Implementation and management of structural deformations into Historic Building Information Models

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Abstract

Building Information Modeling for the conservation and maintenance of architectural and cultural heritage (HBIM) is an active scientific debate nowadays. The creation of a HBIM model allows to manage the building geometry and exchanging information between the experts involved in the conservation of historic buildings. This paper fosters the creation of an as-built-HBIM containing detailed structural deformations, for which modeling processes with scarce presence in the scientific literature are required. In this sense, focusing on the Pavilion of Carlos V in the Real Alcázar (Seville, Spain), two modeling procedures are proposed to register quantitative structural deformations within the BIM environment. Also, two states of the structural HBIM Project of the Pavilion are geometrically analyzed: 1) theoretical-HBIM, without deformations, generated using measurements from documentary sources, and 2) as-built-HBIM from terrestrial laser scanning point clouds. The results of this paper show significant structural discrepancies in the geometry between both HBIM Projects.

Keywords:

Historic Building Information Modeling; Interoperability; Implementation of deformations; Management of deformations; Scan-to-BIM.

1. Introduction

The evolution of construction management models guarantees the efficiency and effectiveness in large-scale projects. The Directive 2014/24/EU of the European Parliament and the Council on public procurement requires that all public projects whose value exceeds certain thresholds will adopt Building Information Modeling (BIM) systems. As a result of these guidelines of the European Union, certain international associations emerge, whose priority is the exchange of information between software related to the construction sector. The Industry Foundation Classes (IFC) format, an open specification data format developed by International Alliance for Interoperability (IAI) and currently promoted by Building Smart International, eases the interoperability of software and the connection between operators in construction and engineering, such as in simulations and calculations. The IFC format is essential within the BIM methodology to share the information of the model with different software specific to each engineering and BIM architecture platform. This conception of the project gathers all the information necessary for its development: geometry, structures, construction systems, building services, measurements and quantities, as well as sustainability and management. In this line, the different uses of the buildings influence the application of the BIM methodology. The stakeholders such as property developers, contractors and administration, demand the level of detail (LoD) and the model definition in the design, construction, maintenance and deconstruction processes (Volk, Stengel, and Schultmann 2014).

A large part of the scientific literature on the preservation of cultural heritage acknowledges the importance of ICT to generate building models on a multidisciplinary planning basis in both the data processes and diagnosis stages. However, these projects are frequently based on mere drawings and photographs that do not cover the whole building. Undertaking the creation of a geometric model as a catalogue of cultural assets is essential in the process of the architectural restoration. Here, metadata associated with aspects of multidisciplinary planning are recorded.

Nevertheless, one of the great challenges nowadays is to solve the data handling, dispersed by the different stakeholders involved in the restoration. The processing of this information must be digitized and interconnected in order to avoid its incoherence and the duplication of efforts.

This is the stance of the International Council on Monuments and Sites (ICOMOS), although it has not specifically addressed the application of BIM technologies in conservation and safeguard projects for heritage. Notwithstanding, it is expected that this non-governmental organization whose mission is to promote the theory, methodology and technology applied to conservation, will state its position on these new technologies imposed legally on the new building sector in other countries.

2. Objectives

The main objective of this research is the implementation and management of structural deformations in BIM for the generation of a Historic Building Information Model (HBIM).

In addition, this paper quantifies these deformations and geometrically analyzes two states of the structural model of a historic building: the theoretical-HBIM model generated using documentary sources, and the as-built-HBIM through laser scanning. The model with orthogonal geometry is taken as the reference to compare the deformed model.

3. Literature review

A review of the literature on BIM applied to cultural heritage shows that it is relatively recent. Penttilä, Rajala, and Freese (2007) were the first researchers who evaluated the possibility of applying BIM to heritage buildings, and mentioned the complexity to model their facades. The work is a mere intention of a modeling project on basic software, since the parametric tools were not yet implemented. Pauwels et al. (2008) worked under the term of AIM + Virtual Heritage to propose the three-dimensional Architectural Information Modeling (AIM) for digitization and archiving processes applied to international cultural heritage. Arayici (2008) addressed the application of BIM to structures of existing buildings through terrestrial laser scanning (TLS) data capture, automated data processing and pattern recognition. An advance in information systems for heritage management appeared in the work by Murphy, McGovern and Pavia (2009). It was the new term Historic + BIM, which consisted of a new modeling system for historic structures using TLS and digital cameras. This system improved the application of the geometric language of figures creating parametric objects and creating libraries of more complex geometries based on the patterns of Vitruvius. The relevance of the research lies in the creation of 3D parametric objects of historic buildings. From here, there was an important scientific advance in information modeling systems that translates into the diversity and complexity of BIM technology, for which there are numerous software platforms (Logothetis, Delinasiou, and Stylianidis 2015). As stated in the literature review by Megahed (2015), the variety in the semantics of the construction systems shows that complexity. The appearance of five literature reviews (Fai et al. 2011; Volk et al. 2014; García et al. 2018; López et al. 2018; Logothetis et al. 2015) evidences the impact of BIM in this field of knowledge. Moreover, diverse guides or handbooks have been created, such as BIM for Heritage by Historic England (Paul Bryan et al. 2017) and BIM for Cultural Heritage, recently published in Spain (Armisén Fernández et al. 2018).

The conservation, consolidation and restoration of architectural heritage require a multidisciplinary treatment, considering the intervention from the point of view of the integrity within the cultural context to which it belongs (Lombillo and Villegas 2012). The coordination skills of the intervention team may favor the historic research, and discover structural phenomena and behaviors. The objective of the study of heritage buildings is to understand the conception, skills and construction techniques that took place in their structure, environment and the events that may have caused the damage.

From the standpoint of the structure technology, it is essential to know its geometry, physical and mechanical properties. The volumetric analysis and structural behavior assessment can verify the tensional levels caused by the actions and therefore estimate the structure lifetime, considering safety coefficients. In this line, structural behavior is particularly based on a geometric and stratigraphic exploration of interrelated elements, connecting historic hypotheses and environmental events (Oreni and Brumana 2014a).

In the field of architectural heritage, the data connection from non-destructive tests (NDT) to HBIM models has not been studied in depth. In this HBIM, the geometric modeling process includes information on the data studied by the different operators in the field of restoration. In this sense, Saisi and Gentile (2015) proposed a multidisciplinary approach based on the information obtained through visual inspection and geometric survey with environmental vibration tests (AVT) to evaluate historic buildings. This approach uses dynamic tests to evaluate the structural behavior and seismic vulnerability of Torre della Gabbia in Mantua (Italy).

Recently, Bassier, Hadjidemetriou, and Vergauwen (2016) worked on complex roof structures of heritage buildings modeled through Scan-to-BIM for structural analysis with finite elements (FEM). They developed a method to model accurate structures from 3D scanning to be used as data input in FEM. In the same line, Barazzetti et al. (2015) combined methodologies for point cloud management and BIM to apply FEM on the model. However, it is important to take into account the difficulties related to this evaluation of structural stresses in historic buildings (Roca et al. 2010). On this basis, this paper supports the management and analysis of structural deformations of walls and ceilings of the building in the same HBIM project, which provides a more realistic view of the building.

After briefly introducing the current situation of BIM in building and heritage, it is worth mentioning that this article promotes the use of BIM in historic buildings to represent existing deformations. These deformations are managed and analyzed by comparing two digital models obtained through two different procedures: the theoretical-HBIM model generated using existing drawings from documentary sources or traditional measurements, and the as-built-HBIM model based on point clouds from TLS.

3.1 High-definition data capture and processing

There is a lot of research on the use of the photogrammetric technique and the laser scanner applied to cultural heritage (Pieraccini, Guidi, and Atzeni 2001; Yastikli 2007; Pavlidis et al. 2007; Yilmaz et al. 2007; Mostaza et al. n.d.; Mañana-Borrazás, Rodríguez-Paz, and Blanco-Rotea 2008; Almagro, n.d; Muñoz et al. 2010; Pérez García et al. 2011). The complex geometry of historic buildings, together with their numerous decorative elements, such as columns, capitals, vaults, tiled parapets and walls, make it necessary to use accurate technologies to capture these geometric data.

