Development and Demonstration of a HBIM Framework for the Preventive Conservation of Cultural Heritage

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Abstract

Building Information Modelling (BIM) methodology is becoming widespread with many potential uses, such as facility and asset management for new buildings. Recently, it has also been applied for the maintenance of built heritage, within the so-called Historical BIM (HBIM) field. A BIM model, empowered by detailed embedded information, is an excellent tool to monitor and infer on the behaviour, performance, and deterioration of heritage buildings, collecting and classifying diverse data that can co-exist in an asset model. However, three main issues must be tackled: lack of standardization, insufficient interoperability and inherent complexity of the information. It is essential to balance model's geometrical and non-geometrical features, such as the level of detail accuracy and the quantity of linked information, to make the methodology cost-effective and hence more attractive for end-users. The present work focuses on the development of easy-to-implement strategy to report and monitor damage evolution over time. Standardization and simplification of the procedures are pursued by using Product Data Templates (PDTs) and focusing on interoperability of information through specific provisions of export/import definitions for Industry Foundation Classes (IFC). The developed methodology is tested on the Ducal Palace in Guimarães, Portugal, one of the most prominent monuments of the country.

1. Introduction

1.1. State of the art

The value of heritage buildings reaches far more fields than mere architectonical and material aspects, being also related to specific artistic, historic, social, and scientific dimensions. Documentation and preservation of such built systems is of multidisciplinary nature and involves different approaches,

each one with its own terms, methods and sources, aiming both at qualitative and quantitative information [1]. Recently, the promising results of Building Information Modelling (BIM) methodologies for new buildings fostered their application to the management and the exchange of such complex information, leading to the wide-spreading towards the concept of Historical BIM or HBIM [2]. Although some HBIM workflows have been produced resulting in guidelines for owners, end users and professionals, as the initiatives of Historic England [2], [3], the definition of a standardised procedure that stresses the differences and specifications, with respect to new constructions, is still an open issue. Research in the HBIM field has mainly focused on modelling elements with extremely high '*as-is*' level of geometric detail, supported by accurate survey techniques as photogrammetry (PG) or terrestrial laser scanner (TLS) [4]–[7]. With the purpose of documentation for preventive conservation, the same approach has been applied to damage modelling [5]. To this end, a common solution has been to reproduce, in a 3D BIM environment, 2D decay maps, by creating entities overlaying on the element surface, as attached colourmaps or imported as rendering materials [5], [7]–[9]. Simplifying tools have been implemented to allow the definition of such maps in a 2D environment and then to project them onto the 3D surfaces [10].

However, accurate survey tools produce, in the first place, a large amount of indiscriminate information that requires a long time consuming processing to become significant for preventive conservation [11]. This might hinder the feasibility of the methodology for practitioners and companies involved in conservation and maintenance. Indeed, demanding a high level of geometrical detail increases significantly both the time requirement and the costs of survey and modelling stages [12], irrespective of the use of simplified 2D drawing approaches or orthophotos for deterioration mapping [13]. A feasible framework should not require that the stakeholders, excluding the BIM modeller, are expert in the field of BIM and be independent of specific software or tools, as the TLS, which is only one possible source of data, to minimise economic investment and holding licenses [14]. Moreover, while accurate surveys and inspections are, commonly, driven by single intervention impulses [15], providing a detailed documentation to support diagnostic analysis and restoration

projects (e.g. in [5]), preventive conservation needs systematic management, consecutive inspections and a consequent continuous information storage and exchange among the stakeholders (e.g. inspectors, BIM manager, engineers in charge of the structural analysis, among others). This interoperability is often prevented by the use of proprietary formats [16], therefore the IFC (Industry Foundation Classes) standard for open BIM data exchange is of utmost relevance [17]. In view of consecutive inspections, graphical accuracy increases the computational burden also to update the model, since each localised anomaly is likely to evolve and change in shape and severity. However, geometrical data form only one of the attribute of the level of information need for specific model components and purposes, as recently reiterated by international standards as the ISO 19650-1 [18] and the EN 17412-1 [19]. The extent and granularity of the information for each element of a BIM model is, in fact, defined by the combination of geometrical data, alphanumerical data and documentation. Therefore, a viable alternative, to ensure a significant level of information for the purpose of the model, is to balance a low level of graphic accuracy with a large quantity of linked data [3], [20]. To one extreme, ontological models, based on a web of interlinked data, have been recently explored to collect information about building defects, even in the absence of a geometrical model [12], [21]. However, a graphical description of the building might support the information management and speed up the inspection tasks. For preventive conservation purpose, the relevant information regarding decay and anomalies can be simply linked to the affected elements as written boards and datasets [14], [22]. Several authors, explored the use of specific model objects, like markers, to point out the damage location and stand in as link to relevant documents [3], [23]. This minimum level of geometrical information can be increased, for instance by introducing a colour key indicating the urgency of repair and maintenance [24]. The suitability of such a low-level graphical representation has been exploited in bridge management [25]–[27]. This is a field that is largely concerned with preventive maintenance, sharing methodological similarities with heritage preservation. Although very practical and timesaving, the use of the markers renounces any graphical information regarding the type or the extent of the damage. A larger information content through

graphical representation can be achieved by changing the marker shape based on damage extent [27]. As said, a sufficient level of information need is achievable through a trade-off between geometrical and non-geometrical data. In HBIM, a standard definition of the alphanumerical information content is still an open issue [3]. For new industrial products, this is lately been addressed by the definition of Product Data Templates (PDT), namely, electronic data sheets which collect information for new industrial products [28].

1.2. Objectives

In view of the several research/technical gaps identified in the previous section, the present work aims at introducing a newly developed framework for preventive conservation, including identification and tracking of pathologies, in a BIM-based environment. Although the approach is mainly meant for heritage buildings, it is easily adaptable to any existing structure subjected to consecutive inspections and exchange of data. The framework aims at the interoperability and the feasibility of the methodology for the stakeholders involved. A process map based on Business Process Model and Notation (BPMN) [29] is presented to clearly identify the tasks and roles of the involved stakeholders and the information produced and exchanged among them. This process map can be used as a reference by stakeholders in similar projects, as the authors did not encounter any similarly built diagram in the literature. The methodology is based on a simplified modelling strategy for the element and the damage geometry. Level of information need for this BIM use is defined according to the recently issued EN 17412-1 [19]. The interoperability and the standardization of the approach are pursued so that the inspectors can quickly interrogate, on site, the model and update it to the survey reports collected into electronic forms. This is achieved by exploiting the IFC format for the BIM model and PDTs tailored to the peculiarity of historical objects. During the development of the PDT, the authors were aware of the prEN 17473:2020 document [30], currently submitted to the CEN Enquiry.

The remainder of the paper is organised as follows. In section 2.1, the workflow of the methodology is described. The strategy to achieve the required level of information need is further described in

sections **Erro! A origem da referência não foi encontrada.** and **Erro! A origem da referência não foi encontrada.** analysing, respectively, the geometrical and the alphanumerical information required. The issues related to interoperability are discussed in section 2.4. In section 3, the methodology is then tested on a real case study, namely the Ducal Palace sited in Guimarães, Portugal, one of the most relevant examples of the Portuguese heritage. Finally, the conclusions are drawn in section 4.

2. The proposed methodology

2.1. Workflow

The methodology proposed in this work concerning the damage surveying within management of historical buildings is meant to address the aforementioned open issues. Three main stakeholders are identified: asset manager, BIM modeller and inspector. Nonetheless, whenever the same person or team assumes more than one role, the framework can be easily adapted. In the most generic structure, as illustrated in the process map of Figure 1, the asset manager and the inspectors do not need any BIM knowledge nor holding licensing of any proprietary software as all the tasks related to modelling are performed by a third party with experience in the field and several free viewer software are available. The interoperability is improved by defining inspection forms as spreadsheets structured in a way that standardises and facilitates the creation of an electronic database and the translation of the information to the BIM model. Moreover, the BIM model that is generated according to the present methodology is not only suitable for supporting inspections, but it can be also integrated in facility and asset management or even refurbishment, namely for other BIM uses related to the building's performance assessment (e.g. design authoring, structural analysis, lighting analysis, energy analysis, etc.).

