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WEB-GIS APPROACH TO PREVENTIVE CONSERVATION OF HERITAGE BUILDINGS

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Abstract

The effective implementation of preventive conservation approaches demands the employment of standardized and robust tools able to integrate the data coming from multiple sources, inspection and diagnosis techniques, as well as to ensure the proper information transfer between expert and non-expert users. Aiming to make a step forward in the state of the art of current conservation approaches, a cutting edge Web-GIS technology resorting to the intuitiveness of 360° panoramas and 3D point clouds in combination with the Internet of Things is presented in this work, demonstrating how physical and digital worlds can be linked for proper documentation and management of cultural heritage. To validate such a pioneering approach, one of the most representative and complex heritage buildings of Spain is used as a case study: the General Historical Library of Salamanca.

Keywords: Geoinformatics; Historical constructions; Preventive conservation; Web-GIS; Internet of Things; PlusCare system; HeritageCare platform; Geospatial database; Monitoring network

1 Introduction

Preventive conservation can be considered as the most efficient approach for maintaining and protecting heritage buildings and sites [1-3]. Unlike remedial approaches, this strategy is able to save between 40% and 70% of the total maintenance costs by avoiding major interventions and promoting systematic inspections and monitoring routines [2]. However, its effective implementation entails different challenges [3], demanding the use of standardized and integrated workflows for documentation, registration and management of the information along with proper communication protocols between technicians (expert users) and buildings' owners/managers (non-expert users) [4]. In the light of these considerations, and given the absence of a systematic policy, the European project HeritageCare (Monitoring and preventive conservation of historic and cultural heritage, ref. SOE1/P5/P0258) has been promoting the implementation of a hierarchical digital-based preventive conservation system in South-West Europe. This system draws inspiration from the Flemish Monumentenwacht [5,6] – a public organization which influences daily maintenance practices in The Netherlands and Flanders – but introduces new substantial developments in the form of digital tools to keep abreast of the times and enhance the quality of the services provided [4]. The HeritageCare system relies on three complementary levels of services, whose main pillar is a systematic inspection and monitoring process supported by the latest advances in digitization and smart technologies (e.g. photogrammetry, drones, laser scanning or Building Information Modelling, among others [7]). Service Level 1 (SL1 or StandardCare) aims at providing a feasible, low-cost and rapid condition assessment of the heritage buildings; Service Level 2 (SL2 or PlusCare) is devoted to integrating the information collected during SL1 with an in-depth condition assessment of the building and its indoor assets, including the monitoring of the most relevant physical and mechanical parameters; finally, Service Level 3 (SL3 or TotalCare) integrates and manages all data gathered from SL1 and SL2 through the Building Information Modelling (BIM). Focus of the present paper is to present the PlusCare protocol in detail, exploring the role played by the main social actors (inspectors on the one hand and owners/managers of the heritage sites on the other hand) within the entire conservation process.

The integration of information from different inspection and diagnosis techniques, core of the PlusCare protocol, is reached through the geoinformatics [8]. This discipline, which includes data acquisition methods such as photogrammetry, laser scanning or remote sensing, promotes the use of geoinformation approaches, for preserving cultural heritage, like Geographical Information Systems (GIS) or Building Information Models (BIM) [8]. The former are rooted in the employment of a geospatial database that is able to store a great variety of alphanumeric information as well as raster and vectorial products, all of them properly geolocalized [9]. Thanks to this ability, there are plenty of applications that use GIS for heritage preservation at city [10,11] and building levels [12-14] in which the information can be filtered according to different criteria. The latter have emerged as an intelligent management system focused on the creation of full 3D digital models populated with meaningful attributes related with the materials, construction systems, damages, monitoring networks, and the like. This information integration is carried out within an interoperable framework, which makes BIM approaches a very powerful tool for the management of preventive conservation plans [15-17].

Complementary to GIS and BIM, several authors have proposed in the last few years the use of virtual tours as potential tools for integrating information related with the valorisation and conservation of heritage [18-20]. The main advantages of these tools are the intuitiveness of the output - obtained by means of 360° spherical projections - and its low-cost, requiring only the use of digital cameras equipped with fisheye lenses or even as-built 360° cameras [18-20]. This way, the information contained within the heritage system is statically loaded through the software used for generating the virtual tour. Among these applications, it is worth highlighting the work carried out by Sánchez Aparicio et al. [18] which integrates 360° virtual tours populated by different information sources with a geospatial database for the valorisation of the Mediaeval Wall of Avila, also featuring filter options in order to make advanced GIS queries.

Taking into consideration these developments, the HeritageCare project aimed to make a step forward towards the systematic implementation of a digital-based preventive conservation system for the historical and cultural heritage in Southwestern Europe. To this end, a new WEB-GIS tool was developed to exploit the potentialities offered by the geoinformatics through the combination of the latest advances in virtualization, Internet of Things (IoT) - i.e. monitoring networks, and interoperability protocols. All these technologies are blended into a unique web platform called PlusCare system, integral part of the HeritageCare platform. The system is complemented by a robust geospatial database that allows for advanced queries in order to improve the user experience through immersive virtual tours across the heritage.

After describing the main goals of the PlusCare protocol in Section 2, together with the methods and materials used to develop and implement it, Section 3 discusses the application of this tool to the General Historical Library of the University of Salamanca, one of the most relevant heritage structures within the Spanish territory. Thereafter, Section 4 describes the user experience using the PlusCare system. Finally, Section 5 summarizes the main conclusions emerged after testing this new digital-based preventive conservation tool.

2 The HeritageCare digital-based approach

2.1 The PlusCare protocol

As highlighted in the introduction, the main goal of this work is to show in detail the development phase of the PlusCare protocol, which corresponds to the second service level (SL2) of the HeritageCare method. This level is conceived to increase the knowledge of the inspected heritage buildings and related indoor assets, integrating and complementing the information collected in SL1. The protocol includes two similar workflows depending on the existence or not of a previous SL2 inspection (Figure 1).

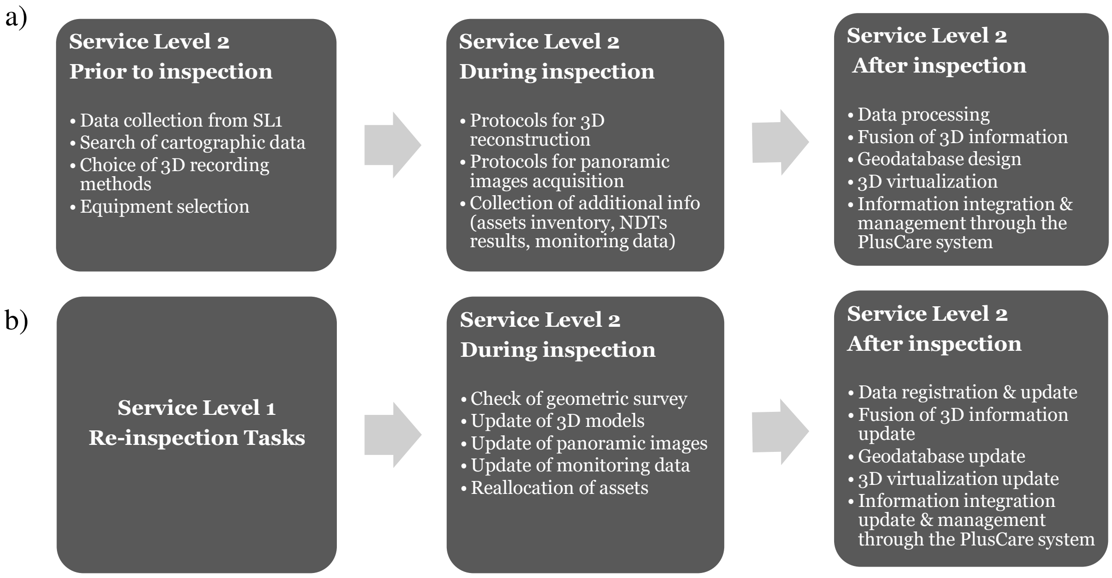


Figure 1: Workflows for the application of the PlusCare protocol according to the starting condition: a) absence of a previous SL2 inspection; and b) existence of a previous SL2.

In either case, the application of the PlusCare protocol depends upon the execution of a prior SL1 inspection and it is a mandatory stage for the application of the subsequent inspection level (SL3). The selection of the service level depends on the conservation needs of the building as well as on the owner's requirements/financial availability. For a thorough description of the workflow and tools required to implement the first and third levels of service (SL1 and SL3), the reader is referred to Masciotta et al. [4].

2.2 The PlusCare system

The efficient implementation of the PlusCare protocol required the development of a tool able not only to integrate different data sources (including the IoT), but also to provide an intuitive environment from which buildings' owners and managers (non-expert users) could access all the significant information for the effective preventive conservation of their heritage. To make this possible, a novel Web-GIS system was created: PlusCare. Such a tool combines the latest advances in geodatabase models, interoperability protocols and digitalization strategies, to enable the proactive conservation of historical constructions. Figure 2 shows the flowchart of the system as well as its main engines. As schematized, the PlusCare system converges into a dual web environment: i) one for expert users; ii) another for non-expert users. Both environments will be detailed in the following sections.

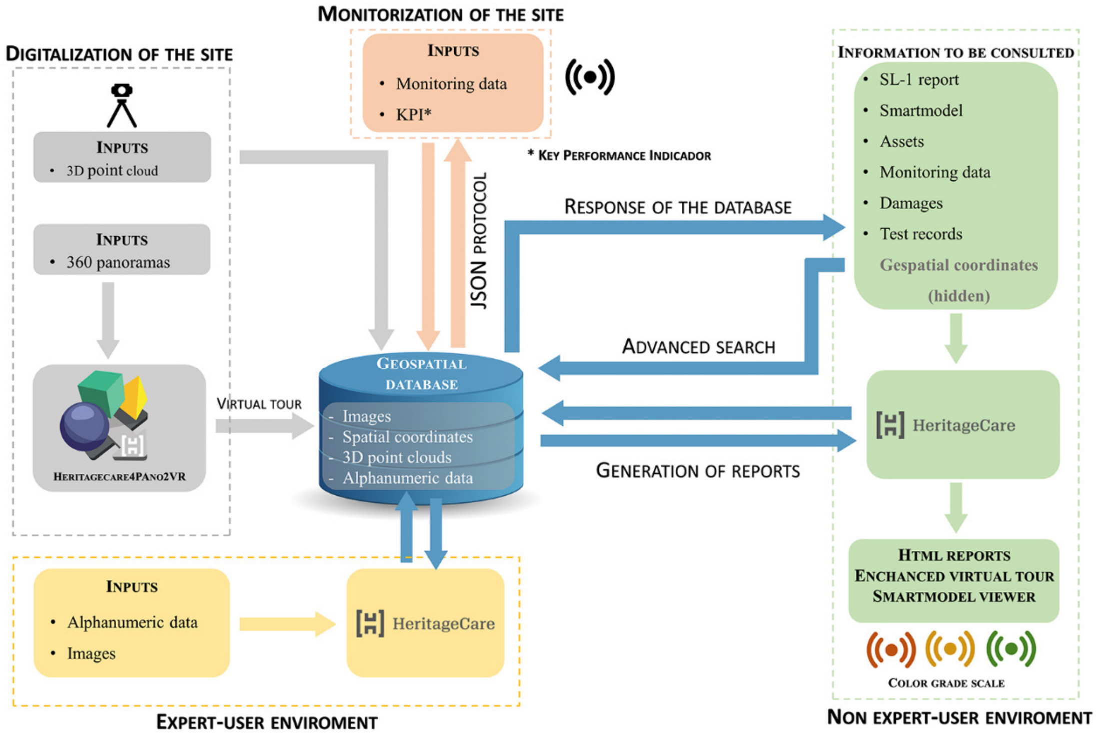


Figure 2: Flowchart of the PlusCare system and its main engines. The workflows carried out by the inspector are presented in grey and yellow.

