of the same rooms and the relatively minor internal gains. The building was undergoing another energy retrofit thanks to the installation of a novel geothermal system based on horizontal slinky type ground source heat exchangers coupled with an adsorption heat pump that will be able to provide both heating and cooling in the future, as detailed in [2,8]. The whole monitoring, control, and facility management of the same building has been then reported into the open access paper [2] as currently operating, with the integration of the new geothermal plant. Moreover, the operation of the system will be controlled by the BMS installed in the building and aimed at monitoring: electricity consumption of the partial and the whole building grid, thermal consumption and exchange through the geothermal boreholes, natural gas consumption in the case of boiler operation, and multidomain (thermal, acoustic, and air quality) indoor microclimate. Specifically, two operating indoor stations are installed and able to measure indoor air temperature, relative humidity, CO_2 concentration level, noise levels, air velocity (in both the rooms and the inlet/outlet ventilation ducts). Additionally, a fully equipped outdoor weather station is installed and operating, able to measure outdoor dry bulb temperature, relative humidity, global solar radiation, atmospheric pressure, rainfall intensity, wind speed and its direction, in order to be able to tailor control systems on very local ambient parameters. In particular, the previous paper [2] reports all the facility management

operation programs aimed at identifying both active and passive systems performance, together with occupants' comfort conditions.

2.2.1. HBIM model

A digital 3D model of the case study building was built in the BIM design authoring platform Revit by Autodesk [43]. The HBIM model, shown in Fig. 3, faithfully reproduces each architectural component of the building, including some historical elements, such as the columns, the pavilion roof, and the barrel vault, for which new Revit families were developed starting from existing templates in the original software library whenever possible [8]. For the sake of completeness, the 3D model also includes the representation of the courtyard.

2.2.2. Vibration monitoring

Between November 30th and December 10th 2020, excavation activities were performed in the courtyard of the case study building, to the purpose of the installation of the new geothermal system, by producing relatively large vibrations in the surrounding area. Vibration phenomena exceeding a certain entity and lasting for long periods of time, such as those induced by construction sites, can adversely affect the structural performance of nearby buildings by causing structural damages, as well as, discomfort of their occupants. Considering this, acceleration measurements were carried out on the case study building to meet the following purposes.

In order to investigate the possible occurrence of modifications in the structural performance of the case study building due to the performed excavation activities, a first campaign of AVTs was conducted before the excavation operations, on November 27th 2020. These tests aimed at determining the baseline modal features characterizing the global dynamic response of the case study building under ambient vibrations and were performed by using nine high-sensitivity (10 V/g) seismic accelerometers model PCB 393B12 mounted on steel supports deployed at the level of the first and second floor as depicted in Fig. 4(a). Acceleration measurements were acquired with a sampling frequency of 1652 Hz by using a CompactDAQ ethernet chassis, model NI cDAQ-9188, mounting three data acquisition modules NI-9234 (24-bit resolution, 102 dB dynamic range, and antialiasing filters). The duration of each measurement record was of 30 min, a time span quite larger than 2000 times the fundamental period of the monitored structure, which usually ensures an accurate estimation of the modal parameters. A second campaign of AVTs was repeated at the end of the excavation activities, on December 11th 2020, by considering the same methodology. These tests permitted to assess potential alterations in the modal features of the case study building, a circumstance, signs of possible damages occurred on the structure. Complementary to these monitoring activities, acceleration measurements were also carried out during the operation of the excavator, on December 5th 2020, to detect the possible development of vibration-induced structural damages on the case study building through the assessment of the entity of the vibration phenomenon. In this case, three accelerometers were installed on a steel support positioned at the level of the second floor to perform measurements along with the three main orthogonal directions, as illustrated in Fig. 4(b). The methodology of recording, as well as the employed equipment, was the same adopted for performing AVTs. This last set of acceleration records was also considered to investigate the influence of the vibrations induced by the performed excavation activities on the comfort conditions of the occupants of the case study building. The methodologies adopted to process acceleration data are described in the following sections of the paper.

2.2.3. Indoor microclimate monitoring

The monitoring of indoor microclimate conditions inside the building has been carried out since May 2019. It allows to continuously measure key environmental parameters characterizing the thermal and indoor air quality (IAQ) conditions in the conditioned area of the building and outdoor microclimate parameters. In detail, the monitoring system is composed of an indoor module, located in a representative room inside the building, and two outdoor modules, as shown in Fig. 4 (c), that collect data every 5 min and store them in a dedicated server. The monitoring stations are properly designed in order to be small in size and easy to integrate in the building [44]. The indoor station measures air temperature, relative humidity, pressure, CO_2 concentration, and sound level. The two outdoor stations collect data of dry-bulb temperature, relative humidity, wind speed and direction. The last two parameters are measured every 6 s and aggregated to have a value collected every 5 min. The characteristics of the sensors are summarized in Table 1. To the purpose of this research, one-year monitored data, namely from July 21st 2020 to July 20th 2021, are considered. Moreover, the human-centric monitoring developed at this stage focuses on thermal comfort and IAQ; therefore, air temperature, relative humidity, and CO_2 data are specifically used in this work. In addition, as previously mentioned, the building is equipped with a BMS that is able to monitor and control the air temperature in all the conditioned areas of the building. These data are not taken into account into the application software developed in this work. However, they could be integrated in future developments of the software, as well as other parameters addressing IAQ and additional spheres of human multi-domain comfort [45].

3. Software description and application

The methodology proposed in Section 2.1 to evaluate the structural performance of historic buildings and the human-centric comfort of their occupants was implemented in HBIM by means of the development of a Revit add-in application, named "H2BIM" (Fig. 5). Built by exploiting the pyRevit plugin [46] and conceived to allow an efficient processing of the monitoring data by directly operating in Revit environment using Python, this new multidisciplinary tool is extensively described in the following sections of the paper through its first application to the case study building.

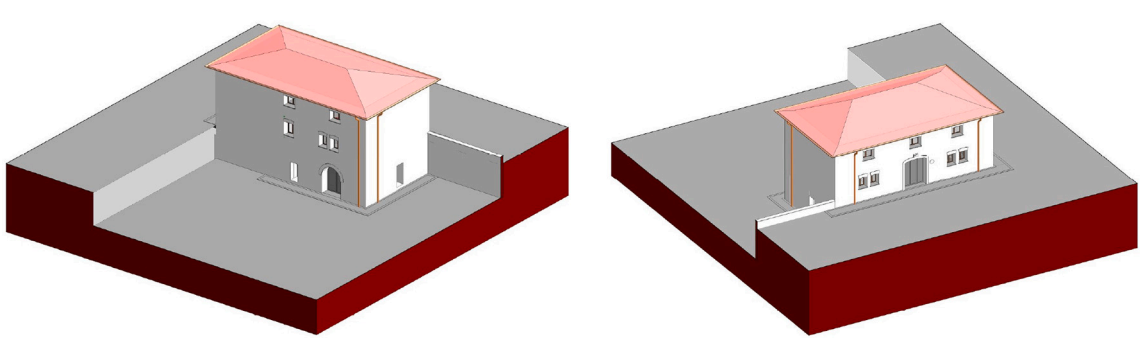

Fig. 3. Views of the HBIM model of the case study building.

