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HBIM application in historical timber structures: a systematic review

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Abstract

Despite the recent significant increase on the use of Building Information Modelling (BIM) in the cultural heritage field, its application on heritage timber structures aiming at their conservation and assessment has not yet been fully established. Comparing with other construction materials, timber presents singular features which must be addressed in order to carry out a proper condition assessment. For this reason, this review summarizes existing works on historical timber structures using Historical BIM (HBIM), focusing not only on various geometric surveying and 3D modelling methods, but also on non-geometric information included in the model which are especially related with conservation, testing and monitoring. In addition, this work illustrates the effectiveness increase given by a structural analysis, as to assess structural heath, after being implemented within a HBIM based framework. To that aim, a global framework is proposed where the development and implementation level of different analysis stages are described.

Keywords: HBIM; timber structures; conservation; point clouds; structural health; 3D modelling

1. Introduction

Timber as construction material has been extensively used throughout history in a wide range of structures. Nevertheless, as a biodegradable material it is vulnerable to decay caused by both abiotic agents (e.g. sun, wind, moisture variations) and biotic agents (e.g. fungi, xylophagous insects), which can compromise the structural performance of the elements (Cabaleiro et al. [18]). Furthermore, it is not atypical that older timber structures have irregular cross-sections in terms of geometry, which can be caused either by decay or by the techniques used in their construction (Lourenço et al. [52]). Due to this, it is highly important to use tools which allow to accurately collect information on the structural health and geometry information as to make a proper assessment of these type of constructions.

In recent years, BIM (Building Information Modelling) has been introduced as a new process in the architecture, engineering and construction (AEC) industry. BIM allows to create 3D models from parametric elements, often called as "smart-objects", which contain geometric, physical and functional properties of the object (Azhar et al. [6]). In addition, using non-proprietary standards like IFC (Industry Foundation Class) enhance data exchange between different BIM systems on object level minimizing information loss (Volk et al. [78]). Nevertheless, BIM main applications are found for design and management of new buildings and structures.

BIM has also been recently applied to cultural heritage buildings. HBIM (Historical Building Information Modelling) offers several advantages in directly obtaining two-dimensional drawings and in the management of a large amount of data concerning each shape (Quattrini et al. [68]). However, as BIM was originally conceived for architectural design, parametric objects are not suitable for modelling of existing historical architectural elements due to their high level of irregularity and unique shapes. Furthermore, because of the nature of most of the available data format for 3D encoding, which is not suitable for the necessary portability required by 3D information across different systems, storage, portability and interoperability, issues among architects and cultural heritage actors dealing with 3D technologies remain a huge challenge (Felicetti et al. [32], Quattrini et al [69]). Another problem is the lack of available complex historical elements currently in BIM libraries (Dore et al) [31]. In order to solve this problem, some studies created libraries with historical elements such as that described in Baik et al. [7] where Arabian architectural elements were included. Nevertheless, it must be noted that HBIM is not limited to the geometry aspect of the parametric objects, but actually is of extreme importance for the data enrichment of an element. Information about through different sources can be attributed to the elements allowing for a much more holistic comprehension of the structure itself.

Taking into consideration the need to further develop the use of HBIM for existing timber structures, the objective of this review is to analyse the processes and needed information to create a HBIM model enriched with geometric and non-geometric multidisciplinary data, focusing on cultural heritage conservation. This work will present the state-of-the-art surveying techniques and methods used for existing timber buildings. It will also explain how this information is used to create as-built 3D models, not only for visualizing but also for its structural analysis. Thus, the current literature will be reviewed accounting where progress has been made to accelerate and automate the as-built modelling in software HBIM using surveying data acquired from tools as laser scanner or photogrammetry, to model old timber constructions (Bassier et al. [12], Masssafra et al. [54]).

The methodological structure used for this review is based on the phases of the inspection and intervention framework proposed in Cruz et al. [26], which shows the steps required for the assessment of an historical timber structure and the planning and execution of required interventions (Figure 1). The phases of this framework were divided in: (i) preliminary assessment; (ii) structural analysis and detailed assessment; (iii) assessment results and future actions. To each of these phases, the information related to the development of a HBIM model are given in parallel to evidence where each HBIM stage may retrieve information from a normal inspection and intervention procedure of an existing timber structures. In order to do this, the framework has been adapted for the creation of a HBIM model, divided in several phases, which will be explained in each section of this review. With this it is aimed to provide more information and tools that will allow that the obtained information is implemented in a HBIM analysis as to optimize the structural assessment of existing timber structures.

The first three parts of this work will address different kinds of existing information which can be embedded in HBIM, and can be divided in: (i) general information of the construction, where relevant data of the construction (architectonic and historical information, plans, photograph, among others) will be included without considering neither geometrical or structural health information; (ii) structural health information acquisition, where it will be explored the most commonly used NDT (Non-Destructive Testing) tools, along with visual inspection, for structural health assessment of timber structures, highlighting the kind of information that can be obtained from them; (iii) geometric information acquisition, which will focus on the most used surveying techniques in cultural heritage, mainly photogrammetry and laser scanner; the next point is (iv) HBIM model, which will cover the 3D model creation, along with the introduction of the rest of the non-geometric data in HBIM environment, pointing out the latest advances and measures taken in literature for the information management and organization. After the realization of the HBIM model the next section, (v) structural analysis, will explain how the FEM (Finite Element Method) analysis inclusion in a HBIM environment would improve the structural health assessment and conservation actions. In addition, (vi) preventive conservation will deepen into how all information stored in BIM is used so as to make a correct diagnosis and a proper maintenance plan. Finally, it will explain the interrelationship between all the points of this process (Figure 1).