The methodology is divided into two main stages. The first stage consists in the generation of the BIM model, whereas the management stage itself follows it, consisting in a cycle of inspection surveys and model updating. In the case a model of the system already exists, the methodology may

start directly with the second stage. Following the illustration of the process map in Figure 1, it is possible to identify the tasks of each party, the data that are exchanged between them and the interoperable software used to manage and exchange the information. The asset manager promotes the process by collecting all the existing information on the building and its assets (task M1). If the information is enough to develop a BIM model, the manager sends it to the modeller (data E1), otherwise, a survey is firstly requested to complete it (task M2) and then sends the information (data E2). The exchanged data include any kind of graphical representation of the metric survey, images and written reports. An accurate data acquisition through photogrammetry or terrestrial laser scanner can be performed if the involved practitioners are able to correctly implement the methodologies and process the records. The BIM model is generated based on such data (task (B1) on a proprietary software (in the present study Autodesk REVIT has been used). If the building or its assets are already affected by anomalies, these are represented in the '*as-is*' model according to the strategy described in sections **Erro! A origem da referência não foi encontrada.** and **Erro! A origem da referência não foi encontrada.**. The modeller sends to the asset manager the model in the proprietary format, for future editing and/or further analyses, and in an open format, to support the inspections (Data E3). Additionally, the modeller generates and shares a set of inspection forms, namely standard editable spreadsheets distinctively recognised through a unique identification code of the BIM object of the element to be inspected and the BIM object of the existing anomaly to be monitored. This can be the Global Unique Identifier (GUID), or, as in the case study, the element unique identification code generated by the proprietary software.. The template of the spreadsheet is customised based on the requirements of the asset manager and the inspectors and it is structured according to the PDT (see section **Erro! A origem da referência não foi encontrada.**) in order to automatize the model updating process by transferring the information after the inspection into the BIM platform. Finally, the asset manager defines the inspection schedule based on the characteristics and the condition of the building (task M3). Each inspection follows the same process reported in Figure 1 as n-th inspection process. In due time, the asset manager requests the inspection (task M5) by appointing

the inspectors and sharing with them the pre-defined forms and a model in an open format (data E4). This can be explored and interrogated on a free license software, during the inspection design (task I1) and, on site, during the actual survey (task I2). This and the photographic documentation (data E5) are collected through portable devices and sent to the modeller. The model is thus updated (task B2), through the proprietary software, and translated again into the open format being then available for the following inspections. Although the main goal is the inspection and monitoring of the anomalies, any kind of information provided by the inspectors can be uploaded in the model following the same process, for instance interventions that modify the characteristics of the structural elements or change in the placement or in the number of the assets.

The model updating process, which is the core of this damage management, is simplified by the use of the template, since the information exchange is standardised, and by a trade-off between geometrical and non-geometrical information (e.g. alphanumerical information and documentation) that aims at balancing a moderate extent of the former with a high quantity of the latter. The effectiveness of the proposed methodology strongly depends on the definition of the level of information need, on the completeness of the PDT spreadsheets that are used to collect the non-graphical features of the model and on the interoperability among all the involved software. The next sections provide more details with the aid of examples.

2.2. Geometrical information

2.2.1. Asset and construction elements

Based on the inspectors needs, an effective BIM model to support the damage survey must be precise enough to define the limits and the position of each component of the building within the 3D environment. Each graphical element serves as a collector of relevant information and sets a reference system based on its own real geometry and its position inside the building. Using this reference system, it is possible to locate the damage and quantify its extent.According to the EN 17412-1 standard [19], the extent of geometrical information of an object is defined by specifying the detail,

the dimensionality, the location, the appearance and the parametric behaviour. The methodology developed in the present paper aims at providing a description of all the architectural features and the major service details by using generic components and elements, whereas ornamental details are not required, as a more accurate description would be considered detrimental for the practicality of the model. This corresponds, in accordance with the specification of EN 17412-1, to a simplified representation of the detail, with 3D dimensionality and symbolic appearance, described in absolute location. This definition of the geometry is inspired by the third level of detail of the scale proposed for heritage assets by Historic England [3]. The representation of construction elements in the BIM platform can be carried out mostly through the use of native object classes available on the software. This approach keeps modelling costs as low as possible, while still enabling the same use of information that would be possible with a very accurate model from the geometrical point of view. Traditional survey techniques may provide a sufficient database for the definition of the BIM model. However, taking into account the ease of deployment and richness of information of techniques such as PG and TLS, their use is seen as recommendable for verification of the LoA (deviation of the modelled object respect to the point cloud), and also to assess matters of relevance for structural integrity. Indeed, any deviation from the ideal surface (e.g. out of plane deformations, settlements, identifiable rigid body movements) are to be neglected in the graphical representation of the approach proposed herein. Such information is to be stored in a quantitative manner as non-graphic data (example to be shown later on in the paper).

Due to the uniqueness of each component in built heritage, these general rules must be taken with due consideration as the generation of HBIM models is a very case specific task. However, some examples can be provided as common guideline. The walls may be represented as simple solid elements where different masonry units are not distinguished (Figure 2a). The windows and the doors may be modelled as native objects in the style of the actual objects, where stone frames and stone sittings geometry is modelled (Figure 2b). Usually, timber roof elements modelling is a challenging task due to the complex geometry, intricate connection system and presence of elements with irregular

cross-section. In that case, proprietary software might be not equipped with suitable native families or classes. The strategy followed aims at using parametric objects as much as possible, allowing that any improvement of the information regarding the geometry can be easily implemented. Complex shapes are simplified, for instance by keeping the section constant or approximating the generatrix of curved elements, as for the pointed arches in Figure 3. The definition of the geometrical features that are needed is more complicated for the elements which, despite being structural, have a relevant ornamental function. For instance, the corbels and the columns are represented through a geometry which envelopes and resembles the actual one, but moulding and decorations are smoothed away, e.g. in the capital (Figure 4). Finally, a more case-specific decision making is required for purely ornamental elements as statues. In this case, for instance, a smooth enveloping geometry is considered sufficient.

2.2.2. Damage objects

Regarding damage modelling, two main types of damage are addressed. The first type is related to one or more global parameters of the entire constructive element (e.g. tilt of a wall). Due to the intended geometrical information, in the present methodology, the elements are not modelled in their as-damaged condition and the information about deformation is allocated as non-geometric data. The second type concerns damage that is localised in a portion of a constructive element (e.g. moisture, cracks, detachment, corrosion), thus, it is necessary to graphically identify and represent its position within the element. This is achieved by a simple parallelepiped patch with fixed thickness (0.01m). The aspects of its geometrical information, according to the EN 17412-1 standard [19] are, in this case, simplified detail and symbolic appearance, described in relative location against the damaged object. The dimensionality is 3D, but with fixed thickness, and the parametric behaviour is requested, to update the extent. All the relevant features of the damage and of the interventions are linked to the patch. In order to minimise the subjective decision during the inspection, the anomalies are classified according to a damage atlas that is well-known to the inspectors and available for reference during the in-situ survey. In the present work, the damage atlas developed within the HeritageCare project

[31] is used. This atlas is structured as a database contained in the HeritageCare server that lists 87 typologies of alterations or deteriorations for buildings and 79 for assets. These are organised according to three levels (classes, sub-classes and sub-sub-classes). Nomenclature, descriptions and main parameters needed to define each anomaly are translated into four languages. All the localised defects are represented through the same patch-type element object , perpendicularly overlaying the constructive element in the approximate location of the damage. Whenever the element is not planar the patch follows its curvature. Each class is represented by a colour, namely, considering the seven classes reported in the damage atlas: (1) biological colonization – green; (2) discoloration and deposit – orange; (3) material loss – grey; (4) detachment – blue; (5) cracks – red; (6) deformations – purple; (7) others – yellow. Sub-sub-classes may be further distinguished through the hatch's patterns in a future development of the work. In the model, the size of the patch changes according to the real extent in order to cover completely the affected area, two examples are shown in Figure 5. In case the damage spans through two different surfaces of the same element or through two adjacent elements, a patch per each surface should be applied. Although the patch is a model object, it can be easily distinguished from the building components by applying filtering views. Modelling the damage through objects facilitates its translation to the IFC format, thus, fosters the interoperability.

2.3. Alphanumerical information

2.3.1. Asset and construction elements

Aiming at a standardisation of the approach, a PDT is proposed to track the damage evolution in historical construction elements. The PDT consists of a spreadsheet divided into different categories of information, each one with a list of parameters to fill. The layout of the template is based on the CIBSE examples [28] for new manufacturer's products, but adapting them to the peculiarity of historic construction elements and the intended potential BIM uses. For instance, Table 1 shows a full data template of a historic stone masonry wall. The first section includes the metadata required for the definition of the template: (1) the template name (viz. type of element); (2) the suitability for

use (viz. a set of parameters related to the purpose of the information); and (3) the template custodian (viz. the organization or person responsible of the curation of the template). The second section provides information relevant to the state of conservation of the element, information about previous inspections, and information about the performance related to safety assessment (mechanical parameters of structural elements). Six categories of parameters were defined for built heritage elements: (1) construction data; (2) inspection data; (3) dimensional data; (5) structural data for load bearing elements; (4) sub-elements characterization; and (6) global level damage information. For the conservation, it is a paramount concern to define the evolution of the building in its phases, identifying, among the construction data, the main stages of constructions and interventions and the reliability of the date provided. Historical buildings often undergo different modifications along time and the differential degradation may reflect past interventions or may be due to wrong interventions. The accuracy of the time is defined on a 6 levels scale (from 0, in case of no support for the estimation, to 5, when totally sure). Similarly, among the inspection data, all the previous surveys are tracked down, reporting all the data needed to identify who performed it and where further data have been stored. In the case of load bearing elements, the structural data category is an essential support when the model is intended to interact with structural analysis software. Here, the main mechanical properties are reported together with other information that is relevant to structural modelling and assessment. For instance, in the case of masonry walls, relevant information is the type (e.g. single or multi-leaf) or the characteristics of the joints (e.g. dry, mortared, etc.). Moreover, it is implemented the Masonry Quality Index (MQI) classification method. This is a simple though effective method to perform a qualitative evaluation of the masonry behaviour, through a set of metrics. The MQI metrics check the existence, partial existence or absence of construction devices that improve the structural behaviour of masonry systems (e.g. wall-leaf connection, continuous horizontal joints and staggered vertical joints) and assess the characteristics of the mortar and the shape and dimension of the blocks. A guide to the methodology is provided in [32].