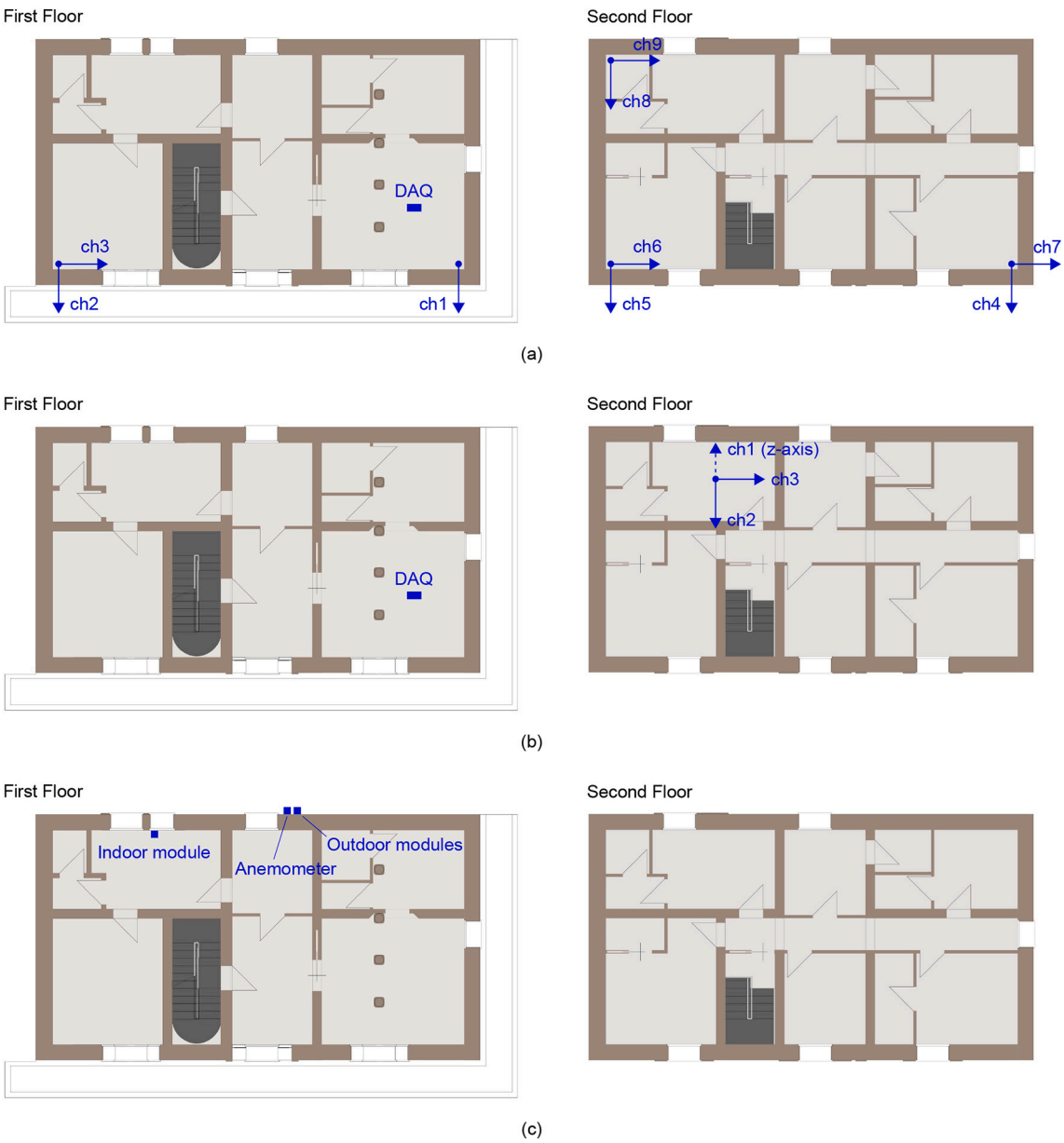

Fig. 4. Sensors deployment: (a) Accelerometers setup adopted to perform ambient vibration tests; (b) Accelerometers setup adopted to perform acceleration measurements during the excavation activities; (c) Setup adopted to monitor the indoor microclimate conditions.

3.1. Monitoring data management

H2BIM allows the management of digital archives containing monitored and potentially modeled data. Considering the case study building, the measurement setups adopted in the experimental campaigns described in Sections 2.2.2 and 2.2.3 were carefully implemented in its HBIM model by positioning digital replicas of the measurement devices/DAQs in the architectural geometry. To this aim, new Revit Families were developed to represent sensors and DAQs in the 3D model, including relevant information in their properties, such as data sheets and wiring configurations. Settings relating to each measurement setup were saved in a specific configuration file, hence stored, together with the corresponding monitoring data, in a cloud-based repository synchronized on the computer running Autodesk Revit. Performing continuous monitoring activities leads to collecting large amounts of data. In light of this, H2BIM has been conceived to operate within a digital archive external to the HBIM model, thus avoiding software slowdowns. A measurement setup can be loaded in the 3D model by using the Sensor Configuration modules in the Revit ribbon panel, which allows the selection of the desired configuration file among those defined by the user. This procedure represents the first step leading to the inspection and processing of the data sets.

As a practical example, Fig. 6(a) shows the digital reproduction of the measurement setup adopted for performing AVTs on the case study building on November 27th 2020 in the HBIM model. In this case, acceleration measurements corresponding to the chosen layout can be selected and visualized via the Acceleration Processing module in the Revit ribbon panel, which generates an interactive plot, such as that shown in Fig. 6(b), on which the signals to display can be chosen. Similarly, Fig. 7 shows the implementation of the sensors adopted to perform indoor and outdoor microclimate monitoring in the HBIM model of the case study building.

3.2. Structural performance monitoring

Modules included in H2BIM to evaluate the structural performance

Table 1
Sensing Hardware characteristics in the indoor and outdoor microclimate monitoring stations.

Station	Sensor	Parameter	Measure range	Accuracy
Indoor	Thermo-hygrometer	Air temperature [°C]	0 to 50 °C	± 0.3 °C
		Air relative humidity [%]	0 to 100%	± 3%
	CO_2 meter	CO_2 concentration [ppm]	0 to 5000 ppm	± 50 ppm (from 0 to 1000 ppm) or ± 5% (from 1000 to 5000 ppm)
	Barometer	Pressure [mbar]	260 to 1260 mbar	± 1 mbar
	Sound meter	Sound level [dB]	35 to 120 dB	–
Outdoor 1	Thermo-hygrometer	Air temperature [°C]	−40 to 65 °C	± 0.3 °C
		Air relative humidity [%]	0 to 100%	± 3%
Outdoor 2	Anemometer	Wind speed [m/s]	0 to 45 m/s	0.5 m/s
		Wind direction [°]	–	5°

of historical buildings are hereinafter described with reference to the analyses carried out for the case study building.

3.2.1. *Vibration-induced damage assessment module*

This module is intended to assess vibration-induced structural damages under the prescriptions provided by the Italian Technical Standard UNI 9916 [30]. Accordingly, its application includes vibrations produced by sources that are both internal and external to the monitored structure, such as those induced by explosions, traffic, and construction sites, yet excluding vibrations of seismic nature. The module permits a pre-processing of the acceleration measurements through basic operations as downsampling, linear detrending, and a Hanning window filter attenuating the signals at both ends of the time record to zero through appropriate time windowing. As suggested by the Technical Standard, a high-pass Butterworth filter of order six and a cutting frequency of 1 Hz is also applied to the records. Afterward, peak velocities are determined by considering the maximum values along the three main directions obtained by integrating the corresponding discrete-time acceleration signals through the trapezoidal rule, hence compared with the limiting velocities reported in the Technical Standard, the exceeding of which indicates the possible occurrence of modifications in the structural performance of the building being assessed.