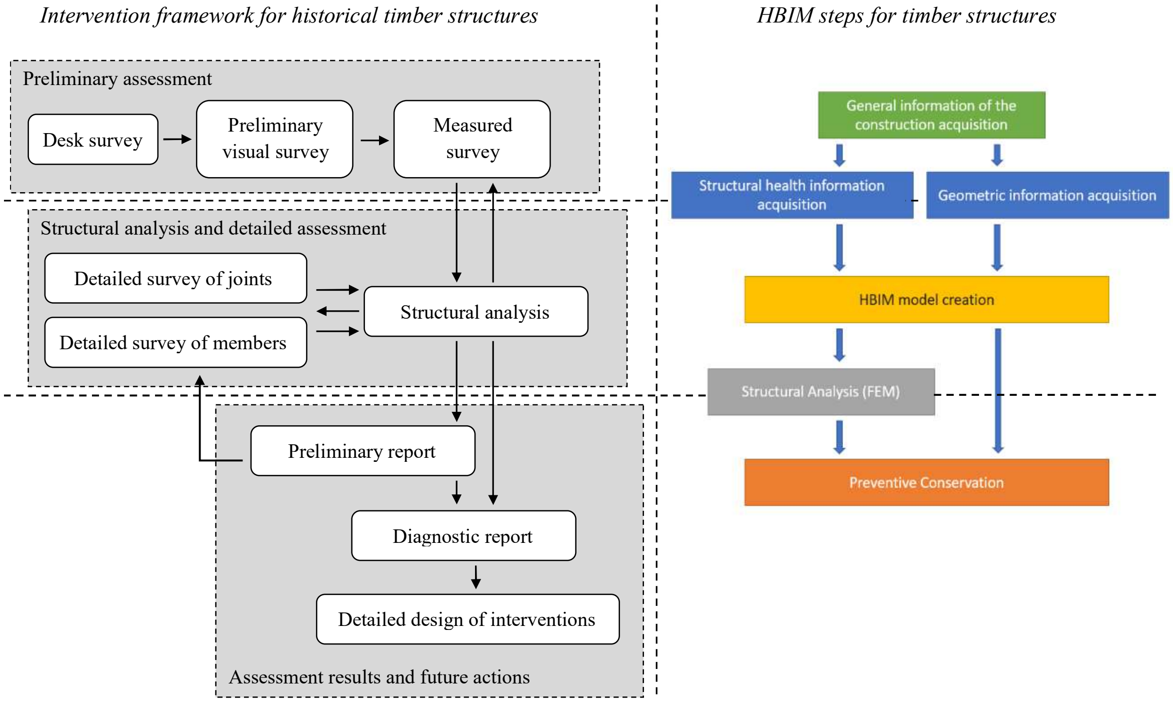


Figure 1: Steps required for the assessment and planning of interventions in historical timber structures, adapted from Cruz et al. [26] (left side) and interaction with a HBIM framework oriented to the assessment and conservation of timber structures (right side).

2. General information of the construction

Data enrichment represents the crucial part of any HBIM model, as it is intended to be more as a data collector rather than a geometrical representation (Quattrini et al. [69]). In this scenario, an important step to multidisciplinary documentation is the incorporation of historical and architectonic files which can contribute to the structural assessment. A historical research can provide information about changes and interventions the structure has been subjected throughout time, which allows to better know the methods and techniques used in the construction and its current condition (Tsilimantou et al. [77], Balletti et al. [8]). For example, in Balletti et al. [8] drawings and historical representations of a timber dome structure were acquired and added to the model. Furthermore, in Tsilimantou et al. [77] the documentation research of a historical Greek villa provided information about the different expansions that were carried out in the building. These expansions did not follow the same construction process, which led to changes through time due to different vulnerability of the structure to degradation.

General information of the construction may be obtained from different sources (e.g. historical records, interviews with local people and authorities, among others) and can be collected in the form of text, plans, sketches, photographs, spreadsheets or others (Previtali et al. [67], Sztwiertnia et al. [75], Cheng et al. [24]). This information is quite diverse and ranges from material characterization, constructive methods, descriptions or year of construction of renovation.

Although significant efforts have been made to collect and store documentation about the general information of heritage timber structures, there is still a lack of proper data treatment to enrich a HBIM framework, especially accounting for the safety assessment of the structure. For timber structures, most historical data is still being used only to address modifications and changes that occurred during the lifespan of the structure, but still it is needed to treat that information in a way that it is useable for a proper management planning.

3. Structural health information acquisition

Attending to its long lifetime, historical structures are vulnerable to decay agents, especially when they have not been subjected to a proper maintenance, thus compromising its structural health. With regard to timber structures, they are affected by numerous pathological agents. These can be abiotic agents (e.g. solar radiation, wind exposure, moisture content or external damage) or biotic agents (e.g. fungi action, xylophagous insects), and its long-time presence can decrease the cross-section area of structural elements, and affect to the construction performance (Cabaleiro et al. [18]). For this reason, non-destructive tests (NDT) and semi-destructive tests (SDT) are used to assess in-situ the internal and external structural health condition of the elements without damaging them (Kasal et al. [43] Cabaleiro et al. [18]).

NDT and SDT for timber elements may provide both quantitative and qualitative data that will improve the structural assessment and allow for a better decision making process when managing the intervention and maintenance of these structures. In that perspective, there is an increase in research for including quantitative data within a HBIM framework, mainly related to changes in geometry (e.g. definition of residual cross-sections) and to material properties derived from the results of the tests. On the other hand, the use of qualitative data, (e.g. damage maps, comparison between elements) is not so straightforward and requires still a phase of pre-processing of information. In both cases, information should be compiled and made available for all the agents involved the assessment of the timber structure. This information should preferably be given in both raw and processed data versions, allowing to each agent to make their own analysis aiming at their own objective, or just to use the results as provided. Moreover, due to the large variability found when using NDT and SDT on timber elements, the results must be carefully analysed as they will greatly influence the HBIM model and posterior decisions made regarding interventions on the structure. The inclusion of raw data, will therefore allow the user to verify if the uncertainty and variability related to the test is adequate for the analysis. Although several efforts have been made for including the information of NDT and SDT in HBIM frameworks of timber structures, the interoperability between databases and their use in structural assessment is still in an initially phase.

This section will address the most commonly used NDT and SDT for timber elements, highlighting the kind of information which can be obtained from them so it can be later introduced in a HBIM framework.

