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An historical building information modelling approach for the preventive conservation of historical constructions: Application to the Historical Library of Salamanca

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ABSTRACT

This work presents an approach for the preventive conservation of historical constructions by means of Historical Building Information Modelling (HBIM) strategies. To this end, the methodology exploits the latest advances in inspection protocols, digitalization tools -by means of the novel back-pack mapping systems- as well as wireless monitoring networks. All this information is integrated in the HBIM environment by using ad-hoc families and interoperable communication protocols that allow obtaining a complete knowledge of the conservation status of the site. Additionally, the approach uses key performance indicators in order to evaluate the environmental conditions of the different assets presented in the site. All these features have been validated in one of the most representative heritage buildings in Spain: The General Historical Library of the University of Salamanca.

1. Introduction

Nowadays preventive conservation could be considered the most effective preservation approach for heritage buildings. This strategy is able to safe around 40–70% of the total maintenance costs in contrast with traditional remedial approaches by avoiding major interventions and promoting the use of monitoring networks as well as periodic inspections [1]. However, there are several challenges that turn difficult its effective implementation, requiring the development of standardized and integrated protocols for documenting and managing all the information needed to preserve the site. In this context, BIM-based strategies have been placed in as one of the most promising technologies. These approaches aim at improving the building life-cycle process by introducing the concept of interoperability, increasing cost- and time-effectiveness as well as improving the communication between agents [2]. In the context of built cultural heritage, this approach is commonly named as HBIM (Historic Building Information Modelling). It is emerging as a new management system, focused on digitalizing historic structures by creating full physical models populated with meaningful attributes, namely the construction system, constituent materials, existing damages, monitored quantities or maintenance costs among others [3–6]. This approach offers several advantages compared to traditional methods, such as: i) centralization of information; ii) analysis of the different interventions carried out and; iii) fluid communication between agents. This set of advantages makes possible the use of HBIM approaches for structural analysis [7,8], damage assessment [4–6,9], restoration [6], documentation [10] and digital representation [11], requiring all the appropriate definition of the different elements. This definition needs of establishing a set of rules, which could be grouped in: i) the Level of Detail (LoD) and; ii) the Level of Information (LoI).

The first level of definition demands the 3D modelling of the elements. In this context Murphy et al. [12] propose using remote sensing approaches to capture the data, enabling to create accurate digital replicas of the building and its assets. This issue is especially important

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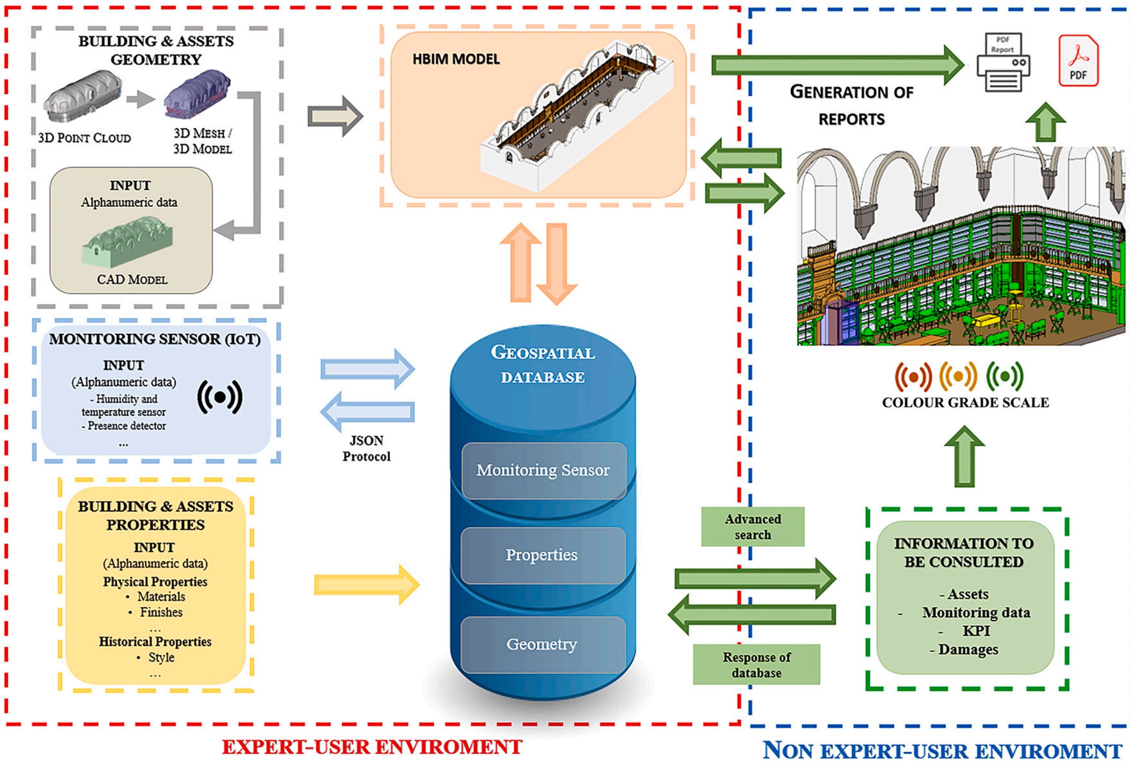


Fig. 1. Graphical representation of the HBIM methodology implemented.

in historical constructions since these elements -construction or not- are often unique pieces with specific geometrical features. Within this context, it is possible to find plenty of applications on which the laser scanning and photogrammetric approaches are used to digitalize historical sites for HBIM applications [10,12,13]. Besides the aforementioned advantages of these solutions, digitalizing heritage sites usually requires the use of a large number of images or scan stations, turning time consuming and involving a possible error accumulation along the network [14]. To cope with these limitations, hybrid solutions, such as the mobile mapping systems (MMSs), have emerged in the last few years. Among the MMSs systems available nowadays, the wearable mobile laser systems (WMLS) have been placed in a privilege position for capturing cultural heritage scenarios [14,15]. This solution combines a 2D laser scanning technology and an inertial measurement unit (IMU) in a portable device which could be handled by a unique operator. The system acquires information while the operator is walking around the heritage site. Then, the 3D point cloud is created by applying the Simultaneous Location and Mapping algorithm (SLAM) [16]. According to di-Filippo et al. [14] and Sánchez-Aparicio et al. [17], this system is ten time faster than laser scanning procedures, providing accuracies that range from 1 to 3 cm.

As stated by Diara and Rinaudo (2019) [18], HBIM models extend the possibilities of CAD models by adding semantic relations between the 3D objects and information. This relation could be understood as the LoI of the object, demanding the proper definition of materials or degradation processes among others. For example, Brumana et al. [19] uses custom properties in the objects to map the damages presented in the building, increasing the objects' LoI by adding historical information. Quattrini et al. [20] proposes the use of shared parameters to establish the same LoI for different HBIM elements. According to Azenha et al. [21], external sources, such as 360 images and laser-scanning data, could be used in this group to complement the geometrical definition of the objects.

Complementary to these considerations, the diagnosis and preventive conservation of cultural heritage sites require the use of monitoring networks to evaluate relevant parameters along the time. These analysis allow to understand the interferences between the assets and their environment [2] or even to evaluate the structural condition of the building, including the possible relation between these parameters and the environmental ones [22]. The first of these aspects is especially relevant in museums and libraries due to the use of active building conditioning systems that control critical variables for the conservation of assets such as the temperature, humidity or luminosity among others [23]. However, the great amount of data generated could be hardly interpreted by non-expert users [24]. To cope with this limitation, several authors propose the application of the so-called Key Performance Indicators (KPI). These indexes are commonly used for a quick and easily readable assessment of heritage structures [22] as well as for evaluating the bioclimatic conditions in museums and libraries [25,26].

Under the previously exposed basis, this work shows an HBIM methodology for the preventive conservation of heritage sites. This methodology integrates geometrical data coming from a WMMS and the information derived from a monitoring network with the standardized inspection protocols developed by the European initiative HeritageCare [27,28]. This initiative attempts to implement standardized protocols for preventive conservation. These protocols are articulated in a total of three complementary levels: i) the Service Level 1 that aim at providing a rapid condition screening of the heritage site; ii) the Service Level 2 that use Web-GIS tool for providing an extended knowledge of the site and its assets and; iii) the Service Level 3 that integrated all the data in a HBIM environment. For more details about these Service Levels reader refers to Masciotta et al. [27]. More specifically, this work will show the results obtained during the implementation of the third service level in one of the Spanish pilot cases: The Historical Library of the University of Salamanca. This implementation gives a step-forward in the current preventive conservation policies of the Library based on the work carried out by Sánchez-Aparicio et al. 2020 [29]. In this work a new Web-GIS platform, based on the use of 360° images and a geospatial database, is developed, corresponding with the second service level of conservation. This platform is mainly focused to the manager of the site, plotting

Fig. 2. WMMS used: a) user working with the wearable laser scan (Zeb-Revo). b) Zeb-Revo equipment.

the essential information for the preventive conservation of the site by means of easy-readable reports as well as the use of KPI based on a unique tolerance defined by the guideline PAS 198:2012 [30]. The main novelties of this work in comparison with this one are: i) the use of HBIM approaches instead of GIS methods for the management of information related with the constructions elements and the assets placed within the Library; ii) an improvement in the use of KPI for preventive conservation by exploiting the data coming from the BIM families as well as a set of tolerances in accordance with the type of material presented; iii) the capacity of filtering the assets with respect to the type of damage presented or its conservation risk and; iv) the possibility of downloading technical information related with the monitoring network.

According to this, the paper is structured as follows: after this initial Introduction, Section 2 describes the materials and methods used for the implementation of the preventive conservation system. Section 3 exposes the experimental results obtained. Finally, the conclusions and future perspectives are drawn in Section 4.

2. Material and methods

The proposed HBIM methodology will be based on three interconnected steps (Fig. 1): i) the 3D digitalization of the heritage site by means of WMMS; ii) the monitoring of the main bioclimatic parameters for the preventive conservation of the assets placed within the library and; iii) an HBIM model that manages the information derived from the previous steps and the information related to the assets. Additionally, the HBIM automatically computes and stores different KPI to evaluate the bioclimatic conditions in each asset according to its materials.

Table 1
Zeb-Revo specifications.

WMLS Zeb REVO	
Measuring principle	Time of flight
Operating time	4 h
Field of view	270° (H) x 360° (V)
Wavelength (nm)	905
Scanner resolution (°)	0.625H x 1.8 V
Orientations system	MEMS IMU
Scanner dimensions (mm)	86 × 113 × 287
Total weight (kg)	4.10
Scanner weight (kg)	1.00
Dimensions (mm)	220 × 180 × 470
Working range (m)	0.60–30 m indoors 0.60–15 m outdoors
Measurement rate	40,000 points per second
Accuracy (cm)	1–3

2.1. Digitalization system

The WMMS used for the present work was the ZEB-REVO back-pack mapping system. This device, commercialized by the GeoSLAM company [31], comprises a 2D rotating laser scanner head Hokuyo UTM-30LX-F (Hokuyo Automatic Co., Ltd. Osaka, Japan) rigidly coupled to an IMU on a rotary engine. The data captured by these sensors is stored in a processing unit placed in a small backpack (Fig. 2). The 3D point cloud is generated by combining the information coming from the scanning head with that from the IMU sensor. To this end, the full SLAM approach of the robotic operative system (ROS) library is used [32]. This approach uses an incremental and interactive procedure to register the segments captured by the scanning head one-by-one. Finally, this registration is refined following a similar framework to the well-known Iterative Closest Point algorithm. The error accumulation derived from the incremental procedure is minimized by a global registration on the basis that the starting and ending points are the same (closed-loop solution).