Specifically, Fig. 8 shows the results obtained by processing the acceleration measurements, acquired from the sensors installed on the case study building on December 5th 2020 (see Section 2.2.2), through this module. Raw acceleration records were preliminarily processed by applying a resampling from 1652 Hz to 160 Hz, hence by removing their mean and by forcing the signals to zero in correspondence of the beginning and end of the recording time. The peak velocities obtained from the computation were compared with the lowest threshold values prescribed by the Standard and suitable for the assessment of historical buildings under long-term vibrations, as illustrated in Table 2. Overall, excavation operations produced peak velocity values that were within the regulatory limits, therefore not capable of inducing structural damages.

3.2.2. *Operational Modal Analysis module*

This module allows the assessment of the dynamic response of a structure under ambient vibrations by means of the retrievement of its modal features. Acceleration measurements are pre-processed in the Acceleration Processing module, which permits the downsampling and linear detrending of the data sets, as well as the application of a Hanning window filter. Meaningful parameters of the Fast Fourier Transform (FFT) [47] can be also specified through this user interface. Once the pre-processing phase is completed, the Operational Modal Analysis (OMA) module can be employed to perform system identification

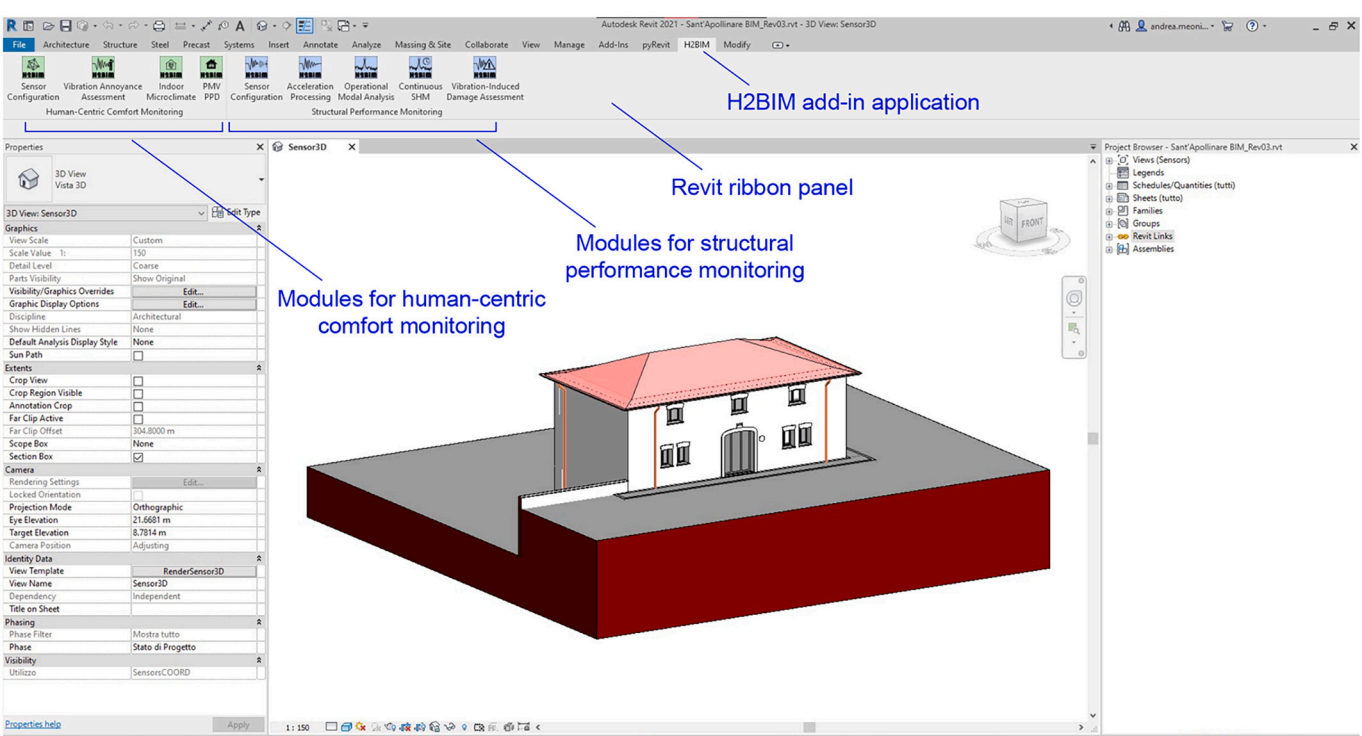

Fig. 5. Front panel of H2BIM, a Revit add-in application for structural performance and human-centric comfort monitoring in HBIM.

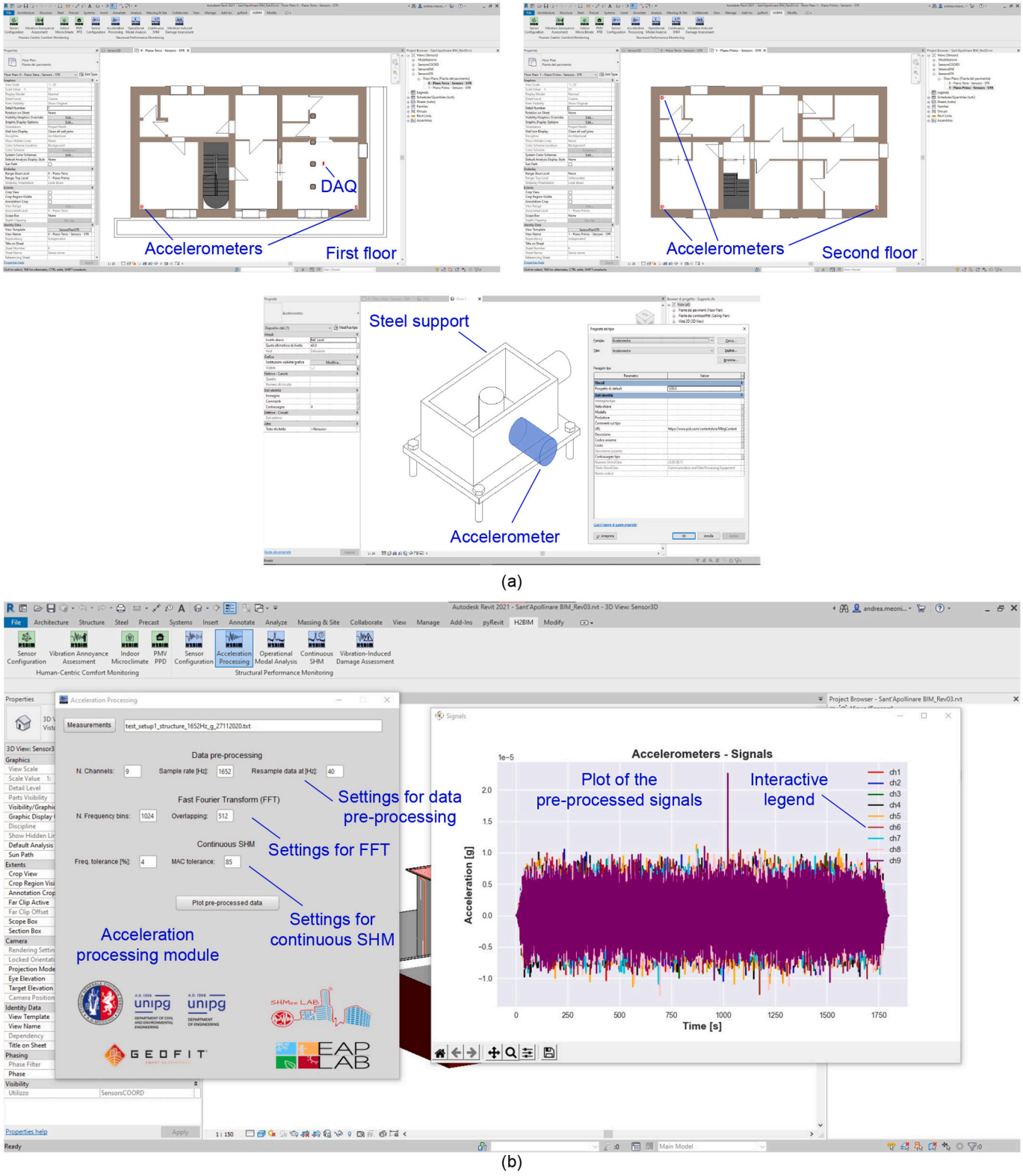

Fig. 6. Example of structural monitoring data management: (a) Measurement setup adopted for performing ambient vibration tests on the case study building on November 27th 2020, with details of the Revit family designed to represent accelerometers and their steel support; (b) Screenshot displaying the Acceleration Processing module and the plot of the pre-processed signals from the ambient vibration tests.