3.1. Visual Inspection

Visual inspection for timber structures allows to identify not only damages related with degradation, as cracks, external decay, deformation, biological attack or natural defects (knots, grain misalignment), but also damages related with the techniques used in the construction or renovation. For example, the work of Stepinac et al. [74] allowed to detect large extent damages in some of the column assemblies due to water flow or accumulation in those areas. Visual inspection is also used as to grade timber structural elements based on natural defect detection, estimating its mechanical properties with a certain degree of uncertainty, which also depends on operator experience (Cruz et al. [26], Branco et al. [15]).

Elements' conservation state provides information of the structure that can be stored in tables or spreadsheets, enumerating each one of the elements, in addition to adding drawings, photographs and diagrams which allows to visualize and locate the defects, damages and decay of the study case (Riggio et al. [70]). This information can be gathered in damage maps for a better visualization of the location, extent and type of damages (Figure 2). For instance, in Jiao et al [41] photographs are made to the most significant defects of the structure.

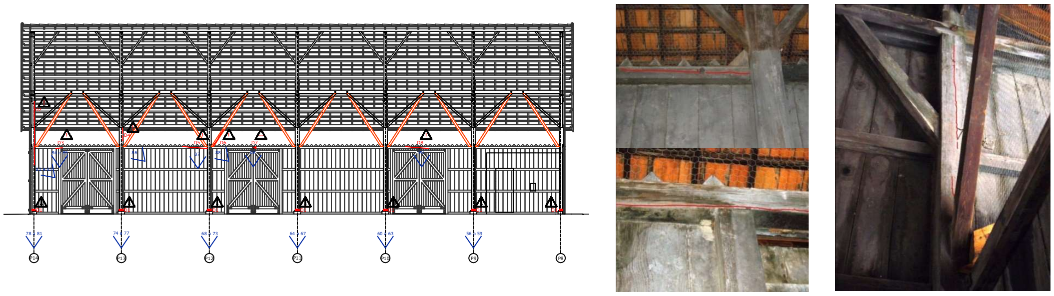

a) b)

Figure 2: Visual inspection of a timber warehouse: a) damage map; b) photographic record of damages.

Results from the visual inspection of timber structures can be introduced in a HBIM model by incorporating that data into information fields of parametric models, such as indicating the specific visual grade for each element, or by including patch elements that describe the type, extent and severity of a given defect or damage [11]. In this way, also the alphanumerical data of the patch-type objects may provide information on the classification of the damage/defect (according to specific standards or guidelines) and the identification of causes, consequences and even an indication of state risk based on the exposure of the element and consequences of its failure.

3.2. Moisture content measurements

Moisture content is one of the most influent factors affecting wood properties like strength, stiffness, and size variations in addition to contributing to biotic attack appearance. Moreover, different values of moisture content may influence and compromise the validity of the results obtained from NDT and SDT (Kasal et al [43]). In Frontini et al. [34], the moisture content of each element was measured in the assessment of a historical timber structure, revealing a higher content of humidity in areas closer to the floors. In data collection, apart from moisture content, it should be identified each one of the elements, in what part of it was made the measurement, along with the depth of the measurement (Figure 3). For example, in Riggio et al. [70] the measurements positions were represented and the results were stored in the form of a table. Information gathered through this technique can be stored within a variable of a parametric element together with information of the date and specific location of the test. Moreover, moisture content test results can be used as indication for the vulnerability and probable exposure to biotic attack. Therefore, a HBIM model may use these values within a management system by setting thresholds limits.

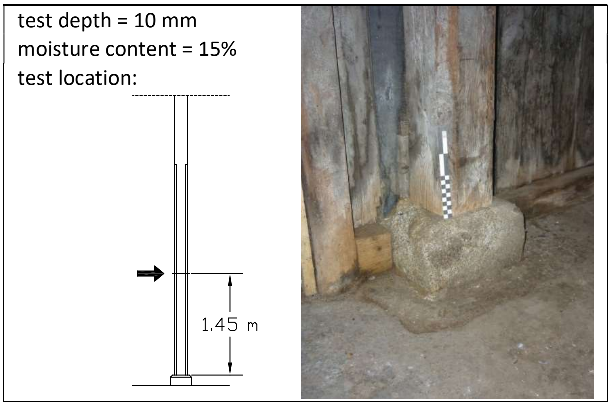


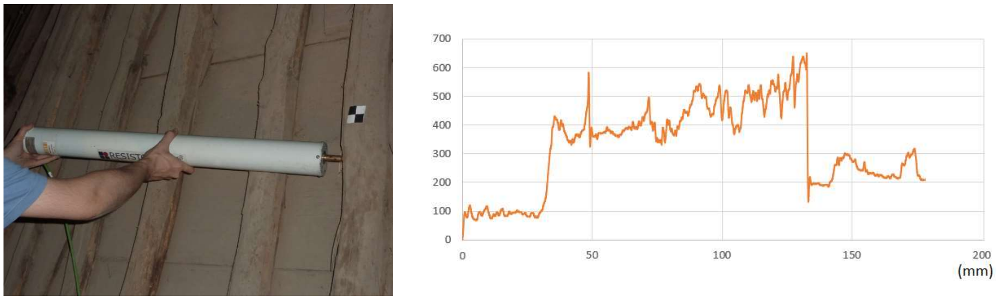
Figure 3: Example of a moisture content measurement to a timber column with description of location.