3.2 Point cloud management within the HBIM Project

Current BIM platforms allow to obtain 3D models with typological information and historic annotations as geo-structural references to spatial information (Pauwels et al. 2008). This is possible thanks to laser scanning and photogrammetry. Although the management of these two data acquisition methods for building, engineering and construction differs in terms of software and processing, the workflow to insert the resulting point cloud into a HBIM model is the same. However, the accuracy of these technologies to develop complex 3D elements has to be taken into consideration. Most of the researches (Remondino et al. 2012; Fassi et al. 2013; Remondino et al. 2013; Teza et al. 2016) focus on the measurement analysis using these techniques; they prove that their accuracy are not quantitatively dissimilar in the case of small geometric elements. The procedure of incorporating the point cloud into the BIM platform sometimes required a geodetic network to set the project's reference point, eliminating deformations during the scan registration and orientation phase (Oreni and Brumana 2014b). This facilitates the inclusion of irregular geometries and their comparison with the 3D model. Although there are issues to be resolved, the representation of architectural heritage in BIM platforms is subject to the implementation of a library of historic parametric objects based on algorithmic methodologies. The TLS point cloud becomes the basis to model complex shapes in the isotropic BIM environment (Murphy, McGovern, and Pavia 2013; Dore and Murphy 2013; Dore and Murphy 2014; Chevrier and Charbonneau 2010).

Among the first implementations of scan data into BIM platforms, GreenSpider, a plug-in for Autodesk Revit, was developed by Garagnani and Manfredini (2013) to reduce the gap between computational conceptual design, TLS and BIM. On the other hand, Pointools for Bentley© allows the precise modeling of these irregular structures from TLS data. However, this methodology to represent the geometric complexity becomes slower, since it requires several interchangeable applications.

For its part, the manual reconstruction in interiors still presents low productivity and inaccurate mapping results (Sassine 2016). Besides, clutter has a negative effect on data capture and subsequent processing for semi-automatic reconstruction (Thomson and Boehm 2015).

All these procedures are aimed at avoiding simplifications in the HBIM model details, and facilitating a more methodological modeling process focused on protecting the singular geometries of historic buildings. Here, the prevailing difficulty is to represent the complexity and conservation status of the heritage studied. The analysis of irregular and complex shapes, such as the modeling of vaults or column capitals, can be managed through Rhinoceros©, using Boolean operations and NURBS (Non-uniform rational B-splines) surfaces, and then exported to the BIM platform in order to be managed (Oreni and Brumana 2014b). However, most of these geometries are theoretical; that is to say, they do not show structural deformations or they are excessively simplified.

The generation of HBIM models from the TLS point clouds —this can be named "Scan-to-BIM"— is a complex task (Barazzetti et al. 2015), for which there are commercial applications capable of modeling the irregularities of historic buildings (Antón et al. 2018). However, BIM library objects and software are developed for modern constructions. This entails a limitation in the case of historic buildings, since they contain complex elements and different from the predefined BIM objects. A review of the scientific literature shows restoration works in the architectural heritage where the point cloud has been inserted in BIM platforms, using specific software to manage scan data. One of the cases is the 3D model of the Basilica of Collemaggio (Oreni and Brumana 2014b). In this study, the structural elements were divided by following the construction logic of the building; that is, columns, walls, vaults, wooden elements of the roof, stone ashlars and decorative elements, using Boolean operations and NURBS surfaces of Rhinoceros©.

If the priority is to generate documentation efficiently, the workflow in the BIM environment should be optimized, simplifying the previous procedures to manage all the geometric and alphanumeric data within a single platform.

4. Methodology

4.1 Background

The Reales Alcázares in Seville are home of unique gardens of Nazari origin, where the Pavilion of Emperor Charles V is located. This building dates from the Muslim period (12th century) and was transformed between 1543 and 1546 by Juan Fernández, the Master of the Alcázar (Fidalgo, 1990). The Pavilion's structure is similar to an Abbadid *qubba* dedicated to prayer or burial. It is structured by walls of 60 centimeters and covered with a wooden dome. Surrounding the walls, four galleries are bounded by arches supported by twenty columns with capitals carved by Italian stonemasons, in which the ends have a greater thickness to support the stresses from the roof. It is worth noting the pure Mudejar tradition of its decorative elements —tiles, plasterwork and mosaics of the floors— that is shown both in the central walls, tiled on both sides, and in the interior flooring (Figure 1).

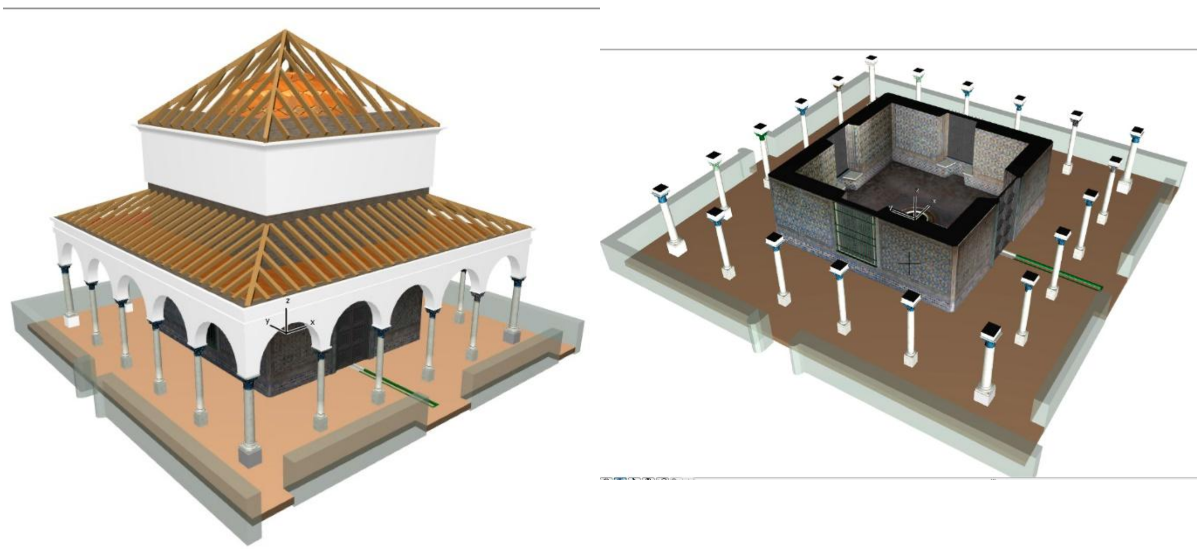

Figure 1. a) 3D Model of the Pavilion of Carlos V, showing its roof structure. b) Horizontal section of the building.

BIM methodology is able to show the historic building's main problems in the 3D model, including the deformations of the building components, which can be used in simulations for structural behavior analysis.

Nieto et al. (2016) showed that inserting point cloud data in the BIM software (ArchiCAD and Revit) is essential to contrast the real measurements from the scan with the documentation coming from more traditional techniques (Almagro 2003). In this way, dimensional discrepancies between the theoretical-HBIM and the as-built-HBIM are detected, and thus it is revealed the existence of significant deformations in walls, porticoes and pillars of the historic building.

This research aims to propose a new methodology, based on point cloud management within the same HBIM project with a single platform (ArchiCAD), to represent, manage and analyze the structural deformations of the historic buildings. The add-on of Cadimage Point Cloud was in experimental stage with versions 16 and 17 of Graphisoft ArchiCAD, but the import of point clouds is integrated in the software since version 19 as an interoperability tool. Nowadays, the insertion of point clouds can be conducted in xyz and e57 file formats, preserving the RGB colors of the scanned object. Also, the management speed of the point cloud in ArchiCAD increased significantly. In this way, the modeling process has been referenced to the spatial coordinates of the points captured by TLS, which define the real geometry of the historic building.

Figure 2. View of the TLS point cloud overlapping the theoretical-HBIM model.

4.2 Data processing

The creation of the theoretical-HBIM model is based on drawings from the Spanish CSIC School of Arab Studies led by Antonio Almagro (2003), who carried out a photogrammetric survey of the most emblematic buildings and palaces of the Reales Alcázares in Seville. Considering the measurements from the top view and elevations of the Pavilion, the modeling is conducted in a theoretical state without deformations, using the predefined tools of ArchiCAD for walls, pillars, Morph elements, etc. These objects are based on an internal parametric programming language called Geometric Description Language (GDL), which allows their generation and modification, whether they belong to the standard library or external sources.

On the other hand, the TLS point cloud data of the structural variations of the building was obtained using the 3D laser scanner Leica ScanStation C10 for walls, columns, ceilings, beams and roofs of the Pavilion. Concerning detailed components of great historic value such as the column capitals, the handheld Artec MHT 3D optical scanner (OS) was used. These techniques achieve accurate measurements of 3D objects, although they need to be processed. The reconstruction of the building from the resulting point clouds is possible through reverse engineering (Dore and Murphy 2013) and semi-automatic procedures (Antón et al. 2018), but it is worth analyzing the accuracy of the modeling methods presented in this paper in relation to the primitive model (Nieto and Moyano 2014).