This sensor has a default range of 0.60-30 m for indoors environments and 0.60 to 15 m for outdoor ones, capturing 40,000 points per second (Table 1). Additionally, to the scanning head, the device has a GoPro camera that allows recording a video when the laser is capturing the scene. The manufacturer ensures an accuracy of 1–3 cm for a 10 min scan, with the closing of a single loop [33]. Further detailed specifications of this device are included in Table 1.

2.2. Monitoring system

In parallel to the digitalization of the site, a monitoring network was installed (Fig. 3). The aim was understanding the conservation needs of the indoor assets of the Library. This monitoring network focused on measuring the main bioclimatic parameters by means of the commercial system MHS (Monitoring Heritage System) [34]. This monitoring system has been developed by the Santa Maria La Real Foundation (*https://www.santamarialareal.org/*), highlighting for its minimal visual impact and great autonomy. The number, location and type of node depend on the specific needs, thereby requiring a pre-monitoring stage to define them property. Table 2 shows the general specification of the nodes used by this monitoring network.

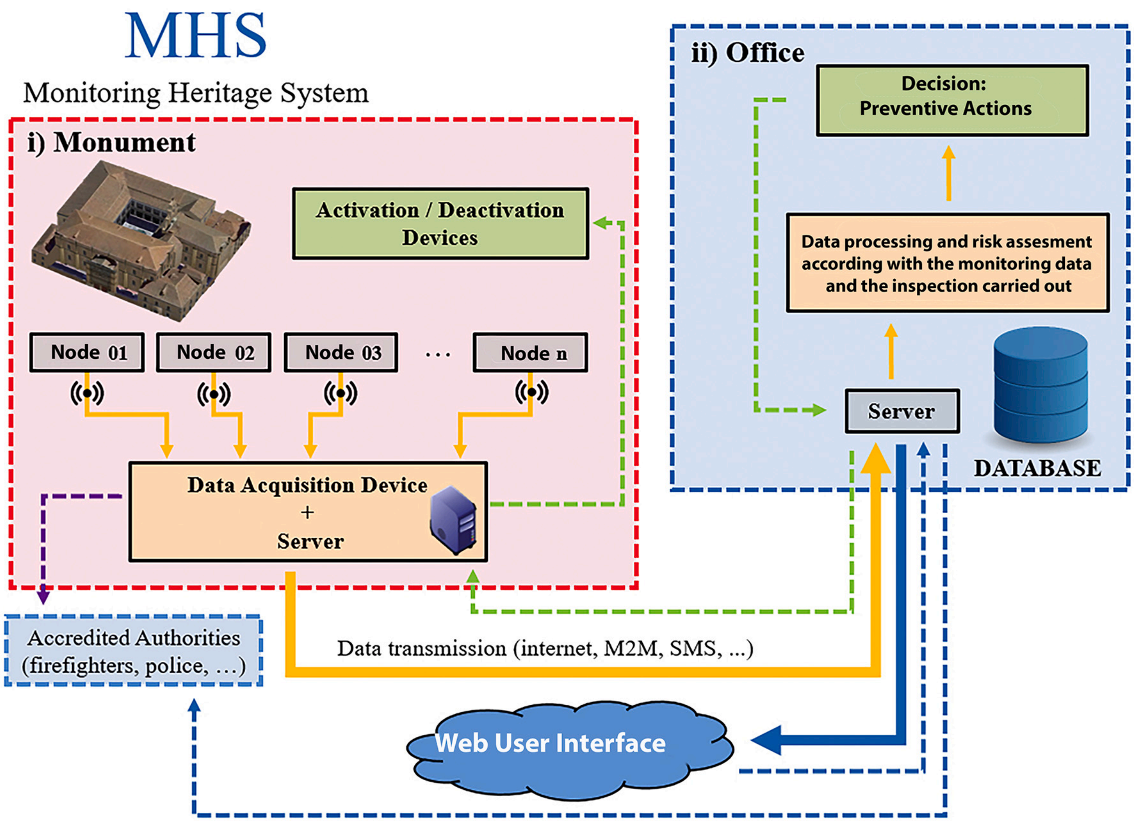


Fig. 3. Scheme of the monitoring network implemented.

The information captured by the local nodes is transmitted to a central node through a Zigbee communication protocol with a bandwidth from 900 MHz to 2.4 GHz. Finally, this information is sent to a dedicated server and can be consulted through a web-based application, as shown in Fig. 3.

2.3. Definition of the HBIM

Even though the relevance of HBIM within the context of historical constructions is assumed, the BIM methodology has been mainly oriented to new buildings, thereby not having a standard consensus for the historic ones yet [35]. This issue makes that some aspects, such as the level of detail (LoD) or the level of information (LoI), should be considered as critical. The LoD determines the graphic aspect of the assets, such as geometry, location in the building, size or orientation; while the LoI stores relevant but non-graphical information of the assets, such as maintenance data, monitoring data, manufacturer information, inspection periods or additional images. In HBIM works objects have so many details difficult to model with unique and non-parametric shapes, specially the ornamental parts, so depending on the purpose of the HBIM it is necessary a higher LoD or a lower LoD. Under this basis, and taking into account that bioclimatic conditions are the main risk for the proper conservation of the assets placed within the Library, the following criteria was adopted: i) a low LoD and; ii) a high LoI. Table 3 shows the different LoD and LoI adopted for each family in accordance with the recommendations exposed by Barmes [36] as well as the international guideline G202TM – 2013 [37] and the Spanish recommendations exposed in the Spanish Chapter of BIM Forum [38].

On the one hand, the geometry of each object (LoD) was based on the data provided by the WMMS, simplifying ornamental elements as well as assuming ideal shapes for the arches and the vault, but defining properly

Table 2
Technical specifications of the nodes used in the monitoring network.

Technical specifications	Values
Communication protocol	ZigBee
Frequency	900 MHz or 2.4 GHz
Programming interface	JTAG/Bootloader
Input/Output	Analogical/Digital
Communication protocols	I2C/ADC/SPI
Energy supply	5 V by means of a converter 3.6 V AA batteries
Signal sensitivity	Up to −110 dBm
Connexion topology	Star / Tree / Mesh
Working temperature	−20 °C/ +70 °C
Limit humidity	80%

Table 3
Level of Detail and Level of Information adopted for each family included in the HBIM model.

Type of object	Level of Detail (LoD)	Level of Information (LoI)
Construction elements	300 Elements properly represented in terms of quantity, size, shape, location and orientation	400 Technical system specification, including components to allow product selection
Assets	300 Elements properly represented in terms of quantity, size, shape, location and orientation	500 Detailed specification of manufacturer's product, testing operation and maintenance
Nodes	200 Generic system, object, or assembly with approximate quantities, size, shape, location, and orientation	500 Detailed specification of manufacturer's product, testing operation and maintenance
Damages	200 Generic system, object, or assembly with approximate quantities, size, shape, location, and orientation	500 Detailed specification of manufacturer's product, testing operation and maintenance

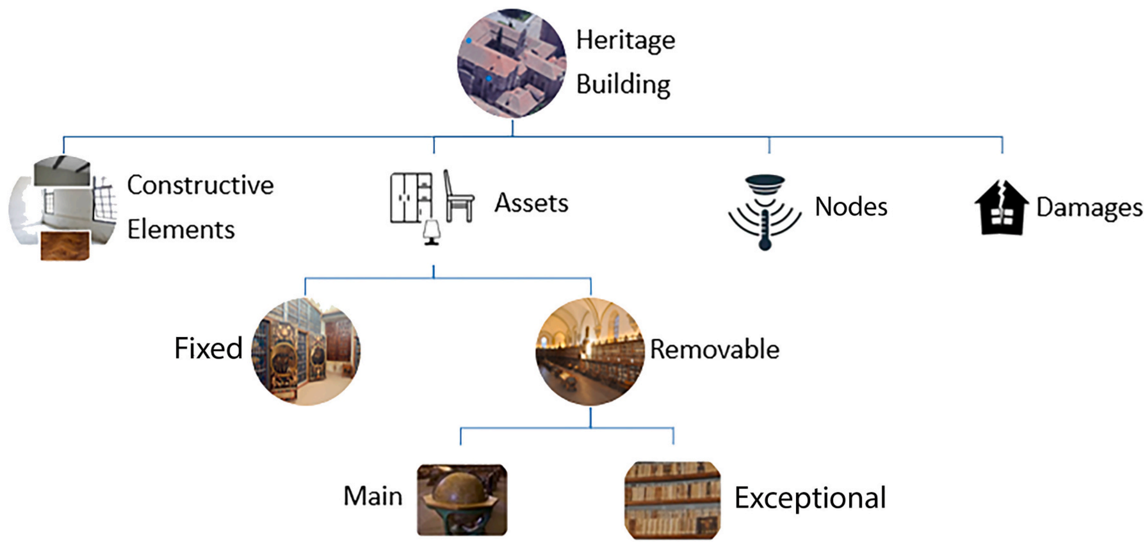
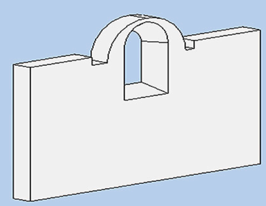


Fig. 4. Object classification proposed.

Name ID Historic Masonry Wall

Category Construction



Parameter Name	IFC Type data	Notes
Geometric Data		
Height	IFCReal	Example: 1.20 m
Length	IFCReal	Example: 4.23 m
Thickness	IFCReal	Example: 0.65 m
Material Characterization		
Stone Type	IFCText	Example: Granite
Stone Origin	IFCText	Only if known
Stone Density	IFCReal / IFCMassDensityMeasure	Kg / m3
Other Materials	IFCText	If it is known the presence of other materials
Outdoor Finishing System	IFCText	Finished system of exterior wall
Indoor Finishing System	IFCText	Finished system of interior wall
Facade Composition	IFC Text	Example: 1Leaf / 2Leafs
Conservation Data		
Previous Intervention	IFCText	Type of intervention
Last Intervention Date	IFCText	Date last intervention
Conservation State	IFCText	Good, Medium, Bad
Photographic Survey	IfcRelAssociates	Link to Image

Fig. 5. Construction elements family structure with the IFC parameters added to complete the information.

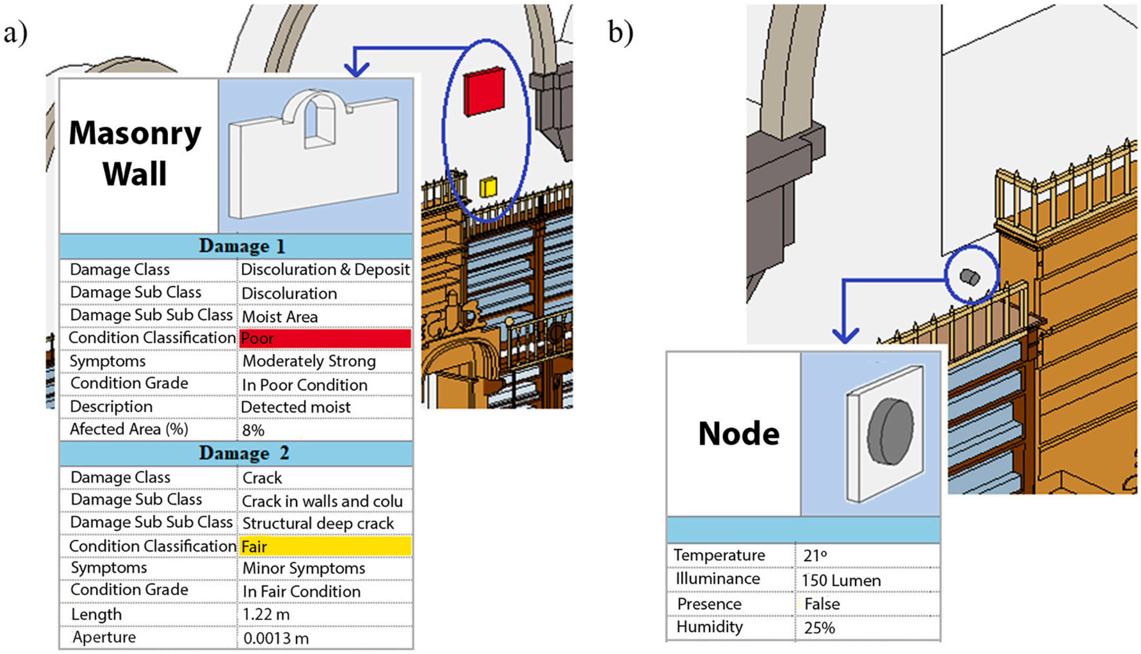


Fig. 6. Damage and node objects within the HBIM model. a) Two damages with different risk attached in a construction element. b) Node patch placed in the library and its parameters.

the materials presented on them. The pass from the point cloud to the CAD model was carried out by means of reverse engineering procedures, similar to those showed by Bautista de Castro et al. [39] or Sánchez-Aparicio et al. [40]. The geometrical information omitted, e.g. the ornamental parts, was included in the LoI of each object.