Other features of the object that are relevant for its preservation and assessment are reported within the sub-element characterisation parameters, where the single components of the object are analysed (e.g. the stone blocks). Knowing these features may facilitate the interventions in terms of authenticity and material compatibility, moreover it might highlight specific needs in terms of maintenance. Finally, the decay affecting the whole element is described through non-graphical linked features. In the example, a set of possible deformations are tracked, according to the damage atlas (in plane and out of plane deviation, buckling, leaning, bending or bulging, excessive deflection and lateral buckling). A sufficient level of information need for the element is thus guaranteed increasing the information content and admitting a less accurate representation of the "*as-is*" geometry. Hence, similar objects can be easily modelled and the process is hastened by avoiding a time-consuming alteration of each instance based on the actual condition.

A third category of features addresses the facility/asset management, providing details as the maintenance timeframe (e.g. daily, monthly, annually) and a link to the manuals with the description of the activities to carry out. CIBSE PDT includes a set of parameters that do not hold for historical architectural elements, as the manufacturer data, the application data, the electrical data or the sustainability data that are thus not considered in the present template. For each parameter it is necessary to define, in a specific column of the template, its name, its value with the used format and unit, and the notes, namely every piece of information about the parameter that helps understanding it, including examples and clarifications of how to fill the parameter.

2.3.2. Damage objects

For the localised damages, the level of information need is mainly reached through non-graphical features. The alphanumerical data of the patch type objects includes the classification of the damage and the identification of causes, consequences, and state risk. The HeritageCare damage atlas is the main reference for the definition of the parameters that are needed to describe each type of anomaly. A PDT is defined to standardise the required information. An example for the case of structural deep crack is reported in Table 2. Similarly to the construction elements, after the first section dedicated

to the required metadata, the parameters of the PDT for such objects are organized into five categories: (1) classification data; (2) inspection data; (3) geometric data; (4) symptoms and diagnosis; and (5) evolution control data.

The anomaly is classified through the definition of the class and the sub-sub-class, namely the first and the last level of the HeritageCare classification system. In order to support the building inspection and the condition monitoring in a BIM environment, it is essential to define an effective procedure to collect data that change with time. The inspection data collect all the previous inspection dates, and all the relevant information as linked databases and pictures. Similarly, the last three categories, namely geometric data, symptom and diagnosis and evolution control, provide an overview of all the significant metrics to identify the damage extent, and its evolution in all the previous inspections until the current aspect. All the anomalies are quantified in terms of the size of the area affected, the condition grade and the urgency risk. These last two parameters are defined by the HeritageCare on a 4-level scale, respectively, as an index of the damage severity and an index of the risk in terms of consequences for the building and the user's safety. This distinction is necessary since not all the anomalies endanger users, facilities and assets in the same way, thus a combination of the two metrics can be used for a risk-based prioritised design of the intervention. The evolution control data, instead, are specific of the current type of damage. For instance, cracks are characterised in terms of length, depth, pattern and form, as these parameters can change based on the causes of the damage and can lead to different consequences. Hence, keeping track of their evolution is essential for damage diagnosis and prognosis.

The information is stored in the BIM objects in order to comply with international standards, as [33]. The authors are also aware of the ISO/CD 22014 document for library objects, which is still in the review and comment stage [34]. Hence, particular attention is payed to the way the parameters are named and assigned. These are correctly distinguished between type and instance properties. For the values, the international system of units is adopted, whereas for the names, the PascalCase with Shorter Oxford English Dictionary as default spelling guide is used. To sort logically the properties,

some are prefixed with a parent class name and the naming fields are separated by the underscore character, as for the MQI parameters in the example of the stone masonry wall (see Table 3). The same rule is applied to files, object and material naming. In case the information is unknown, the value is set to n/a instead of being left blank, to avoid confusion. When native objects are used, with built-in parameters, special attention is payed to avoid multiple occurrences of the same property. Boolean variables are identified through an interrogative name, as "IsLoadBearing" in the example of the stone masonry wall (see Table 3). Based on the software, it is possible to use native parameters or create new ones. The parameters that refer to a specific inspection can be grouped together, thus, the parameter group allows to create a vector field that shows the evolution of the damage over consecutive inspections.

2.4. Interoperability

In the BIM context, software can be considered interoperable if they can read and write the same file formats or if they can use direct communication protocols (e.g. direct API exchange of information). Interoperability is essential for the activities of the BIM modeller (tasks B1 and B2 of the workflow in Figure 1). A first level of interoperability allows a fast and automatic exchange of the information between the BIM platform and the tools used by the parties, namely the inspection form spreadsheets in the present work. Moreover, interoperability at a higher level aims at building a legacy of the model by translating it into a format which is independent of the specific software used to interrogate or edit it. These two aspects are further analysed in the following subsections.

2.4.1. Exchange between BIM platform and spreadsheets.

The inspection form is an electronic spreadsheet that arranges all the parameters collected into the PDTs in a user-friendly graphical interface. The template of the spreadsheet should be predefined by all the parties in agreement, since the location of each piece of information cannot be changed and only the fields with the parameters' values can be edited. Based on this fixed structure, it is easy to develop algorithms that automatically search for the information in the spreadsheet and import the

values into the BIM model or, in the opposite direction, pre-fill in specific fields of the spreadsheet reading the values from the model. In the present work, this is done through Dynamo, an open source tool whose plug-in in Revit allows to customise the information workflow, but different software and/or programming languages allow similar processes.

After the generation of the model (task B1 in Figure 1), the BIM modeller generates the inspection forms and relates each of them to a specific existing object of the model, either asset or existing anomaly, by naming the spreadsheet and reporting in the specific field of the form the unique identification code (ID) of the object. The form of a specific asset can be used to record new anomalies that affect it or report the effect of interventions, whereas the form of an anomaly is used for its monitoring. Blank forms are available to describe and reference within the building new elements or assets. Hence, the inspector always works on a familiar software and with a familiar template and does not need any BIM knowledge. Moreover, using any available software free of license which is able to read the IFC format, the inspector can navigate the model for queries, for instance related to the ID of the objects or to the results of previous inspections. To this end, the BIM modeller generates also a version of the model in the open format (task B1 in Figure 1). After the inspection, when the information is to be updated (task B2 in Figure 1), the parameter values can be tracked down easily as the structure of the template does not change, and the instance to be updated is identified through the ID. An example of these procedures is to be shown in section 3.4.

2.4.2. IFC property mapping in BIM platform

For the BIM use described in the present work, the higher level of interoperability is achieved through IFC-based exchanges in full compliance with the PDT. The IFC scheme chosen is IFC4 Add2. In general, it is possible to export native or even customised property sets from the modelling platform, once it is provided that they are named according to the IFC manual. It is only necessary to verify, in the authoring tool, how to define the IFC mapping, as this process can be software specific. Data mapping lists, namely tables reporting the translation PDT data into proprietary software and IFC, help keeping track of how the information is stored in each step. For instance, Table 3 and Table 4

report the map for the stone masonry wall and the structural deep crack, respectively. It is possible that some features of the PDT might not be readily available in the IFC schema. In the examples shown herein, specific custom property sets have been defined. The use of the open standard format ensures interoperability and continuity of the information, making the generated elements available in an open BIM scheme.

3. Application to a case study

The methodology proposed in this work has been applied to the Ducal Palace of Bragança, located in Guimarães, Portugal. Commissioned around 1420-1422 by Afonso, 8th Count of Barcelos and illegitimate son of King João I and Inês Pires Esteves, the palace is one of the most relevant structures of the Portuguese built heritage as well as one of the most visited Portuguese monuments. The construction, begun in 1420, stopped after the death of the Count Afonso and restarted only in 1478 by the order of Fernando II, Duke of Bragança. The organization of the spaces dates back to this period with a division in a first floor with the servants' quarters and support rooms, and a second floor for the nobles' residence and the chapel. The Duke also ordered the insertion of a 3rd floor, but in general, due to the move of the court to Vila Viçosa, the palace remained incomplete and abandoned since the beginning of the XVI century.

The building suffered a long period of decay being also subjected to partial dismantling and reuse of the materials. In 1807, it was turned into a military barrack undergoing several interventions until 1935, when the property changed and a significant restoration process began. Such intervention, led by architect Rogério de Azevedo, took place between 1937 and 1959 aiming at a possible original aspect of the building, by undoing the changes due to the military occupation and the houses built in the surrounding. Among the main interventions of this period, it is worth mentioning the replacement of the floors with reinforced concrete ones, the refurbishment of the roof also with reinforced concrete beams and the construction of some of the chimneys. New services were installed in the building (e.g.

sewage networks, sanitary facilities, water distribution, electricity and illumination facilities). Since 1969 the palace hosts a museum.

3.1. Survey

The global geometry was first defined according to the available evidences, such as drawings obtained from the reconstruction and documentation in literature (Figure 6 and Figure 6) [35]. Using the symmetry of the building in the two-principal axes, the survey has been carried out only in the quarter hosting the administrative offices (South wing). Among the 23 spaces of this area, there is also the principal dining room. The inspected rooms were labelled according to the following notation: the first number refers to the level and the second to the room. In Figure 7, the inspected rooms are highlighted in yellow and red, where the red indicates the location of the tower. In each inspected room, digital pictures of the construction elements and spherical panoramas were taken, with 36 distinct construction elements being identified.