Nowadays, great effort has been made for the automation of the modeling of heritage buildings from point clouds. Nevertheless, the current BIM platforms do not have the capacity to automatically convert geometric primitives yet, which were created with modeling tools from reverse engineering into BIM design objects (Tang et al., 2010). Implementations have been carried out (Bassier et al 2016; Angelini et al 2017; Quattrini et al 2017), but there is still a long way to achieve it (López et al., 2018). Semi-automatic approaches that complement a manual adjustment to the point cloud have been proposed (Bosché et al 2015; Hong et al 2014; Jung et al 2014), but the historic buildings have their own architectural peculiarities, intrinsic deformations and transformations throughout their lifetime, which currently makes it inconceivable to automate the characterization process of elements.

This paper is intended to achieve the transformation of parametric objects of the theoretical 3D model into deformed geometry by reverse engineering.

5. Interoperability in the HBIM model for deformation management

Transforming the theoretical-HBIM model by considering point cloud data is essential for a comparative study of the deformed structures, being currently one of the great advantages over previous methodologies that were aided by templates of 2D sections linked to the point cloud.

Although only the column capitals are part of the structure of the building, the modeling of the rest of decorative pieces with complex geometries was carried out using OS data, which provides a more precise resolution and texture. These objects can also be inserted into the non-structural HBIM project of the building, although the high number of points must be taken into account. In addition, it is currently complex to discriminate components from historic buildings accurately using algorithms. Therefore, they should be previously delimited in the point cloud for subsequent transformations.

5.1 Localization and management of deformations in the southern wall

In a new stage, the research focuses on the management of the deformations captured in the global point cloud, which is imported in the theoretical-HBIM in order to evidence the irregularities of the heritage building and to obtain a real model. According to Bassier et al. (2016), the quality of the realistic models has a great impact on the subsequent structural analysis. It must be taken into account that the elements of the models are mass entities that represent the construction systems of the building during the course of history.

In the inspection of the building, important pathologies are detected in the southern wall, which shows bulges of the tiling in a third part of its height, as well as detachments in the tiles, cracks in the plaster strips and subsidence in several areas of the pavement.

Two procedures are proposed to represent the irregularities in the southern wall by altering the geometry of the theoretical model.

The first procedure entails dividing those structural components containing deformations in the real building, such as walls, beams and columns, into sectors whose contours are to be adapted to the point cloud. Those alterations of the building justify the use of the Morph BIM design tool to create the exterior cladding of the four walls that enclose the central room. This tool offers great advantages in modeling compared to the Wall tool, since it is able to deform the elements' faces and adapt them to the irregularities of the wall. The left tiled sector of the south facade is the most evident example, given the considerable bulge in the doorjamb. The walls are inserted, prepared and mapped in the HBIM Project before adjusting their faces to the deformed geometry. On the external face, a plate modeled with the Morph tool is attached to the wall, taking its width and height dimensions from the area bounded by the border tiles in the sector, and thickness of 1 cm. Subsequently, the exterior ortho-photographs can be mapped according to the location of the tiles (Figure 3).

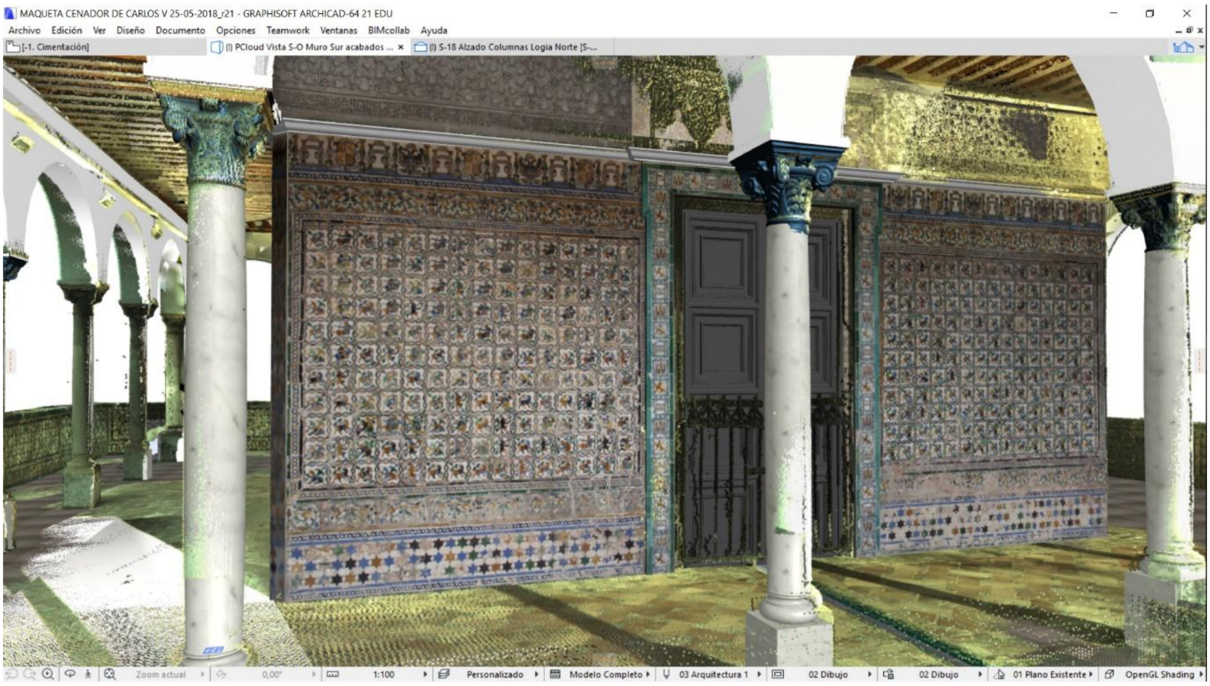

Figure 3. Theoretical-HBIM – Southern wall.

The next step is to deform the geometry of the theoretical wall, based on the deformations of the cladding in the TLS data. To this end, a mesh is created from the point cloud.

In the case of the southern wall of the Pavilion, this sector was delimited from the global point cloud for its subsequent transformation into mesh using specific software —Rapiform, Geomagic, 3DReshaper, etc.—. It was then inserted into the ArchiCAD HBIM Project by converting the 3ds file into a GDL parametric object (gsm file format). Figure 4 shows this conversion process in the wall, where the deformations are visible.

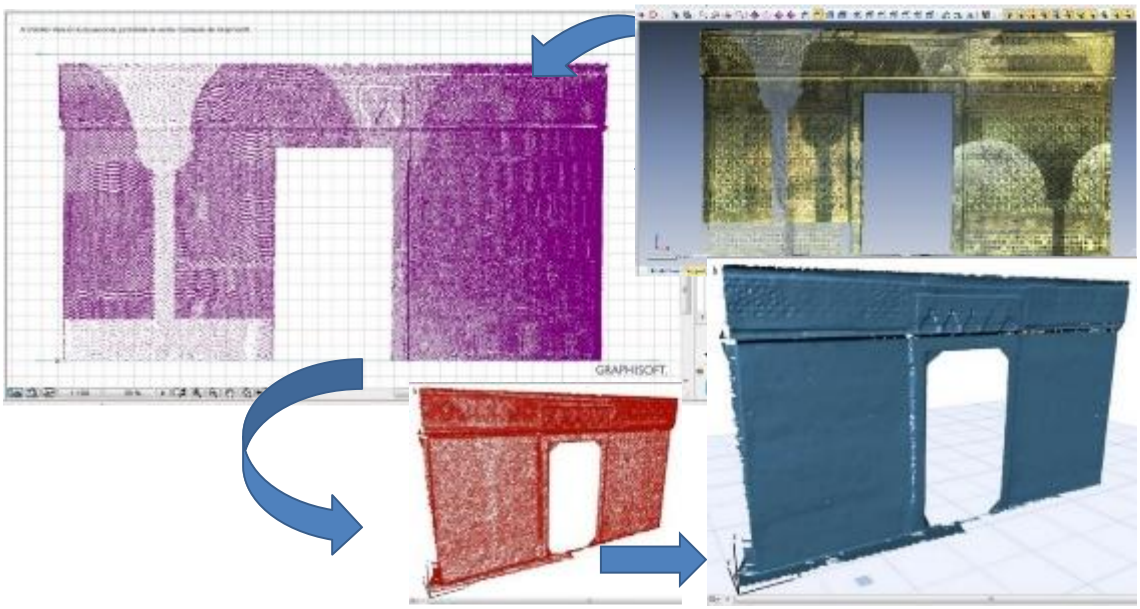

Figure 4. From point cloud to mesh – Southern wall.

Inserting the deformed mesh in the HBIM Project allowed the comparison with the theoretical model and the analysis of the deformations of the walls. Figure 5 shows the interoperability process in the HBIM project (Open GL visualization mode): a) South wall of the Pavilion with the textured tiles and the mesh added; b) the layer of the tiles (Wall-Cladding) is hidden.