In contrast to this low LoD, the current methodology introduces an exhaustive LoI to handle the properties of each material, changes suffered, or damages presented. In order to establish this LoI correctly to each object, the elements were classified depending on the information each one needs into 4 main groups (Fig. 4) (Table 3): i) construction elements; ii) assets; iii) nodes; iv) damages.

All this graphical and non-graphical information was translated into the open exchange format IFC4 (Industry Foundation Classes version 4), thereby ensuring the inter-operability between different tools and HBIM scalability. IFC allows to export any kind of information so that all the custom parameters created for the new assets, damages and nodes are well contemplated.

2.3.1. *Construction elements*

According to the purpose of the HBIM, only the inner envelop of the library was modelled. In this sense it was necessary to take into consideration four different types of families: i) masonry walls; ii) vaults and arches; iii) windows and; iv) slab. The information inserted in the walls and vaults has been defined with the aim of including all the relevant construction parameters, namely (Fig. 5): i) number of leafs; ii) material used in each leaf; iii) finishing material. The main door and the windows, made up by glasses, include the following information labels: i) number of layers; ii) type of glass in each layer and; iii) type of frame. Finally, the timber floor was defined by the following tabs: i) number of joint's sets; ii) type of wood; and iii) finishing material.

Complementarily, these families include all the relevant information with respect to its conservation state. In this sense, the following fields were included: i) previous interventions; ii) last interventions date and iii) conservation state. Due to simplifications during the geometrical modelling, each family includes the possibility of inserting different images that allow complementing the spatial definition of the element defined.

Table 4
Options for the labels condition classification and status risk. The text between brackets is the value assigned to the third information label.

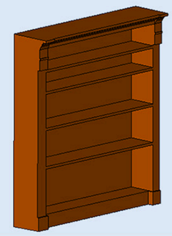
Label	Values
Condition classification	Good
	Fair
	Poor
	Bad
Status risk	Low (long term)
	Moderate (intermediate term)
	High (short term)
	Severe (urgent and immediate)

2.3.2. *Damages*

Damages are represented by means of custom patch-objects, as proposed Sousa et al. [41]. Path-objects are geometrically simple elements with a low LoD, but with a very complete LoI. In this sense the geometry of each damage is modelled by means of rectangular patches attached to some construction element or asset. Each patch has different size and colour depending on the affected area and relevance of the damage (Fig. 6a). The LoI of this object includes an exhaustive definition of the damage according to the damage atlas developed within the framework of the HeritageCare project [27,28]. This atlas classifies each damage according to a three-level system, i.e. class of damage, sub-class of damage and sub-sub-class of damage. Moreover, these objects include: i) a condition classification; ii) a status risk; iii) urgency to take an action; and iv) affected area. It is worth mentioning that the third information label depends on the values adopted by the status risk (Table 4). The fourth information label refers to the extension of the damage, allowing that the user can introduce the metric values of the damage in two ways: i) by introducing the percentage of the affected area with respect to the constructive element (HeritageCARE approach) [27] or; ii) by introducing the area or volume of this damage. In the case of cracks, this second approach uses two metric parameters: i) the length of the crack and; ii) the aperture of the crack. These parameters allow to monitor the evolution of the damage through time.

Name ID Shelving

Category Removable Asset

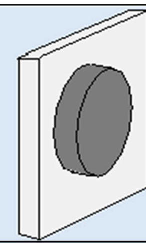


Parameter Name	IFC Type data	Notes
Geometric Data		
Height	IFCReal	Example: 1.20 m
Length	IFCReal	Example: 4.23 m
Depth	IFCReal	Example: 0.65 m
Shelves Number	IFCInteger	Example: 1 - 2 - 3
Shelves gap Separation	IFCReal	Example: 0.40 m - 0.50 m
Identification Data		
Asset ID	IFCInteger	Example: 121
Asset Name	IFCText	Example: Shelving with original books
Asset Code	IFCInteger	Example: 111
Asset Category	IFCText	Example: Furniture
Inspection Periods	IFCDate	Date of known inspections
Owner Name	IFCText	Owner's name if known
Owner Contact	IFCTExt	Telephone to contact
Changes / Modifications	IFC Text	Kind of changes suffered for the asset
Short description	IFCTExt	Description of the asset
Material	IFC Text	Main Material
Support Material	IFC Text	If exist any other material
Techniques Manufacture	IFC Text	Types of tools used
Photographic Survey	IfcRelAssociates	Link to the image of the asset
Damages Assesment		
Class of Damage	IFCText	Example: Biological Colonization
Sub-Class of Damage	IFCText	Example: Rot
Sub-Sub-Class of Damage	IFCText	Example: White rot
Condition Classification	IFCText	Example: Good, Fair, Poor, Bad
Symptoms	IFCText	Example: No Symptoms, Minor Symptoms
Condition Grade	IFCText	Example: In good condition, in fair condition
Extent	IFCReal	Example: 10.2 %
Length *	IFCReal	Example: 0.52 m
Aperture *	IFCReal	Example: 0.05 m
Condition Risk	IFCText	Example: Low, Medium, High
Urgency Risk	IFCText	Example: Long Term, Intermediate Term
Status	IFCInteger	Example: 1, 2, 3

Fig. 7. Asset family structure with the IFC parameters for the asset, including conservation and preventive ones, created ad-hoc for the HBIM. In the upper right is the geometric model. * refers to those metric parameters related with the crack damage.

Name ID Node

Category Monitoring Network



Parameter Name	IFC Type data	Notes
Geometric Data		
Radius	IFCReal	Example: 0.10 m
Identification Data		
Node ID	IFCInteger	Example: 8
Date Installation	IFCDate	Example: 11 / 01/2019
Connection Type	IFCText	Example: Zig-Bee
Monitoring parameter	IFCText	Example: C, S for CO2 and Solar radiation
Inspection Periods	IFCDate	Date of known inspections
Status	IFCInteger	Example: 1, 2, 3 depending of the KPI
Parameters Data (example of tow parameters)		
Temperature	IFCReal	Example: 21°
Humidity	IFCReal	Example: 25%

Fig. 8. Node family structure with the IFC parameters for the monitoring network.

2.3.3. Assets

Both the main and removable assets have been represented by instances of new families, created ad-hoc for this job. The families have their own geometric parameters, which are different for each object type. However, in order to make it reusable and scalable, these families show the same conservation and preventive information parameters. These new set of parameters have been structured in two groups as follows (Fig. 7): i) the data related with the identification and location of the assets and; ii) the data related with the damage presented in the asset.

2.3.4. Monitoring network

The monitoring network is a collection of different instances of a new family, representing each node of the system. This family has also been represented by means of patch-objects (Fig. 6b), which are always attached to a main object, such as construction elements or assets. To represent the nodes, these patches are modelled by cylindrical disks of the same size. The information added to these objects refers to the parameters registered by each node (Fig. 8). The current version of this family integrates 27 parameters including bioclimatic (temperature, CO2, luminosity), structural (e.g. inclination or crack width) and biological (e.g. presence of xylophagous). Each node stores information of the manufacturer, installation date and maintenance protocols, as well.

2.4. Integration of the monitoring data within the HBIM environment

The data acquired by the monitoring network is processed following a workflow specifically designed to make periodic queries to the monitoring server (Fig. 9a). The data of these queries is encapsulated and transmitted through the use of a JSON file, which includes the node description attributes (id, location, description, dimensions, weight, date of installation and custom information provided by the manufacturer) as well as all the parameters showed in Section 2.3.4. (Fig. 9b). The data captured by each node is stored in a MySQL database that allows plotting graphs to analyse the evolution of specific parameters along the time. Moreover, the data can be exported into a tabulated format, i.e. an EXCEL file, to process it by an external software.

It is worth mentioning that each object defined in the HBIM environment includes a label defined as *Status* (Fig. 7 and Fig. 8). This field allows to classify the conservation risk of each object according to its current bioclimatic condition. In this sense, the current version of the API implements the KPI proposed by Corgnati et al. [25] (Eq. (1)). These KPI have been implemented in the previous Service Level of the HeritageCARE method [29].

$$KPI = \frac{N_{in}}{N_{tot}} \tag{1}$$

where N_{in} represents the number of measurements within the defined tolerances and N_{tot} the total number of measurements.

These KPI define the percentage of measurements in which the monitored parameter lies within a required range of tolerances (Eq. (1)). A value of 100 means a perfect match (all the measures are within the limits). Meanwhile a value of 0 represents a total mismatch being all the measures out of tolerance. If the value of the KPI is above 90%, the HBIM