Globally, the inspection tasks took around 8 hours, divided into two stages. The first was mostly targeted to the identification of the elements/rooms, whereas the second was performed for in-situ clarification of doubts (e.g. survey of the windows hidden behind furniture, identification of reinforced concrete beams covered by wooden surface finish, among others). During the survey, the types of elements were grouped according to the material and the topological relation between their components. To support the model development, a list of all the elements in each room was created. In Table 5 an example is presented where the list provides a quick indication of the existing elements, their quantity and the connection between different rooms of the building.

3.2. Modelling strategies

In the modelling stage, the geometry was represented in a 3D numerical environment and information was linked to each created object. This task was divided into two steps. The first consisted in the development of the classes of objects, whereas the second aimed at the allocation of the elements in

the space, in a specific relation between each other. A total of 25 families of elements from the initially 36 identified in the first inspection were modelled in the proprietary software. Every object was parametric, so the model was created only once for any type of element and then the parameters were modified according to the specific element characteristics. Most of the objects were created hereditarily, based on native families of the software (e.g. walls, slabs, concrete beams used under the slabs). The classes of objects created were the windows, the doors, the arches and the columns. Table 6 shows some examples of the surveyed elements with the correspondent virtual geometric representation in the proprietary software. Figure 8 and Figure 9 show the global view of the final model and some detailed views. Following the methodology presented in this paper, the geometrical precision of the representation does not allow to consider this model as an extremely accurate restitution of the real actual state of the building. However, it is accurate enough to support the inspection and the monitoring over time, creating a spatial reference system to which the localised damages can be attached (see Section 3.4).

3.3. 3D scan acquisition

The model generated based on the available documentation and a traditional survey was enriched by performing a laser scanner survey of the building. In reality, the laser scanner survey should have happened before the actual BIM model was built, as to operate as a supporting base. In many practical cases, however, the involved parties may not be familiar with advanced acquisition methodologies, as the TLS, or they simply may not have access to them during the development of the model. Indeed, for the present case study, a private company was appointed to perform the laser scanner survey and the service was only available after the BIM model had been made. Nonetheless, traditional survey techniques can provide sufficient information for the intended geometrical information for the model, according to the methodology here developed (see Section **Erro! A origem da referência não foi encontrada.**). At this, stage, the 3D scan of the building had, thus, a twofold purpose: to validate the

implemented geometry and to easily identify global deformation to be allocated as non-geometric data.

In each room, the laser location was defined in order to reach the maximum amount of information. Moreover, acquisitions were taken from the doors, to connect the information of different spaces, and from the open windows, to connect the inner points to the exterior survey. Leica P20 was used for the survey and the original 40Gb *.pts point cloud file of the South wing of the building was processed by the proprietary BIM software (Figure 10). The final 1.164.664.694 points file proved a good accuracy of the initial geometry (e.g. location of the windows, slopes and elevation of the elements) (Figure 11), but also some differences were pointed out. Such geometric differences can be neglected considering the purpose of the model, which is to reach the pre-defined needed level of information, by linking to the model elements the non-geometrical data about their current state.

3.4. Damage survey

An inspection was carried out on the interior of the South wall in order to test the validity of the methodology presented in section 2.1. During the survey, it was possible to navigate and query the BIM model by means of a free model viewer software, reading the IFC file exported from the proprietary software environment. Together with the model, the inspectors were also provided with an Excel spreadsheet, developed and used to record any relevant information regarding the damage (Figure 12), as class and sub-sub-class according to the pre-defined damage atlas, position within the affected element and characteristic according to the PDT of the specific anomaly. During the survey, after the identification of a new anomaly, it was only necessary to find in the model the proprietary software generated ID of the affected element and to report it on the form. Being the first survey, no previous information of the anomalies was available. However, in case of following inspections, a set of forms identified by the ID of the damage objects would be also provided, to monitor their evolution and to allow a quick on-site comparison with the recorded extent. The filled in spreadsheets were made available for model updating by saving them directly in a common data environment

during the inspection. Finally, the information was uploaded into the model by processing each form through a plug-in of the proprietary software developed to automatise the data flow. The final aspect of the model with the patch-type elements used to represent the existing anomalies is shown in Figure 13.

4. Conclusion

Building Information Modelling (BIM) methodology already demonstrated to be effective for facility and asset management of new buildings, but its application to the maintenance of the built heritage, within the scope of the Historical BIM (HBIM) field of research, although promising, is still challenging. A widespread application of HBIM approaches should be promoted by pursuing three main goals, namely, standardisation of the procedures, interoperability of the software components and simplification of the methodologies. In the light of these general goals, the present work focuses on the development of an easy-to-apply strategy to survey the damage and track its evolution over time. Six main open issues concerning this BIM use have been identified, namely low BIM knowledge of asset managers and inspectors, lack of 'as-is' models to support the inspection, need for interoperable strategy to collect data onsite, need for a system to query previous inspection results during a new survey, lack of standardisation of the information to upload in the BIM model, lack of easy-to-implement but still informative methodology to model and monitor the damage evolution over consecutive inspections. In this regard, an approach is developed considering a first stage of survey and model development and a second stage further divided in cyclic inspections. All the tasks that require a BIM knowledge are performed by an expert, here called BIM modeller, thus asset manager and inspectors do not need to master BIM skills nor to hold a proprietary software license as they can always navigate and query the model by mean of free software even onsite. The IFC open standard format is used for this purpose. The level of information need for this BIM use was achieved by balancing a moderate graphical accuracy with a high information content through non-graphical

linked data. Each component itself acts as a collector of relevant information and sets a reference system, based on its real geometry and its position inside the building.

The damage survey methodology is based on the definition of two types of damage. The first concerns the global characteristics of the element and is reported as a linked non-graphical feature among the element properties. The second, being a localised damage, is graphically represented to define its position within the element through a simple patch-type element family. All relevant features of the damage are linked to the patch. Such a symbolic representation of the localised damages is unambiguous, consistent and, thus, prone to standardisation. Furthermore, it is easy to implement and to adapt due to the parametric nature of the patch objects, reducing the costs, complexity and time requirement of the inspection and the modelling stages. Aiming at a standardization of the information content, a template for the different classes of damage was created, inspired by the concept of Product Data Templates for new manufacturer's products.

Finally, all the proposed processes were tested on a case study, namely the Ducal Palace in Guimarães, where the information of an inspection was linked to the 3D model within a BIM-based environment, which can be updated with future inspection information, aiming at a more sustained management of the building.

Palace and for kindly sharing her knowledge about the building. The authors would like also to acknowledge Nuno Moreira (TopArcos) for carrying out the laser scanner survey.

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Table List

Template name (for)	Historic masonry wall		
Suitability for use	Asset management		
Template custodian	HeritageCare		
Parameter name	Value	Units	Notes
Masonry wall construction data			
Construction date		Years	Example: 1500
Construction date degree of accuracy		0 to 5	0=rough estimation without support, 5=totally sure – Example: 2
Previous intervention dates		Years	Example: 1590, 1650, 1900, 2015
Intervention dates degree of accuracy		0 to 5	0=rough estimation without support, 5=totally sure- Example: 0, 5, 4, 5
Inspection data			
Inspection dates		Date	Example: 1985/07, 1994/05, 2010/05
Last inspection reference			Name, address or any other reference to track the source
Brief description			General description of last inspection
Survey picture URL			
Dimensional data			
Thickness		m	Example: 1.25
Height		m	Example: 2.55
Length		m	Example: 15.23
Wall structural data			
Load Bearing			Yes, No
Compressive Strength		MPa	
Elastic Modulus		MPa	
Type of Wall			Single leaf, Multiple leaves.
Morphology			Bond Type
Joint Type			"Dry Joint", "Mortared Joint", or "Other"
MQI_SS (Stone Shape)			NF, PF, F
MQI_WC (Wall Leaf Connection)			NF, PF, F
MQI_HJ (Horizontality Bed of Joints)			NF, PF, F
MQI_MM (Mortar Properties)			NF, PF, F
MQI_VJ (Vertical Joints)			NF, PF, F
MQI_SM (Stone/Brick Mechanical Properties)			NF, PF, F
MQI_SD (Stone/Brick Dimensions)			NF, PF, F

Stone Characterization		
Stone Type		Example: Granite, Basalt, Limestone
Stone Origin		Fill this if you can track the origin of the stone
Stone Hardness		Mohs scale.
Stone Density	kg/m^3	
Stone Porosity		
Stone Compressive Strength	MPa	
Stone Tensile Strength	MPa	
Stone Elastic Module	MPa	
Deformation		
In Plane Deviation	m	From Damage Atlas HC
Out of Plane Deviation	m	From Damage Atlas HC
Buckling	m	From Damage Atlas HC
Leaning	m	From Damage Atlas HC
Bending/Bulging	m	From Damage Atlas HC
Excessive Deflection	m	From Damage Atlas HC
Lateral Buckling	m	From Damage Atlas HC
Asset management (maintenance)		
Operation and Maintenance Manual		Hyperlink to Manufacturer O&M Data
Daily		Maintenance tasks or SFG20 codes
Weekly		Maintenance tasks or SFG20 codes
Monthly		Maintenance tasks or SFG20 codes
Quarterly		Maintenance tasks or SFG20 codes
6 Monthly		Maintenance tasks or SFG20 codes
Annually		Maintenance tasks or SFG20 codes
Bespoke Timeframe		Maintenance tasks or SFG20 codes

Table 2: Data Template of Damage Information about a Structural Deep Crack.