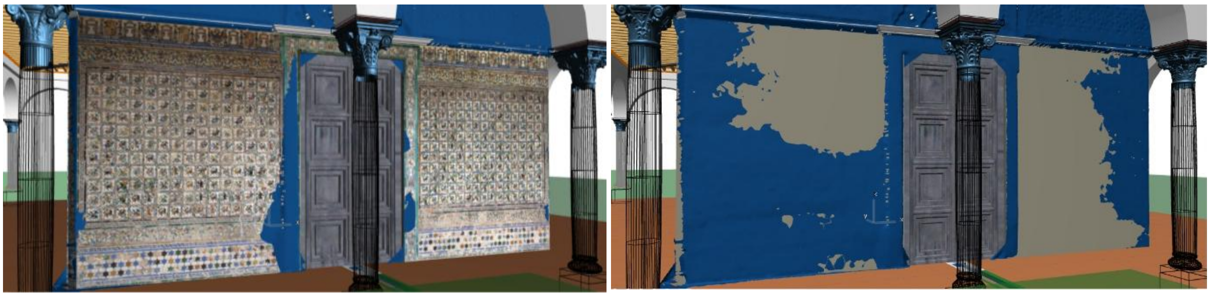

Figure 5. Southern wall and deformed mesh in the theoretical-HBIM model.

In case of the existence of gaps in the parametric object from the mesh due to the lack of points in the cloud, it is possible to convert the mesh into an ArchiCAD object in order to manually move the vertexes and thus close those gaps.

Both the point cloud and the mesh in the HBIM model can be used as references to adjust the geometry of the Morph element that has been created. For this, the tools of Modify Morph are used —Bulge, Smooth & Merge Faces, Modify Segmentation— (Figure 6.a). Those areas of the mapped tiling whose nodes remain under the mesh are then moved to the mesh vertexes, as in the case of the area beside the doorjamb (Figure 6.b). On the contrary, those nodes in the areas over the mesh are translated in the same way, but towards the hidden mesh inside the wall.

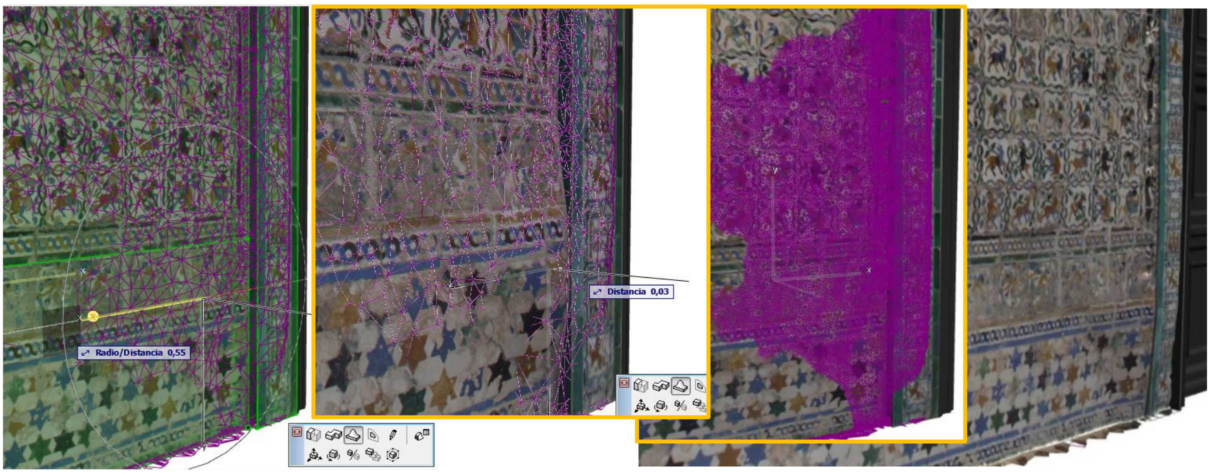

Figure 6. a) Surface edition. b) Node translation. c) Morph smoothening. d) Texture mapping.

This flexible adjustment procedure is very laborious and slow, since it requires modifying the position of the surface nodes manually. Therefore, it does not offer an accurate result due to the large number of coordinates that should be modified. For this reason, this article proposes a second procedure, based on Boolean operations.

Figure 6. a) Surface edition. b) Node translation. c) Morph smoothening. d) Texture mapping.

The Wall elements inserted are converted into Morph objects. Next, performing the subtraction Boolean operation, the deformed mesh becomes an operator object as the cutting surface that splits the volume of the pure parametric element (a wall of constant thickness). The remaining part of its geometry, a new GDL object, has the same geometrical and parametric properties and deformations as in the real element (Figure 7).

Figure 7. Boolean operation in the southern wall.

At this point, the structural deformations of walls and beams in the three-dimensional model are analyzed, contrasting the geometry of the ideal model with the mesh obtained from the point cloud inserted in the HBIM project.

There are applications and plug-ins complementary to the BIM software —such as Realworks, Pointsense, Imaginit, and Edgewise—, which allow importing the point cloud and comparing it with the model geometry in order to exhaustively determine the movements and structural deformations. This procedure, together with the generation of horizontal and vertical reference sections, quantifies these variations.

BIM software allows to create sections of the historic building structural components, thus determining the extent of the deformations. Figure 8 shows the vertical sections of the bulge of the south wall beside the left doorjamb of the Pavilion entrance. The sections are created every 20 mm, and the total wall thickness is 0.64 m. In this way, the data collection is eased by using control points in the model.

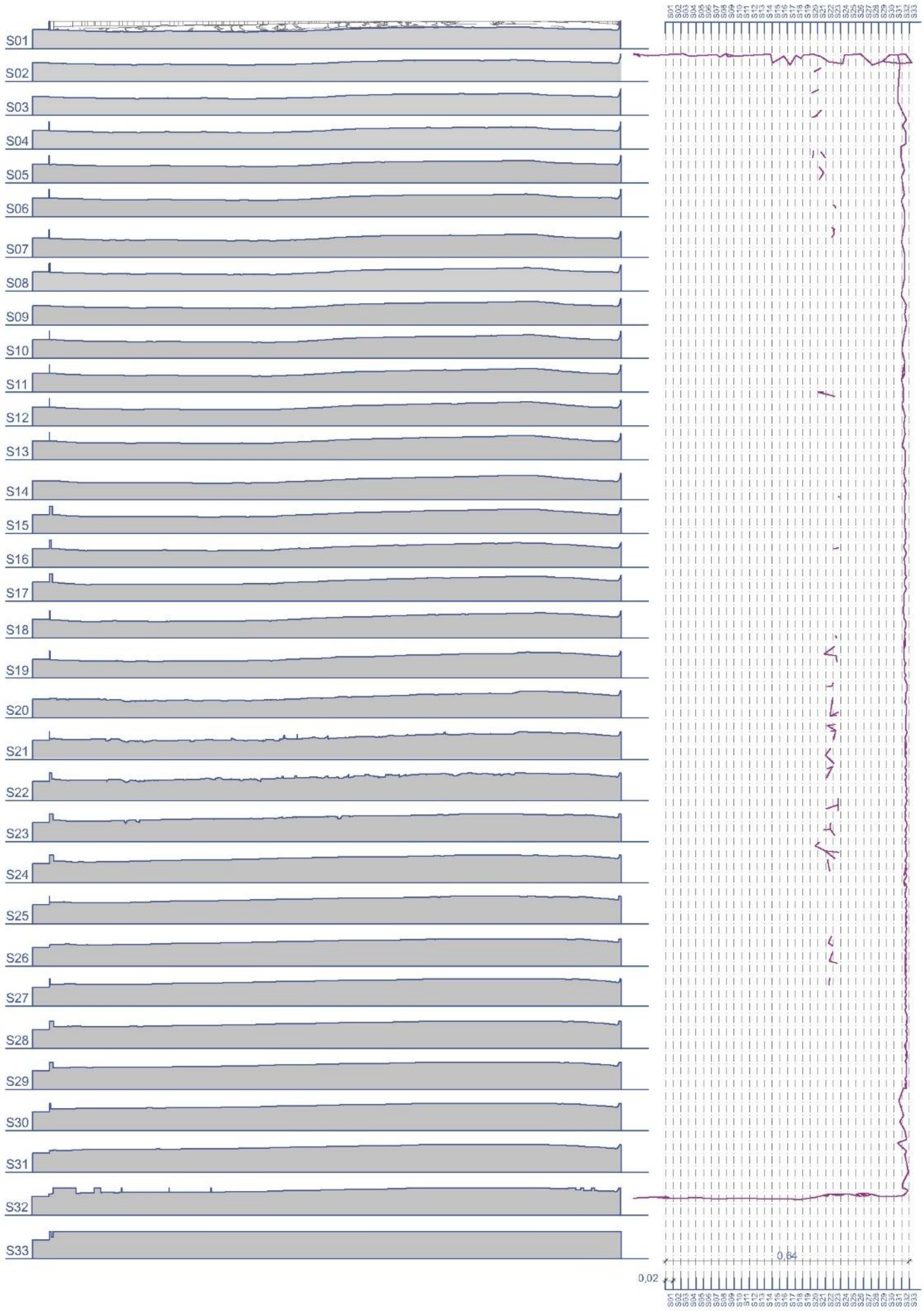

Figure 8. Sections of the south wall every 20 mm.