3.3. Drilling resistance tests

Drilling resistance tests (Figure 4) are a technic which allows to analyse the material condition, both in its surface layers and in its interior. In this method a drill is driven into the material at a constant speed and feed rate, recording the energy needed for it to proceed, which depends on several factors such as density or decay presence (Kasal et al. [43]). From the results, a graph is obtained which records the torque energy required to maintain the constant cutting speed with respect to the penetration depth. From this diagram a RM parameter may be obtained which is the ratio between the integral of the area of the drill diagram and the height of the test specimen h (Kasal et al. [43]).

$$RM = \frac{\int_0^l Area}{l} \tag{1}$$

The drilling resistance test permits to know the decay depth, and in works as Branco et al. [15], Cabaleiro et al. [18], Mol et al [55], it is used to reconstruct the resistant cross-section, representing the part of the section which is effectively supporting the load demand. In Cabaleiro et al. [18] the resistance drill results are used to obtain part of the section geometry which is not visible or accessible by other measuring tools. Finally, in order to store the results, besides their numerical value it is of big importance to indicate the element and the position of all made tests. The information of drilling resistance tests may be stored within the element using an uniform resource locator (URL) link, which leads to a database, as to access the raw data or pre-analysed data [55], or by assuming a parametric model based on the geometry of the apparent and of the resistant cross-section [73].



a) b)

Figure 4. Example of a drilling resistance test: a) onsite test; b) drilling resistance profile.

3.4. Stress wave

The use of stress waves in non-destructive testing is based on the propagation of sound waves through a given material, being able to analyse parameters such as velocity, time of flight or frequencies. It is widely used for detecting interior voids and deterioration in structural members, as well as for mechanical property measurement. Stress wave analysis can effectively measure modulus of elasticity. Nevertheless, it requires to know the density material beforehand (Kasal et al. [43]). In Lechner et al. [46] in the study of two historical timber floors, this method showed decay presence inside the support area of one of them.

In the same way as previous NDT, it is important to store the position of the measurement along with the element which has been measured. That information may be stored within the input variables of a parametric object considering the velocity or time of flight of the measurement together with the location of the test.

3.5. Pin penetration test

The pin penetration test procedure is based on the release of a spring, which transforms the elastic potential energy into impact energy. This way the penetration of a metallic needle can be measured and the depth is inversely proportional to the density of the wood, being as well a useful method to identify superficial decay on the element (Lourenço et al. [51], Branco et al. [15]). Henriques et al. [36] used this technic to assess the effectiveness of a conservation process applied to a timber structure in a historical palace. Measurements were taken before and after the intervention and a higher average value was found after the intervention process. The results of pin penetration tests may also be used to locate segments of a timber element that may present higher decay levels, allowing for a qualitative comparison between segments and elements of a timber structure (Figure 5). Due to localized nature of this test, indication of its measurement location is important and must be considered in the HBIM model. The results from the pin penetration tests may be included in a dataset linked to the HBIM model by an URL or by use of an input variable on the parametric object.

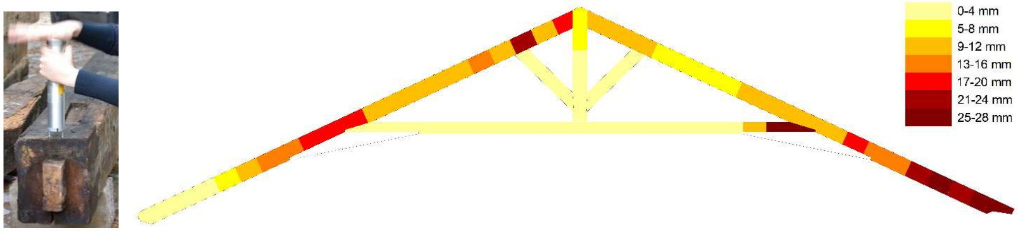


Figure 5: Example of a pin penetration test and mapping of a structure by penetration depth.

3.6. Other methods

Between other less used methods is radiography, from which it can be obtained an image of the internal structure of the object. Lechner et al. [46] used this technic to obtain quantitative density values of the objects subjected to analysis and determinate the current condition of the structural details. The images acquired by this method can be stored digitally through software and digital devices, (Kasal et al. [43]). Other relevant method is thermography, which allows to locate areas with humidity apart from being able to detect cracks and defects on the elements surface (Ludwig et al. [53]). Finally with thermal vision systems it is possible to take photographs that show the temperature variation in elements (Riggio et al. [70]).

4. Geometric information acquisition

As previously noted, historical constructions usually have elements with a wide range of shapes and irregularity in their geometry. This can be observed in numerous historical timber structures, as seen in Lourenço et al. ([52]) where coefficients of variation for cross-section geometry varied between 10% to 40% due to the techniques used in the original construction or external decay presence. Therefore, timber structures can present irregular cross-sections that vary significantly along the length of the element. Because of this, in the cultural heritage field, it is frequent to use tools that allow to obtain the geometry information of the structure in an accurate and rapid way without direct contact. The geometric survey outcomes, usually point of clouds, can be used to create 3D models in HBIM software, and even provide information for a structural analysis (Massafra et al [54], Barazzetti et al [10]). The more frequently used methods are photogrammetry, laser scanner and other topographic methods, which will be further detailed in this work. The amount of information obtained from photogrammetry and laser scanner techniques is often depending on the available resources, both in terms of equipment as well as time. In many case, the combination of both are used in a complementary way depending on the object in characterization. For instance, laser scanner provides more precise data with easier processing automation for the geometric dimensions of the structures, but less detail and data regarding the state of conservation. On the other hand, photogrammetry provides less detail and harder data treatment for geometric measurements, but provides much more data on the state of conservation of the structure. In addition, photogrammetry can also be applied in combination with UAV technology, which allows rapid surveying in areas that are difficult to access with the laser scanner. Regarding topographic methods, currently they are only used as a complementary means to photogrammetry and laser scanner for an easier and more precise registration of the different obtained data. In all these techniques, the great challenge is how to solve the acquisition of data that is hidden from the view of the equipment. For the application of these techniques in the HBIM Model, the information provided by laser scanning is usually the main source of data for 3D geometric modelling, but then the information provided by photogrammetry is one of the main sources of data for registration and subsequent evaluation of the state of conservation. According to the mentioned references, for timber structures, the use of geometric information obtained by these methods are mainly included in the initial steps of a HBIM framework as to assess the apparent section and geometry of the elements. However, the value of this information could be increased if considered for a long term management of the structure. A recent increase is noted on research to obtain geometrical surveys in different time periods, allowing to extend the regular structural assessment to management of interventions and maintenance planning. Moreover, the possibility of combining the information obtained by geometric data with other sources of data is gaining interest both within the research area, as well as for structure managers that have to deal with the preservation of that asset.