Template name (for)	Damage, Structural Deep Crack		
Suitability for Use	Asset Management		
Template Custodian	HeritageCare		
Parameter Name	Value	Units	Notes
Classification Data			
Class of Damage			From Damage Atlas HC
Sub-Sub-Class of Damage			From Damage Atlas HC
Inspection Data			
Inspection Dates		Date	Example: 1985/07, 1994/05, 2010/05
Last Inspection Inspector reference			Name, address, or any reference to track the source.
Brief Description			General description
Survey Picture URL			
Geometric Data			
Area		m^2	Example: 1.5
Symptoms and Diagnosis			
Possible Causes			Describe causes and clues
Possible Consequences			Describe consequences if there is no intervention
Condition grade		0 to 3	0=perfect condition, 3=very poor condition – Example: 2
Symptoms			Describe the effects of the damage over the structure
Urgency Risk Classification		0 to 3	0=no urgency, 3=immediate need – Example: 2
Works Carried Out			Describe works carried out
Evolution Control Data			
Type of crack			
Length		m	
Depth		m	
Pattern			
Form			

Table 3: Data Mapping (Data Template / Revit / IFC) for Historic Masonry Wall.

Parameter Name	Revit Group Parameter / Parameter Name	Revit Type of Parameter	Revit Data Type	IFC Property Set / Parameter Name	IFC Data Type
Historic Masonry Wall Data Mapping					
Construction Data					
Construction Date	Construction / ConstructionDate	Instance	Text	HBIM_ConstructionData / ConstructionDate	IFCTEXT
Construction Date Degree of Accuracy	Construction / ConstructionDateDegreeAccuracy	Instance	Number	HBIM_ConstructionData / ConstructionDateDegreeAccuracy	IFCREAL
Intervention Dates	Construction / InterventionDates	Instance	Text	HBIM_ConstructionData / InterventionDates	IFCTEXT
Intervention Dates Degree of Accuracy	Construction / InterventionDatesDegreeAccuracy	Instance	Number	HBIM_ConstructionData / InterventionDatesDegreeAccuracy	IFCREAL
Inspection data					
Inspection Dates	Construction / InspectionDates	Instance	Text	HBIM_ InspectionData / InspectionDates	IFCTEXT
Last Inspection Inspector reference	Construction / InspectorReference	Instance	Text	HBIM_InspectionData / InspectorReference	IFCTEXT
Brief Description	Identity Data / Description	Type	Text	HBIM_InspectionData / Description	IFCTEXT
Survey Picture URL	Identity Data / Image	Instance	File	HBIM_InspectionData / PictureURL	IFCLABEL
Geometrical data					
Thickness	Construction / Width	Type	Number		
Height			Number		
Length	Dimensions / Length	Instance	Number		
Wall structural data					
Load Bearing	Structural / Structural	Instance	Yes, No	HBIM_WalStructuralData / IsLoadBearing	IFC BOOLEAN
Compressive Strength	Structural / CompressiveStrength	Type	Area Force	HBIM_WallStructuralData / CompressiveStrength	IFCREAL
Elastic Modulus	Structural / ElasticModulus	Type	Area Force	HBIM_WallStructuralData / ElasticModulus	IFCREAL
Type of Wall	Structural / WallType	Type	Text	HBIM_WallStructuralData / WallType	IFCTEXT
Morphology	Structural / Morphology	Type	Text	HBIM_WallStructuralData / Morphology	IFCTEXT
Joint Type	Structural / JointType	Type	Text	HBIM_WallStructuralData / JointType	IFCTEXT
MQI_SS (Stone Shape)	Other / MQI_SS	Instance	Text	HBIM_MasonryQualityIndex / MQI_SS	IFCTEXT
MQI_WC (Wall Leaf Connection)	Other / MQI_WC	Instance	Text	HBIM_MasonryQualityIndex / MQI_WC	IFCTEXT
MQI_HJ (Horizontality Bed of Joints)	Other/ MQI_HJ	Instance	Text	HBIM_MasonryQualityIndex / MQI_HJ	IFCTEXT
MQI_MM (Mortar Properties)	Other/ MQI_MM	Instance	Text	HBIM_MasonryQualityIndex / MQI_MM	IFCTEXT

MQI_VJ (Vertical Joints)	Other/ MQI_VJ	Instance	Text	HBIM_MasonryQualityIndex / MQI_VJ	IFCTEXT
MQI_SM (Stone/Brick Mechanical Properties)	Other/ MQI_SM	Instance	Text	HBIM_MasonryQualityIndex / MQI_SM	IFCTEXT
MQI_SD (Stone/Brick Dimensions)	Other/ MQI_SD	Instance	Text	HBIM_MasonryQualityIndex / MQI_SD	IFCTEXT
Stone Characterization					
Stone Type	Structural / StoneType	Type	Text	HBIM_StoneCharacterization / StoneType	IFCTEXT
Stone Origin	Structural / StoneOrigin	Type	Text	HBIM_StoneCharacterization / StoneOrigin	IFCTEXT
Stone Hardness	Structural / StoneHardness	Type	Number	HBIM_StoneCharacterization / StoneHardness	IFCREAL
Stone Density	Structural / StoneDensity	Type	Mass density	HBIM_StoneCharacterization / StoneDensity	IFC MASSDEN SITY MEASURE
Stone Porosity	Structural / StonePorosity	Type	Number	HBIM_StoneCharacterization / StonePorosity	IFCREAL
Stone Compressive Strength	Structural / StoneCompressive Strength	Type	Area force	HBIM_StoneCharacterization / StoneCompressiveStrength	IFCREAL
Stone Tensile Strength	Structural / StoneTensileStreng th	Type	Area force	HBIM_StoneCharacterization / StoneTensileStrength	IFCREAL
Stone Elastic Module	Structural / StoneElasticModul e	Type	Area force	HBIM_StoneCharacterization / StoneElasticModule	IFCREAL
Stone Poisson Ratio	Structural / StonePoissonRatio	Type	Number	HBIM_StoneCharacterization / StonePoissonRatio	IFCREAL
Stone Thermal Expansion Coefficient	Structural / StoneThermalExpa nsionCoeff	Type	Thermal Expansion Coeff.	HBIM_StoneCharacterization / StoneThermalExpansionCoeff	IFCREAL
Deformation					
In Plane Deviation	Other / InPlaneDeviation	Instance	Length	HBIM_Deformation / InPlaneDeviation	IFC LENGTH MEASURE
Out of Plane Deviation	Other / OutOfPlaneDeviati on	Instance	Length	HBIM_Deformation / OutOfPlaneDeviation	IFC LENGTH MEASURE
Buckling	Other / Buckling	Instance	Length	HBIM_Deformation / Buckling	IFC LENGTH MEASURE
Leaning	Other / Leaning	Instance	Length	HBIM_Deformation / Leaning	IFC LENGTH MEASURE
Bending/Bulgi ng	Other / BendingBulging	Instance	Length	HBIM_Deformation / BendingBulging	IFC LENGTH MEASURE
Excessive Deflection	Other / ExcessiveDeflectio n	Instance	Length	HBIM_Deformation / ExcessiveDeflection	IFC LENGTH MEASURE
Lateral Buckling	Other / LateralBuckling	Instance	Length	HBIM_Deformation / LateralBuckling	IFC LENGTH MEASURE

Symmetrical deformation	Other / SymmetricalDeformation	Instance	Length	HBIM_Deformation / SymmetricalDeformation	IFC LENGTH MEASURE
Asymmetrical deformation	Other / AsymmetricalDeformation	Instance	Length	HBIM_Deformation / AsymmetricalDdeformation	IFC LENGTH MEASURE
Undefined deformation	Other / UndefinedDeformation	Instance	Length	HBIM_Deformation / UndefinedDeformation	IFC LENGTH MEASURE

Parameter Name	Revit Group Parameter / Parameter Name	Revit Type of Parameter	Revit Data Type	IFC Property Set / Parameter Name	IFC Data Type
Structural Deep Crack Data Mapping				
Classification Data				
Class of Damage	DamageClass	Type	Text	HBIM_ClassificationData / DamageClass	IFCTEXT
Sub-Sub-Class of Damage	DamageSubSubClass	Instance	Text	HBIM_ClassificationData / DamageSubSubClass	IFCTEXT
Inspection Data				
Inspection Dates	Construction / InspectionDates	Instance	Text	HBIM_ InspectionData / InspectionDates	IFCTEXT
Last Inspection Inspector reference	Construction / InspectorReference	Instance	Text	HBIM_InspectionData / InspectorReference	IFCTEXT
Brief Description	Identity Data / Description	Type	Text	HBIM_InspectionData / Description	IFCTEXT
Survey Picture URL	Identity Data / Image	Instance	File	HBIM_InspectionData / PictureURL	IFCLABEL
Geometric data				
Area	Dimension / Area	Instance	Area		
Depth	Dimension / Depth	Instance	Length	HBIM_GeometricData / Depth	IFC LENGTH MEASURE
Pattern	Dimension / Pattern	Instance	Text	HBIM_GeometricData / Pattern	IFCTEXT
Form	Dimension / Form	Instance	Text	HBIM_GeometricData / Form	IFCTEXT
Symptoms and Diagnosis				
Possible Causes	Other / PossibleCauses	Type	Text	HBIM_SymptomsDiagnosis / PossibleCauses	IFCTEXT
Possible Consequences	Other / PossibleConsequences	Type	Text	HBIM_SymptomsDiagnosis / Possible Consequences	IFCTEXT
Condition grade	Other / ConditionGrade	Type	Integer	HBIM_SymptomsDiagnosis / ConditionGrade	IFC COUNT MEASURE
Condition Classification	Other / ConditionClassification	Type	Text	HBIM_SymptomsDiagnosis / ConditionClassification	IFCTEXT
Symptoms	Other / Symptoms	Type	Text	HBIM_SymptomsDiagnosis / Symptoms	IFCTEXT
Urgency Risk Classification	Other / UrgencyRiskClassification	Type	Text	HBIM_SymptomsDiagnosis / UrgencyRiskClassification	IFCTEXT
Works Carried Out	Other / WorksCarriedOut	Type	Text	HBIM_SymptomsDiagnosis / WorksCarriedOut	IFCTEXT
Evolution Control Data				
Type of Crack	Other / CrackType	Instance	Text	HBIM_EvolutionControlData / CrackType	IFCTEXT
Length	Other / Length	Instance	Length	HBIM_EvolutionControlData / Length	IFC LENGTH MEASURE

Depth	Other / Depth	Instance	Length	HBIM_EvolutionControlData / Depth	IFC LENGTH MEASURE
Pattern	Other / Pattern	Instance	Text	HBIM_EvolutionControlData / Pattern	IFCTEXT

Table 5: Extract of the construction elements survey by room.