Concerning the outer face of the south wall, it is possible to analyze the dispersion of the mesh vertexes and quantify the deviation (Antón et al. 2018) between the aforementioned theoretical and as-built geometries. To do this, CloudCompare v2 can be used. This software requires two point clouds, or a point cloud and a mesh, to compute the distances and then compare both objects. In this sense, an ideal point cloud should be created for the theoretical-shape wall in order to conduct a more coherent comparison with the mesh of the deformed wall. This process starts by exporting the model from ArchiCAD to Rhinoceros in its specific 3dm file format. In this case, the coordinates —considered XY— of the mesh points are taken. That is, if these coordinates of the mesh points remain in the vertical plane of the ideal wall face, the deformation of the mesh will exist only in the Z coordinate (see Figure 5). It is then necessary to map the mesh points onto the exterior walls of the theoretical BIM model to create the aforementioned ideal point cloud. For this task, the Rhinoceros ProjectToCPlane command can be used, which flattens the selected objects in the construction planes —CY planes— previously defined on the ideal wall face.

Once the new ideal point cloud is obtained with the flat coordinates of the deformed mesh, the comparison using CloudCompare can be performed. It should be mentioned that, in order to prevent misalignments of the 3D entities to be compared, their original coordinates must be maintained. After importing these entities, it is necessary to compute the normal vectors of the ideal point cloud in order to calculate the distances with respect to the mesh. The following graph (Figure 9) shows the deviation of the points between both 3D objects, considering the number of points for each distance interval.

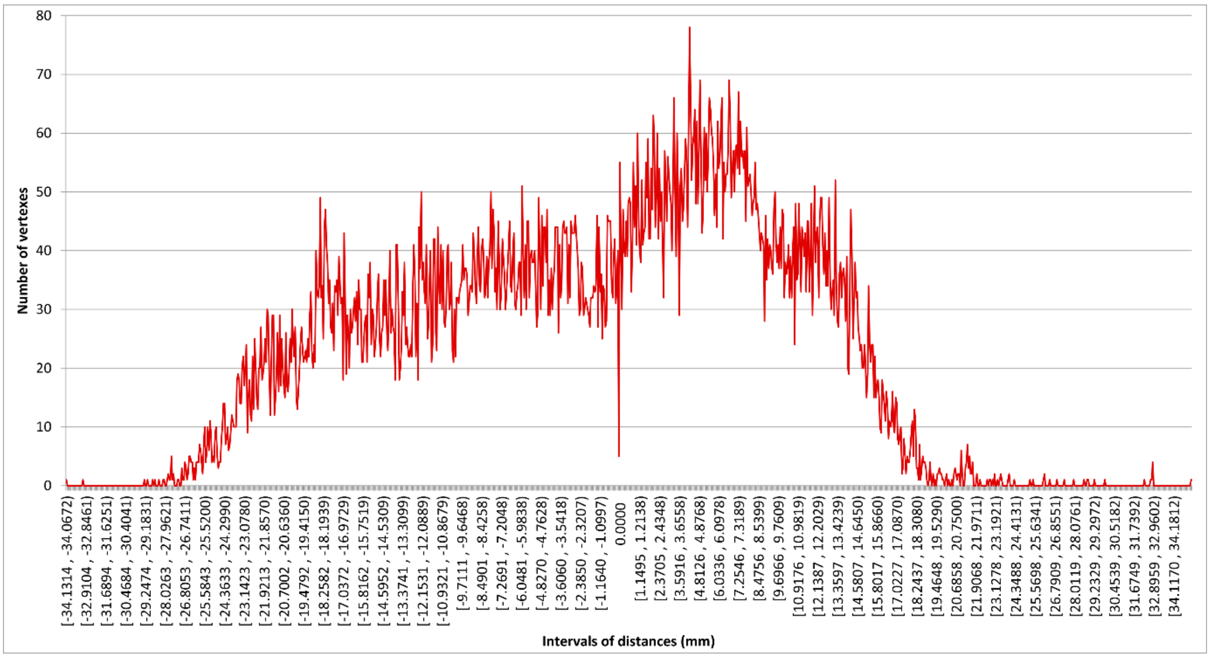

Figure 9. Graph of points deviations between real mesh and ideal point cloud in the south facade.

It should be noted that it is not possible to list all the intervals of calculated distances, given the limited space on the chart. Therefore, they will appear in a number proportional to the width available. The zero value is inserted among the 1,082 intervals, which represents the equality of coordinates between the points of the deformed mesh and the ideal point cloud; that is, the place at which the distance between points is zero. This requires interpolating the zero value in the interval that starts with a negative value and ends positive. The number of points corresponding to the zero value is calculated from the histogram produced by CloudCompare for a given number of intervals. 5,000 intervals are established, because the greater this number is, the more precise number of points can be delimited within each interval.

5.2 Localization and management of deformations in the coffered ceiling of the northern gallery

In the coffered ceiling of the north-facing gallery, due to the deflection of the main beam, the deformations are located over the arches.

The TLS point cloud is essential to measure the displacements caused by the pathology. Figure 10 shows the point cloud overlapping the theoretical-HBIM model in ArchiCAD, as well as a photograph of the affected area.

Figure 10. a) TLS point cloud over model without deformations. b) Photograph of the rafters and beam’s displacement.

For its part, Figure 11 shows a section of the theoretical model and point cloud, which provides displacement measurements between both situations.

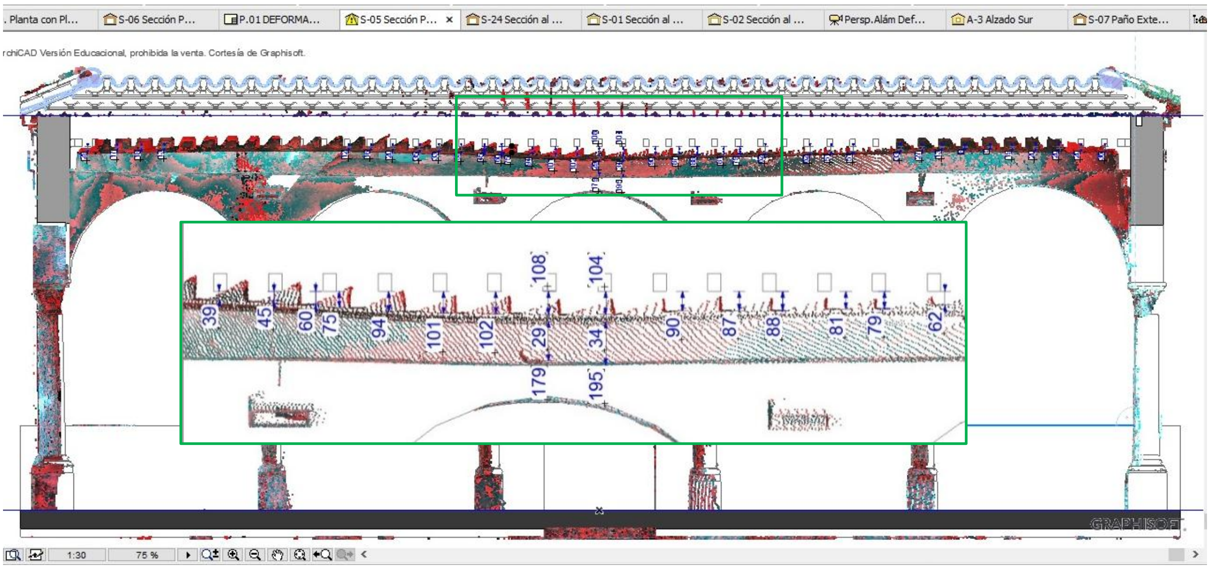

Figure 11. Section of the theoretical-HBIM and the point cloud.

The identification of the elements affected by pathologies is also important. In this study, the ArchiCAD Marker tool was used in the inspected sector, which allows to incorporate a new Entry (record) called ‘Pathology by Filtration’. This input is associated with the active view where the affected elements are marked. Then, they are identified and highlighted with red color and labeled using their ID (identifier) (see Figure 12) at +4.05 m over the ground floor or pavement. For instance, the current top view is saved as “Dampness_1st-slab_north” inside the folder "F03.3.Pathologies" in the HBIM Project Navigator.