4.1. Photogrammetry

Photogrammetry is a technic from which it can be obtained accurate measurements and 3D geometric information using photographs. It is based on a triangulation method (López et al. [50], Beraldin et al [13]) and orthographic images, point of clouds and even surfaces with texture can be acquired from it (Arias et al. [4] Andrews et al. [2]). Photogrammetry proves to be a suitable method to determinate the irregular cross-section geometry in timber structures, allowing to obtain accurate 3D models of these structures, with a considerable low cost (Armesto et al. [5]).

A new photogrammetric method called SfM (Structure from Motion), is currently used in the cultural heritage area, giving accurate results. With this technic Andrews et al. [2] obtained clouds of points and orthographic images with high precision for the exterior facades of a XV century timber barn.

In addition, photogrammetry is used as well with UAV (Unmanned Aerial Vehicle) technology, allowing a fast surveying in areas of difficult access. In Jeong et al. [40] a UAV equipped with a high definition camera was used in traditional timber building surveying with good results.

4.2. Laser scanner

Laser scanner is a tool that allows surveying geometry without direct contact provided the element is within the range of vision of the scanner. In Balleti et al. [8], laser scanner was used to acquire geometric information of a complex shape timber structure in a relative short period of time and with high precision. Also in the works of Cabaleiro et al [19,20], irregular timber beams and trusses were modelled using laser scanner information. There are several types of laser scanner depending on the method they use to take measurements, such as by triangulation, time-of-flight or phase (Dawson et al. [28], López et al. [50]), having different advantages depending on the surveying needs. In Dawson et al. [28] two types of laser scanner are used for a timber shelter located in the Artic, whereas Wilson et al. [79] used time of flight and phase in a library surveying after a fire, attending to the needs of each case study.

From the laser scanner survey, a cloud of points is obtained which can contain coordinate information (X, Y, Z coordinates) (Figure 6), intensity of the return signal and RGB colour values. The RGB values can be acquired by some laser scanner models, but also by photogrammetry data (Wilson et al. [79] Dawson et al. [28]). After acquiring the clouds of points, it is needed to align the data in a common coordinate system using a process called registration. In that process, the user (automatically or manually) will pinpoint the position of specialized targets that were used to identify specific locations (Tang et al. [76]).


a) b)

Figure 6: Laser scanner used for timber structures: a) example of a cloud of points; b) example of a laser scanner scanning a timber roof.

Nevertheless, laser scanner is only able to collect data from the visible faces of the elements. In Cabaleiro et al. [18] to solve this problem, a method was proposed to obtain the cross-section of beams with any of its faces hidden combining the results of the laser scanner and drilling resistance tests. Also, according to the works of Cabaleiro et al. [21] it was possible to model and analyse burned beams by combining data from laser scanner surveys and drilling resistance tests.

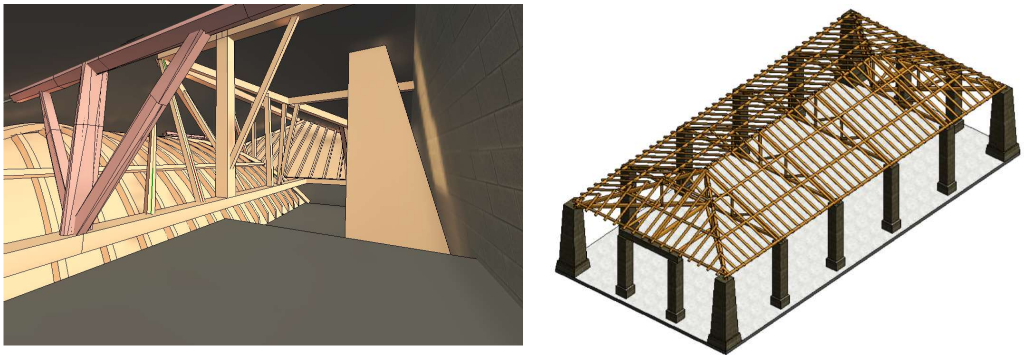
4.3 Topographic methods

It is also common the integration of topographic methods in photogrammetry and laser scanner (Armesto et al. [5], Pocobelli et al. [63]) where by topographic tools, such as a total station, the surveyed elements are geo-located. In Andrews et al. [2] along with the scanning made by laser scanner, a total station was used to aid in the location registration. Also, in Armesto et al. [5] a total station was used as topographic support, measuring the 3D coordinates of the control points in order to level the model in space and to assist on the scale drawing.

5. HBIM model

5.1. 3D modelling

Creating a 3D model allows for different types of analysis and uses related to the assessment of cultural heritage structures. Firstly, it facilitates the structure visualization allowing to view, in an easy way, complex structures from any angle (Figure 7), and hide or show the elements depending on the study needs. For instance, in Perria et al. [59] a pagoda roof of a castle was modelled, allowing to view clearly the changes on the missing beams of the structure. Another advantage of modelling is to aid in the assessment process, being able to be used later in a structural analysis (Perria et al. [59], Yang et al. [80], Bassier et al. [12]). On the other hand, it helps in the information preservation and diffusion regarding the construction, in addition to being a support for future investigations. In Koehl et al. [44] a model of a historical timber structure roof was done so as it can be showed to the public, manipulated and viewed from any angle.



a) b)

Figure 7: 3D modelling of historical timber roofs: a) Former Town Hall (Guimarães, Portugal); b) ‘‘El Lavadero del Arenteiro” (Ourense, Spain)