through the Frequency Domain Decomposition (FDD) method [48]. Specifically, the module first processes the acceleration signals to estimate the spectral density matrix by exploiting the Welch method implementing the FFT algorithm, then performs the singular value decomposition of the latter. Natural frequencies can be identified in the plot of the singular values of the spectral matrix by means of the peak picking technique. Once peaks are selected by the user, the module automatically extracts the first singular vector evaluated at each picked frequency to obtain the corresponding mode shape. This can be inspected via the user interface through a plot representing its complex

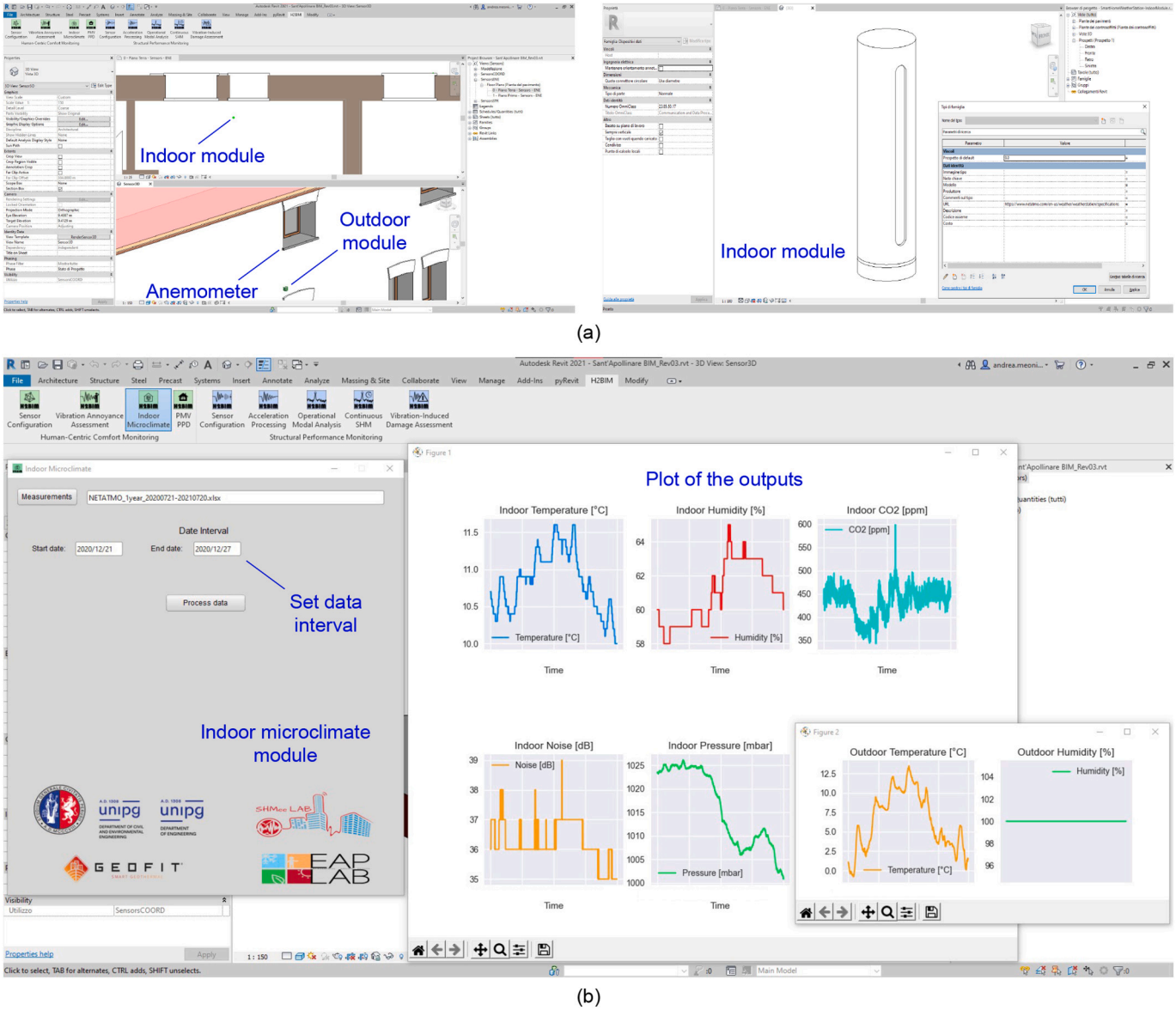

Fig. 7. Example of climate monitoring data management: (a) Measurement setup adopted to perform indoor and outdoor microclimate monitoring with details of the Revit family designed to represent the indoor module; (b) Screenshots from the Indoor microclimate module used to process and visualize the microclimate measurements acquired from the sensors installed on the case study building on December 21st-27th 2020.

animation. The Mode Phase Collinearity (MPC) has been selected as quality factor for the assessment of the accuracy of the identified mode shapes [49]. Accordingly, a MPC value equal to one indicates that the complex mode shape is nearly real which is often an indicator that the accuracy of the identified mode is high, whereas MPC values close to zero represent a mode characterized by a high grade of complexity not representative of the dynamic behavior of the structure under investigation. Fig. 9 shows the results obtained in H2BIM by processing data acquired from the AVTs performed on the case study building. Here, raw acceleration records were resampled from 1652 Hz to 40 Hz, hence their mean was removed by also forcing the signals to zero in correspondence of the beginning and end of the recording time. Figs. 9(a) and 9(b) report the main natural frequencies identified from the AVTs performed on the building on November 27th and December 11th 2020, respectively, while Figs. 9(c) and 9(d) illustrate the corresponding mode shapes. A comparison between the modal features retrieved from the two AVTs was carried out to evaluate possible alterations in the structural performance of the case study building caused by the performed excavation activities. In particular, differences in the picked natural frequencies were evaluated through the computation of their relative variations, while the modal assurance criterion (MAC) was considered to assess the correlation between the identified mode shapes [50]. According to that, MAC values close to one indicate a high correlation between two modes, whereas MAC values close to zero denote a poor correlation. Table 3 reports the comparison between the sets of picked frequencies, while the obtained MAC values are plotted in Fig. 10. Overall, the comparison between these modal features points out only slight changes in the natural frequencies, most likely attributable to changes in outdoor environmental conditions, and a good correlation between the mode shapes. Accordingly, excavation operations did not result in significant modifications of the structural performance of the case study building.