2.2.1 *Expert-user environment*

The main functionality of the expert-user environment is to store all the technical information collected prior, during and after HeritageCare inspections with the aim of better addressing the specific needs of the buildings and designing proper preventive conservation plans. This environment was developed with different web-based languages, such as PHP and JavaScript (programming language), HTML (markup language) and CSS (design language), among others. Due to the multiple and heterogeneous information progressively gathered through the application of the HeritageCare method, the platform was conceived to include several tabs according to the nature of each information source. With specific reference to the PlusCare system, after inserting a few general data about the inspection (e.g. date, duration, tools and methodologies, etc.), specific information is demanded (Figure 3): i) assets; ii) panorama photos; iii) monitoring data; iv) point clouds; v) data records; vi) damages. The right body of the environment shows all the fields that the expert user needs to fill in depending on the tab selected on the left sidebar.

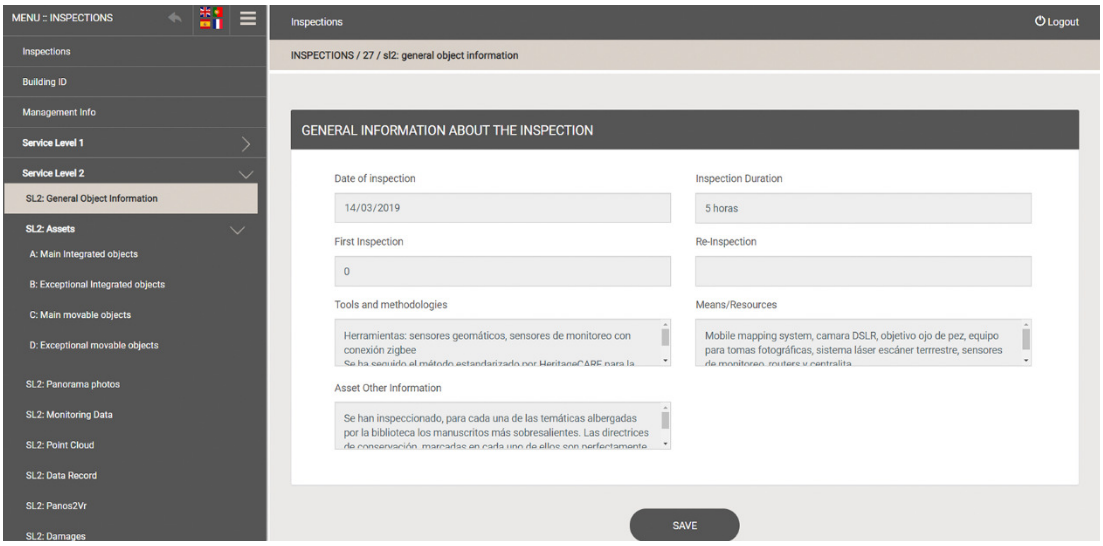


Figure 3: Expert user interface of the PlusCare System.

It is worth recalling that SL2 fields can only be filled upon completion of the SL1 inspection report of the building under consideration, namely after the application of the StandardCare protocol to that building. This 'restriction' is intrinsic to the HeritageCare method, as the system consists of three sequential service levels, where each level includes the previous one and adds new information for a more extended knowledge of the heritage ensemble. Further details in this regard can be found in Ramos et al. [21] and Morais et al. [7].

2.2.1.1 *Assets*

The proper execution of the PlusCare level involves an in-depth evaluation of the conservation state of the assets found within the heritage building/site. Based on a common cataloguing framework, assets are classified into four different groups: i) main integrated objects; ii) exceptional integrated objects; iii) main movable objects; iv) exceptional movable objects. Each of these groups includes a total of twelve categories, as exposed by Masciotta et al. [4]. For each group and each asset, the expert user is required to fill a four-section form specifying the following information (Figure 4a):

- *Asset identification:* this first part includes all the general metadata related to the inspected object, such as the asset name or the asset category, among others. Its geospatial location within the 3D model as well as within the panoramic photos must be included via spatial coordinates (*x,y,z* for the point cloud and *pan, tilt* for the panoramas).
- *Environmental assessment:* this section comprises a few key information related to the environmental conditions at the moment of the asset inspection: i) main bioclimate indicators: luminosity, temperature and relative humidity; ii) environmental condition classification; iii) specific comments for the owner; and iv) possible consequences if the condition is not maintained. After assigning the grade, the condition classification is filled in an automatic way according to the rating system shown in Figure 5a.
- *Assessment of the conservation state:* this section includes the damage affecting the assets. To this end, the platform is linked to the HeritageCare Damage Atlas, which represents a fundamental supporting tool for the preliminary diagnosis of the observed pathologies during inspection activities as well as for the identification of appropriate mitigation actions (Figure 5b). For more details about the Damage Atlas, refer to Masciotta et al. [4]. For each identified damage, the technician has to report information related to its severity and risk, as well as a short description of the damage with complementary images and further comments on possible consequences, if no action is undertaken, or recommendations to prevent the damage progression.
- *Damage summary:* this part of the form is automatically filled according to the information reported in the aforementioned fields. A summary of the asset inspection is shown, including the condition classification, the damage extent, the risk and urgency of remedial measures. The final condition classification of the asset is computed as the round weighted sum of the singles grades assigned to each detected damage.

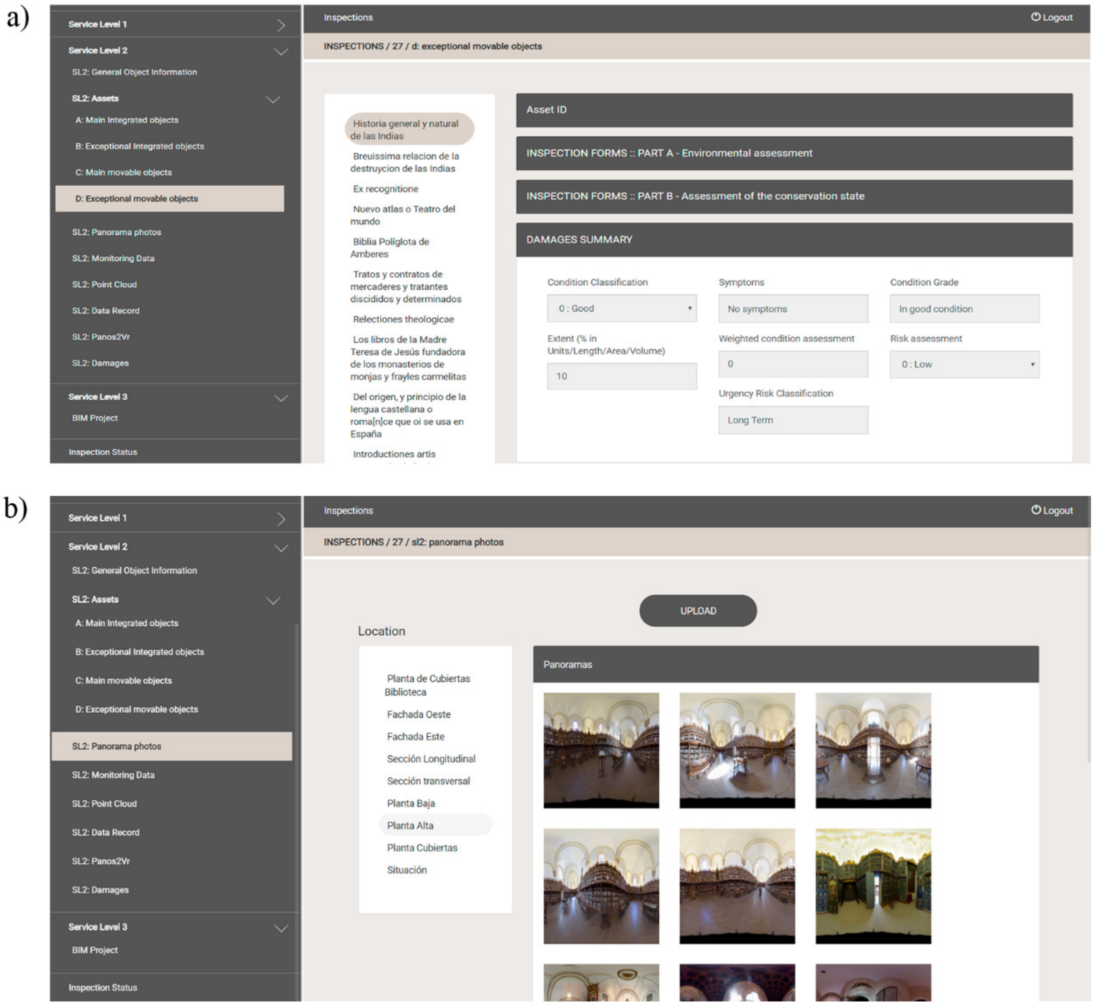


Figure 4: Graphical appearance of the expert-user environment: a) when the technician fills a "movable asset" form; b) when the technician uploads the panoramic images used for generating the virtual tour of the building/site.

a)

Class No.	Condition Classification	Symptoms	Urgency Risk Classification	Comments
0	Good	No symptoms	Long term	No immediate actions required | Preventive monitoring is necessary
1	Fair	Minor Symptoms	Medium term	The condition of the fabric is not perfect but does not need immediate action | Monitoring is necessary to prevent further decay
2	Poor	Moderately Strong Symptoms	Short term	The condition of the fabric is such that it needs timely repair or additional inspection and diagnosis work
3	Bad	Major Symptoms	Urgent and Immediate	Urgent repair is necessary |Urgent additional inspection and diagnosis work
NA/NI	Not Accessible	Parts not (safely) accessible	Not Inspected	Parts that are 'not inspected' are either not (safely) accessible for the building inspectors or not visible

b)

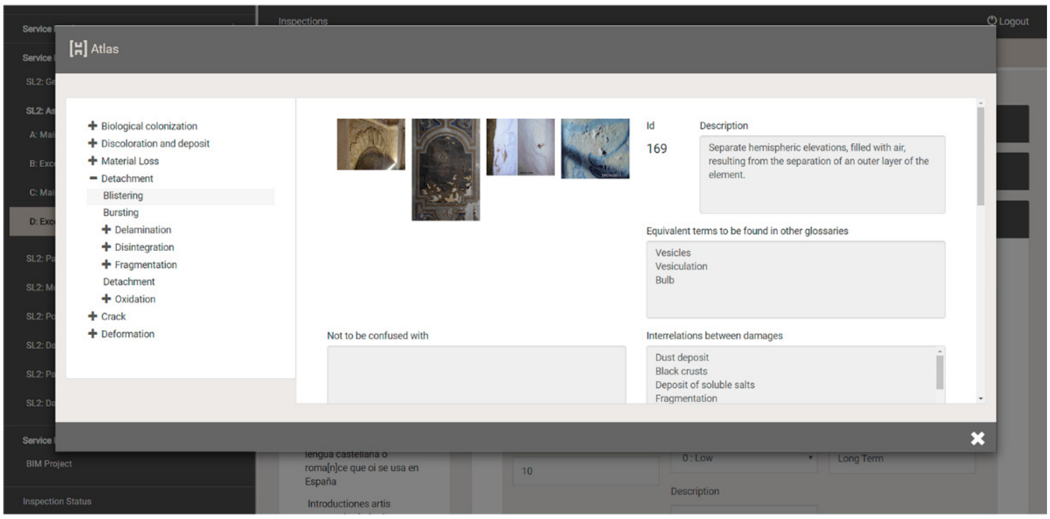


Figure 5: Inspection protocol for assets: a) condition classification (environment and conservation assessment); b) excerpt from the damage Atlas used to support the inspection stage of the assets.

2.2.1.2 *Panorama photos*

The form entitled *Panorama photos* is devoted to the storage of 360° images for the generation of the virtual tour of the heritage building/site (Figure 4b). The technician only needs to upload the panoramic photos in one of the most common formats, such as *.JPG, .PNG or .TIFF*, together with the location in which each panoramic image was taken, and a short description of the protocol used for data acquisition and data processing.

The virtual tour is generated in the external low-cost solution Pano2VR®. In order to adapt this software to the requirements of the platform, the in-house plugin *HeritageCare4Pano2VR* was created (Figure 6a). Some extra features were added for preventive conservation purposes, namely a menu integrating a direct link to the SL1 inspection report as well as to the 3D point cloud of the building/site, and the possibility of creating hotspots of damages, assets, monitoring points and data records linked to the corresponding information stored in the HeritageCare database.