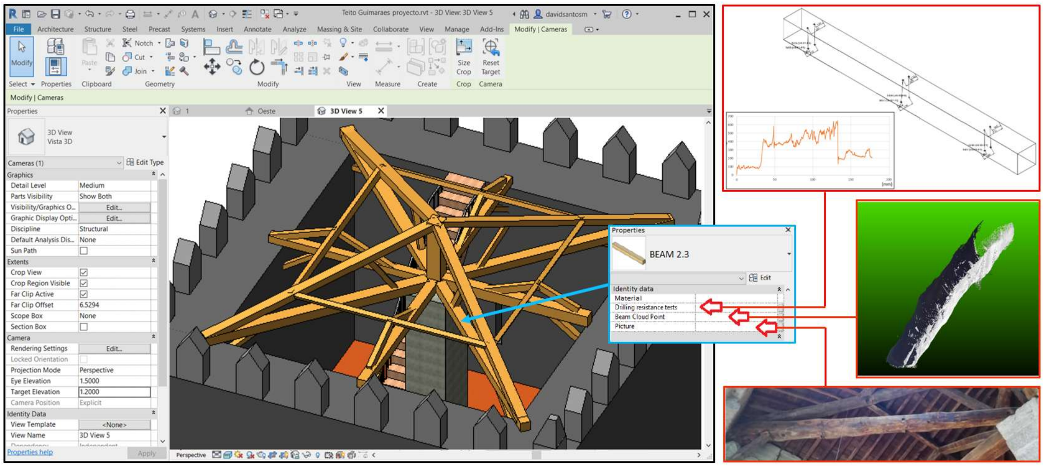
Due to the geometric complexity that historical timber structures usually have, modelling them in a 3D modelling software is laborious and time-consuming. For instance, in Balletti et al. [9], creating a 3D model of a highly complex timber structure, without applying geometric simplifications translated into several months of work. For this reason, some studies in the cultural heritage field, and in the historical timber structures area (Pöchtrager et al. [61] y Yang et al. [80]) have aimed at increasing the automation in the modelling process, accelerating and reducing costs of its elaboration. In Pöchtrager et al. [62] a method was developed with the objective of reconstructing historical timber roof structures, managing to reach a high automation level. In the process the cloud of points is divided in segments, from which are created cuboids with every segment belonging to the same beam. However, this makes the process not suitable for highly irregular structures.

Modelling tools in the existing platforms perform very simple operations that are not always sufficient to geometrically describe the complexity of the real object (Quattrini et al. [69]), for that reason some works have developed new methods to accelerate modelling in a BIM software with higher precision. For example, in Bassier et al. [12], in the analysis of a historical timber roof, the add-in ScanTo3D was used in order to generate parametric elements from cloud of points meshes. In other works, such as Yang et al [80] and Massafra et al. [54], the modelling process is automated. In Yang et al. [80] through a plug-in developed in the API (Application Program Interface) a timber historical roof is directly modelled in a BIM environment from points obtained by a total station. In Prati et al. [66] and Massafra et al. [54] Grasshopper® generative algorithms are used to model old timber trusses with great precision. Later a BIM model composed of rectangular cross-sections is created applying the Grasshopper® algorithms. On the other hand, in Liu et al. [48] a method is developed to automatically model elements belonging to historical Chinese structures, according to the required level of detail.

The mentioned works reveal that significant efforts are being made on the automation of processes for 3D modelling of timber structures within a HBIM framework. However, the main scope of the automation still remains within the definition of the geometry of individual elements. Moreover, consideration of the variability of geometry along the length of each element is still an issue when converting the model to a structural assessment.

5.2. Information inclusion

Creating a BIM parametric 3D model means that every modelled object is linked to a table/spreadsheet, where its parameters and characteristics are displayed (Pocobelli et al [63]). This applied to cultural heritage can be of big usefulness to store all kind of required information to the assessment and conservation of historical buildings (Figure 8), aiding in the data management and analysis (Quattrini et al. [69], Tsilimantou et al. [77]). The kind of data that can be embedded in the HBIM model has been divided in: (i) general information of the construction, (ii) structural health information, and (iii) geometric information. In this section, the works that have introduced some kind of non-geometric information in the model related to these points will also be addressed.



Properties

3D View
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Graphics
Detail Level: Medium
Parts Visibility: Show Both
Visibility/Graphics O...: Edit...
Graphic Display Opti...: Edit...
Discipline: Structural
Default Analysis Dis...: None
Sun Path: ☐

Extents
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Crop Region Visible: ☑
Far Clip Active: ☑
Far Clip Offset: 6.5294
Scope Box: None
Section Box: ☐

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Locked Orientation: ☐
Projection Mode: Perspective
Eye Elevation: 1.5000
Target Elevation: 1.2000
Camera Position: Explicit

Identity Data
View Template: <None>
View Name: 3D View 5

Properties help Apply

Properties

BEAM 2.3

Edit

Identity data
Material
Drilling resistance tests
Beam Cloud Point
Picture

Figure 8. Example of the data linked to a timber beam in a model HBIM including cloud of points, photographic record and drilling resistance tests of the beam.

In Sztwiertnia et al. [75] information regarding date, material, elements' author are inserted, in addition to descriptive information of the most important objects. In order to reflect the state of decay, it is usual to take photographs, which in Han et al. [35] are added into the BIM model. In other works, the different parts of the structure are divided according to the material characteristics and the state of deterioration (Brumana et al. [16], Barazzetti et al. [10], Donato et al. [29]), and even to its historical origin (Angulo-Fornos et al [3]). In Pocobelli et al. [64] and Barazzetti et al. [10] information acquired by NDT is inserted in the model to define the material characteristics (Barazzetti et al. [10]) and moisture concentration (Pocobelli et al [64]).

Currently, BIM software are not prepared to manage and share the usually complex and heterogeneous data related with cultural heritage. To solve this problem, in works as Quattrini et al. [69], Previtali et al. [67] it is suggested to use semantic webs so the BIM models can be linked with external information from other ecosystems, collecting the data using ontologies, being able to query data for different purposes (Costa et al. [25]). In other works, such as Tsilimantou et al. [77] and Dore et al [30], software BIM is combined with GIS platforms offering new opportunities to analyse, document and manage data related with conservation. For example, in Tsilimantou et al. [77] the GIS platform is used to make maps of the structure depicting the state of decay.