3.2.3. *Continuous SHM module*

Once the baseline natural frequencies of a structure are identified, this module allows their tracking over time, which can be used for damage detection via statistical pattern recognition approaches in long-term monitoring applications by using control charts [51]. While this work focuses on modal matching, due to the limited number of data sets

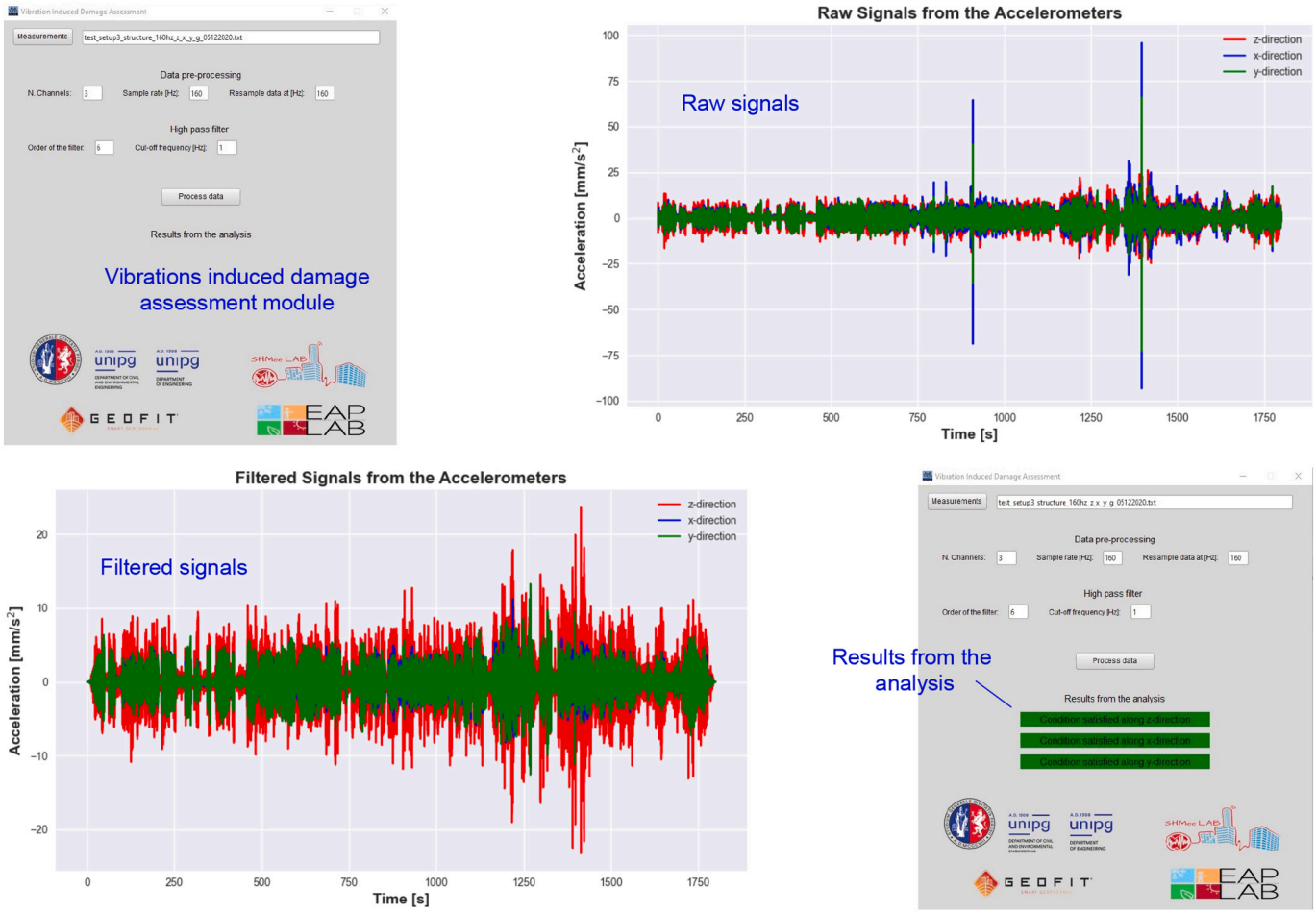

Fig. 8. Vibrations-induced damage assessment module used to process acceleration measurements acquired from the sensors installed on the case study building on December 5th 2020 (during excavation works).

Table 2
Comparison between the peak velocity values obtained from the processing of the acceleration measurements acquired from the sensors installed on the case study building on December 5th 2020 (during excavation works), and the limiting thresholds prescribed by UNI 9916.

Measurement direction	Peak velocity value [mm/s]	Limiting threshold from UNI 9916 (category: historical building) [mm/s]
z	0.16	2.5
x	0.04	2.5
y	0.05	2.5

available for the considered case study, the implementation of a control chart is left for future work. The automated extraction of the time series of natural frequencies consists of the following steps: automated modal identification and modal tracking. Each acceleration record is first processed through the FDD method, yet this time the peak picking technique is automated by means of an algorithm that automatically recognizes relevant peaks in the singular values. The consistency of each peak is assessed through an allowable range of variation defined by considering the baseline value of the corresponding natural frequency, previously determined, and its maximum allowed relative variation, set by the user via the Acceleration Processing module. Peaks of adequate consistency represent the natural frequencies. Considering these, mode shapes are retrieved and subjected to a check evaluating the correlation with the corresponding baseline mode shapes within a specific tolerance. After this last assessment, the identified set of natural frequencies is included in the tracking, otherwise, it is discarded. In any case, the module seeks another acceleration record to continue the processing. The interruption of the frequency tracking, therefore, indicates a change in the dynamic response of the structure with respect to the initial reference conditions. This circumstance may be attributable to the development of damages to the structure.

Given the lack of a monitoring system able to continuously record acceleration measurements, this module was mainly setup to provide a comprehensive description of the potentialities of H2BIM. In this regard, Fig. 11 shows an example of tracking of the main natural frequencies, MAC and MPC values computed for the corresponding mode shapes of the case study building based on a dummy data set composed of two parts. The first part was built by extracting six acceleration records of duration of 10 min each from the measurements acquired by carrying out AVTs; the second part was defined by replicating once the first part to obtain a total of twelve acceleration records. The maximum relative variation of the natural frequencies was set as 4%, while 0.85 was chosen as minimum MAC value for mode shape correlation. According to these settings, three sets of natural frequencies were included in the frequency tracking following the processing of the first part of the dummy data set. Consistently, the same natural frequencies were also tracked by completing the processing of the available acceleration records.

3.3. Human-centric comfort monitoring

Modules included in H2BIM to evaluate the human-centric comfort of building occupants are described below. The results obtained from the application case study are also presented.