It is worth mentioning that each time the technician uploads new information to the platform and fills the fields corresponding with its spatial location, the platform creates a new hotspot inside the virtual tour which is directly linked to a HTML page containing all the relevant information concerning that specific hotspot. The damages detected during SL1 inspection can be also georeferenced by adding their coordinates to the corresponding label (Figure 6b).

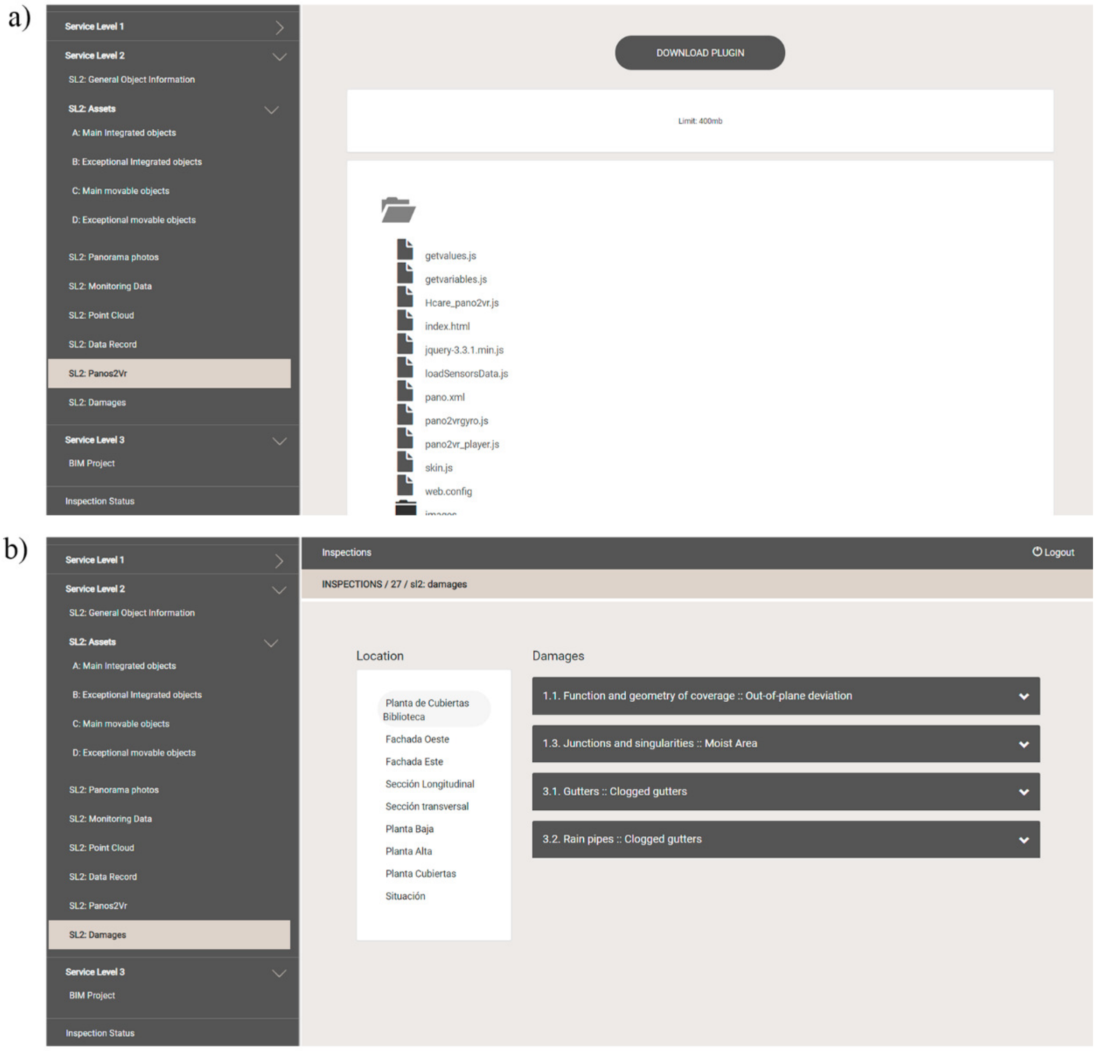


Figure 6: Visual appearance of a) *Pano2VR* and b) *Damages* tabs.

2.2.1.3 *Monitoring data*

Monitoring tasks can be considered an essential part of a proper preventive conservation plan. Hence, the PlusCare system includes a specific tab to store and manage all the information associated to the monitoring sensor network installed in the inspected heritage building. In this regard, the technician needs to specify (Figure 7a): i) the identification number of the nodes composing the network; ii) the monitored parameters measured by each node; iii) the date of installation; iv) the main technical characteristics of the sensor; v) the type of connection; vi) the weight and dimensions of the nodes; vii) the maintenance requirements. Regarding the second label, i.e. the monitored quantities, the current version of the PlusCare system offers a total of 27 different parameters, including bioclimate (e.g. temperature, CO_2, luminosity or relative humidity), structural (e.g. inclination, crack width or maximum acceleration) and biological (e.g. presence of xylophagous) parameters.

To obtain the information associated with the periodic or continuous measurements recorded by the sensors, the PlusCare system implements a *JavaScript Object Notation* (JSON) communication protocol between the platform itself and the server that stores the monitoring data [22]. In this file, the information demanded by the platform concerns the node identification number, the measured parameters, the values captured by the different sensors placed within the same node, and the sensor status. This latter is used to apply a specific colour grade to each monitored parameter in the non-expert user environment. To this end, the PlusCare protocol resorts to the use of key-performance indicators (KPIs) in order to define different threshold ranges for which the structural behaviour of the building or its environmental conditions can be considered good, acceptable or non-acceptable [23-25]. These KPIs are defined within the monitoring server, which sends this information in the form of integer values to the PlusCare system. These values range from 0 to 2 according to the detected degree of risk/acceptability: 0 for a good status; 1 if a potential risk exists; and 2 if the risk is high.

a)

b)

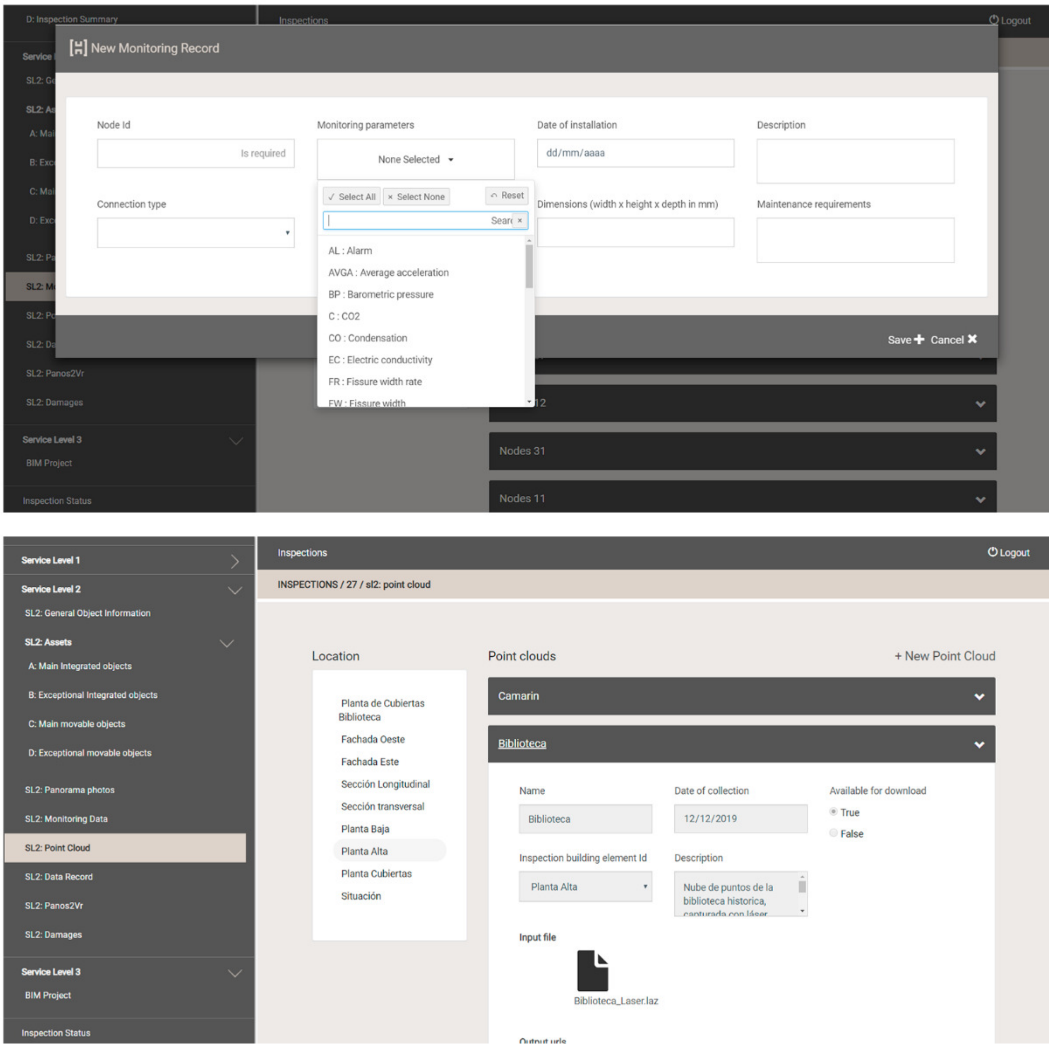


Figure 7: Interface of the PlusCare system: a) *Monitoring Network* tab; b) *Point Cloud* tab.

2.2.1.4 *Point clouds*

This form is conceived for the inspector to upload the whole 3D point cloud of the heritage building/site. The PlusCare protocol allows the use of different recording strategies depending on the complexity and size of the cultural heritage site that needs to be digitalized [4].

The current version of the PlusCare system implements the Potree library [26], since it allows to render large point clouds through the use of an Octree visualization system. Additionally, this viewer includes instruments for both expert and non-expert users, such as measurement tools, clipping tools to visualize different parts of the model, and navigation tools. Besides, Potree viewer is able to integrate, by means of the so-called annotations, graphical and text information within the point cloud [26]. This feature is used by the system to plot relevant information on the 3D point cloud, thus creating a dynamic 3D model.

According to what exposed hitherto, the inspector needs to upload the point cloud and then the platform automatically computes the Octree structure. For documentation and management purposes, the technician is also required to insert information about the name of the place digitalized, its location, the date of collection as well as a short description about the capturing and processing of data (Figure 7b).

2.2.1.5 *Data records*

This tab is dedicated to the uploading and storage of all supplementary data and information that can contribute to improve the knowledge about the heritage building/site (e.g. in situ investigations, like sonic or borescope tests, dynamic identification tests, etc.), as well as its history and conservation state (Figure 8). To this end, the technician needs to fill in and upload a standardized *PDF* form summarizing this additional data records and highlighting the principal results obtained. To complete the form, the type of data record and its spatial coordinates both in the point cloud and in the panoramic photos must be specified.