Specifically, in the timber structure field, Cheng et al. [24] developed an ontological model where it is included information for the conservation, as materials, constructive methods and previous interventions, oriented to the study of a Taiwanese structure. On the other hand, in Mol et al. [55] the results from NDTs, like drilling resistance tests, are implemented in the model for the study of two historical timber roofs. Finally, it is necessary to point out that despite NDT are broadly used in the assessment of structural condition in timber structures, there are few studies that introduce their results in a HBIM environment.

6 Structural analysis

Being a valuable tool with regard to structural health assessment of constructions, the structural analysis by finite elements method (FEM) may be used for cultural heritage in order to determine the impact that deterioration and modifications had in the structure throughout time (Figure 9). Due to the geometric complexity of historical buildings, it is necessary to establish a proper level of detail in the 3D model creation so that the analysis provides accurate results (Bassier et al. [12], Barazzetti et al. [10], Hermida et al. [37]).

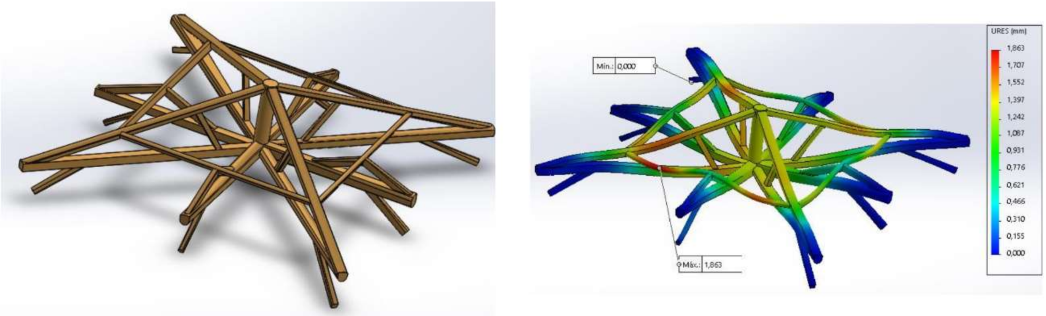

Figure 9. Structural analysis of the timber roof of the Guimarães Castle (Portugal).

In the historical timber structures field, some works have carried out the structural analysis to check the effectiveness of past interventions, such was done in Bertolini-Cestari et al. [14] in order to evaluate interventions done 30 years before in a timber structure of a castle. On the other hand, the structural analysis can also be performed to assess the effectiveness of future interventions (Longarini et al. [49], Li et al. [47]). For example, in Li et al. [47] the structural analysis was done to support a restoration process in a leaning Chinese structure.

In other cases such as Kujawa et al. [45], the structural analysis was carried out to identify the possible causes of defects, in this case crack appearance and walls damage in a masonry church. In the analysis the corresponding timber roof structure of the church was also calculated, introducing the properties of the material obtained from tests carried out in laboratory conditions.

The structural analysis FEM also proved to be a useful tool to evaluate the performance of historical structures under seismic actions. In the timber structures field, Longarini et al. [49] used numerical analysis to validate the effectiveness of the reinforcements on avoiding collapse mechanisms, performing several types of linear and non-linear analysis. Whereas in Bassier et al. [12], a numerical analysis was carried out in a representative section of a timber vault severely damaged, characterizing its dynamic properties and its static linear response.

On the other hand, a method proposed in Massafra et al. [54] considered the assessment and analysis of historical timber trusses. In this work, through Grasshopper® algorithms, an ideal model of the trusses was created which reconstructs their possible structural configuration at the moment of its construction, tracing their displacements and deformations the structure has suffered throughout time. Later, this model was compared with a model that reflects the real state of the structure, providing information of its current condition.

Inside a BIM environment, numerous researches outside the scope of timber structures have made significant advances towards the development of BIM models with a high level of detail. In some of these cases, from the models a structural analysis is carried out, offering high accurate results in order to assess the structural condition (Barazzetti et al [10], Bassier et al [12], Abbate et al. [1], Pepe et al. [58], Rolin et al. [71]). For example, in Barazzetti et al. [10] a BIM model of a castle generated by NURBS curves along with regular shapes is turned into a 3D mesh for its structural analysis. In Abbate et al. [1] the structural analysis of a concrete vault followed a similar process using NURBS curves to model the complex elements.

With regard to timber structures, in Bassier et al. [12] a method was presented to generate the geometry of historical timber roofs in a BIM environment with the built-in ScanTo3D, being used as input to carry out the structural analysis in a FEM software. Finally, in Massafra et al. [54] after the creation of a simple BIM model, formed by rectangular cross sections, and created by Grasshopper algorithms, this model could be calculated in Robot Structural Analysis® using BIM-integrated workflows to exchange data continuously with Revit®.

The current efforts made for implementation of HBIM frameworks for existing timber structures have already produced significant advances on the modelling phase regarding structural safety assessment. It is noticeable the use of HBIM for a better representation of the geometry of the structure, both at element and structure level, as well as the use of information related to the material properties. In that case, the use of that data is still very dependent on the interoperability with the safety assessment software. The reliability of the results from the structural analysis, evidenced in the mentioned works, is greatly dependent on the value of information that was included together with the analysis of its variability. A higher detail on the geometry of the elements and of the connections led to more reliable results when validating the models within the different case studies, with similar situation occurring when including data obtained from in situ tests.

7. Preventive conservation

Preventive conservation can be considered as the more efficient approach for the cultural building protection and maintenance. This strategy would allow to save between 40% and 70% of the maintenance costs, avoiding major interventions and promoting systematic inspections and inspection routines (Sánchez-Aparicio et al. [72]). In Sánchez-Aparicio et al. [72] an approach for the conservative preservation was proposed where a web-GIS is used for the introduction of information related with historical buildings, having the data collected by monitoring systems.