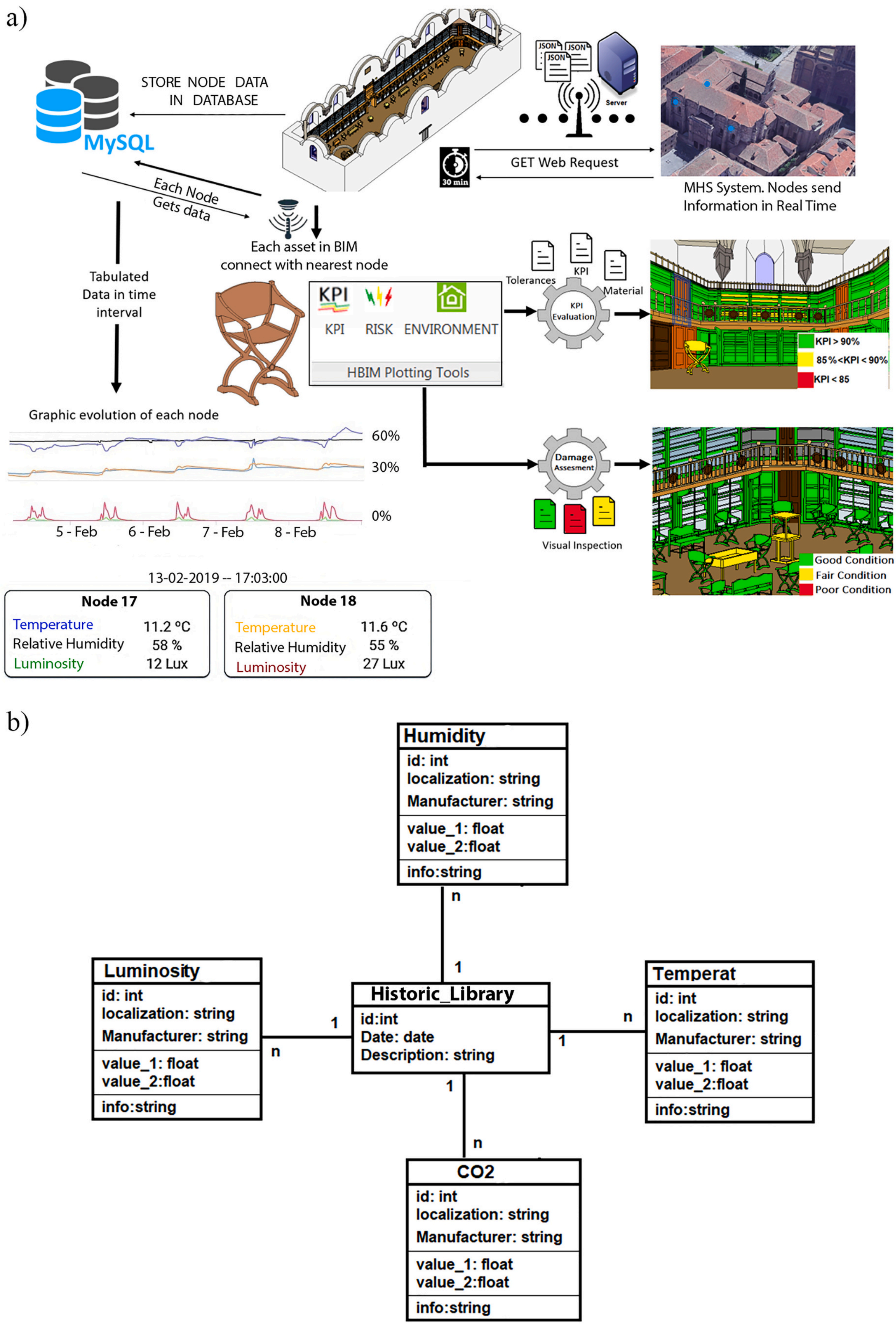


Fig. 9. Connection of the monitoring network with the HBIM environment: a) general workflow; b) Structure of the MySQL database.

Table 5
Admissible tolerances for assets in accordance with its material. Adapted from Adcock [42].

Material	Temperature (°C)	Humidity (%)
Paper	18–22	40–55
Scroll	18–22	45–60
Leather	16–20	45–60
Textile	16–20	30–50
Wood	17–21	45–60
Metal works	18–22	15–55

Table 6
Admissible levels of luminosity for different type of materials. Adapted from Sharif-Askari and Abu-Hijhel [43].

Object Type	Lux lumen/m^2
Very Sensitive[a]	0–50
Sensitive[b]	0–200
Insensitive[c]	0–300

[a] Very sensitive: book, manuscript.
[b] Sensitive: Oil/tempera painting, undyed leather.
[c] Insensitive: Metal, ceramic, stone.

system assigns to the *Status* label a value of 1 (low risk). If the value is below 90% but above 85%, the HBIM system assigns a value of 2 (medium risk). Finally, if the value is below 85% the HBIM system assigns a value of 3 (high risk).

2.5. Tolerances for the bioclimatic monitoring

The preventive conservation of museums and libraries requires a rigorous control of the bioclimatic conditions in order to maintain the assets, e.g. books, manuscripts or painting among others, in optimal conditions. According to Pavlogeorgatos [23], the five main environmental parameters that can promote the degradation of the assets placed in libraries are: i) temperature; ii) relative humidity; iii) illumination; iv) atmospheric pollutant and; v) noise and vibrations. Out of tolerance values in the first four parameters could promote the presence of chemical and physical degradation processes. Meanwhile the last one could promote physical damages.

From this variety of parameters previously shown, the proposed HBIM approach implements the concept of KPI in three of the five fields in accordance with the nodes installed in the monitoring network. In all of these indicators different types of tolerances were taken into consideration according to the materials defined in the HBIM objects (Table 5 and Table 6). These set of tolerances extend those proposed previously by Sánchez-Aparicio et al. [29], including specific tolerances of the different materials presented on the library. Then, this parameter was used to define the label *Status* of each object. Additionally, the system includes a KPI for the xylophagous detector. In this case, only two values were included in the label *Status* [29]: i) 1 if the node does not detect the presence of xylophagous and; ii) 3 if the node detects the presence of xylophagous.

3. Experimental results

3.1. Study case: the Historical Library of the University of Salamanca

The General Historical Library of the University of Salamanca dates back to the XV century and is part of the *Escuelas Mayores*, placed in the historical centre of Salamanca (Castilla y León, Spain). The Library is located on the second floor, behind the main Plateresque style facade (Fig. 10), which is an emblematic symbol of the oldest Spanish University.

The building has been modified several times since its creation in 1254, when the king Alfonso X reorganized the academies. In the reorganization it was created the stationary house. During the XV century, the manuscripts were moved to a specific room in the San Geronimo chapel, inside the building of *Escuelas Mayores*. The General Historical Library was built between 1509 and 1526. In 1749, it was restructured according to the instructions of Andrés García de Quiñones, and it has maintained its appearance since then (Fig. 11). With respect to the architecture, the Gothic door stands out. It was forged in 1526 with an arch carpanell, archivolts decorated with plant and animal elements

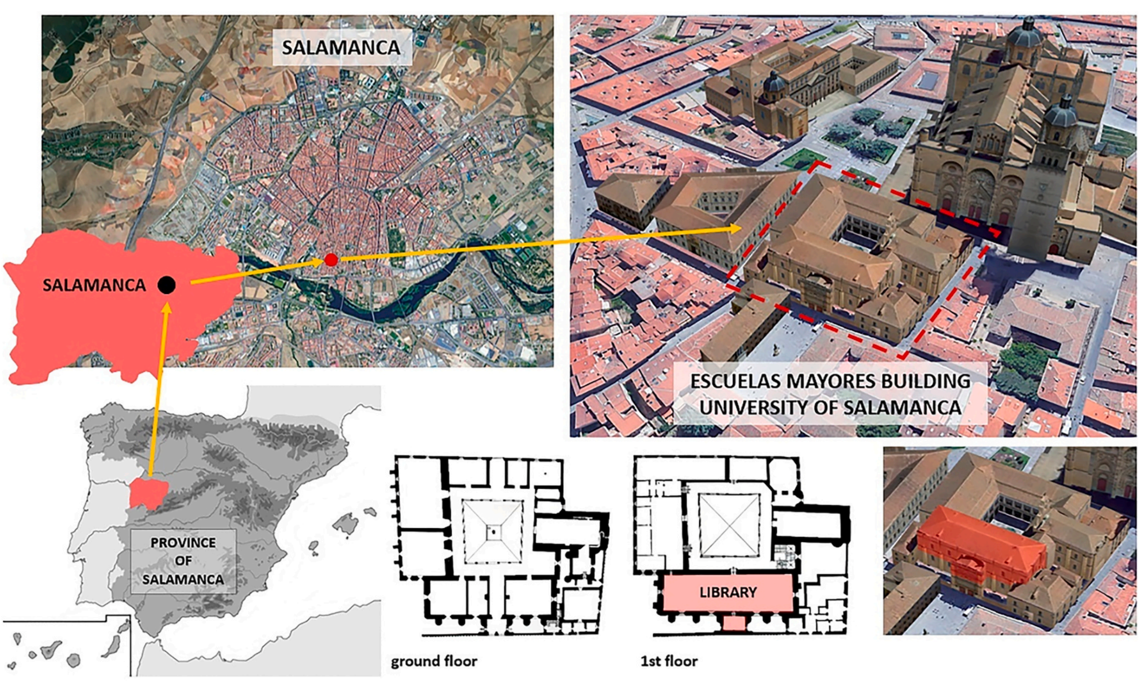


Fig. 10. General Library of the University of Salamanca location.

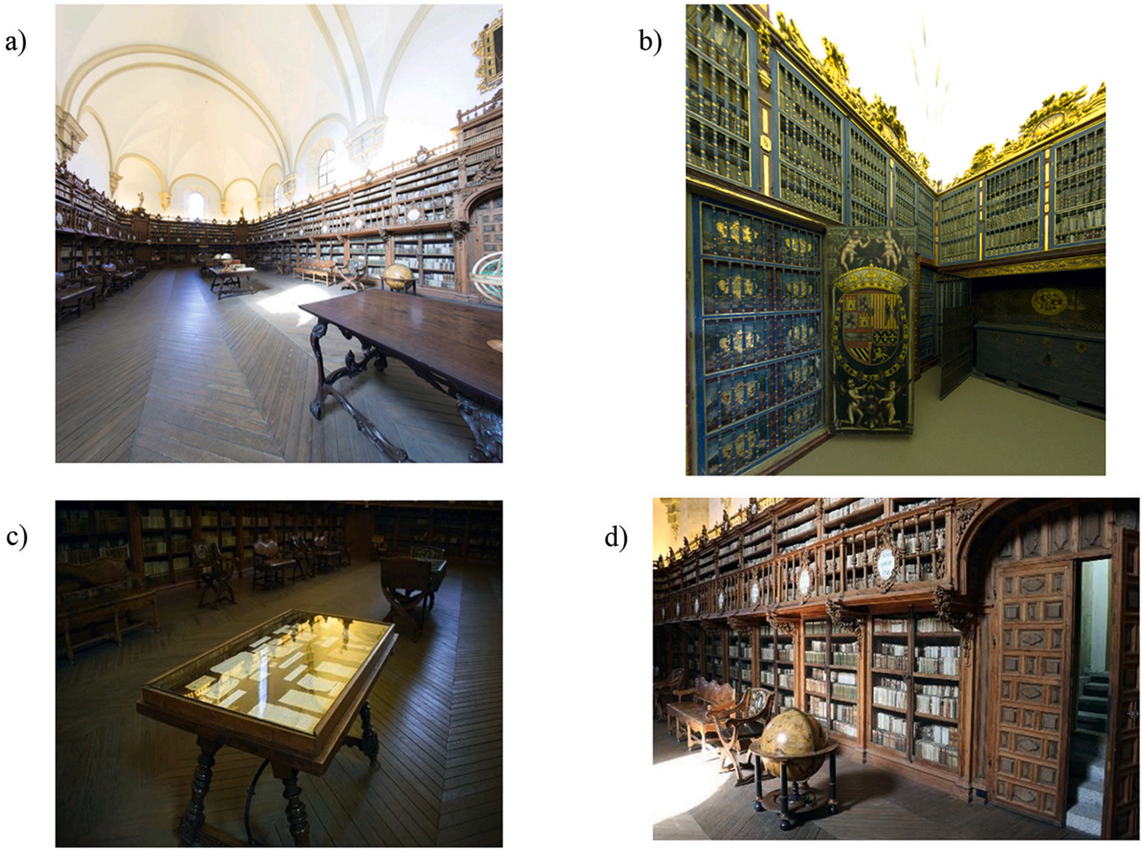


Fig. 11. a) General view of the Library and arrangement of the shelves. b) Manuscript Room. c) Table where several manuscripts are exhibited. d) Books and world globes.

and closed with a Renaissance grille. The gallery is covered with a lunette vault in the centre and a polygonal shape at its ends [44] (Fig. 11a).

The library contains an extensive bibliographic collection formed by 483 incunabula, 2774 manuscripts, and 62,000 printed volumes. All these elements have many different origins so, in order to have them ordered, they are divided in different fields of knowledge. There are eight categories: i) Literature; ii) Maps; iii) Language; iv) Natural; v) History; vi) Religion; vii) Medicine-Science and Technique; viii) Laws and History. The codex *Las Virtuosas y Claras Mujeres,* the incunabulum *Libro de Ajedrez, Libro del Buen Amor* or *the Appian's Cosmography* stand out among the books contained in the library. All of them are stored in wooded Baroque style shelves, designed by Manuel de Lara Churriguera [45]. Apart from the documents and books, there are several celestial and armillary wooden spheres, tables, leather and wood chairs and vitrines (Fig. 11).