GROUND FLOOR				FIRST FLOOR		
Element name	Quantity	Shared with		Element name	Quantity	Shared with
ROOM 01				ROOM 15		
Stone pointed arch + columns	2			Stone arch siting window	19	
Double stone arch wood door	1	R02		Stone chimney	1	
Rectangular window	2			Double stone arch wood door	5	R14, Stairs, Cloister, Room S.M.
Wood beams flat ceiling	60 cm			Stone masonry wall	-	
Stone masonry wall old	-			Roof ventilation	4	
Brick floor	1			Brick floor	1	
ROOM 011				Timber roof rafter	-	
Stone chimney	2			Timber roof metal tie	-	
Double stone arch wood door	2			Timber roof metal hanger	-	
Rectangular window	4			Timber roof collar tie	-	
Stone floor	1			Timber roof purlin	-	
Brick floor	1			Timber roof ridge piece	-	
Wood beams flat ceiling	60 cm			Timber roof support beam	-	
Stone masonry wall old	-			Timber roof arched brace	-	
CLAUSTRO GROUND FLOOR				Timber roof longitudinal flat truss	-	
Wood beams flat ceiling	60cm			Timber roof support beam	-	
Stone floor	1			CLAUSTRO FIRST FLOOR		
Stone masonry wall	-			Timber roof rafter	-	
Stone masonry wall old	-			Stone wall	-	
Stone pointed arch patio	6			Stone floor	1	
				Timber roof support beam	2	
				Column	14	

SECOND FLOOR				THIRD FLOOR		
Element name	Quantity	Shared with		Element name	Quantity	Shared with
ROOM 21				ROOM 31		
Stone arch siting window	2			Unidentified door	2	
Stone chimney	1			Rectangular window	8	
Double stone arch wood door	5			Stone floor	1	
Stone stairs	1			Stone masonry wall	-	
Brick floor	1			Timber roof rafter	-	
Stone masonry wall	-			Timber roof support beam	-	
Timber roof rafter	-			Timber roof horizontal beam	-	
Timber roof metal tie	-					
Timber roof metal hanger	-					
Timber roof collar tie	-					
Timber roof purlin	-					
Timber roof ridge piece	-					
Timber roof support beam	-					

Table 6: Extract of the elements' representation in the proprietary software.

Name	Survey picture	Virtual representation
Concrete slab + brick floor		
Column		
Double stone arch wood door		
Stone arch sitting window		
Beams flat ceiling		

Figures List
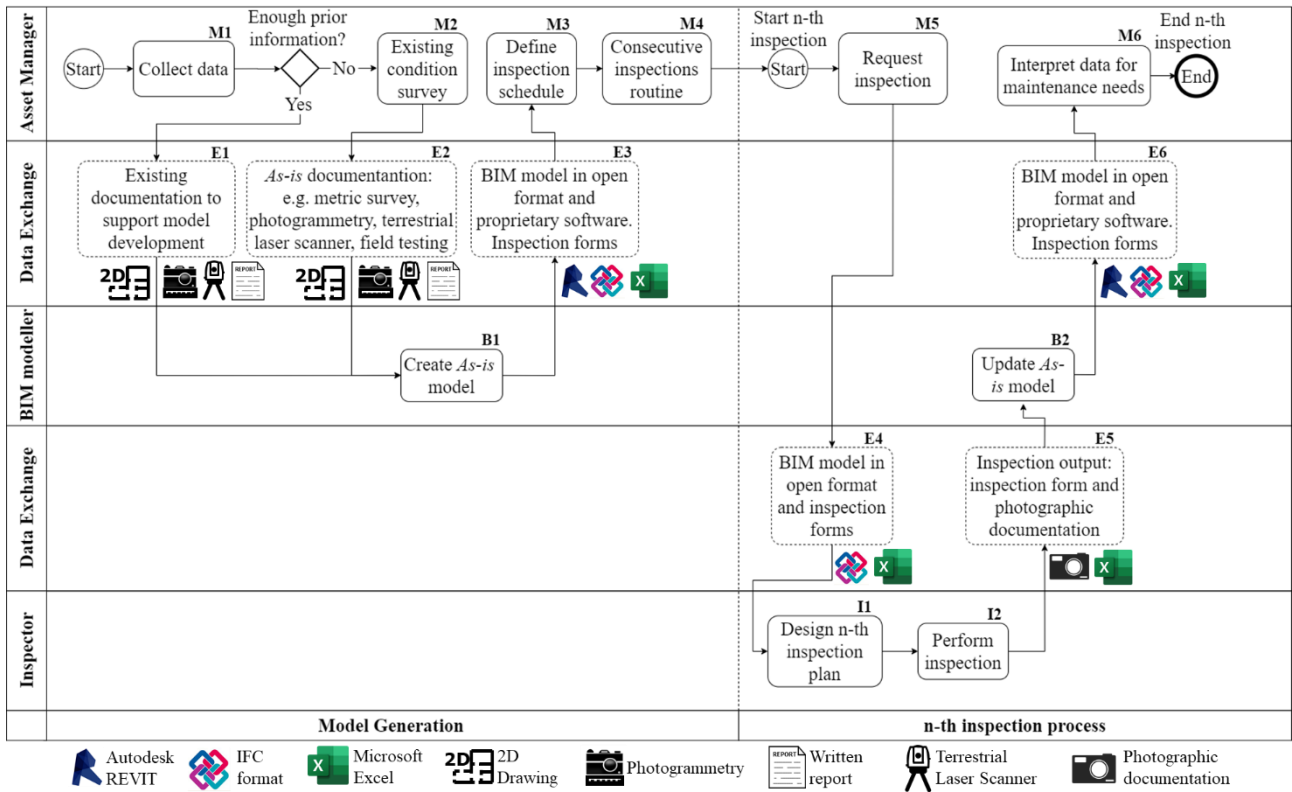
Figure 1: Process Map illustrating the workflow of the BIM methodology for damage surveying and monitoring.