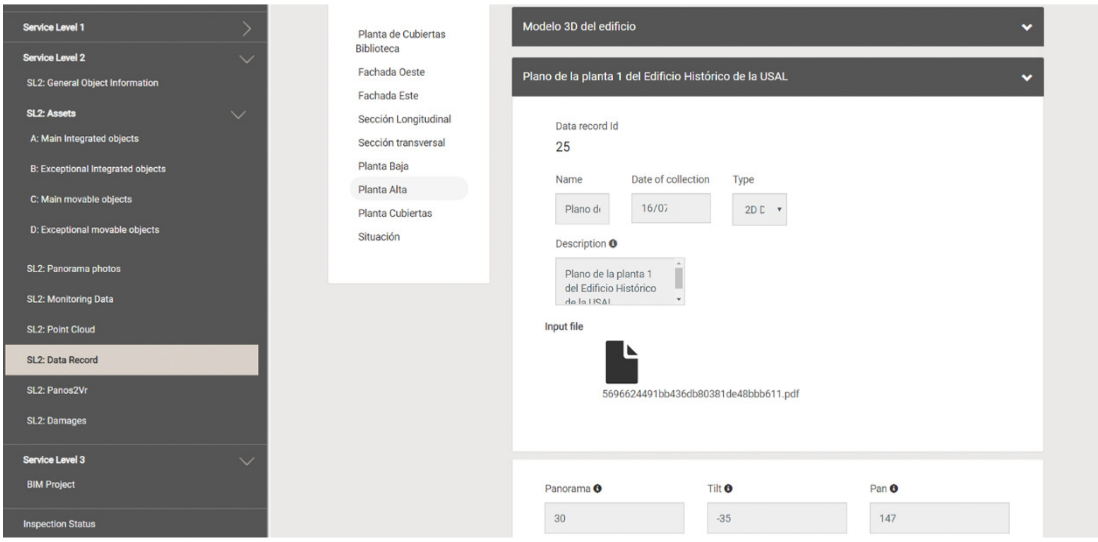


Figure 8: Apperance of the *Data Record* tab.

2.2.2 *Non-expert user environment*

As highlighted in the introduction, the success of any preventive conservation plan passes through the proper and fluid communication between the technician(s) and the owner or manager of the heritage building/site. In order to facilitate this transfer of information, the PlusCare system includes a non-expert user environment that allows to consult all essential data reflecting the conservation state of the inspected historical artefact in a friendly way. The intuitiveness of this environment originates from the use of 360° photos and a 3-colour grading scale that automatically rates the acceptability and degree of risk of the monitored values. This imagery input is enclosed into an improved virtual tour with a geospatial database that enables to access the information related to the inspections carried out by the technicians. Accordingly, the interface integrates two main sections (Figure 9): i) a left sidebar showing all the information accessible from the database; ii) a right section including the virtual tour composed by 360° panoramic images in spherical projection with pre-defined hotspots associated with the assets, monitoring nodes, data records and damages created by the inspector in the expert-user environment. This graphical user interface is complemented by a bottom navigation bar that allows to consult the 3D point cloud of the site and the SL1 condition report (Figure 10a). As shown in Figure 9, this navigation bar includes nine different groups of buttons (from left to right): i) button *a* to show/hide the map; ii) button *b* to enable/disable the gyroscope app; iii) button *c* to visualize the environment in full-screen mode; iv) button *d* to see or hide the hotspots of the virtual tour; v) group of buttons *e* to move the panoramas up, down, left and right; vi) button *f* to load the SL1 condition report; vii) button *g* to connect the virtual tour with the 3D point cloud viewer; viii) button *h* to define the language; and ix) button *i* to hide/unhide the sidebar menu. It is worth mentioning that the platform includes a specific library for reading the data coming from the inertial units of mobile devices (tablets/smartphones). The use of this library makes possible to generate an augmented reality system since it lets synchronize the real point of view of the user with the virtual point of view of the platform.

Figure 9: Interface of the non-expert user environment with the tab *Additional Tests* unfolded in the left sidebar. The buttons placed inside the red rectangle correspond to the group of buttons *e*.

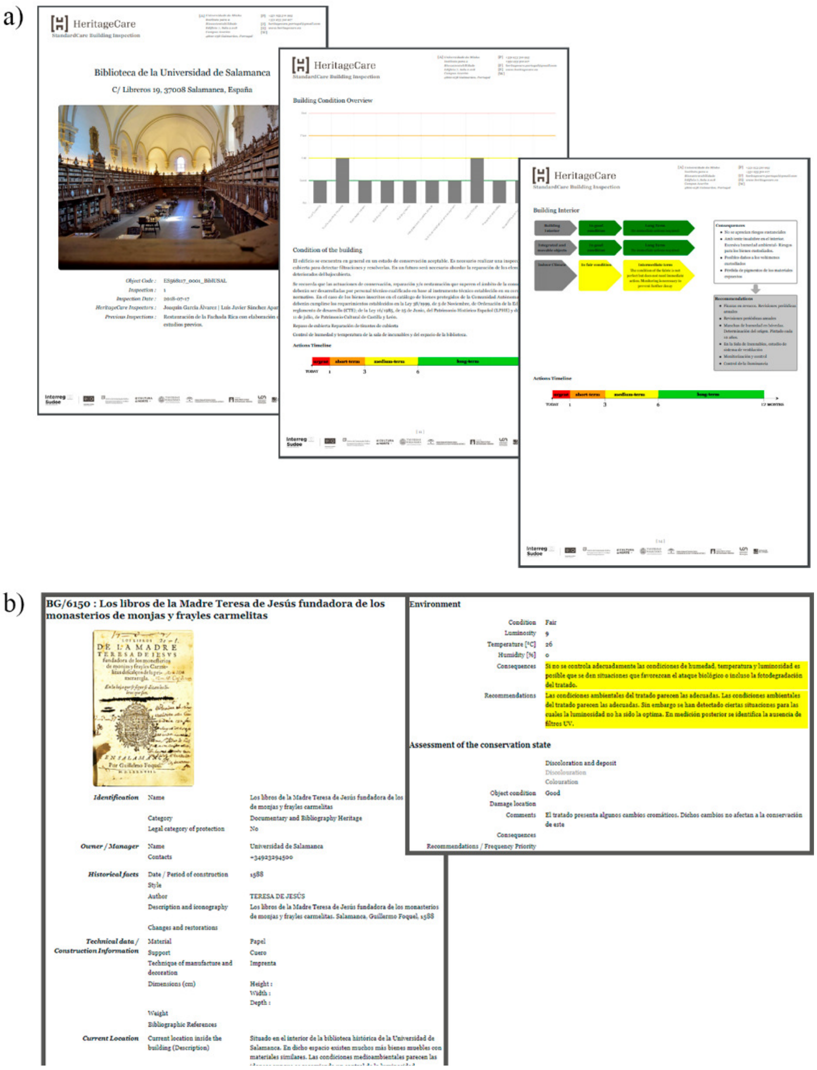


Figure 10: Reports automatically generated from the platform based on the inspection outcome: a) SL1 report about the building condition; b) SL2 report about the asset condition.

The left sidebar of the graphical user interface is structured in a hierarchical way with the aim of grouping data properly. This structure consists of four levels:

- *Assets:* this tab includes the four main groups defined in Section 2.2.1.1.
- *Damages:* this tab comprises the possible damages that can be found during the inspection organized into four macro-categories: i) building envelope; ii) building interior; iii) technical installations and equipment; iv) accessibility and hygiene.
- *Advanced monitoring:* this tab lists all the nodes belonging to the monitoring system installed in the heritage building/site.
- *Additional tests:* this tab is used to link information about further tests carried out onsite and incorporates 6 sub-levels: i) 2D drawings; ii) test results; iii) reports; iv) photos; v) detailed historical survey; vi) other documents.

Whenever the platform is accessed, the PlusCare system makes a request to the database to load all the information collected by the inspector(s) for the preventive conservation plan of the building, showing the number of items available in each tab of the left sidebar (Figure 9). Complementarily, the platform stores in hidden fields the associated spatial data, namely: i) number of panoramas; ii) *pan* and *tilt* angles. These data permit, by means of a JavaScript order, to place the point of view of the virtual tour directly in the area to which the information belongs (e.g. if users click on node 1, the platform places the point of view of the virtual tour in the area where node 1 is located). This information is showed in a 360° environment through the so-called hotspots. Each hotspot includes information about a particular asset, damage, test record or monitoring node, generally in the form of a simple and easy-to-read report (Figure 10b and Table 1). Additionally, each hotspot has a direct link to the 3D point cloud viewer where pertinent data about the consulted item are shown.

Table 1: Hotspot system used by the PlusCare system (non-expert user environment).

Data category	Icon	Data associated	Information shown in the point cloud
Damage		Damage Atlas form about the specific damage observed.	Class, sub-class and sub-sub-class of damage, features description, condition classification, symptoms, risk and urgency of intervention.
Asset		Inspection report of the asset(s).	Name of the asset, detected damages and damage summary (condition classification, symptoms, risk and urgency of intervention).
Advanced monitoring		Real-time updates of the values of the monitored parameters, each one with the relevant symbol coloured in accordance with the established threshold levels.	Symbols and values of the monitored parameters. These symbols have a specific colour grade according to the KPI implemented and the relative threshold values.
Additional tests		Report(s) with data and meaningful information from other tests	Name of the record, date of collection, description, data interpretation.

2.2.2.1 *Advanced search*

Given the considerable amount of information stored, the PlusCare system includes an advanced search tool to ease the seeking process. This functionality allows to filter all the data according to different criteria, namely:

- *Assets:* the assets inspected in the building can be filtered based on their category, overall condition, recommended inspection periodicity and location across the building.
- *Damages:* damages can be filtered by overall condition, inspection periodicity, class of damage and location across the building.
- *Advanced monitoring:* all the sensors connected to the installed monitoring network can be filtered by type of sensor, node status as well as by their spatial location.
- *Additional tests:* further tests and information stored within the HeritageCare platform can be filtered according to the test/record location across the building.

It is worth mentioning that several filtering criteria can be used within the same search, e.g. users can filter all the sensors placed in the first floor that are able to measure the relative humidity (Figure 11).

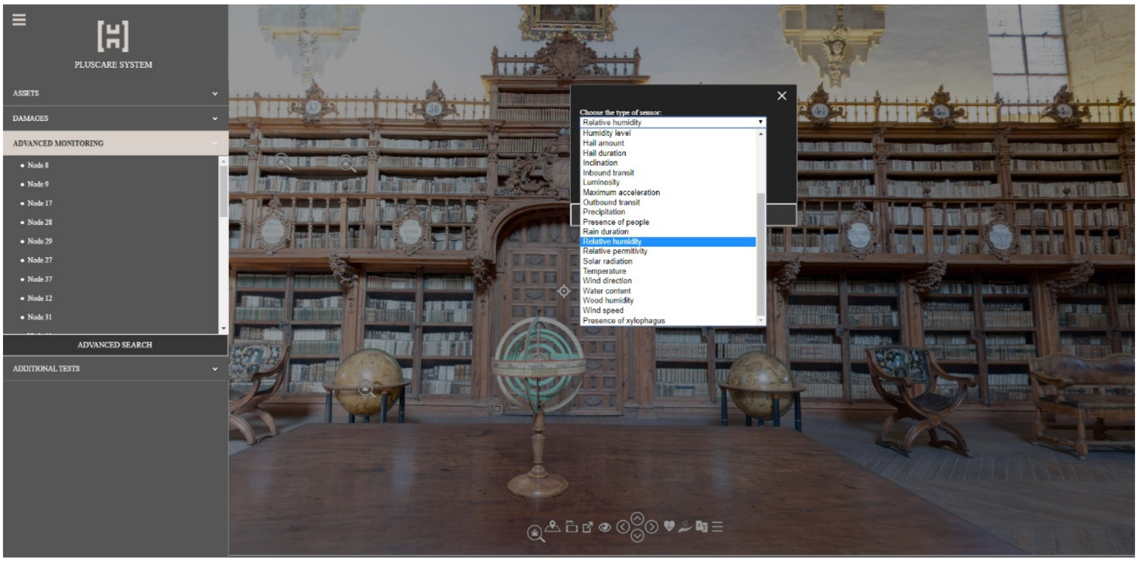


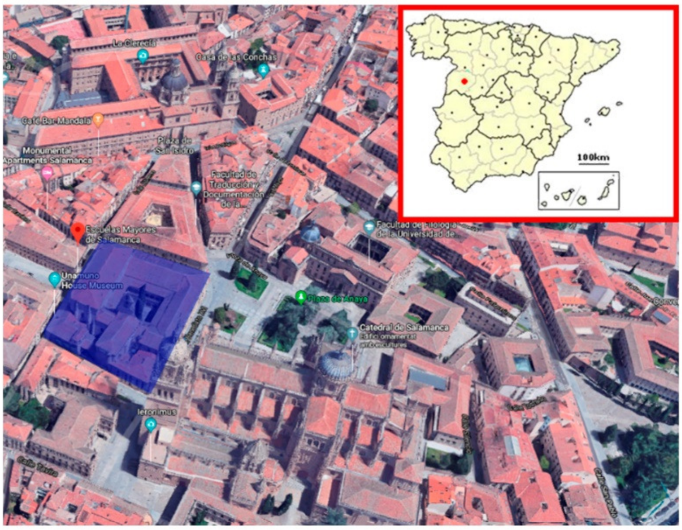
Figure 11: Example of advanced data filtering in the PlusCare platform.