Besides the Historical Library, there is a small *incunabulum* room that occupies the interior of the Plateresque façade and holds manuscripts of

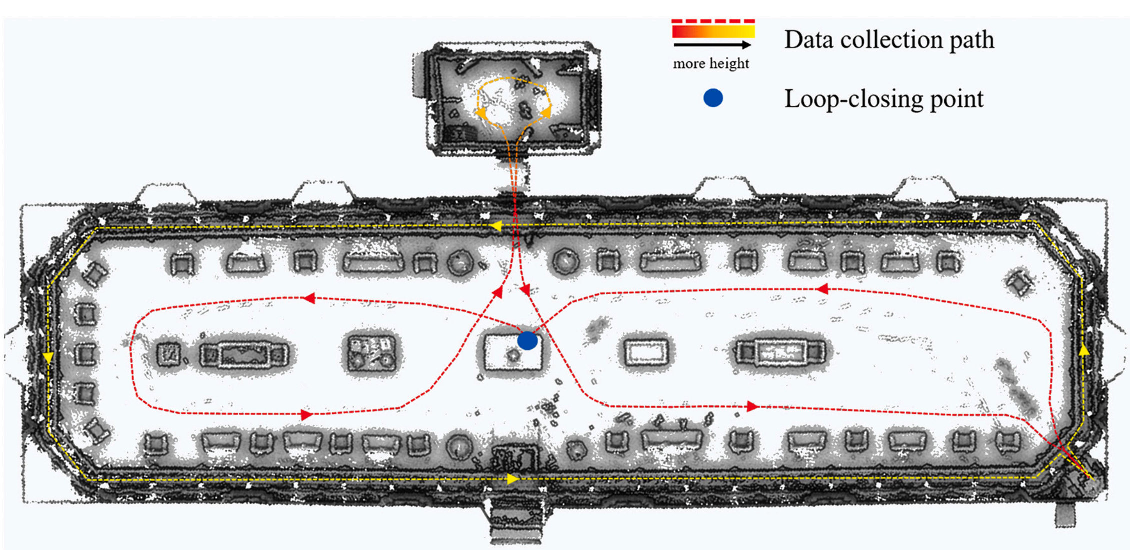


Fig. 12. Data collection path executed for the digitalization of the Library.

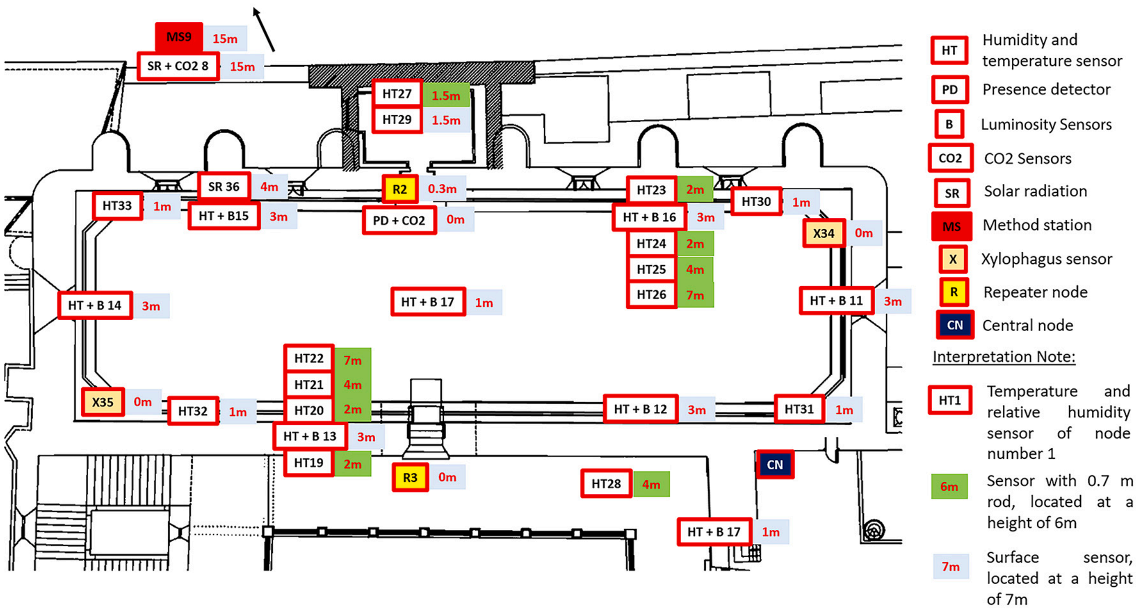


Fig. 13. Nodes distribution in the Library.

the 11th century and the incunabula of the XV century (Fig. 11b). These books are organized in two themes of study: i) Canon Law and; ii) Theology. This room is the old medieval ark of the university, initially used to keep money and, later on, forbidden books.

3.2. *In-field works*

The in-field works were mainly focused on capturing the different type of information required for define the HBIM. Three steps were carried out to this end: i) a visual inspection to improve the knowledge about the conservation state of the Library and its assets; ii) a digitalization of the Library by means of a WMMS and; iii) the installation of a wireless monitoring network.

3.2.1. *Inspection of the library*

The visual inspection of the Library was carried out following the guidelines proposed by the HeritageCare initiative [27,28]. Specifically, the first and second level of inspection protocols were applied. In order to maintaining a common metric during the survey, a mobile app was used, allowing to capture all the necessary data by means of standardized checklists.

On the one hand, the first level of inspection allows to obtain a rapid condition screening of the conservation status of the building. During the inspection, a conservation assessment of each construction element was carried out as well. This assessment included an analysis of the damages presented on the elements following the approach proposed by Masciotta et al. [27]. Each damage is defined by the following variables: i) the class of damage; ii) the condition grade; iii) a short description of the damage; iv) its extension along the construction element and; v) a risk assessment. The result of this inspection allows identifying different types of damage located in the following construction elements: i) structural deep cracks on the bearing wall and on the lunette vault due to the initial accommodation of the structure; ii) moist areas on the vault's keystone coming from the timber roof and iii) some discolorations on the timber floor. Apart from these damages the inspection highlighted the absence of UV filter on the windows, which could promote the photo-degradation of some assets as well as inappropriate air ventilation in the *incunabulum* room (Fig. 11b).

The second level of inspection concerned the conservation assessment of the assets presented in the Library by following a similar protocol to the previous one. Due to the huge amount of assets, only the most representative ones were inspected: i) two vitrines; ii) two chairs; iii) one Earth Globe and; iv) twenty-one exceptional books from the different knowledge areas (within its associated shelves). The result of this inspection allowed identifying the different materials presented on the assets as well as the presence of some discolouration and deposits.

Fig. 14. Nodes installation in the Library.

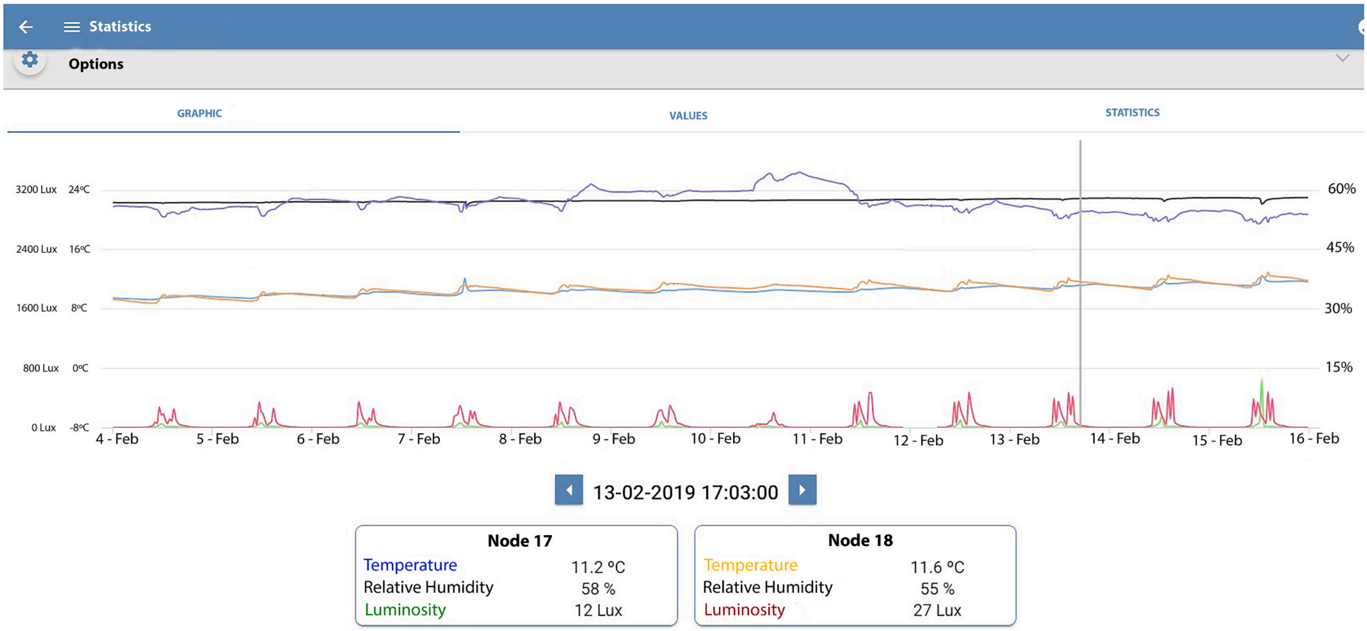


Fig. 15. Real time data captured by the nodes 17 and 18.

3.2.2. *Digitalization of the library*

The Zeb-Revo Wearable Mobile Mapping System from GeoSlam® [33]. was used for digitalizing the library. The Zeb-Revo system consists of a rotatory head that comprises a 2D laser scan head and an IMU. The head is connected to a processing unit, which is carried by the user in a backpack, allowing the digitalization of large spaces while walking through them. The information captured by the scan head and the IMU are finally integrated to create a 3D point cloud by means of a full-SLAM algorithm [16], providing an accuracy that ranges from 1 to 3 cm.

In order to avoid mistakes and get optimal results, the suggestions of di-Filippo et al. [14] were followed, such as: i) remove any disturbing object; ii) leave doors between different room open to make easy the path; iii) add items to help the algorithm works in those places where the geometry is very similar and with no significant changes and; iv) the designed path should be a loop, starting and finishing in the same point, in order to let the SLAM algorithm adjust errors.

Once the environment was prepared, the digitalization was made in a unique loop with a constant speed to have the same density in all the point cloud and being especially careful in transitions over the doors. For the present case study, 14 min were invested to obtain the 3D point cloud of the whole Library (Fig. 12): eight minutes to capture the data and six to solve the SLAM problem. The point cloud obtained had a total of 15 million of points.

3.2.3. *Monitoring system*

The final stage of the in-field works involved the installation of a monitoring network. A total of 39 wireless nodes were placed along the Library (Fig. 13 and Fig. 14): i) 23 for monitoring humidity and temperature; ii) 1 for detecting the presence of people; iii) 8 for monitoring luminosity; iv) 2 for monitoring CO_2 in the environment; v) 2 for monitoring solar radiation; vi) 2 for monitoring the presence of xylophagous; vii) and 1 methodological station. In addition to the two local nodes, there was a central node. This node sent the information to the central computer (Fig. 3). The data thrown by each node can be consulted online, providing real time values (Fig. 15). The monitoring system is active since July 2019.

3.3. *HBIM environment*

The HBIM of the Library was implemented in Revit from Autodesk®. All the features shown in Section 2.3 were included in this framework by means of an in-house plugin named Heritage 5.0 This plugin allows assigning different families to the geometries, with specific LoI, storing and processing the different data captured by the monitoring network as well as calculating the KPI.