(a)   *(b)*

Figure 2: BIM objects: (a) wall element; (b) windows element.
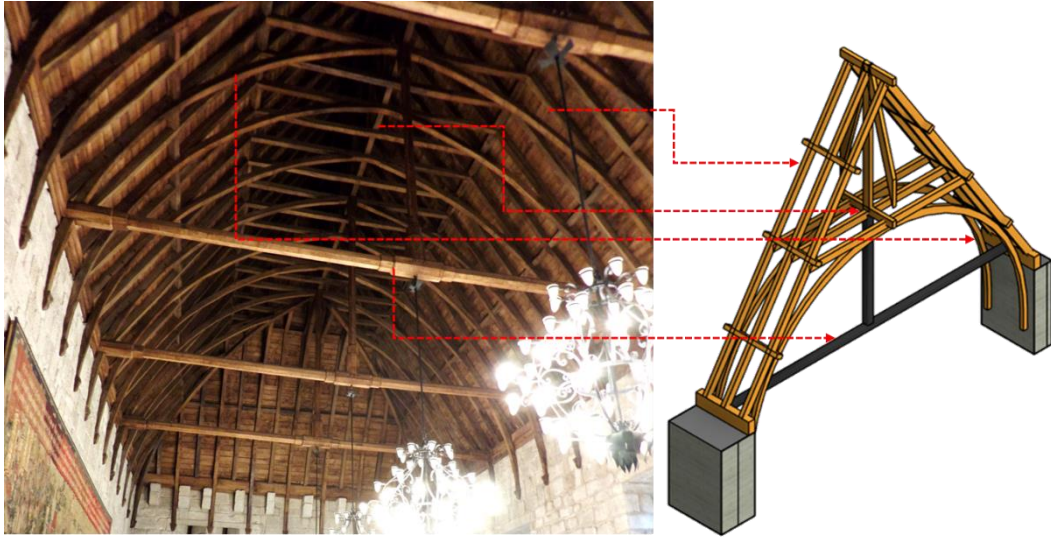
Figure 3: BIM objects: timber roof.
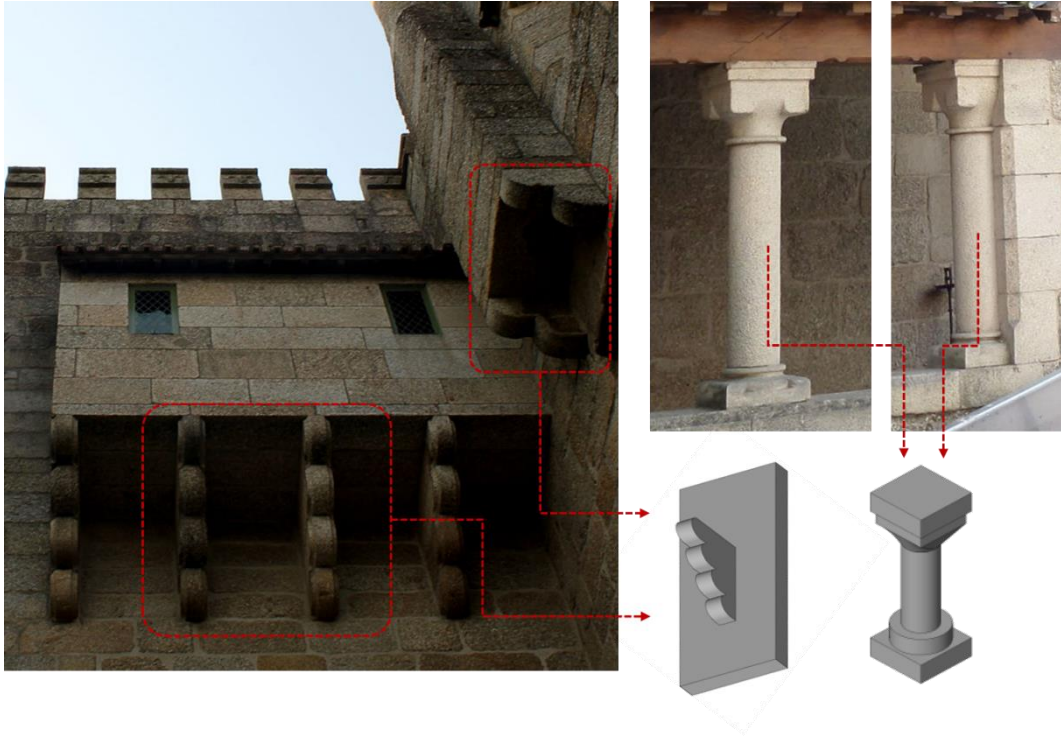
Figure 4: BIM objects: corbels and columns.

(a)   *(b)*

Figure 5: Patch-type object to represent anomalies: (a) crack in the window's frame; (b) stain due to water below a window.
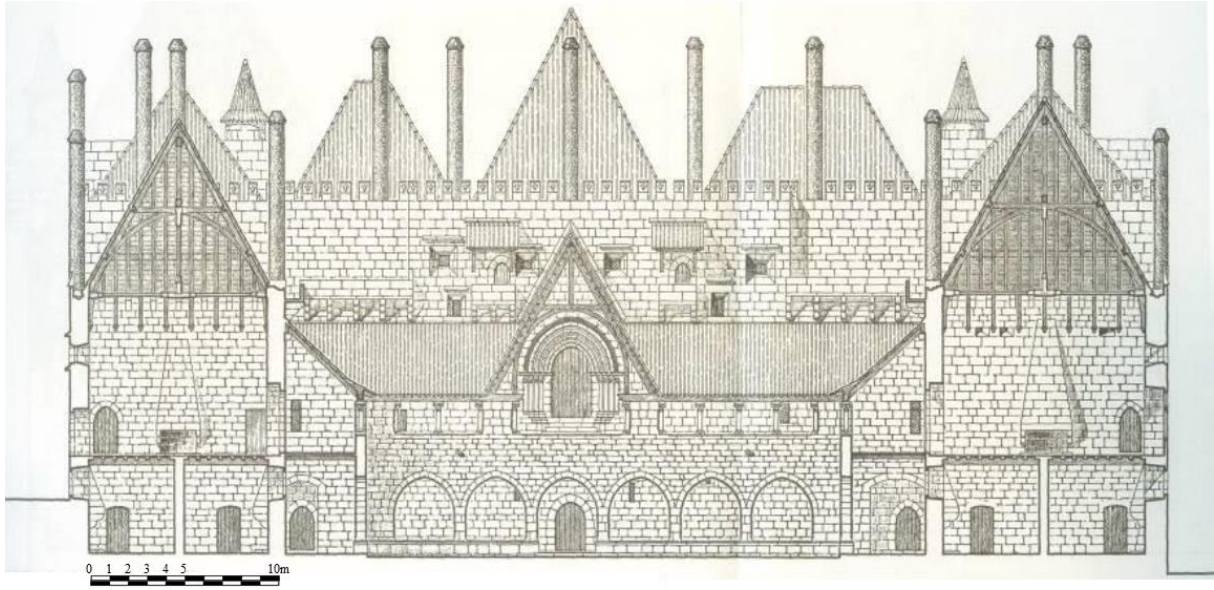
Figure 6: Section of Ducal Palace, adapted from [35].
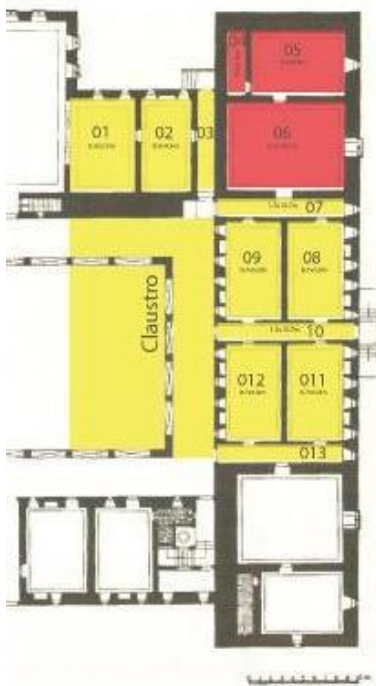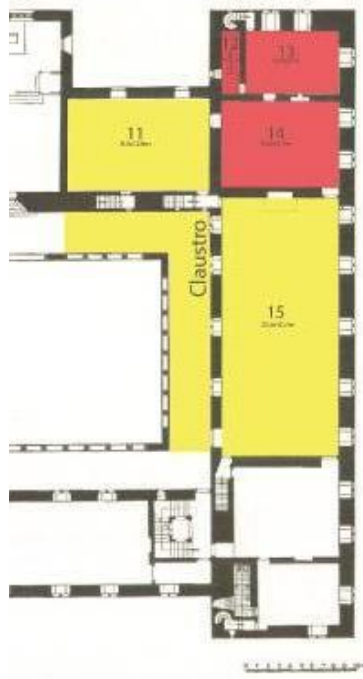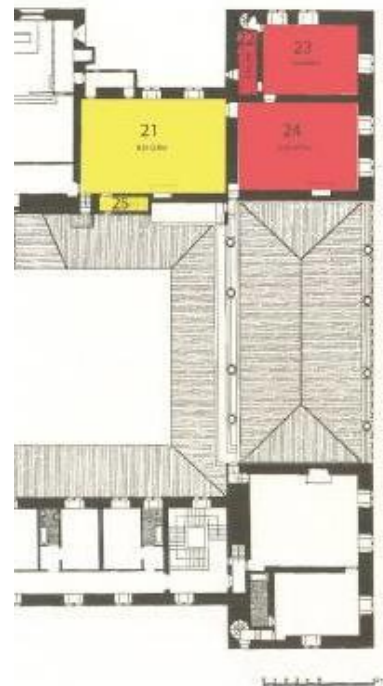
Figure 7: Plans of the Ducal Palace (South wing) adapted from [35]. Left: Ground floor. Middle: First floor. Right: Second floor.
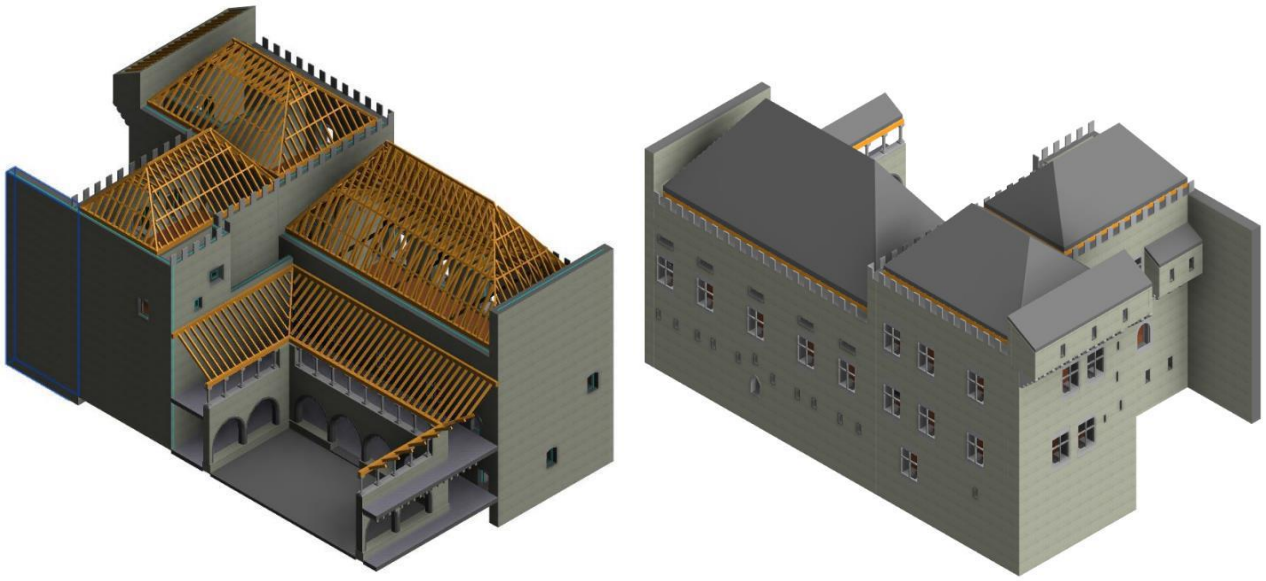
Figure 8: Global isometric view of the BIM model, with a detail of the timber roofs.
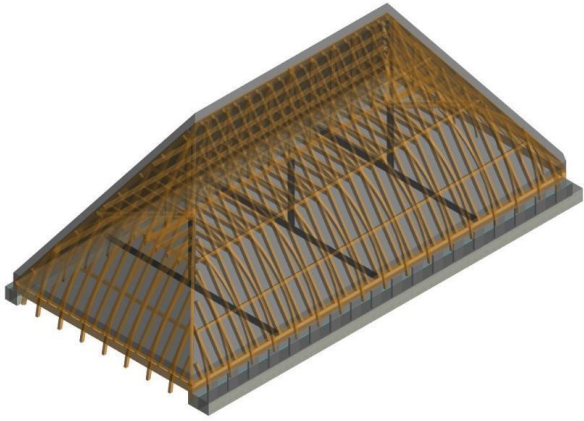
(a)
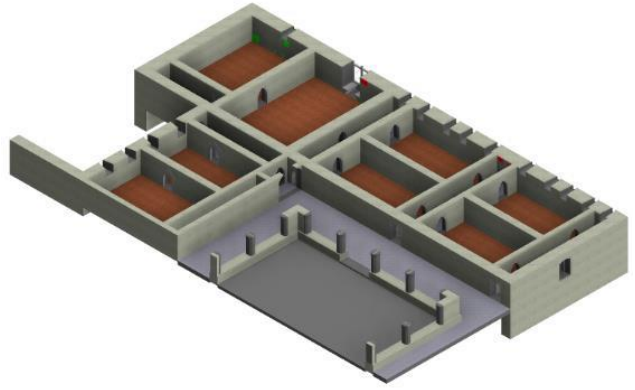
(b)
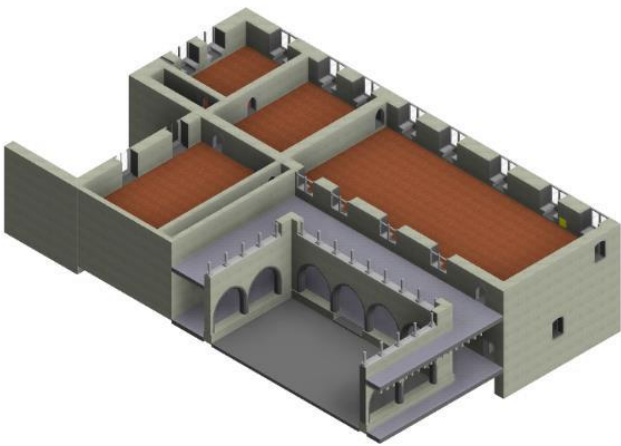
(c)
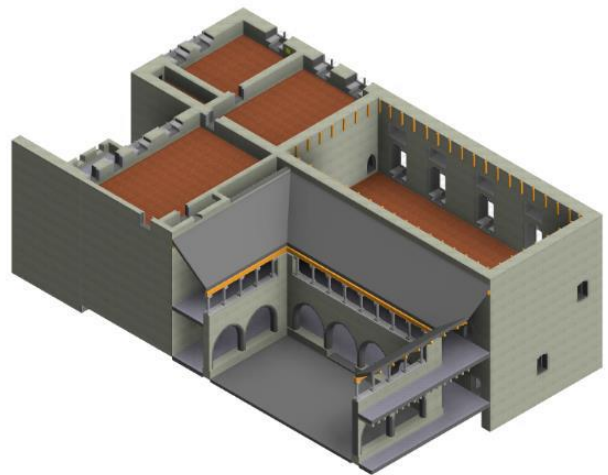
(d)