3 Application to the General Historical Library of the University of Salamanca

3.1 The PlusCare protocol

During the project, the HeritageCare method and its related tools were successfully tested across a considerable number of heritage buildings in Southwestern Europe. Particularly, the PlusCare system was first validated in Spain with the General Historical Library of the University of Salamanca. This building belongs to the well-known *Escuelas Mayores*, declared a Place of Cultural Interest in 1931 (Figure 12a). It is located in the historical centre of Salamanca and dates from the 15th century. The construction suffered several alterations along the history. Nowadays, its main façade is considered the best piece of Spanish artworks executed in Plateresque style (Figure 12b), being the symbol of the third oldest university still in operation in the world, as well as the oldest university in Spain. The General Historical Library stands behind this remarkable façade. It features a squared plan with a length of 41 m and a width of about 11.5 m (Figure 13). Its current appearance dates back to 1749 as a result of the restoration works carried out by Manuel de Lara Churriguera (Figure 14). The inner space of the library is covered with a vaulted system characterized by ten lunettes, four half pointed arches and polygonal vaults at the extremes, hiding the ceramic tiled roof above supported by timber trusses.

a)



b)

Figure 12: *Escuelas Mayores*: a) location; and b) general view of its main façade.

a)

b)

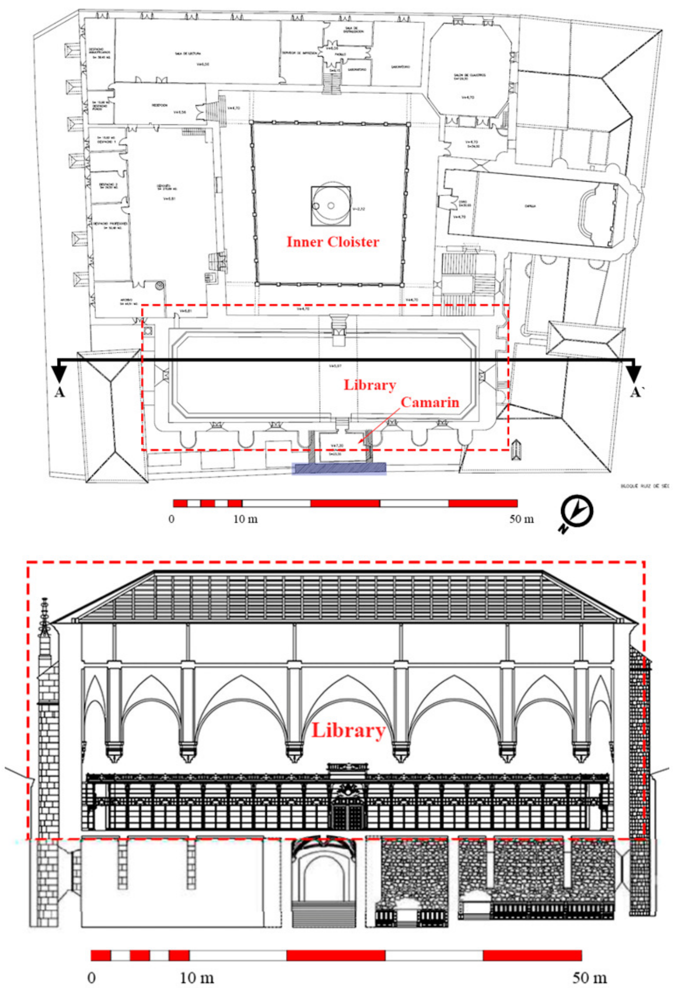


Figure 13: 2D drawings of the General Historical Library of the University of Salamanca: a) plan; and b) longitudinal section A-A`.

Figure 14: Interior view of the General Historical Library.

Today the library is used as a museum and repository, holding 2,774 manuscripts, 483 incunabula and about 62,000 printed volumes from the 16th, 17th and 18th centuries arranged on wooded shelves carved in Baroque style. Additionally, the Historical Library holds ten terrestrial, celestial and armillary spheres made of wood, paper and metal, as well as several vitrines, tables and chairs in leather and wood [27] (Figure 14).

This astonishing diversity and peculiarity of assets requires the elaboration of a robust preventive conservation plan to avoid any possible degradation phenomenon deriving from the inappropriate maintenance of the infrastructure or even from events that can promote aggressive bioclimate conditions.

3.2 Data collection and documentation

The Library was first inspected by an equipped team of HeritageCare professionals who applied the StandardCare protocol foreseen for SL1. This protocol allows a rapid condition screening of the conservation status and uses a 4-colour grading scale to associate a degree of severity to each observed damage [4]. This *modus operandi* permits to rank the overall building condition based on the average grade scored by each inspected building item, thus assisting in the definition of priorities of intervention or, alternatively, additional inspection and diagnosis works (Figure 10a and Figure 15) [4].

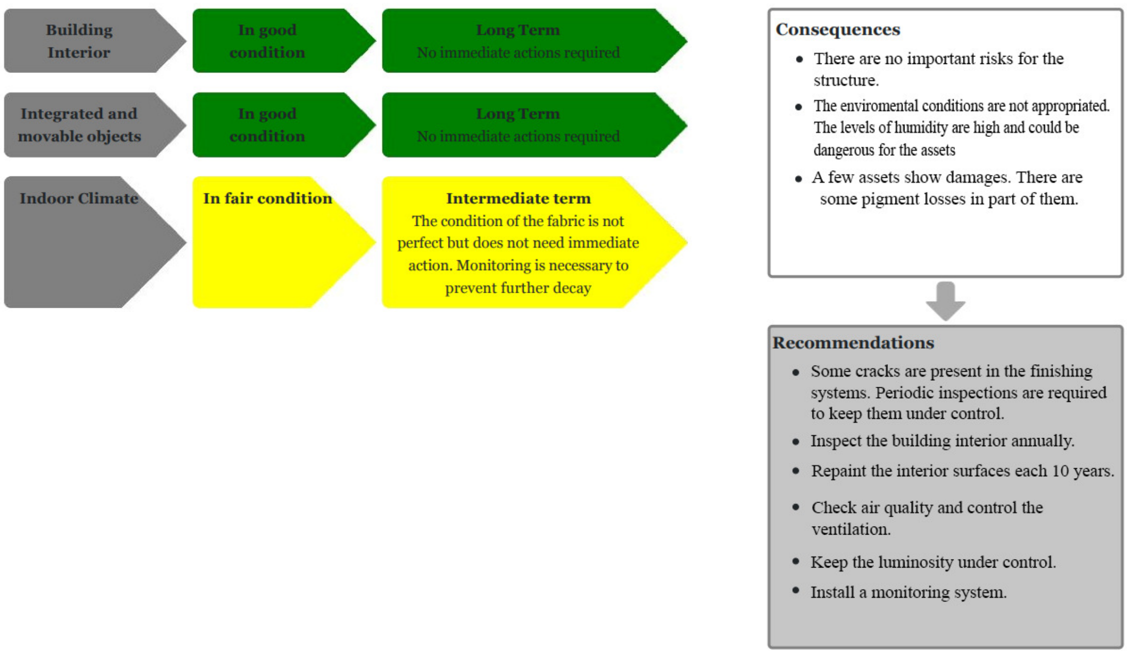


Figure 15: Chart of the building interior highlighting the priority of intervention together with the possible consequences if no preventive measure is adopted.

With respect to the case study analysed, one full working day was necessary to perform the on-site inspection of the Library. To guarantee a real-time digitization of the inspection process and speed up reporting times, the inspection team resorted to a tablet equipped with a specific application developed within the HeritageCare project. Based on the SL1 outcome, the state of conservation of the Library was deemed acceptable. However, a detailed technical inspection of the roof covering as well as the control of bioclimate parameters were recommended to prevent possible degradation processes. As a result, a higher inspection level was implemented by applying the PlusCare protocol, thus involving the stages detailed in Section 2.1.

3.3 Site digitalization

To obtain high-resolution information about the geometry and onsite conditions of the Library, a digitalization campaign was carried out to collect panoramic images and capture 3D point clouds. The former were acquired by means of the Canon 700D® DLRS camera. This DLRS camera has a 22.3 x 14.9 mm CMOS sensor with 18 MPx resolution (5196 x 3463 px), a pixel size of 4.29 µm and a crop factor of 1.61. This device was equipped with a Sigma 8 mm circular fisheye lens with a maximum aperture of f/3.5 and a focus engine. Each station required a total of seven shots with 60% of overlap between them. As for the present campaign, 13 equirectangular panoramas were taken (Figure 16): i) 1 to digitalize the main façade; ii) 4 to capture the outdoor space of the inner cloister; iii) 2 for representing the hall of the inner cloister next to the Library; iv) 6 for the digitalization of the Library. The different shots were stitched with the open-source software Hugin®. It is noted that each panorama was captured in the same position as the laser scanner station aiming at colouring the TLS point clouds. This was possible thanks to the use of the platform designed by Del Pozo et al. [28] (Figure 16b). Afterwards, the "basic" virtual tour was created in Pano2VR® with the assistance of the plugin *HeritageCare4Pano2VR*.

a)

b)

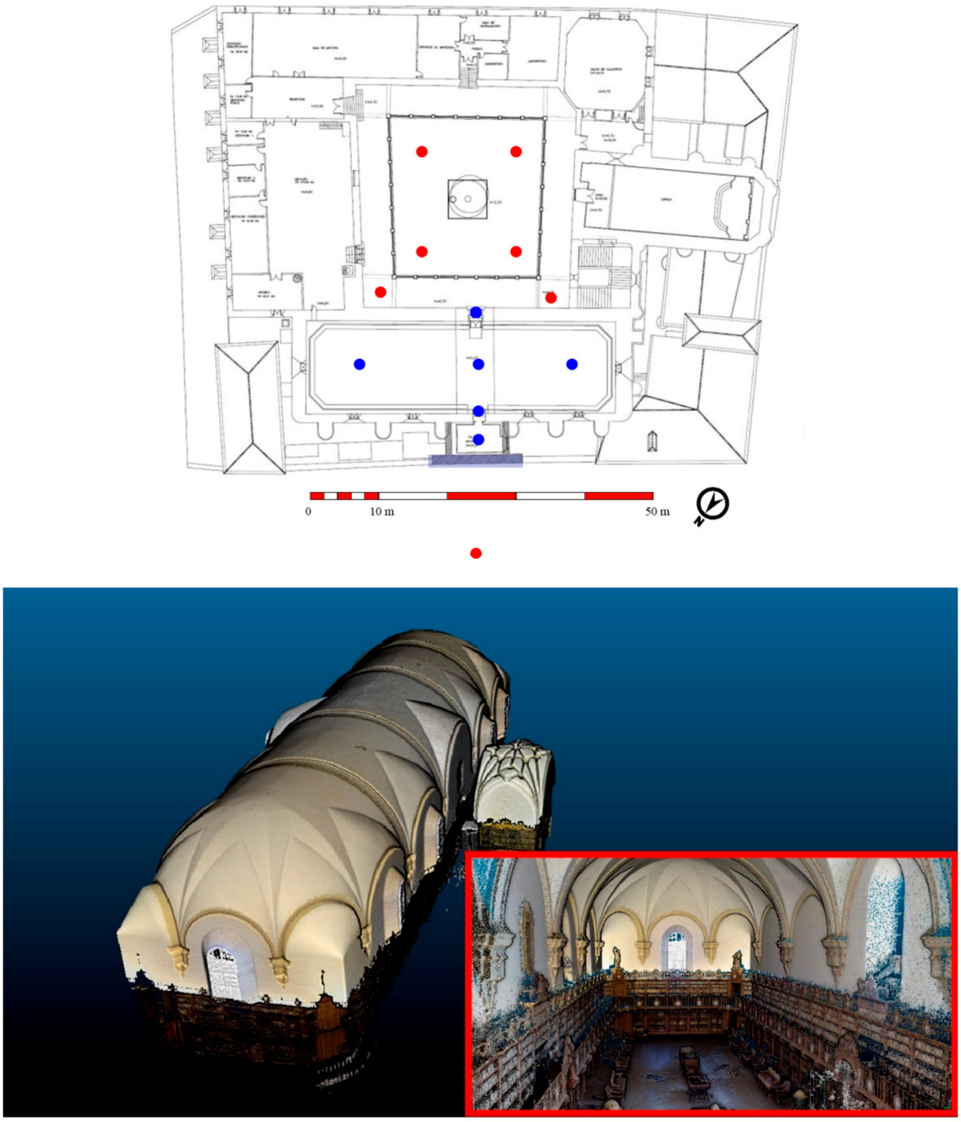


Figure 16: Result of the digitalization stage: a) plan view with the location of the stations; b) optimized point cloud within the open-source software CloudCompare®. Note: blue dots represent scan stations with panoramic images and red dots indicate stations with panoramic images only.