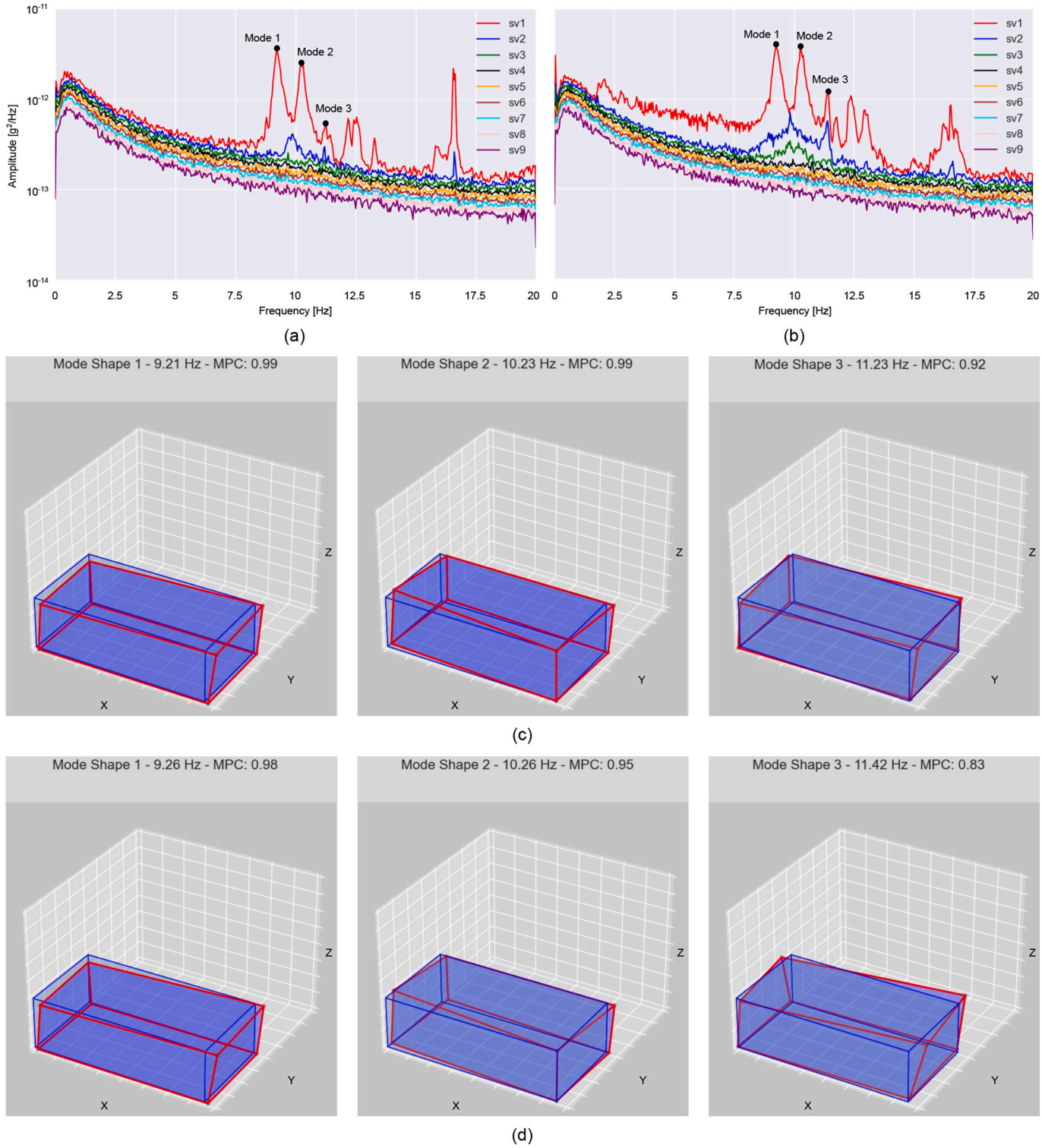

Fig. 9. Operational Modal Analysis module illustrating the results obtained by processing the acceleration records: (a) Plot of the singular values with annotated the selected peaks from the AVTs carried out on November 27th 2020 (before excavation works); (b) Plot of the singular values with annotated the selected peaks from the AVTs carried out on December 11th 2020 (after excavation works); (c) Identified mode shapes from the AVTs carried out on November 27th 2020 including first bending modes F_{x1} and F_{y1} and torsional mode T_1; (d) Identified mode shapes from the AVTs carried out on December 11th 2020 including first bending modes F_{x1} and F_{y1} and torsional mode T_1.

3.3.1. Vibration annoyance assessment module

This module encompasses the vibration annoyance assessment for the occupants of historic buildings according to the prescriptions provided by the Italian Technical Standard UNI 9614 [36]. Similarly to the Vibration-Induced Damage Assessment module, its application includes vibrations produced by sources that are both internal and external to the monitored structure, yet excluding those of seismic nature. The module pre-processes raw acceleration measurements through their down-sampling, linear detrending, and the application of a Hanning window filter. Signals are further treated with band-pass and weighting filters

Table 3
Comparison between identified natural frequencies obtained from the AVTs carried out on the case study building on November 27th (before excavation works) and December 11th 2020 (after excavation works).

Natural frequencies [Hz]			
Mode	AVTs November	AVTs December	% Var
F_{x1}	9.21	9.26	0.54
F_{y1}	10.23	10.26	0.29
T_1	11.23	11.42	1.49

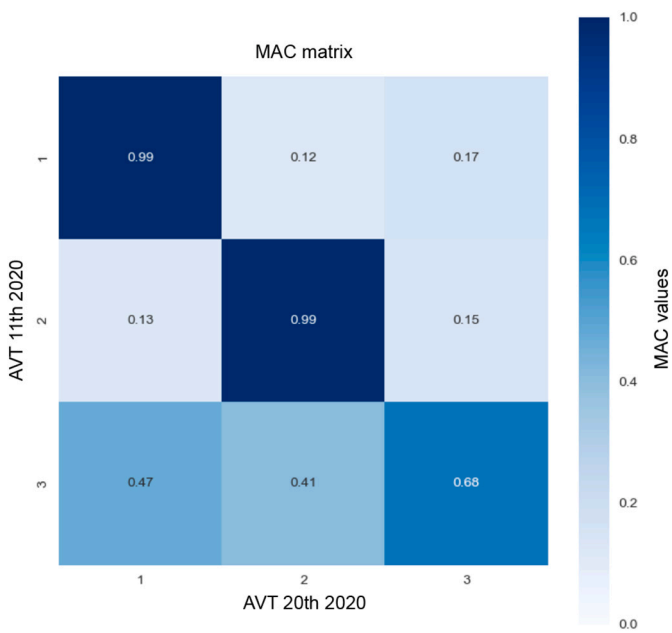

Fig. 10. Comparison in terms of MAC values between the mode shapes identified on November 27th 2020 (before excavation works) and December 11th 2020 (after excavation works).

defined in the Technical Standard by means of their transfer functions. Specifically, the module converts the pre-processed acceleration signals from the time to the frequency domain via FFT, then computes the filters, applies them, hence converts the signals from the frequency to the time domain via the inverse FFT. The module continues the data processing by computing the Root Mean Square (RMS) acceleration along each measurement direction, hence by calculating the total effective weighted acceleration, $a_w(t)$, as follows:

$$a_w(t) = \sqrt{a^2_{w,RMS,x}(t) + a^2_{w,RMS,y}(t) + a^2_{w,RMS,z}(t)}, \quad (1)$$

where $a_{w,RMS,x}(t)$, $a_{w,RMS,y}(t)$, and $a_{w,RMS,z}(t)$, are the values of the filtered RMS acceleration along the three main orthogonal directions at the time interval, t. The maximum value of the total effective weighted acceleration is finally compared to the limit threshold prescribed by the Standard, the exceeding of which indicates that the analyzed vibrations can negatively affect the comfort of the occupants of the building being assessed.

Fig. 12 shows the results obtained by processing the acceleration measurements, acquired from the sensors installed on the case study building on December 5th 2020 (see Section 2.2.2), through this module. Raw acceleration records were first processed by applying a resampling from 1652 Hz to 160 Hz; then, their mean was removed by also forcing the signals to zero in correspondence of the beginning and end of the recording time. The value of the total effective weighted acceleration obtained from the computation was compared with the threshold value prescribed by the Technical Standard for buildings used as offices, as illustrated in Table 4. Overall, excavation operations produced vibrations levels comprised within the regulatory limits, therefore not capable of inducing annoyance to the occupants of the building.

3.3.2. *Indoor microclimate module*

This module is intended to show the measurements made by dedicated microclimate monitoring sensors, both inside and outside the building in a selected time interval. Being able to access the measured data directly within the BIM platform, it allows the integration of monitoring and data analysis. The trend of the monitored indoor and outdoor parameters can be shown for specific periods in time - either longer or shorter - according to the needs of the user.