Figure 9: BIM model isometric view: (a) Timber roof; (b) Horizontal cut ground floor; (c) Horizontal cut first floor; (d) Horizontal cut second floor.
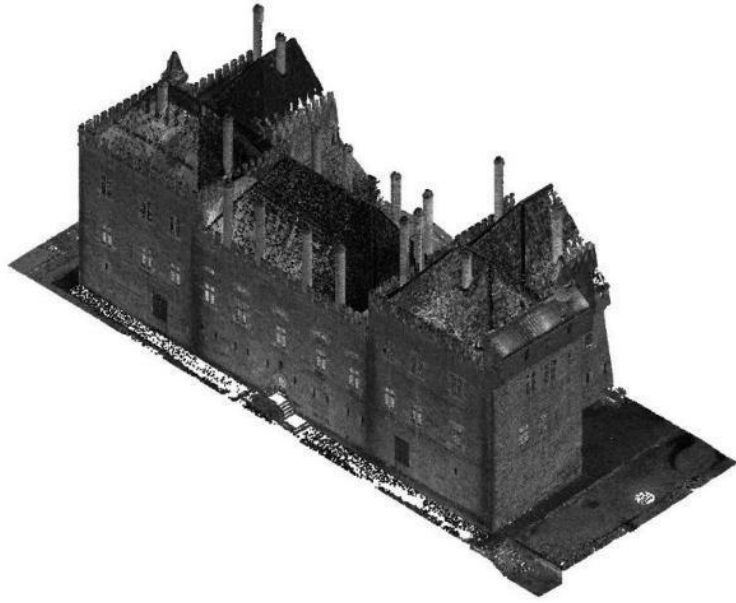
(a)

(b)

Figure 10: Point cloud of the Ducal Palace (South wing): (a) South-West elevation; (b) Horizontal section compared to the BIM model.

<div align="center">

(a)   *(b)*

Figure 11: BIM Model and point cloud overlapping: (a) cloister; (b) outer wall.

</div>

Figure 12: Illustration of an inspection form for the anomaly with ID 6502132 placed on the element with ID 6306313, zoom on the section dedicated to the anomaly survey.
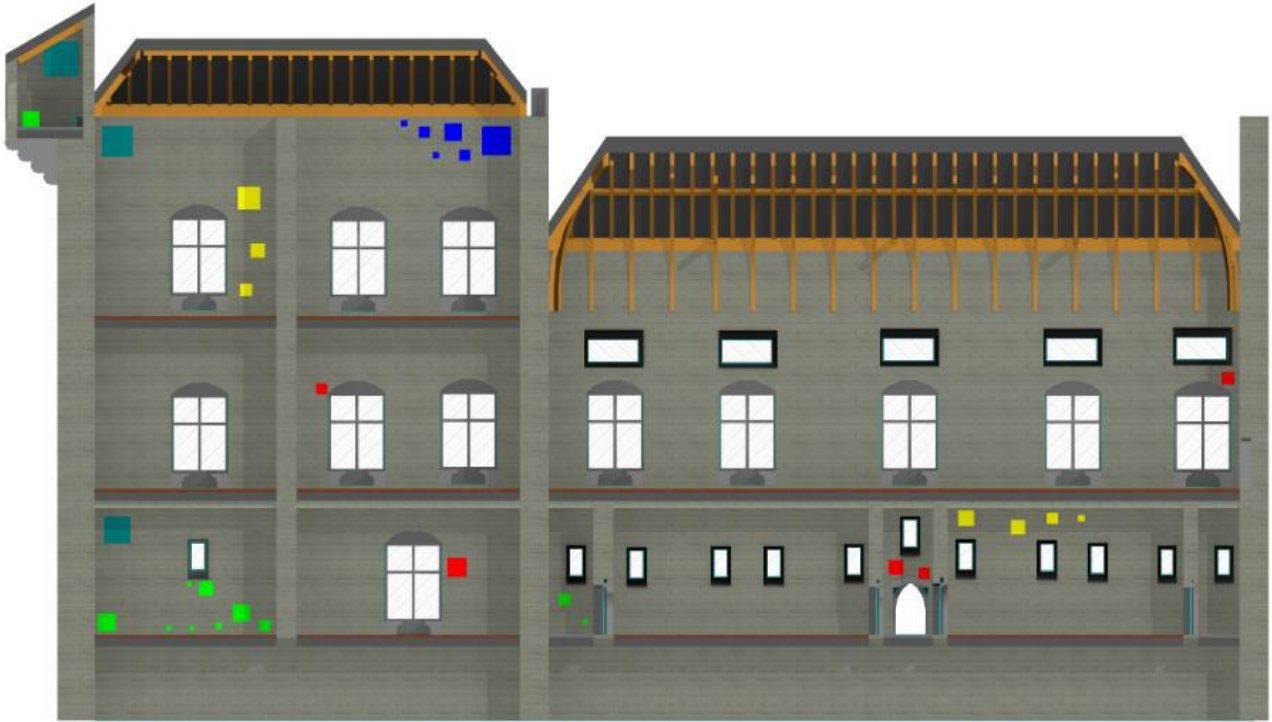
Figure 13: Illustration of a damage survey in the South wing.

Figure Captions

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