The 3D digitalization of the Historical Library was performed by means of the light-weight TLS Faro Focus 120®. This laser scanner is based on the phase shift physical principle with a measurement range from 0.6 to 120 m, a capture rate from 122,000 to 976,00 points per second and a nominal accuracy of 2 mm at 25 m in normal conditions of illumination and reflectivity. As a result, 6 scan stations were needed to record the Historical Library. All these scan stations were registered in a common coordinate system using to this end the Iterative Closest Points algorithm [29] by applying the strategy defined by Sánchez Aparicio et al. [30]. The final error after the alignment of the different point clouds was 3 ± 2 mm. The huge amount of captured data, with a total of 140,070,904 points, required an optimization stage that comprised the use of a spatial decimation filter with a threshold of 0.005 m. This allowed to obtain a reduced 3D representation of the Historical Library consisting of 18,209,138 points, namely 13% as compared to the original point cloud (Figure 16). Finally, this point cloud was uploaded to the PlusCare system in *.LAZ* format in order to be converted by the Potree script for visualization purposes (Figure 16b). The time spent for the complete digitalization process, including data capturing and processing, required two working days by a group of 2 inspectors.

3.4 Tracking the bioclimate parameters

Most of assets located within the General Historical Library of the University of Salamanca are made of organic materials such as wood, leather and paper. Thus, the control of bioclimate parameters is of utmost importance to ensure the proper conservation of such a valuable legacy. According to Pavlogeorgatos [31], the four main environmental parameters that can promote the deterioration of assets located in libraries and museums are:

- *Relative humidity:* out-of-tolerance values of this parameter can cause changes in size, shape as well as biological and chemical reactions of the exhibits.
- *Temperature:* variations of indoor temperature can lead to a variety of reactions such as the acceleration of chemical processes (e.g. corrosion rate of cellulose), the movement of moisture or even material expansion.
- *Luminosity:* natural and artificial illumination sources can induce oxidation of the components, thereby promoting the deterioration and corruption of several materials.
- *Atmospheric pollution:* gasses, such as sulphur and nitrogen oxides, ozone and other atmospheric particles, can promote chemical attacks.

3.4.1 Monitoring network

To better address the conservation needs of the Library, an advanced monitoring network was installed in the hall to keep the main bioclimate indicators under control. The selected measuring equipment was the MHS (Monitoring Heritage System) [32], a monitoring system purposely developed for cultural heritage buildings by the Santa Maria La Real Foundation. Type, number and location of the sensors were decided based on the outcomes of the SL1 inspection and pre-monitoring stage, paying attention to minimizing their visual impact inside the Library. The system is active since July 2019 and consists of:

- 15 relative humidity and temperature sensors (*HT*), of which 10 ambient and 5 surface sensors, plus 8 combined sensors measuring relative humidity, surface temperature and brightness (*HT+B*).
- 2 xylophagous sensors (*X*) to detect the presence of this type of insects into the wooden shelves;
- 1 solar radiation sensor (*SR*) to measure the radiant energy received by the sun and emitted into the surrounding environment;
- 1 carbon dioxide sensor (CO_2) to check average concentrations of this trace gas inside the Library;
- 1 presence detector sensor (*PD*) to track people presence and eventually switch off unnecessary lighting, air conditioning, etc.;
- 1 meteo station (*MS*) to record outer air temperature, humidity, barometric pressure, wind direction and velocity, precipitations, rain duration, hail as well as solar radiation and carbon dioxide.

It is noted that ambient temperature and humidity sensors were placed at different heights in order to catch possible changes in elevation of the monitored parameters. Complementary to the installation, the technician is required to insert in the PlusCare system the metadata associated with the monitoring nodes.

This paper can be found at https://doi.org/10.1016/j.autcon.2020.103304

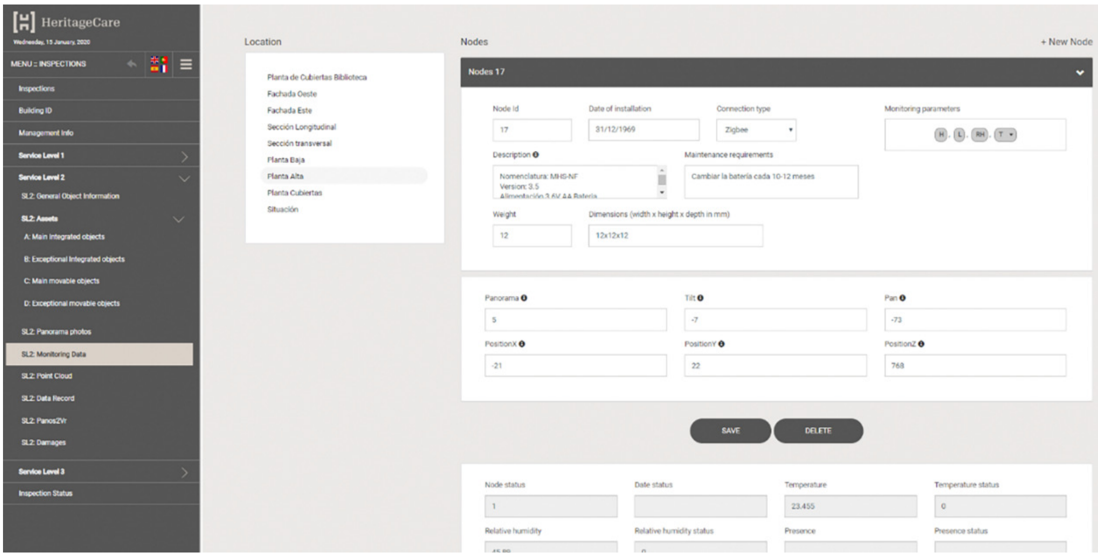


Figure 17: Monitoring network form with the data associated to each node.

The local nodes of the monitoring system collect the relevant values from the sensors and transmit this data to a central node (CN) by means of a Zigbee communication protocol. The PlusCare system makes a *JSON* query to the monitoring database each 30 minutes in order to update the values of the tracked parameters.

3.4.2 Range of tolerances for preventive conservation

As mentioned in Section 2.2.1.3, and with the aim of guiding the non-expert user in the preventive conservation of the building, the PlusCare system integrates the concept of *Sensor Status*. Basically, three colour grades are used to automatically rate the different variables captured by the monitoring network, being possible to check in real-time whether each parameter falls outside the established tolerance range and could promote material degradation. To define this range, the implementation of proper Key Performance Indicators (KPIs) is required. For the present case study, the KPI definition by Corgnati et al. [25] is adopted. Generally, a KPI identifies the percentage of measurements in which the monitored parameter lies within a required range. This way, if the 90% or more of the measurements lies within the pre-established range, the *Sensor Status* throws a value of 0; if this percentage ranges between 85% and 90% the *Sensor Status* throws a value of 1; otherwise, for a percentage under 85%, the *Sensor Status* is set as 2. This concept is extended to all the monitoring network with the exception of the xylophagous detectors, for which only two *Sensor Status* are defined: i) 0, if the sensor does not detect any xylophagous activity, and ii) 2, if the sensor detects the presence of xylophagous activity within the wood. According to what stated above, a KPI can be expressed as follows:

$$KPI = \frac{N_{in}}{N_{tot}} \quad (1)$$

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

The calculation of the KPIs requires the definition of a set of case-specific tolerance ranges for the different monitored variables, including indoor climate parameters. In this regard, various standards can be considered [33]. As for this work, the tolerances defined by the guideline PAS 198:2012 were taken into account [34]. Table 2 shows the set of tolerances implemented for the Historical Library.

Table 2: Tolerances considered for the indoor climate evaluation.

Parameter	Recommended range
Temperature	14-28 °C
Relative Humidity	40-60%
Luminosity	maximum of 50 lux

3.5 Assets condition survey

Complementary to the monitoring activities, the PlusCare protocol entails the inspection of the integrated and movable assets located within the heritage building. Due to the huge amount of assets treasured in the Library, only the most representative ones of each area were inspected: i) the two vitrines (main movable objects); ii) one Earth Globe (main movable object); iii) 21 books (exceptional movable objects).

First, a visual inspection was carried out with the aid of the HeritageCare damage atlas in order to identify possible deterioration processes, but no remarkable damage was observed. Regarding the environmental assessment, several in-situ measures were taken for the most relevant bioclimate parameters: humidity, temperature and luminosity. The captured values were considered acceptable at the time of the inspection. However, the monitoring data allowed to track some period of the year in which the luminosity values exceeded the recommended ones. Accordingly, it was decided to keep the UV levels of this area under control in order to prevent values that could promote the photodegradation of the assets in the long term. This consideration was included in the relevant section of the asset inspection form of the PlusCare system, grading the environmental assessment as poor and recommending the use of UV filters on the library glass windows. The same conclusions were obtained during the assessment of the Earth Globe.

In parallel, a total of 21 books from eight different knowledge areas were inspected. Some common damage was detected in all books, particularly discoloration and material loss. The environmental condition was classified as poor due to the possibility of having photodegradation processes induced by the UV radiation, as highlighted during the inspection of the vitrines.

Apart from the conservation and environmental assessment, the inspection form of each asset was filled with metadata information, as well as with their spatial position within the 3D model and the corresponding panoramic image. Filling this information is compulsory for the PlusCare system to create automatically the asset hotspots within the virtual tour of the heritage building.

3.6 Test records

To finalize the PlusCare inspection of the Library, a re-compilation of the main results obtained during the experimental campaign was included in the tab *Test records*. In particular, the information from both the digitalization campaign and the geometrical survey of the library was uploaded to the platform using the standardized *PDF* template available for download (Figure 18).