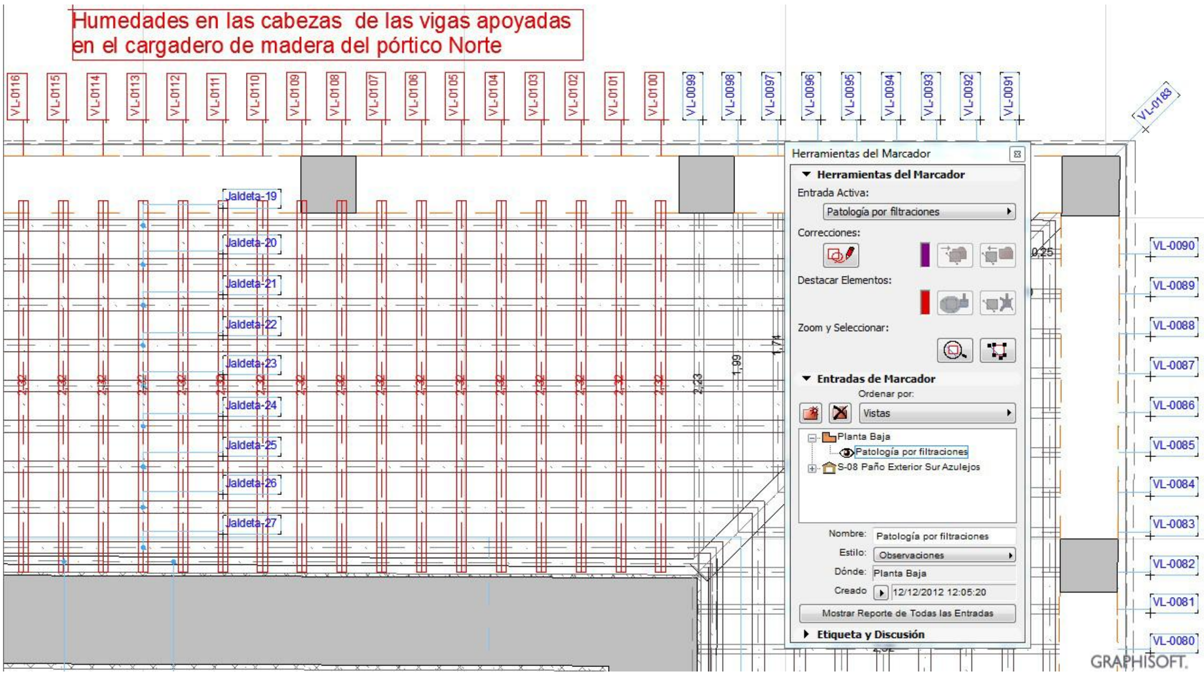

Figure 12. Top view of the affected rafters in northern gallery — theoretical model.

It should be noted that the Marker Tools panel directly allows to select or visualize the elements by simply pressing the icons in the Zoom and Select section.

These marks associated with the active Marker input are visible in all the views of the 3D model, and are therefore easy to identify when exploring the model (Figure 13). These marks can also be hidden any time by simply pressing the "eye" icon (close) within the Marker Entries section.

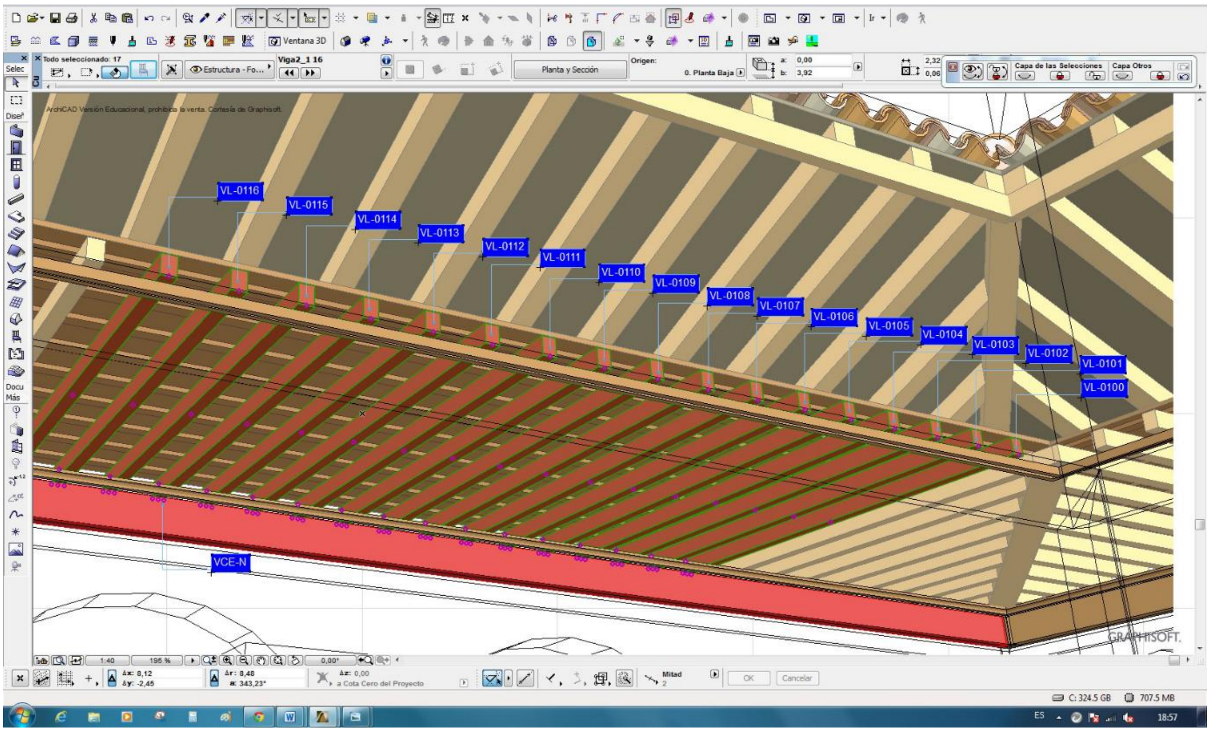

Figure 13. 3D view of the affected rafters in northern gallery — theoretical model.

For this case, the marked beams of the north gallery were edited to associate them with the new Status of Restoration or to be Demolished, which means that they should be repaired or replaced. The restoration assistant plays a determining role in the classification of pieces. The restorer can establish the Restoration Status appropriate to the conservation status of the piece and then incorporate this information in the box enabled as a new item for the Schedule Data Sheet (Table 1).

LRE-08(R) INVENTORY SHEET OF BEAMS OF THE STRUCTURE OF THE LOGIES									
ID	**View**	**Units**	**Zone**	**Length**	**Width**	**Element Class**	**Rehabilitation status**	**Material**	**Pathology**
Layer Structure - Slab									
VL-0100		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0101		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0102		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0103		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0104		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0105		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0106		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0107		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0108		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0109		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0110		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0111		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0112		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0113		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0114		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0115		1	Perimeter loggia	2.32	0.06	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
VL-0116		1	Perimeter loggia	2.32	006	Beam	To disassemble	Pine Wood	Fungi/Moisture & Deformation
TOTAL		**17**							

Table 1. Schedule data sheet of the 17 rafters, in red color, affected in the roof of the north gallery.

In addition, it is possible to assign the data from the previous deviation comparison to the revision markers of the model, in such a way that each ID quantitatively shows the existing deformations. This procedure can be performed automatically through interoperability with .xlsx formats.

6. Results and discussion

The BIM platforms advanced in the Scan-to-BIM processes by accepting the point clouds from the scanning techniques. This allows to compare the theoretical-HBIM and the as-built-HBIM models created in this paper; therefore, the existence of significant deformations in the building becomes evident. The implementation of the proposed methodology enables the subdivision of the structural elements and addresses the problems in detail. The sections generated in BIM revealed deformations in the south wall and in the part of the doorjamb area that is 20 mm thick. Although the two modeling procedures apparently show the same geometry outcomes, the first procedure of adjustment of the wall deformations entails low operability, given the time needed to manually translate the points of the Morph surface to the mesh. On the other hand, the Boolean operations procedure automatically provides the same geometry in the parametric wall as in the mesh.

In order to quantify the deformations obtained through the second procedure compared to the theoretical wall, CloudCompare v2 software is used. The standard deviation calculated for this distribution of points was 19.47. This, in addition to the reduced number of points in the zero value of the graph —only 55 points— shows the great difference in the geometry of both 3D objects. According to Anton et al. (2018), the deviation between two similar objects has two main characteristics: 1) high presence of points in the zero value with respect to the rest of intervals —the more points there are in that value, the more similar the compared objects will be—; 2) high standard deviation, which reveals a great dispersion of the points in the set of intervals. The reason for this increase in the standard deviation is the scarce points scattered about the numerous intervals of distances, while most of the points are at zero; that is, those points belonging to both 3D objects are coincident. By performing the arithmetic mean of the interval furthest from the zero value, which is not shown in Figure 9 for the reasons previously explained, the approximate maximum distance between points of the real mesh and the ideal point cloud can be obtained. The value —deformation— obtained for the outer face of the south wall is 35.24 mm, which constitute 0.055 percent of the wall thickness.