The geometrical model of the Library was obtained by using a semi-automatic reverse engineering procedure. This approach starts with the triangulation of the WMMS point cloud, using to this end a 3D Delaunay triangulation. Then the mesh model is processed by applying the stages proposed by Attene [46], which incorporates several automatic and sequential stages: i) a hole filling stage using the radial basis function [47]; ii) a repair stage based on the minimum threshold distance algorithm [48]; iii) a topological and geometric noise removal stage through the use of local re-triangulation methods and anti-aliased Laplacians filters [49]. After this processing stage the mesh is modelled in order to create a suitable solid model for BIM purposes. For basic shapes (e.g. walls or spheres) the RANSAC Shape Detector algorithm was used [50]. For complex shapes a section-based modelling procedure was applied as suggests Sánchez-Aparicio et al. 2019 [40]. All these stages were complemented with standard reverse engineering procedures such as the extrusion for modelling the thickness of different elements (e.g. the walls or the vaults), as well as Boolean operators for creating the windows. Fig. 16 shows a comparative study between several solid models and their corresponding point clouds. As could be observed, the reverse engineering procedure carried out allows to reproduce with an acceptable accuracy the different constructive elements and assets placed within the Library. The largest discrepancies take places on those parts with complex decorative elements which were considered not relevant for the preventive conservation policies of the Library. These decorative elements were included in the information tab of the families (see

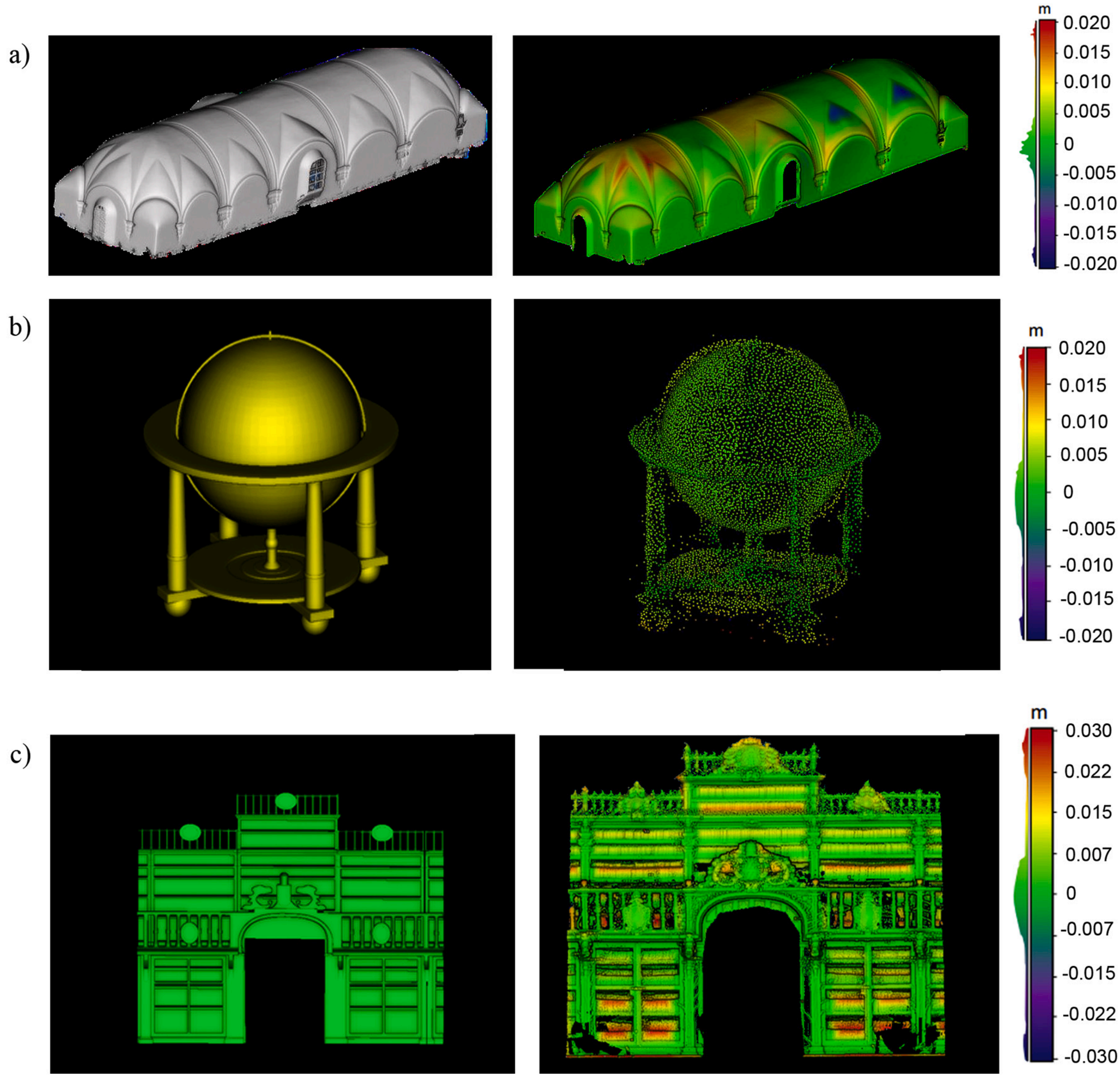


Fig. 16. Discrepancies between the original point cloud and the solid model: a) vault of the Library; b) an armillary wooden sphere and; c) a shelve at the entrance of the Library.

Section 2.3).

The different solid models generated (Fig. 17) were introduced within the BIM environment, using the Heritage 5.0 Plugin to assign the same information attributes to each specific family. The LoI of each asset, node or damage include several common parameters between them (i.e. Condition grade, Inspection Periods, Short Description, Asset ID or Status), which have different values in each particular family. The Heritage 5.0 Plugin allows to add all the common attributes to the desired family in an automatic way, making this task easier and faster (Fig. 18). The data introduced of each family was obtained from the technical inspection (see Section 3.2.1). Additionally, the damages and nodes from the monitoring network were imported by means of path-based families (Fig. 19).

3.3.1. *Checking the monitoring data*

The monitoring network was connected to the HBIM by means of node families according to the disposition shown in Fig. 13. The information shown in each node object corresponds with the latest data received form the *JSON* request. Complementarily, the system stores all this information on its own database (Fig. 9). This allows to plot timeline graphs, thereby assessing the temporal evolution of specific parameters. The user can decide which node and interval is plotted. All this information can be exported in. C*SV* format (Fig. 20).

Additionally, the data stored in the database is used to compute the KPI on each asset of the HBIM. In this case the user can decide the range of dates included in the computation of the KPI. It is worth mentioning that the plugin computes different KPI for the same node according to the different materials presented on the assets (see Section 2.4). Finally, the nearest KPI is assigned to each asset. This KPI is introduced within the *Status* label as an integer value which varies from 1 (green) to 3 (red). Each family has a *Status* label per measured parameter (i.e Status for temperature or Status for relative humidity). In those cases on which the family is integrated by different types of materials, and thus by different ranges of admissible tolerances, the system uses the most unfavourable KPIs to colorize the family (Fig. 21).

Under the basis previously shown different KPI evaluations were

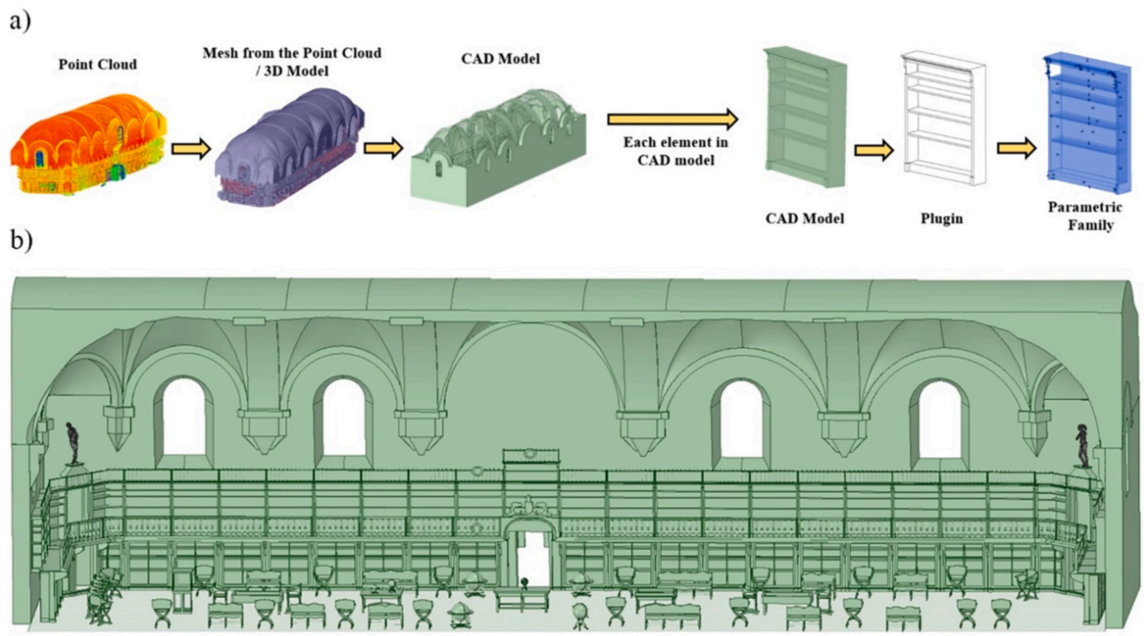


Fig. 17. Geometrical model of the Library: a) workflow; b) detail of the final solid model.

carried out on the Library, considering as the reference period one month. Table 7 and Fig. 22 shows the results of computing the KPI for one cold month such as February. As could be observed, most of the assets are plotted in red which suggest that the bioclimatic conditions could promote some damage on the assets. In all the cases the temperature ranges are not within the acceptable ranges defined in Section 2.5, showing an average value of 12.2 °C with a minimum value of 10.9 °C and a maximum temperature of 16 °C. For this month the relative humidity has an average value of 62% with a minimum value of 58% and a maximum value of 64%, exceeding in most of the cases the admissible ranges (Table 5). Regarding the luminosity, all the nodes of the monitoring network showed optimal values (up to 95%) even for very sensitive assets such as books or manuscripts.

Similar results were obtained for one warm moth (July). In this case the average temperature exceeds the recommended upper bound with an average, maximum and minimum values of 25.4 °C, 27.9 °C and 18.6 °C respectively. These values of temperature could accelerate the degradation of the assets as well as becoming uncomfortable for visitors. The relative humidity during this month was also outside the admissible range, with an average value of 45%. This low value could can cause assets to become dry and brittle.

The results obtained for both months, February and July, corroborates the necessity of a HVAC (Heating, Ventilation and Air Conditioning) control systems for minimizing the possible damage of the assets. This appreciation is in line with the suggestion done during the inspection carried out in Section 3.2.1.

3.3.2. Conservation assessment and damage

Apart from plotting in a graph the KPI of each asset, the plugin allows plotting different parameters of relevance for the preventive conservation of the site, such as the urgency risk. Due to the absence of UV filter in the windows, as well as an adequate ventilation system in the *incunabulum* room, the conservation status of the assets was fixed to fair, implying a mid-term urgency risk (Fig. 23a). Fig. 23b shows the plot in the case of not considering this issue. In this case, some of the assets show a good conservation status (green colour). Complementarily, the plugin highlights the assets with a specific damage (Fig. 23c).

3.4. Discussion of the approaches adopted for the creation of the HBIM model

This section is devoted to discussing the impact of the different approaches adopted in the proposed HBIM methodology.