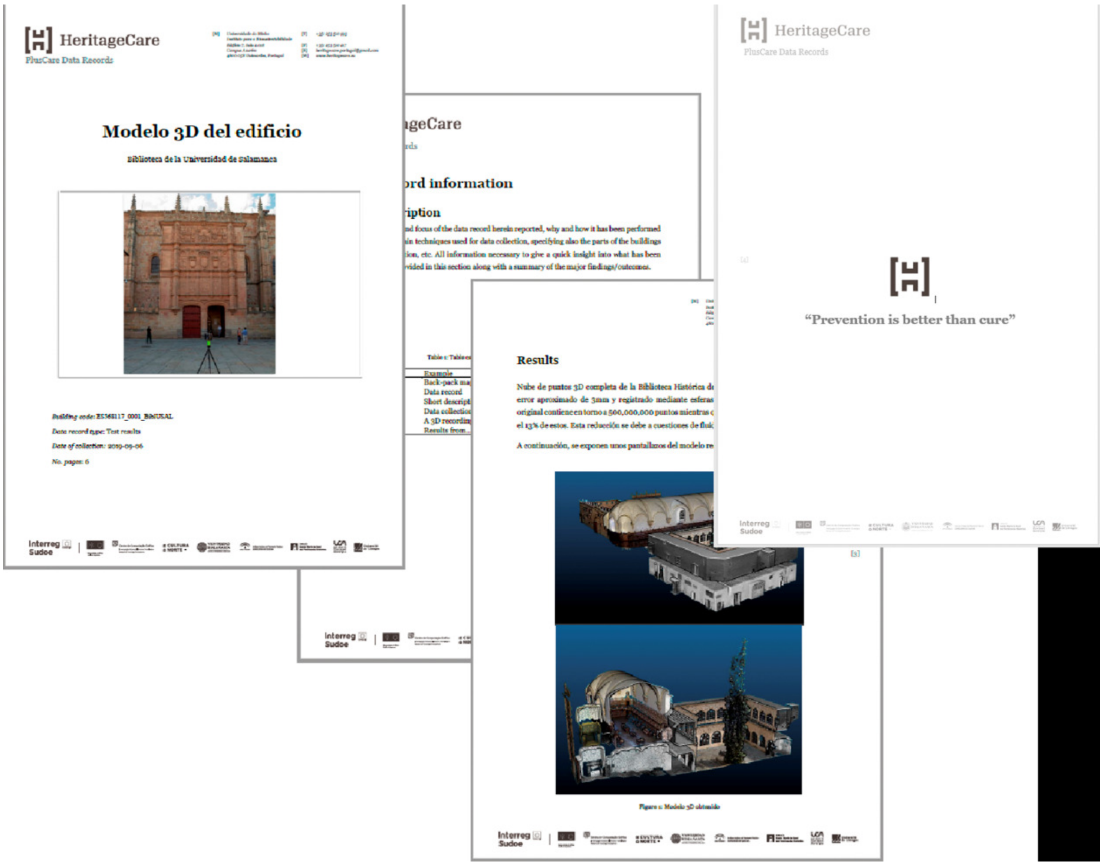


Figure 18: Appearance of the standardized PDF file with the description of the test results.

4 Non-expert user experience

The PlusCare system also features an intuitive environment for non-expert users. The potential of this environment can be measured by the ease in which the multiple and heterogeneous information generated by the expert user is transferred to the non-expert user during the virtual tour, which represents the main output of the PlusCare protocol.

All essential information for the primary conservation needs and ordinary maintenance of the building is condensed into a simple and clear report which can be easily accessed by the end-user while navigating through the virtual tour just by clicking on the heart icon (button *f*) of the bottom navigation bar of the graphical interface (Figure 9a). Across the document, the information appears in different colours. Building items in good conservation state are highlighted in green, implying that no immediate preventive action is required; those in fair or poor conditions are highlighted in yellow and orange, respectively, where the former colour suggests medium-term preventive actions and the latter short-term measures; finally, building items in bad condition are reported in red, meaning that urgent repair actions are necessary to prevent further decay (Figure 19a). Thanks to this graphical system the owner/manager can perceive at a glance which priority of intervention should be considered if some building items do not appear in good condition. This eye-catching content is then complemented with useful information about the possible consequences for the building.

The 3D icon of the bottom navigation bar of the PlusCare interface gives the user the possibility to access and browse through the tridimensional high-resolution survey of the heritage site. The visualization is boosted by the Octree system, allowing to check it on mobile devices (Figure 19b).

a)

b)

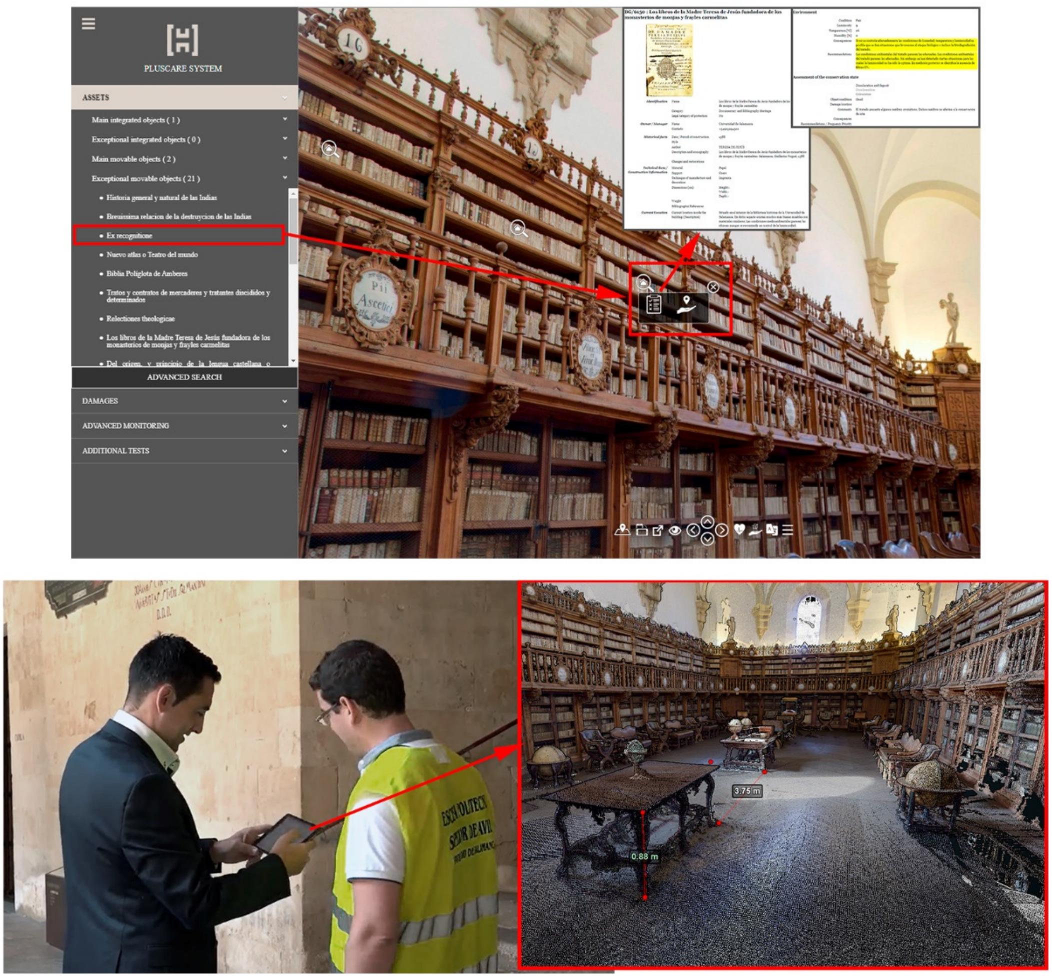


Figure 19: Non-expert user environment: a) consultation of SL2 condition report (yellow paragraphs indicate a fair damage condition, while green means that the damage severity is low); b) consultation of measurements within the 3D point cloud.

4.1 Information available through hotspots

The rest of the information stored by the inspectors into the PlusCare database, such as the assets condition, the damages or any additional record (see Section 2.2.1.5), is plotted in the non-expert user environment by means of pre-defined hotspots inserted within the pertinent 360° photos that compose the virtual tours. The full list of hotspots among which the user can navigate is available in the left sidebar, grouped by category (Figure 20a and b). The optimal connection between the database and the virtual tour ensures a quick browsing among the different objects directly from the sidebar menu of the interface, and regardless of the filter applied for the advanced search. In this way, if the user does look for a specific asset and selects its name, the platform automatically places the user's point of view in the area where the selected asset is located (Figure 20b). Furthermore, if the user clicks on that object hotspot, a window pops up allowing to consult both the asset inspection report (Figure 20b) and its location within the 3D model (Figure 20c). The transfer of information associated with damage and test record hotspots is plotted in the same way.

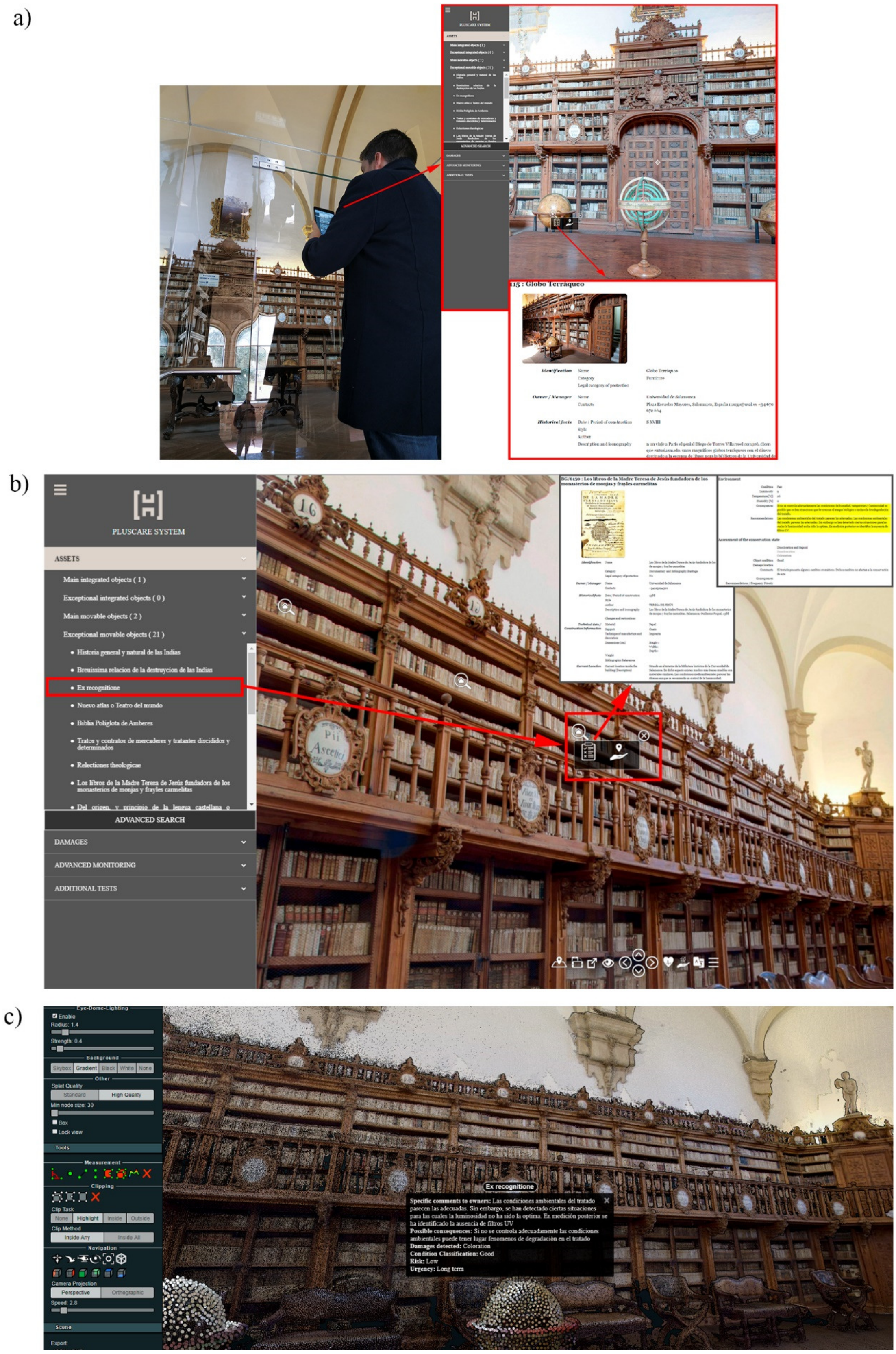


Figure 20: Non-expert user environment: a) consulting information about the asset condition; b) pop-up box related to the asset hotspot (yellow paragraphs indicate that the environmental conditions are not appropriate for the selected asset); c) 3D model

Apart from the aforementioned features, the non-expert user environment includes the possibility of capturing the values of the device gyroscopes. Basically, the point of view of the platform can rotate according to the angular variation captured by the gyroscopes. Such a feature places the PlusCare system of the HeritageCare platform as a potential alternative to standard augmented reality systems (Figure 21).