In a second phase of the study, the use of revision markers allows the visualization and the identification of particular elements with pathologies, such as the rafters in the north gallery. The restoration process can be enhanced by applying the Restoration assistant, and showing the status in a certain stage within the HBIM project.

7. Conclusions

The development of the latest versions of BIM platforms enables significant advances in the analysis of the architectural and cultural heritage. Following two modeling methods, this research focuses on the implementation, management, and quantification of structural deformations for the creation of a HBIM project, which supports a multidisciplinary approach in all phases of the restoration process —research, data registration, preliminary project, project, tender, construction, conservation, prevention and maintenance—. In this way, the restoration process can be analyzed before any intervention on the historic building is performed.

The methodology geometrically analyzes two states of the historic building model, considering its structural elements: the theoretical-HBIM model, generated from documentary sources, and the as-built-HBIM, with precise measurements from TLS data. The final results show that it is possible to quantitatively analyze structural differences and deformations from HBIM models of heritage buildings. When the pathological deformation derives from substantial problems in the construction systems, it is important to identify and mark the affected elements that must be replaced and fitted in their correct place. Structural displacements causing problems and becoming a peculiar aspect to the heritage building analyzed should be modeled to represent the reality of the building.

Concerning BIM operability, another advantage is the Level of Information, Detail and Accuracy (LOD = LOInfomation + LOGeometry + LOAccuracy) achieved. In this case, it is 400 within the range from 100 to 500, since multiple scanned objects were inserted in the as-built HBIM Project. Not only are these elements geometrically defined in detail, but they are also in their actual position in the construction system and contain relevant information.

However, difficulties arise as regards the implementation of the modeling and management of deformations captured by TLS. This real geometry should be associated with a construction system with different interrelated objects, whose connections are possibly hidden behind the visible surface, as in the tiled walls of the Pavilion. Here, the subdivision of the as-built mesh into numerous pieces representing the tiles is a time-consuming task. For this reason, this work was limited to catalogue them separately into a quantification inventory and to map the surface with the ortho-photograph of the wall.

The procedures presented in this paper provide a more methodological modeling process, avoiding the simplifications of the models in HBIM and thus protecting the geometric singularities of the historic building. This eases achieving a consistent model associated with constantly updated, proven databases on a multidisciplinary basis. The potential of this research lies in the analysis and management of deformations, either structural or corresponding to wall surfaces, under the BIM environment. Finally, these quantitative data become a graphic-alphanumeric catalogue, which is not hitherto present in the scientific literature.

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Disclosure statement

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References

Almagro, A. 2003. Planimetría Del Alcázar de Sevilla. *Loggia, Arquitectura y Restauración* 14–15 (4): 156–61. doi:10.4995/loggia.2003.3563.

Almagro, A. 2000. Fotogrametría Para Arquitectos. El Estado de La Cuestión. In *Las Nuevas Tecnologías de La Representación Gráfica Arquitectónica En El Siglo XXI: Actas Del VIII Congreso EGA*, 277–80. Barcelona: Universitat Politécnica de Catalunya, Departament d 'Expressio Gráfica Arquitectònica I. https://dialnet.unirioja.es/servlet/libro?codigo=529751.

Almagro, A. 2013. Análisis Arqueológico Del Pabellón Occidental Del Palacio Al-Badi' de Marrakech. *Arqueología de La Arquitectura* 0 (10): e008. doi:10.3989/arq.arqt.2013.002.

Angelini, M. G., V. Baiocchi, D. Costantino, and F. Garzia. 2017. Scan to BIM for 3D Reconstruction of the Papal Basilica of Saint Francis in Assisi In Italy. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* 42 (5W1): 47–54. doi:10.5194/isprs-Archives-XLII-5-W1-47-2017.

Antón, D., B. Medjdoub, R. Shrahily, and J. Moyano. 2018. Accuracy Evaluation of the Semi-Automatic 3D Modeling for Historical Building Information Models. *International Journal of Architectural Heritage* 12 (5): 790–805. https://doi.org/10.1080/15583058.2017.1415391.

Armisén, A. A., Soria, E., Agustín, L., Alberto, J., Adrián, A., Ereño, B., … De Autor, D. (2018). *BIM aplicado al Patrimonio Cultural Coordinador del proyecto Coordinadores de los grupos de trabajo*. https://www.researchgate.net/profile/Juan_Nieto10/publication/330183791_BIM_aplicado_al_Patrimonio_Cultural_Documento_14_Guia_de_usuarios_BIM_Building_SMART_Spain_Chapter/links/5c328768299bf12be3b3ed0d/BIM-aplicado-al-Patrimonio-

Cultural-Documento-14-Guia-de-usuarios-BIM-Building-SMART-Spain-Chapter.pdf

Arayici, Y. 2008. Towards Building Information Modelling for Existing Structures. *Structural Survey* 26 (3): 210–22. doi:10.1108/02630800810887108.

Barazzetti, L., F. Banfi, R. Brumana, G. Gusmeroli, M. Previtali, and G. Schiantarelli. 2015. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from Laser scans. *Simulation Modelling Practice and Theory* 57. Elsevier B.V.: 71–87. doi:10.1016/j.simpat.2015.06.004.

Bassier, M., G. Hadjidemetriou, and M. Vergauwen. 2016. Implementation of scan-to-BIM and FEM for the documentation and analysis of heritage timber roof structures. In *In Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection: 6th International Conference, EuroMed 2016*, edited by Cyprus: Springer International Publishing Nicosia, d M. Ioann, 1:79–90. doi:10.1007/978-3-319-48496-9.

Bosché, F., M. Ahmed, Y. Turkan, C.T. Haas, and R. Haas. 2015. The value of integrating scan-to-BIM and scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The Case of Cylindrical MEP Components." *Automation in Construction* 49. Elsevier B.V.: 201–13. doi:10.1016/j.autcon.2014.05.014.

Chevrier, C., and N. Charbonneau. 2010. Parametric Documenting of Built Heritage: 3D Virtual Reconstruction of Architectural Details. *International*. http://multi-science.atypon.com/doi/abs/10.1260/1478-0771.8.2.135.

Dore, C., and M. Murphy. 2013. Semi-automatic modelling of building façades with shape grammars using historic building information modelling. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5/W1 (February): 57–64. doi:10.5194/isprsarchives-XL-5-W1-57-2013.

Dore, C., and M. Murphy. 2014. Semi-automatic generation of as- built BIM façade geometry from laser and image data. *Journal of Information Technology in Construction* 19 (January): 20–46. https://scholar.google.com/scholar_lookup?title=Semi-automatic+generation+of+as-built+BIM+facade+geometry+from+laser+and+image+data&author=C.+Dore&author=M.+Murphy&journal=ITcon&volume=19&publication_year=2014&pages=20-46.

Fai, S., K. Graham, T. Duckworth, N. Wood, and R. Attar. 2011. Building information modelling and heritage documentation. *18th International Conference on Virtual Systems and Multimedia, XXIII CIPA Symposium*, 2011 Prague, Czech Republic, pp. 12-16. Retrieved from: https://d2f99xq7vri1nk.cloudfront.net/legacy_app_files/pdf/Fai.pdf

Fidalgo, A. M. 1990. Los Jardines Del Alcázar de Sevilla Durante El Siglo XVII: Intervenciones y Ordenación Del Conjunto En El Seiscientos. *Cuadernos de La Alhambra*, no. 26. Patronato de La Alhambra y Generalife: 207–48. https://dialnet.unirioja.es/servlet/articulo?codigo=299860.

Garagnani, S., and A. M. Manferdini. 2013. Parametric accuracy: Building information modeling process applied to the Cultural Heritage preservation." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS*

Archives 40 (5W1): 87–92. https://pdfs.semanticscholar.org/1682/3b3e272038fec08b38ea9267588efbad5589.pdf%0Ahttp://www.scopus.com/inward/record.url?eid=2-s2.0-84922519650&partnerID=tZOtx3y1.

García, J. L., M. C. López, and I. Jordán. 2018. The Study of Architectural Heritage with HBIM Methodology. A Medieval Case Study BT - Architectural Draughtsmanship. In *Architectural Draughtsmanship*. https://link.springer.com/chapter/10.1007/978-3-319-58856-8_74

González, M. J., A.J. Rueda, R.J. Segura, C. J. Ogáyar, A. Esteban, and J. Lara. 2010. Uso de sistemas basados en escáner 3D para digitalización y estudio del patrimonio arqueológico. *Virtual Archaeology Review*, 99–102. doi:10.4995/var.2010.5128.