Fig. 7(b) shows the interface of the module and the results obtained by analyzing the data acquired in the period December 21st-27th 2020 (see Section 2.2.3). The interface shows the trend of indoor air temperature and relative humidity against the outdoor values, in order to assess the thermal-energy performance of the building. The values of thermo-hygrometric parameters are out of the comfort limits, which are 20 °C for the minimum indoor air temperature and 60% for maximum indoor relative humidity in winter season, according to the Technical Standard EN 16798–1 [40]. Indeed, the plant was not running in the selected period, when the novel geothermal system was under installation. Although buffered, the indoor air temperature trend is consistent with the outdoor dry-bulb temperature trend. On the other hand, the trend of CO_2 concentration is below the limit value (800 ppm) [40], confirming a low occupancy level during the considered week. The access to data potentially in real-time (given the software architecture designed) provides the basis for the application of the second module related to indoor comfort data described in the next section.

3.3.3. *Predicted Mean Vote and Predicted Percentage of Dissatisfied computation module*

This module is intended to assess the human-centric thermal comfort conditions under the prescriptions provided by the Technical Standard EN ISO 7730 [39]. Similar to the other modules, this application processes the data that potentially are continuously monitored in terms of indoor and outdoor microclimate conditions. In detail, the module calculates Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) comfort indexes according to the mentioned standard procedure. The calculated indexes, together with the related microclimate parameters used for the calculation, can be shown for specific periods in time - either longer or shorter - according to the needs of the user. These indexes are evaluated thanks to the integration of the pythermalcomfort module, developed by Tartarini and Schiavon [52], in H2BIM. The evaluation depends on different parameters, which are not all monitored by the existing monitoring system. Therefore, the microclimate parameters that are not available, e.g. indoor air speed and mean radiant temperature, are assumed equal to standard values on default and it is possible to change their values via the user interface. In addition, parameters related to the activity of the occupants and clothing can be selected by the user according to the specified boundaries.

Fig. 13(a) depicts the interface of the module and the results obtained by analyzing the microclimate measurements monitored during July 21st-22nd 2020. Thanks to the module described in the previous section, by setting the same period for the analysis and focusing on the internal conditions (Fig. 13(b)), it is possible to understand the main drivers of the obtained results. For instance, in the specific period analyzed in July 2020, this behavior is clearly induced by the change in the temperature values. Nevertheless, the calculated PMV index is inside the acceptable range $-0.5 < PMV < +0.5$ [39].

4. Conclusions

Historical buildings, and more in general cultural heritage ones, represent the key architectural identity of a community and, frequently,

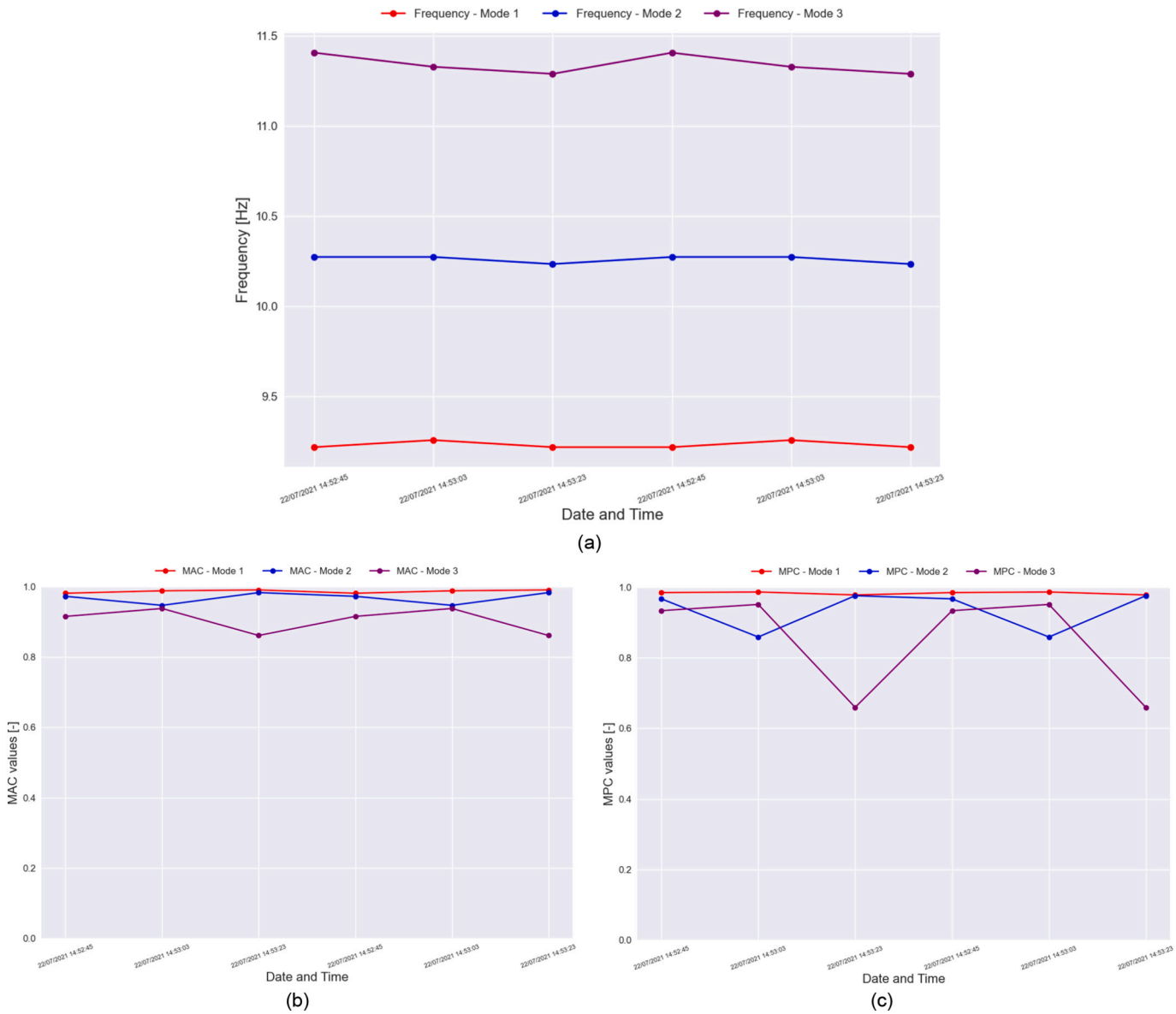

Fig. 11. Continuous SHM module: (a) Tracking of the main natural frequencies of the case study building; (b) Tracking of the MAC values of the tracked mode shapes; (c) Tracking of the MPC values of the tracked mode shapes.

masterpieces that identify local and national cultures. That is the reason why, on a larger view, such buildings need to be preserved, valorized, but for sure lived and experienced. To become fully operative, comfortable, and safe, they would need a major attention, which can be paid only through a modern, multidisciplinary, and holistic framework, with precise implementation strategies and mechanisms, also regulating the human-building interaction, together with the building-environment interaction per se.

In this view, this paper, for the first time, presents a new practical methodology with solid theoretical foundations aimed at integrating structural performance and human-centric comfort monitoring of an iconic historic building, as pilot case to represent the proof-of-concept of such integration necessity and operational control innovative management. This integration has been indeed implemented within a dedicated HBIM environment, which offers the key tools for a true interoperability of the systems, protocols, and usability-to-wellbeing framework for building occupants and facility managers.