Regarding the geometrical aspect, the use of a WMMS proves to be a really efficient solution for the digitalization of heritage sites. This device requires just only 14 min to obtain the whole point cloud of the Library, outperforming the time estimated for a terrestrial laser scanner to digitalize the same area, which could be estimated in 225 min. Apart of this, the flexibility of the system allows to obtain data in complex areas such as corridors (Fig. 11d). The density of the data obtained by the WMMS solution allows to create families with a LoD of 300 (Table 3). This LoD could be considered enough for defining the node, damages and assets. In the case of nodes, this threshold is irrelevant in comparison with the LoI since is a family devoted to capturing the monitoring data. However, this threshold has higher impact in the families that define the damages and the assets. On the one hand, the LoD adopted for the damages allows to define it in terms of urgency, position and orientation by means of patch-families with different sizes in accordance with their severity. The extension and other relevant metric values are considered in the LoI. This approach allows not only the integration and monitoring of the evolution of the damages in a simple way, but also having a rapid screening of the impact of each one (Fig. 19). On the other hand, the LoD adopted for the assets families does not include the most detailed ornamental parts which are included in the LoI by means of the historical data as well as a detailed photographic survey. The adoption of this threshold is in line with the current necessities of the Library in terms of preventive conservation.

The use of KPI and operational thresholds in conjunction with the LoI of the families (in special the material definition) allows to synthetize the big data coming from the monitoring network. This combination allows to obtain an easy-reading and robust screening of the climatic conditions of the assets placed within the Library. This combination

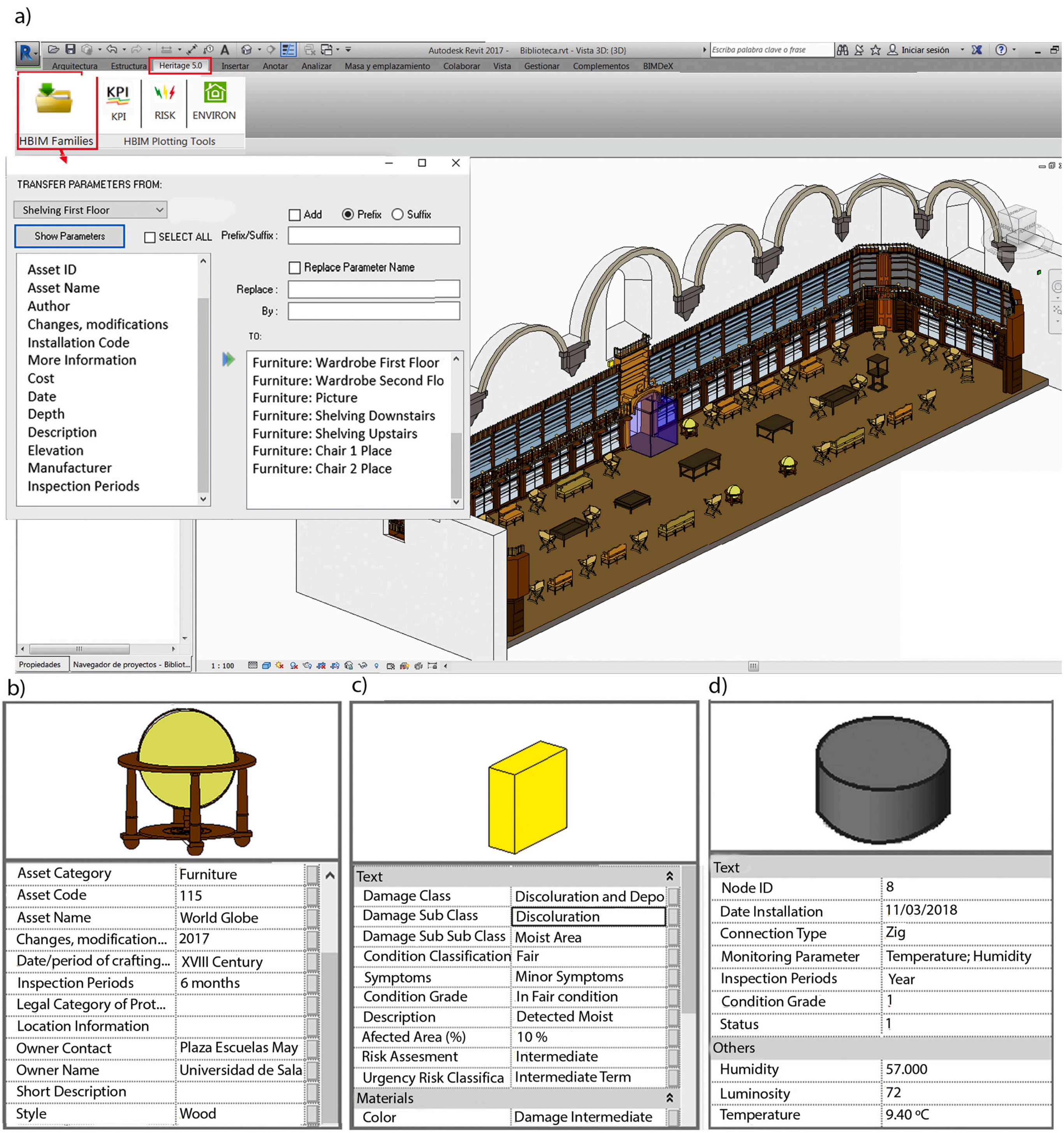


Fig. 18. Application of families to the different solid models created: a) assigning a new family; b) movable asset; c) damage observed in the wall and d) node of the monitoring network.

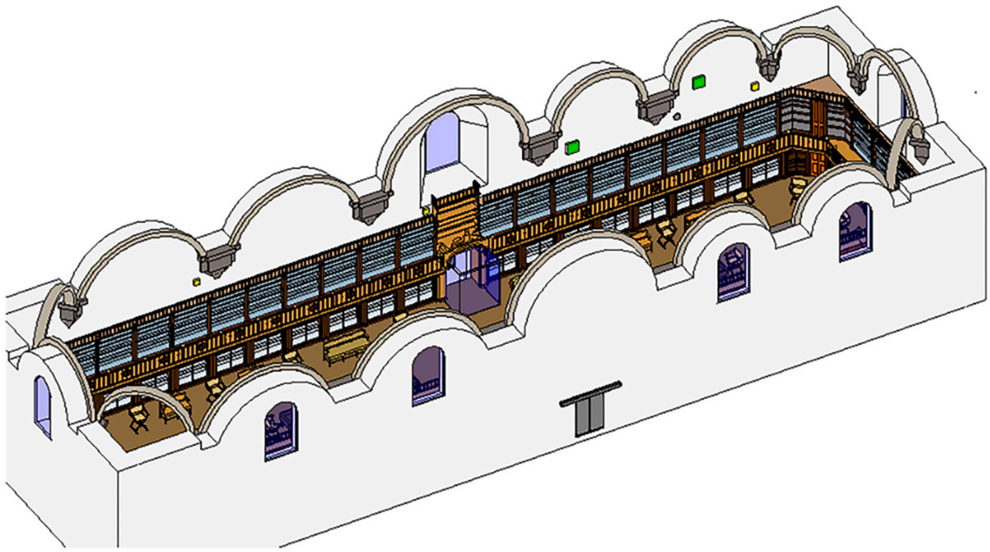


Fig. 19. General view of the HBIM model on which is possible to observe the path-based families used to represent the damages and nodes of the monitoring network.

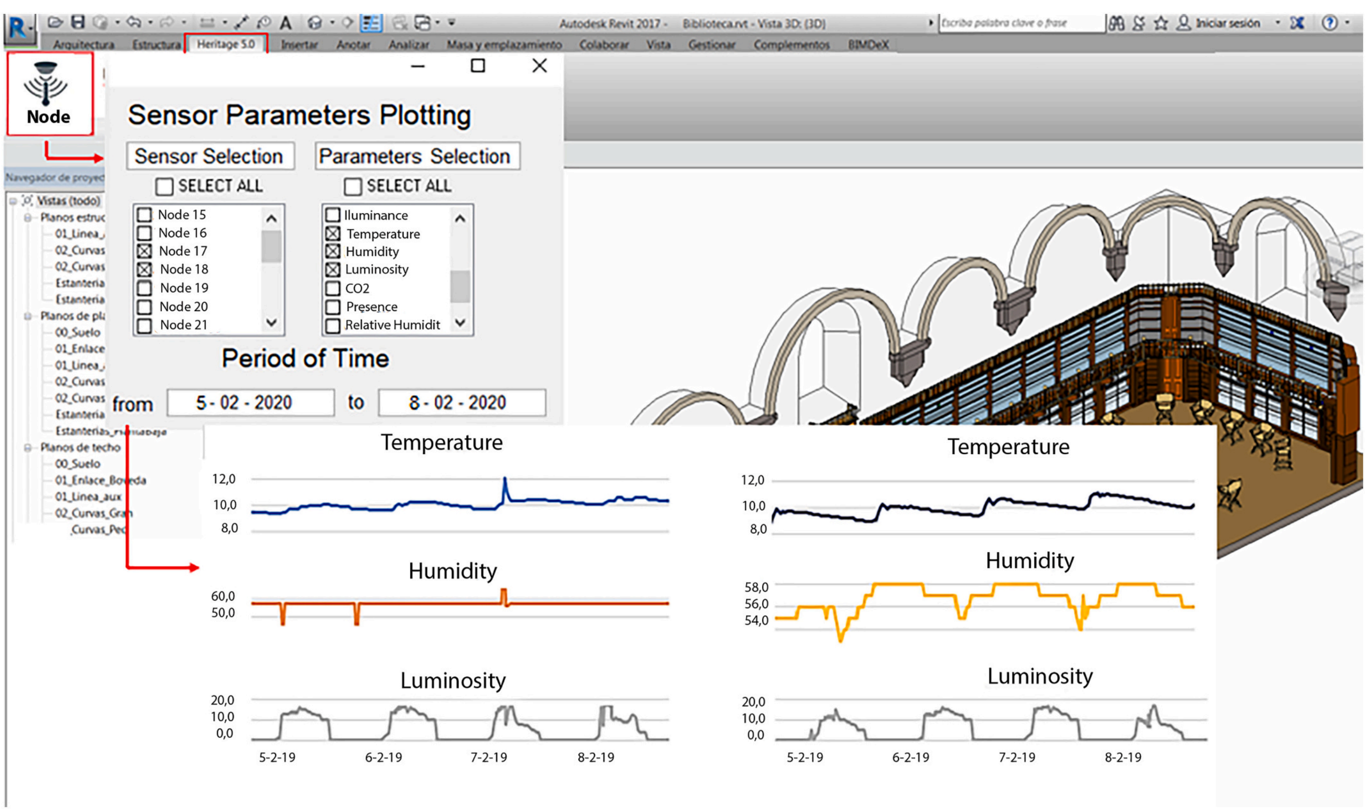


Fig. 20. Appearance of the Heritage 5.0 plugin when the user consults the data of one node.

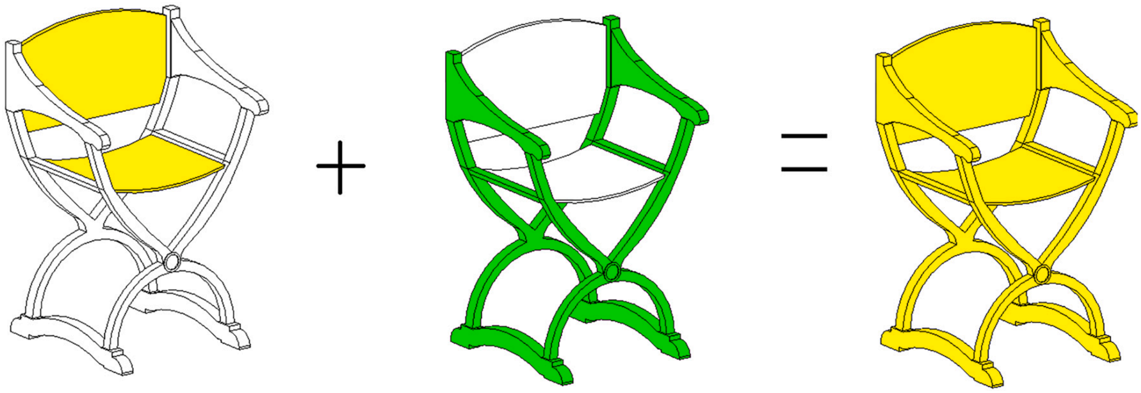


Fig. 21. Computation of the KPI for objects with different materials. Green colour represents a KPI above 90% and Status = 1. Yellow colour represents a KPI between 85% and 90% and Status = 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 7
Results of the KPI computation for temperature and humidity during February. Right KPI comes from the temperature evaluation. Left KPI comes from the relative humidity evaluation. Null values refer to situations in which the measured parameters are out of the recommended tolerances.