On the other hand, one of the characteristics of BIM is the inclusion of information related with the maintenance plan of the building. Inside the cultural heritage scope, this can be associated with the preventive conservation with the objective of preserving the cultural value of the historical assets (Castellano-Román et al. [22]). Some authors propose to use BIM to optimize the maintenance and conservation plan, for which in addition to be vital the identification of the current condition of the building, the cultural value of the historical elements and the economic factor has also a big importance in the process of making decisions (Piaia et al. [60], Jouan et al. [42]). For example, in Hull et al. [38] it was proposed to establish the necessary requirements for the data collection in a BIM environment to be used in the support of conservation repair and management activities. Whereas in Jouan et al. [42], the suggested methodology aimed at the detection of existing risks and the prediction of future risks with regard to historical buildings in order to design conservative strategies where some factors are constantly monitored through a sensor network. The information collected by sensors is introduced in the HBIM model and used to support the maintenance process and to avoid major damages. In Piaia et al. [60], an asset management tool integrated in BIM is developed that provides information to make informed decisions about how to maintain the real state of the historical elements considering the cultural value and the budget. Finally, in Pocobelli et al. [65] other kind of approach was introduced, where it was proposed to introduce in BIM information related with the prediction of degradation produced by the humidity action through Dynamo programming tool. However, its implementation has been postponed for next works.

Preventive conservation in historical constructions offers great advantages so as to conserve historical buildings, including timber structures, minimizing the damages and degradation and the maintenance costs. Furthermore, its implementation in a HBIM environment would be very beneficial due to its capacity of storing a wide range of information regarding the structure conservation, supporting the maintenance and monitoring planning. It is also worth mentioning the studies that have implemented historic data of past interventions and of the condition state of the structure, that even if in an early stage of development for timber structures, already pose as a first step towards a HBIM facility management framework.

8. Comparison of BIM implementation with other construction materials

In the same way that it has been presented in this work, BIM has been implemented for other construction materials following similar workflows. Table 1 shows and organizes the included information in the BIM model with respect to the classification established in this review, including: used BIM software, the methods used to introduce the non-geometrical data, and reference to the works that carried out a structural analysis. For comparison purposes, this table also addresses structures with other materials with the objective of analysing the level of development of BIM in the timber structures field with structures of other materials. It was found that for other materials, such as masonry, a larger number of works have been carried out mainly due to its larger presence in historical constructions. However, it is seen that all phases of research are being attended and efforts are being made towards a full assessment of timber structures using HBIM frameworks.

Table 1. Comparative HBIM related to the different stages of the review framework.

Stage of the framework	Tools and information	Material (reference works)		
		Timber	Masonry	Steel, concrete, others
General information of the construction	Texts, documents	75, 24	17, 77, 69, 67, 3, 16	29
	Architectonic information descriptions	75, 24	17, 77, 69, 67	
	Material properties and characteristics	55, 24	17, 77, 69,67, 3, 16, 10	56
	Photographs	55, 35, 24	17, 77, 69, 64	
	Historical information	24	17, 77, 69, 67, 3	
Structural health information	Degradation, deformation, defects	55, 35	17, 77, 69, 67, 3, 16	29, 56
	Destructive and NDT data	55	77, 67, 10, 64	56
	Decay mapping	35	77, 69, 3, 16, 64	29, 56
	Previous interventions	55, 24	17, 77, 69, 67, 3	
Geometry information acquisition	Photogrammetry		16, 17, 67, 3, 58	29, 1
	laser scanner	55, 75, 54, 12, 48, 57, 19, 20, 21, 73	16, 10, 17, 77, 69, 67, 64, 58, 71, 5	29, 1
Software BIM	Revit	55, 35, 54, 24	16, 10, 17, 77, 69, 67, 3, 64, 58	29, 1
	ArchiCAD	75		
Storing information method	Semantic web/Platform web	24	17, 69, 67	
	GIS platform		77	
	Introduced in the model (links, spreadsheets, databases)	75, 55,35	16, 77, 69, 67, 3, 64	29, 56
Structural analysis	Finite element model	54, 12	10, 58, 71	1

9. Conclusion

In this review it has been presented the phases for creating a multidisciplinary HBIM model, focusing on the analysis of historical timber structures. From the acquisition of the geometric information and the creation of a 3D model, to the acquisition and introduction of the general and structural health information, in addition to the execution of the structural analysis.

With regard to structural health information of timber structures, currently there is a wide range of NDT tools which allows to assess the condition of the structure in a fast way requiring the presence of qualified workers. Nevertheless, concerning the implementation of structural health data in the HBIM model there are not many works that introduce information related with the structural health in BIM, especially compared with structures of other materials. This is contradictory, as several works have been made regarding the use of NDT tools in the assessment of this type of structures accounting their vulnerability to degradation. Thus, more works are needed that address the insertion of this kind of information in a BIM environment, not only by texts and spreadsheets, but also by mapping directly in the model the decay and others parameters related with structural health like moisture content, density or mechanical properties, which can also be used for structural analysis purposes.

Regarding the geometry information acquisition, tools like laser scanner or photogrammetry have accelerated the surveying process, especially with high irregular structures, obtaining accurate results. On the other hand, in the timber structures field, progress has been made to accelerate the 3D modelling process by external tools that allow to automate it. Nevertheless, in the majority of cases, the modelling is either performed considering simple elements that compose highly regular structures to depict the geometry without losing detail, or the model is oversimplified, not respecting the defects and geometric irregularities of the structure, which can be adequate depending on the needs of the study but may also compromise the decision making process. Using BIM models to carry accurate structural analysis of timbers structures is only seen in few cases. Therefore, more study is required in the modelling techniques of this kind of structures, allowing a higher automation and level of detail, in order to develop a higher implementation of the structural analysis FEM in BIM for this type of existing structures. Although it is visible the significant advances made towards implementation of existing timber structures in a HBIM environment, most of the works focus on an individual phase of the process, either regarding data enrichment, geometrical definition or structural assessment. Therefore, the next steps will certainly require the consideration of holistic approaches that will allow for more sustained facility management and decision making process regarding the intervention, maintenance and conservation of historical timber structures.

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