In terms of structural behavior of the building, two complementary methods differing in accuracy were considered in the structural performance monitoring: the first method evaluated the vibratory phenomenon according to the prescriptions of suitable Technical Standards to determine if it could induce damages to the building. The second method exploited OMA to determine and evaluate the dynamic behavior of the building, which can undergo variations following the development of structural damages. A data fusion approach, exploiting specific Technical Standards to assess the influence of vibratory phenomena and microclimate parameters in the comfort conditions of the occupants of a building, was taken into account in the human-centric comfort monitoring. A new Python-based software application, named H2BIM, was developed by the authors to fully implement the proposed methodology in Revit, the BIM design authoring platform by Autodesk. The effectiveness of the novel approach and developed software was demonstrated through an application case study involving an iconic recently renewed historic building included in the medieval complex of Sant'Apollinare in the countryside of Perugia, Italy. AVTs were carried out on the building to investigate its dynamic behavior before and after the execution of excavation activities performed nearby. Acceleration measurements were also recorded during the operation of the excavator

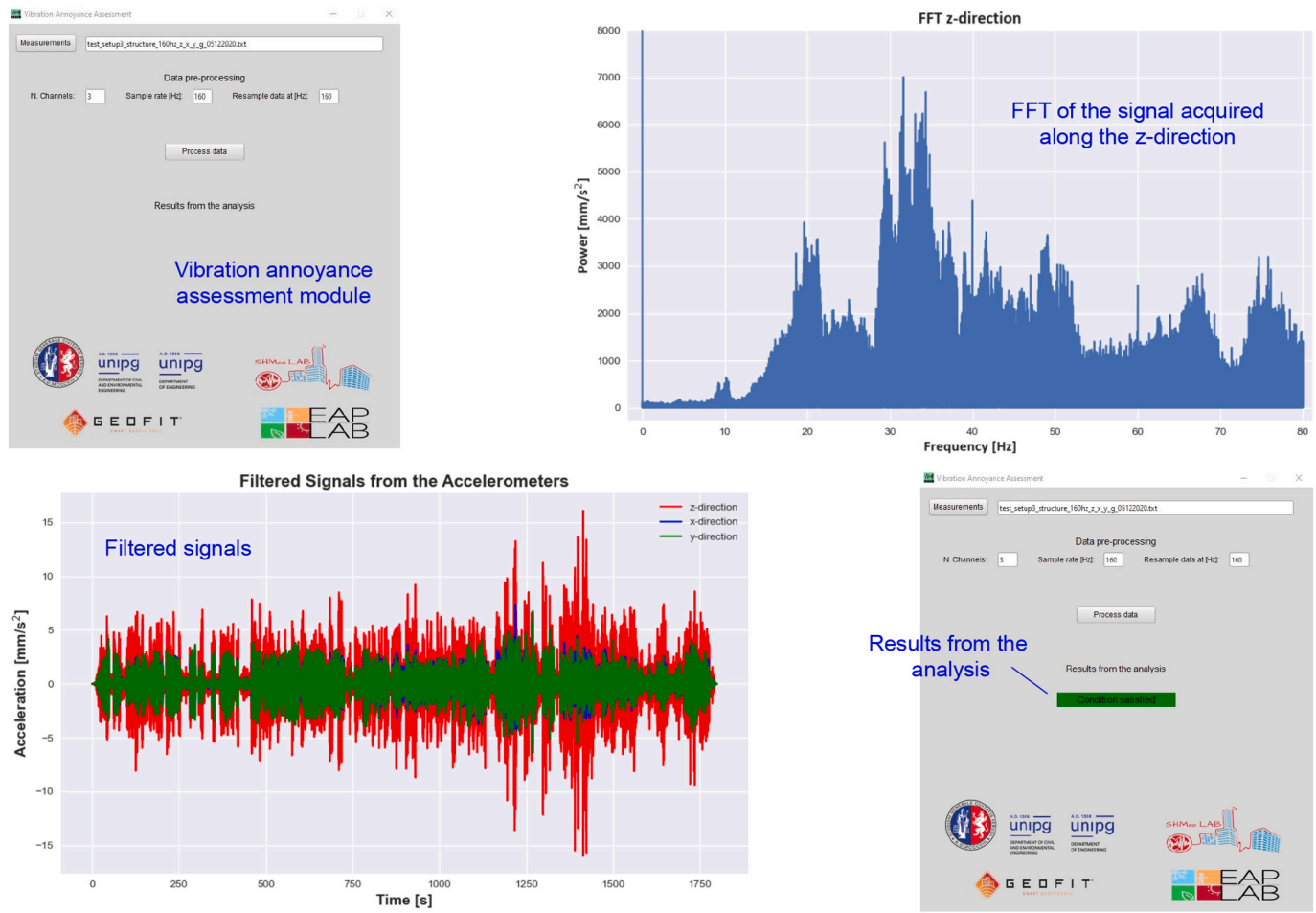

Fig. 12. Vibration annoyance assessment module used to process acceleration measurements acquired from the sensors installed on the case study building on December 5th 2020 (during excavation works).

Table 4
Comparison between the total effective weighted acceleration obtained from the processing of the measurements acquired from the sensors installed on the case study building on December 5th 2020 (during excavation works), and the limiting threshold prescribed from UNI 9614.

Total effective weighted acceleration [mm/s^2]	Limiting threshold from UNI 9614 (category: office building) [mm/s^2]
1.66	14

to evaluate their possible influence on the structural performance of the case study building and the comfort conditions of its occupants.

Environmental parameters, acquired since May 2019 by microclimate monitoring installed in the case study building (both in the indoors and outdoors, together within the energy systems of the HVAC), were considered for the assessment of the thermal comfort conditions of the occupants. The monitoring system highlighted the consistent conservation of specific comfort targets preserved in the pilot building, as also recommended by the LEED-based Green Building Council certification and future developments. The available monitoring data were integrated and processed directly within the HBIM model of the case study building by using the H2BIM Revit add-in. The results obtained in the structural performance monitoring pointed out that the construction works did not produce dangerous vibrations for the building. Likewise, the results from the human-centric comfort monitoring revealed that the vibration and thermal perception of the building occupants were within the limits prescribed by the adopted Technical Standards, also thanks to the conservative but efficient building energy retrofit, widely described in the two previous papers published by some of the authors.

Overall, the application case study provides a key contribution towards the integrated human-centric management and operation control, where people wellbeing and productivity is the target achieved by means of both structural and environmental/energy performance assessment and optimization. The proposed framework results in an interoperable procedure demonstrating its effectiveness by pointing out its multidisciplinary implementation and potential high scalability. This last feature is represented by the systematic integration and processing of multiphysics monitoring data within the HBIM environment, which permits the achievement of a complete assessment of the performance of the case study building during its operating conditions. This aspect is of the utmost importance since it can be exploited to drive the scheduling of future ordinary and extraordinary maintenance activities, whose design can be therefore carried out within the same digital environment, with a larger control and forecast potential, with obvious benefits in terms of performance assessment and cost-efficacy. In this context, the potential of the H2BIM Revit add-in is also highlighted. Besides the research purposes, this tool can be of particular interest to engineers and decision-makers dealing with the renovation and operation maintenance-to-optimization of historic buildings, which need to host the most needed and modern operations to make their conservation also sustainable from a both economic and environmental perspective. In light of that, future methodology and software developments will concern the introduction of new algorithms for data processing, such as time-domain approaches for vibration data analysis, as well as the integration of new monitoring outputs, including strain measurements

Fig. 13. Thermal comfort module: (a) Indoor microclimate assessment module used to process and visualize the thermal comfort data calculated based on the measurements acquired from the sensors installed on the case study building on July 21st-22nd 2020; (b) Graphs from the indoor microclimate assessment module used to process and visualize the microclimate measurements acquired from the sensors installed on the case study building on July 21st-22nd 2020.

and further comfort data.

Declaration of Competing Interest

None.

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