	Node			
Type of material	07	15	17	18
Paper	0.00 / 1.46	0.00 / 0.00	0.00 / 0.00	21.63 / 0.00
Leather	98.07 / 0.35	0.00 / 0.00	16.38 / 0.00	46.59 / 0.00
Textile	0.00 / 0.35	0.00 / 0.00	0.00 / 0.00	1.41 / 0.00
Wood	98.07 / 0.83	0.00 / 0.00	16.38 / 0.00	46.66 / 0.00
Metal works	0.00 / 1.46	0.00 / 0.00	0.00 / 0.00	21.93 / 0.00

allows to design a deeper preventive conservation plan, enhancing.

4. Conclusions

This paper presents an HBIM approach for the preventive conservation of historical buildings. With this aim, the methodology exploits the latest advances in 3D digitalization, inspection protocols and advanced monitoring networks.

The wearable mobile mapping system pops up due to its lightweight and flexibility compared to traditional approaches, such as photogrammetry and laser scanning. This device just requires to perform a close-loop path to capture the whole scene as well as to compensate a possible error accumulation. The density of the point cloud obtained by this device, within the use of reverse engineering approaches, allows modelling the different elements required to define the HBIM model, such as the assets. To this end, the method applies a post-processing approach for meshing the WMMS point cloud. This mesh is then used as geometrical base for reverse engineering, allowing to obtain a suitable solid model of the construction by means of the use of sections, Loft surfaces, extrusions and Boolean operators.

The low LoD applied in the different families of the HBIM model is complemented by a high LoI. Within this context, the method proposes the use of the standardized inspection protocol proposed by the HeritageCare initiative. This protocol allows the appropriate definition of the different damage presented on the assets as well as the urgency risk. All this information is complemented by images that allow defining different details that are not modelled.

Complementarily to the previously mentioned approaches, the methodology suggests the use of an advance monitoring network that enables capturing different variables of relevance, i.e. environmental variables, used to control the microclimate of the assets. This data can be stored in a database that is directly linked to the HBIM model, allowing to plot graphs as well as to export data in a universal format, i.e. the CSV file.

All the information generated by the different methods is integrated into a unique environment by means of the development of an in-house plugin named Heritage 5.0, thereby generating a multidisciplinary environment that stands out due to its interoperability. This interoperability increases work efficiency between the different agents involved in the preventive conservation of heritage buildings. Apart of fusing this information, the plugin allows exploiting the data contained in each family to compute the so-called KPI in accordance with the different materials presented on the assets. This KPI is plotted in a user-friendly way using a colour-grade scale. Moreover, it could be used to activate any intervention that could facilitate the management of the site. This strategy is also applied for the urgency risk as well as the damage, displaying the conservation status and environmental conditions of the assets as images.

This approach has been applied to one of the most representative Spanish heritage places. It allowed identifying deficiencies that could promote the degradation of the assets, such as the absence of UV filter on the windows or the inappropriate ventilation system in the incunabulum room.

Future works will focus on improving the current version of the tool by adding additional features for the preventive conservation, such as: i) the possibility of plotting technical reports about the conservation state of the site and assets; ii) the integration of structural features that allow evaluating the structural stability of heritage sites by means of HBIM approaches and advanced numerical evaluations; iii) the development of approaches that follow the conservation of heritage sites along time and; iv) the integration of CFD approaches for evaluating the distribution of bioclimatic parameters along the heritage sites. Therefore, new information will be added to the families, such as the transmittance of each layer.

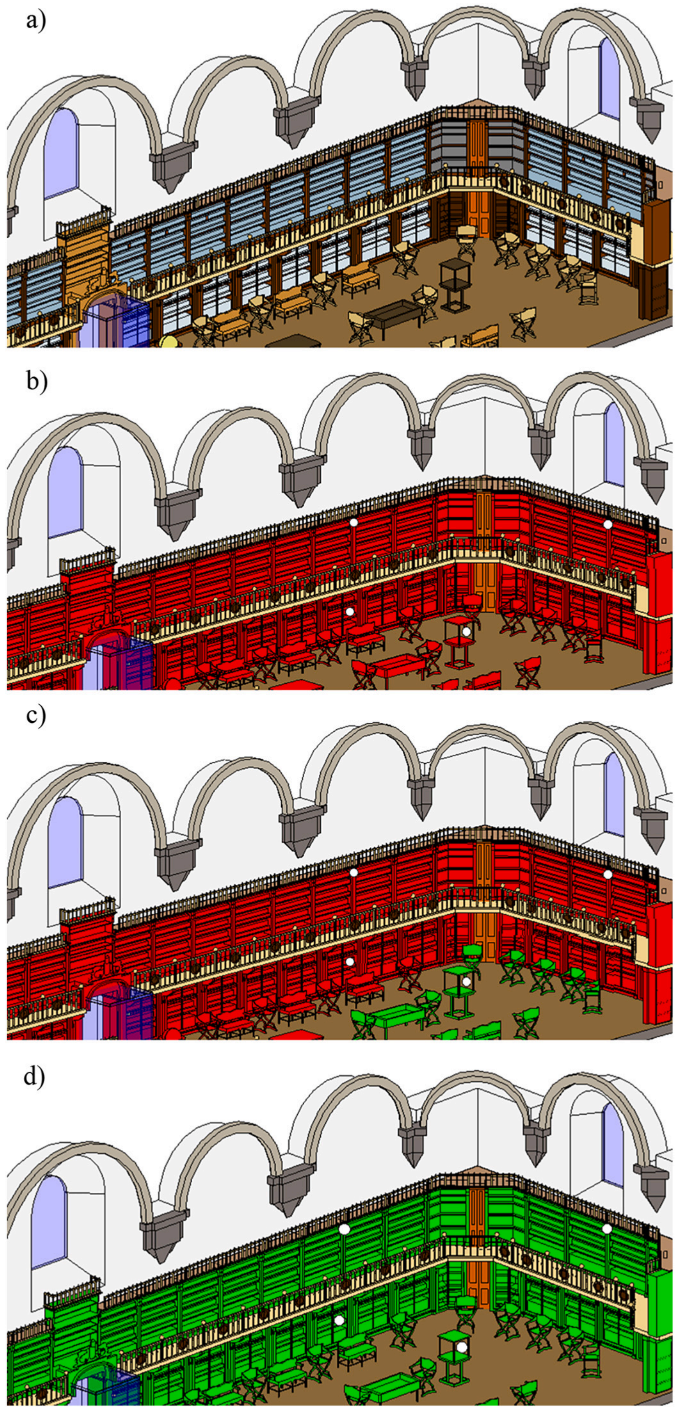


Fig. 22. HBIM model with the KPI plotted: a) general view; b) Computation of the KPI for temperature conditions; c) Computation of the KPI for Humidity conditions And; d) Computation of the KPI for Luminosity conditions. White circles represent the nodes position. The assets plotted in green has a *Status* label of 1, assets in yellow has a *Status* of 2 and assets in yellow a *Status* of 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a)

b)

c)

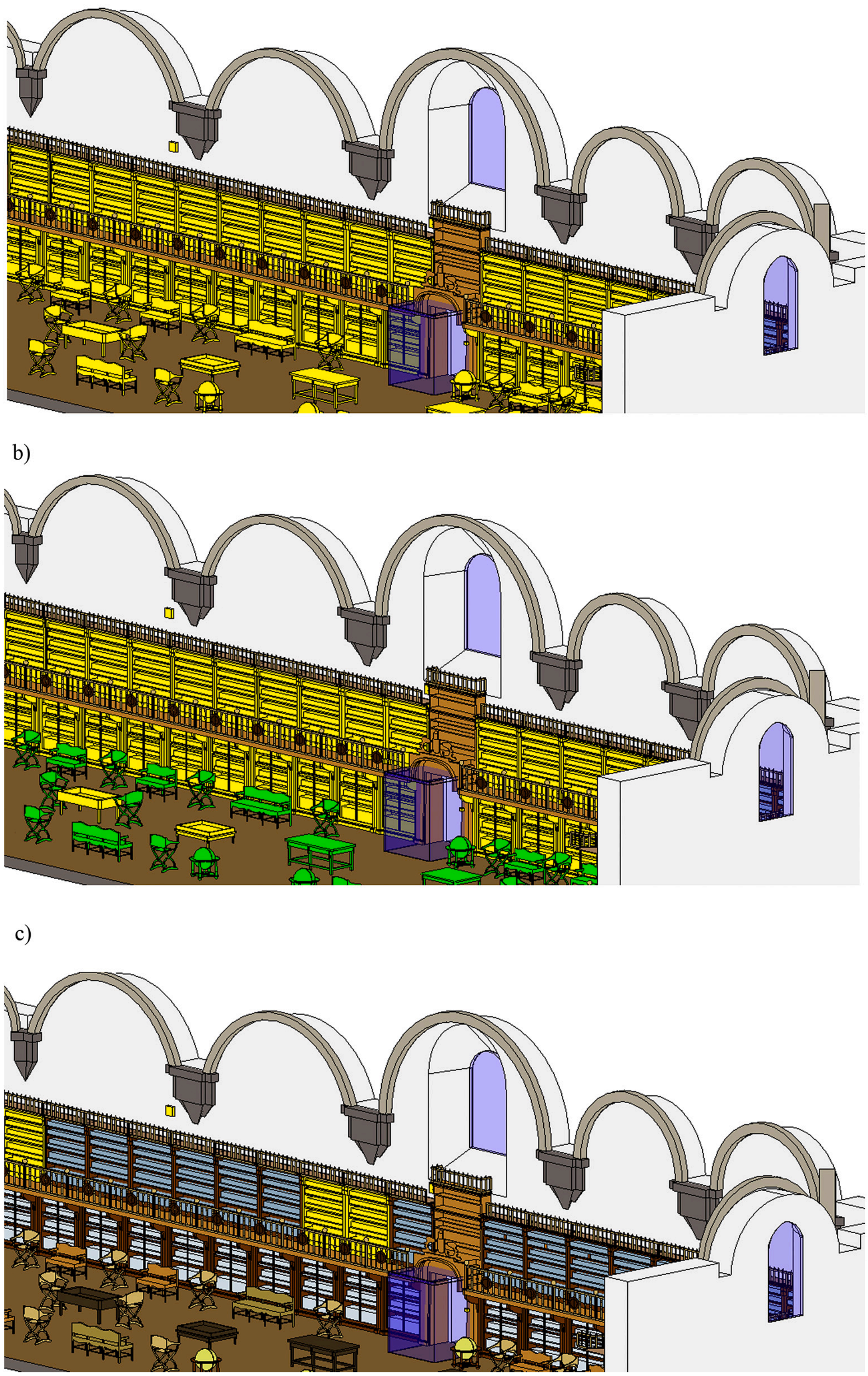


Fig. 23. Graphical plots within the HBIM model: a) Urgency risk considering the absence of ultraviolet (UV) filter and a proper ventilation system; b) urgency risk according with the conservation status of the assets and; c) assets with presence of discolouration.

Declaration of Competing Interest

None.

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