Hong, S., J. Jung, S. Kim, H. Cho, J. Lee, and J. Heo. 2015. Semi-automated approach to indoor mapping for 3D as-built building information modeling. *Computers, Environment and Urban Systems* 51 (May). Pergamon: 34–46. doi:10.1016/J.COMPENVURBSYS.2015.01.005.

Nieto, J. E., and J. Moyano. 2014. The paramental study on the Model of Information of Historic Building or" HBIM Project". *Virtual Archaeology Review*. 5, (11): 73-85. http://www.polipapers.upv.es/index.php/var/article/view/4183.

Jung, J., S. Hong, S. Jeong, S. Kim, H. Cho, S. Hong, and J. Heo. 2014. Productive modeling for development of as-built BIM of existing indoor structures. *Automation in Construction* 42. Elsevier B.V.: 68–77. doi:10.1016/j.autcon.2014.02.021.

Logothetis, S., A. Delinasiou, and E. Stylianidis. 2015. Building information modelling for cultural heritage: A review. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* II-5/W3 (September): 177–83. doi:10.5194/isprsannals-II-5-W3-177-2015.

Lombillo, I., and L. Villegas. 2008. Metodología para el análisis de las estructuras de fábrica del patrimonio construido. *Tecnología de La Rehabilitación y La Gestión Del Patrimonio Construido* único: 69–90. https://scholar.google.es/scholar?hl=es&as_sdt=0%2C5&q=METODOLOGÍA+PARA+EL+ANÁLISIS+DE+LAS+ESTRUCTURAS+DE+FÁBRICA+DEL+PATRIMONIO+CONSTRUIDO.&btnG=.

López, F. J., P. M. Lerones, J. Llamas, J. Gómez-García-Bermejo, and E. Zalama. 2017. A framework for using point cloud data of heritage buildings toward geometry modeling in a BIM context: A case study on Santa Maria La Real de Mave Church." *International Journal of Architectural Heritage* 11 (7). Taylor & Francis: 965–86. doi:10.1080/15583058.2017.1325541.

Mañana-Borrazás, P., A. Rodríguez-Paz, and R. Blanco-Rotea. 2008. Una experiencia en la aplicación del láser escáner 3D a los procesos de documentación y análisis del patrimonio construido: Su aplicación a Santa Eulalia de Bóveda (Lugo) y San Fiz de Solovio (Santiago de Compostela)." *Arqueología de La Arquitectura*, no. 5: 15–32. doi:10.3989/arqarqt.2008.i5.

Megahed, N. 2015. Towards a theoretical framework for HBIM approach in historic preservation and management." *Journal of Architectural Research: ArchNet-IJAR*, 9, 130-147. https://scholar.google.es/scholar?start=70&q=HBIM&hl=es&as_sdt=0,5#4.

Mostaza, T., J.J. Zancajo, J. López, and A. Martínez. 2009. Aplicación del escáner láser 3d a la documentación espacial de yacimientos arqueológicos. *VIII CIA Pósters Teledetección*, no. 1: 403–8. http://www.segeda.net/8cia/pdf/18_1_Teledeteccion_Mostaza.pdf.

Murphy, M., E. McGovern, and S. Pavia. 2013. Historic Building Information Modelling - Adding intelligence to laser and image based surveys of European classical architecture. *ISPRS Journal of Photogrammetry and Remote Sensing* 76: 89–102. doi:10.1016/j.isprsjprs.2012.11.006.

Murphy, M., E. McGovern, and S Pavia. 2009. Historic Building Information Modelling (HBIM). *Structural Survey*. 27 (4): 311-327. http://www.emeraldinsight.com/doi/abs/10.1108/02630800910985108.

Nieto J. E., J. Moyano, F. Rico, and D. Antón. 2013. La necesidad de un modelo de información aplicado al patrimonio arquitectónico. In *Actas 1er Congreso Nacional BIM - EUBIM 2013*, 21–32. Escuela Técnica Superior de Ingeniería de Edificación Universitat Politècnica de València.

Nieto, J. E., J. Moyano, F. Rico, and D. Antón. 2016. Management of Built Heritage via HBIM Project: A Case of Study of Flooring and Wall Tiling. *Virtual Archaeology Review* 7 (14): 1–12. doi:10.4995/var.2016.4349.

Oreni, D., R. Brumana, S. Della-Torre, F. Banfi, L. Barazzetti, and M. Previtali. 2014a. Survey turned into HBIM: The restoration and the work involved concerning the Basilica Di Collemaggio after the Earthquake (L'Aquila). *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* II-5:267–73. doi:10.5194/isprsannals-II-5-267-2014.

Oreni, D., R. Brumana, A. Georgopoulos, and B. Cuca. 2014b. HBIM Library Objects for Conservation and Management of Built HBIM Library Objects for Conservation Abstract: *The Int. J. of Heritage in the Digital Era* 3 (2): 321–34. doi:10.1260/2047-4970.3.2.321.

Pauwels, P., R. Verstraeten, R. De Meyer, and J. V. Campenhout. 2008. Architectural information modelling for virtual heritage application. *Digital Heritage – Proceedings of the 14th International Conference on Virtual Systems and Multimedia*, 18–23. http://biblio.ugent.be/input/download?func=downloadFile&fileOId=481646&recordOId=434809.

Pavlidis, G., A. Koutsoudis, F. Arnaoutoglou, V. Tsioukas, and C. Chamzas. 2007. "Methods for 3D digitization of cultural heritage." *Journal of Cultural Heritage* 8 (1): 93–98. doi:10.1016/j.culher.2006.10.007.

Penttilä, H, M. Rajala, and S. Freese. 2007. *Building information modelling of modern historic buildings.* Predicting the Future 25th eCAADe Conference Proceedings. http://cumincad.architexturez.net/system/files/pdf/ecaade2007_124.content.pdf.

Pérez, J. L., A. T. Mozas, F. J. Cardenal, and A. López. 2011. Fotogrametría de bajo coste para la modelización de edificios históricos TT - Low-cost photogrammetry for the modeling of historic buildings. *Virtual Archaeology Review* 2 (3): 121–25. doi:10.4995/var.2011.4633.

Pieraccini, M., G. Guidi, and C. Atzeni. 2001. 3D digitizing of cultural heritage. *Journal of Cultural Heritage* 2 (1): 63–70. doi:10.1016/S1296-2074(01)01108-6.

Quattrini, R., R. Pierdicca, and C. Morbidoni. 2017. Knowledge-based data enrichment for HBIM: Exploring high-quality models using the semantic-web. *Journal of Cultural Heritage* 28. Elsevier Masson SAS: 129–39. doi:10.1016/j.culher.2017.05.004.

Roca, P., M. Cervera, G. Gariup, and L. Pela. 2010. Structural analysis of masonry historical constructions. Classical and advanced approaches. *Archives of Computational Methods in Engineering* 17 (3): 299–325. doi:10.1007/s11831-010-9046-1.

Saisi, A., and C. Gentile. 2015. Post-earthquake diagnostic investigation of a historic masonry tower. *Journal of Cultural Heritage* 16 (4). Elsevier Masson SAS: 602–9. doi:10.1016/j.culher.2014.09.002.

Sassine, E. 2016. A practical method for in-situ thermal characterization of walls. *Case Studies in Thermal Engineering* 8 (September). Elsevier: 84–93. doi:10.1016/J.CSITE.2016.03.006.

Tang, P., D. Huber, B. Akinci, R. Lipman, and A. Lytle. 2010. Automatic reconstruction of as-built building information models from Laser-Scanned point clouds: A review of related techniques. *Automation in Construction* 19 (7). Elsevier B.V.: 829–43. doi:10.1016/j.autcon.2010.06.007.

Thomson, C., and J. Boehm. 2015. Automatic geometry generation from point clouds for BIM.” *Remote Sensing* 7 (9): 11753–75. doi:10.3390/rs70911753.

Volk, R., J. Stengel, and F. Schultmann. 2014. Building information modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction* 38. Elsevier B.V.: 109–27. doi:10.1016/j.autcon.2013.10.023.

Yastikli, N. 2007. Documentation of cultural heritage using digital photogrammetry and laser scanning. *Journal of Cultural Heritage* 8 (4): 423–27. doi:10.1016/j.culher.2007.06.003.

Yilmaz, H. M., M. Yakar, S. A. Gulec, and O. N. Dulgerler. 2007. Importance of digital close-range photogrammetry in documentation of cultural heritage. *Journal of Cultural Heritage* 8 (4): 428–33. doi:10.1016/j.culher.2007.07.004.