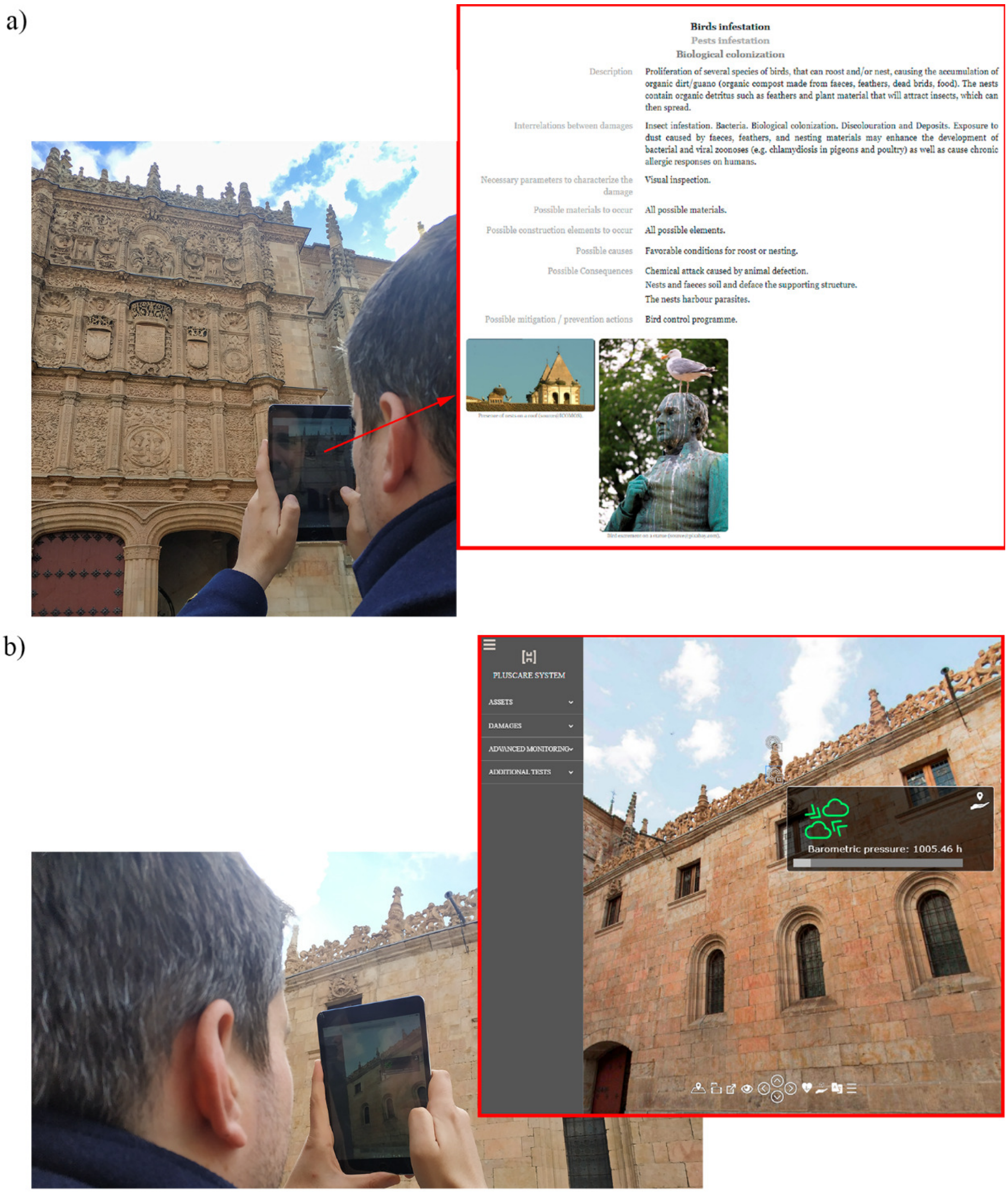


Figure 21: Response of the platform when the gyroscope feature is active: a) consulting a damage hotspot; b) checking a sensor hotspot.

4.2 Visualization of the monitoring data

Like damages, assets and test records, also monitoring data can be consulted directly by the non-expert user just by clicking on the corresponding hotspots. Each of these hotspots gives access to real-time updates of the parameters measured by the sensors along with their location within the 3D point cloud. The environment uses the *Sensor Status* variable described in Section 3.4 to plot colour-based warnings of the monitored quantities through a pop-up window: i) green icon, when the variable has a value of 0, thus the monitored parameter is within the acceptable tolerance range; ii) yellow icon, if it has a value of 1, meaning that the monitored parameter is not always within the defined thresholds; and iii) red icon, if the sensor status is 2, which indicates that the value of the considered parameter deviates from the acceptable limits. By means of this visual grading scale the user can get a quick idea about the microclimate conditions existing within his building (Figure 22a). Moreover, thanks to the advanced search options featured by the PlusCare system, the user can easily filter the nodes of the monitoring network and get to know immediately which sensors are providing values out of the recommended tolerances. The way to consult this information is substantially improved when using the gyroscope values of the smartphone or tablet (Figure 21b). Information about the monitoring data is also shown on the 3D point cloud of the building (Figure 22b).

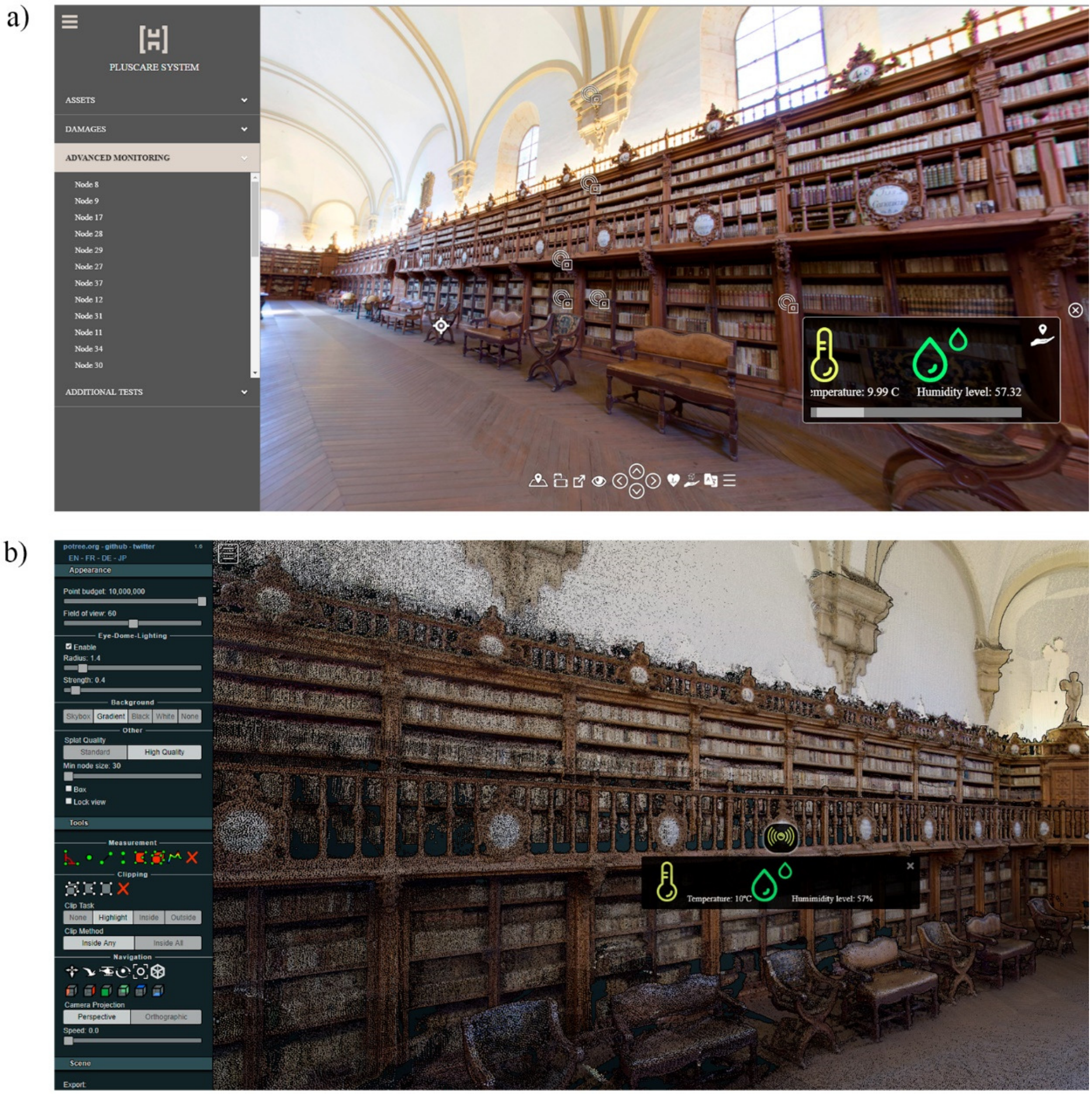


Figure 22: Colour-based warnings applied to the sensor network: a) real-time updates of the monitored parameters for node 30; b) 3D model with superimposed information about the selected node.

5 Conclusions

A new paradigm for the preventive conservation of historical sites was presented in this paper. Considering the leading role that digitization is assuming in the context of heritage conservation, this work aimed to show the progressive development of one the major digital outputs of the HeritageCare methodology, i.e. the PlusCare system. The transfer of information to the non-expert users is smooth and user-friendly, offering owners and managers of heritage sites an interactive and intuitive tool that facilitates monitoring activities and supports decision making on preventive conservation actions. Full details about the PlusCare system are provided in the paper and its validation is performed through a case-study application having as object of investigation one of the most representative Spanish cultural heritage buildings: the Historical Library of the University of Salamanca. From the validation of this digital-based tool, it is possible to draw the following conclusions:

- The PlusCare system is a Web-GIS application of the HeritageCare platform rooted in the latest advances in digitalization technologies, monitoring networks and IoT concepts that is paving the way for a new paradigm in preventive conservation.
- The integration of a geospatial database makes possible to streamline the management of large blocks of multidisciplinary information, allowing to filter the great amount of stored data according to different criteria.
- The use of colour grading scales to rate the conservation state of the assets located within the heritage site allows a better interpretation of the inspection outcome by the non-expert users and can assist them in prioritizing preventive conservation actions.
- The implementation of KPIs and colour-based warning levels associated with the monitoring data also provides a straightforward metric for the end-users to understand the acceptability of the recorded values and adopt condition-based maintenance measures.
- The exploitation of pyramidal loading schemes for both the 3D point clouds and the 360° images enables to optimize the computational requirements. Additionally, according to the tests carried out to evaluate the time response of the platform, when using an ordinary PC, the average response time of the platform is just 1.8 seconds for loading the main interface; 0.5 seconds for loading the results of the advanced search; and 4.1 seconds for loading the whole 3D point cloud (lower Octree level). Instead, if the platform is loaded in a standard smartphone, the average response time is 4.0 seconds for the main interface; 0.5 seconds for loading the results of the advanced search and an instantaneous response of the gyroscopes when this feature is activated; 8.2 seconds for rendering the whole 3D point cloud with the lower Octree level. These results can be considered more than acceptable to guarantee a good user experience.

- The intuitiveness of the panoramic photos combined with geospatial information and mobile devices further enhance the users' experience while navigating across the heritage. This experience can be a great supporting tool to engage the main social actors in the proactive preventive conservation of their legacy.
- Unlike BIM approaches, the PlusCare system does not require any structured data template nor specific object libraries for the 3D virtual reconstruction of the heritage. Metric and morphologic values are equally important, and they can be profitably exploited to cross-check and describe accurately the quantitative information that an HBIM-based model should contain. Moreover, the final output of the PlusCare system is much more user-friendly and accessible by non-expert users. Indeed, PlusCare has been conceived as a preparatory level to TotalCare, the last of the three service levels of the HeritageCare methodology, whose focus is the integration and management of all information collected from previous service levels through an intelligent digital model built in BIM environment.

Future works will be focused on integrating new features into the system. On the one hand, it is planned to improve the uploading process of the expert user environment. This will enable to add new information (e.g. assets, damages, monitoring nodes) directly onsite with a mobile device, thereby reducing the back-office work. On the other hand, efforts will be made to achieve a complete integration between the new digitalization approaches, e.g. back-pack mobile mapping systems, and the as-built 360° cameras in order to speed up the data acquisition.

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