3D Modeling Approach for Cultural Heritage Structures: The Case of Virgin of Loreto Chapel in Cusco, Peru

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***Abstract*—**Nowadays, Heritage Building Information Modeling (HBIM) is considered an efficient tool to represent and manage information of Cultural Heritage (CH). The basis of this tool relies on a 3D model generally obtained from a Cloud-to-BIM procedure. There are different methods to create an HBIM model that goes from manual modeling based on the point cloud to the automatic detection of shapes and the creation of objects. The selection of these methods depends on the desired Level of Development (LOD), Level of Information (LOI), Grade of Generation (GOG) as well as on the availability of commercial software. This paper presents the 3D modeling of a stone masonry chapel using Recap Pro, Revit and Dynamo interface following a three-step methodology. The first step consists of the manual modeling of simple structural (e.g., regular walls, columns, floors, wall openings, etc.) and architectural (e.g., cornices, moldings and other minor details) elements using the point cloud as reference. Then, Dynamo is used for generative modeling of complex structural elements such as vaults, infills and domes. Finally, semantic information (e.g., materials, typology, state of conservation, etc.) and pathologies are added within the HBIM model as text parameters and generic models' families respectively. The application of this methodology allows the documentation of CH following a relatively simple to apply process that ensures adequate LOD, LOI and GOG levels. In addition, the easy implementation of the method as well as the fact of using only one BIM software with its respective plugin for the scan-to-BIM modeling process means that this methodology can be adopted by a larger number of users with intermediate knowledge and limited resources, since the BIM software used has a free student license.

***Keywords*—**Cloud-to-BIM, cultural heritage, generative modeling, HBIM, parametric modeling, Revit.

I. Introduction

THE development of digital technologies in the Architectural, Engineering and Construction (AEC) industry has grown very fast in the last decades. The use of Building Information Modeling (BIM), Geographical Information System (GIS), and Digital Twin (DT) technologies has demonstrated that the virtual representation of civil infrastructure is an imperative issue nowadays for the design, construction, control, and maintenance of these projects [1]-[4]. In the field of existing infrastructure (e.g. cultural heritage (CH), buildings, bridges and factories of the last century, among others), digital technologies have been developing during the last decade and up to now have demonstrated their great potential for the adequate management of diagnosis [5], [6], structural assessment [7] and conservation projects [8]. In particular, the application of these technologies in CH is of special interest given the cultural relevance of such structures. They represent traditions and architectural typologies of ancient cultures and their conservation is currently an imperative issue. Likewise, conservation and restoration projects are needed to maintain the tourist attractiveness of the structures and ensure the safety of visitors.

Nowadays, conservation and restauration projects are developed under the concept of HBIM. This approach allows standardizing both semantic and geometric information in a common digital environment [2]. Several studies were developed mainly in the last decade, intended first as a way to create a repository of parametric elements [9]-[11]. Then, the potential of this tool made it feasible to represent an entire structure with a high LOD and LOI [12]-[14]. Several works then focused on the scan-to-BIM process, modeling directly from the point cloud by means of a Non-Uniform Rational B-Splines (NURBS) surfaces [15], generating structural models for advanced structural analysis of vaults [16], domes [17], towers [18], and even representing deformations observed in the structures [19]. Moreover, HBIM allows to represent graphically pathologies inside the 3D model [20]-[22] manage adequately the process of restoration and conservation [23], set the basis not only for structural analysis but also for the development of DT models for CH [24].

A determining aspect when generating the HBIM model is the geometric modeling stage. Depending on the degree of precision and detail required, as well as the information available, one type of modeling or another will be performed. Simple models can be elaborated based on basic operations with 3D solids, up to complex models by means of NURBS surfaces based on the point cloud [25]. In this investigation, the application of a modeling procedure following the HBIM methodology in an Andean stone masonry chapel is presented. A geometric model based on a Scan-to-BIM procedure is generated; and subsequently, structural diagnostic information is added within the model aiming at validating the use of the HBIM methodology for CH documentation and assessment.

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II. HBIM METHODOLOGY

As mentioned in [26], the use of 3D mesh models obtained from point clouds are heavy models and has no or less operability with BIM software. Besides, the construction phases of the elements cannot be represented, which is a necessary issue in terms of CH conservation and restoration projects. In this regard, the most suitable way to overcome these drawbacks is to model directly from the point cloud, either using a manual approach or semi-automatic/automatic methods for shape detection and generative and parametric modeling.

The methodology used in this investigation consists of a three-step process that allows the user to start from a registered point cloud and semantic data of the structure and move towards a digital model with all geometric and semantic information unified. Autodesk Recap Pro, Revit and Dynamo [27] software are employed to achieve the HBIM model.

A previous step to be done is to import the point cloud into Recap software where a cleaning process is carried out. Then, the Recap file (.rcp) is uploaded into Revit software and the modeling process starts. The first step consists of manual modeling of simple structural (e.g., regular walls, columns, floors, wall openings, etc.) and architectural (e.g., cornices, moldings and other minor details) elements. The idea is to use an easy and rapid process for the majority of the elements while maintaining an acceptable accuracy with respect to the point cloud. The second step is the automatic generative modeling of complex structural elements such as vaults, domes and infills. Parametric mass families based on 3D lines are used which are adapted to the geometry of the point cloud. Then, the 3D curves are selected in the Dynamo interface where the whole modeling process is performed automatically. Finally, in the last step, non-geometrical information (e.g. state of conservations, material, location, among others) and pathologies are added within the HBIM model to document the state of conservation of the structure. A scheme of the methodology adopted is presented in Fig. 1.

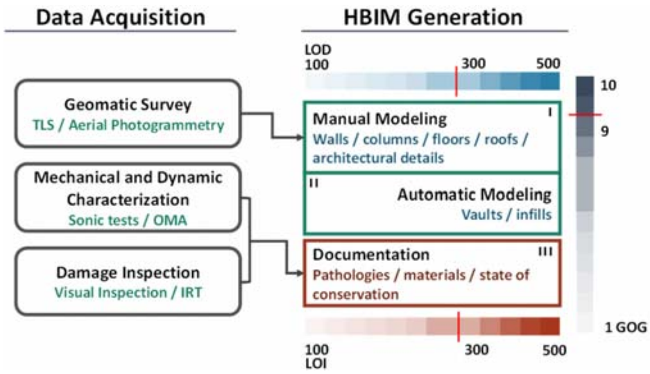

Fig. 1 Methodology adopted in the present investigation

III. DESCRIPTION OF THE CASE STUDY AND DATA ACQUISITION

The Loreto Chapel is located on one side of the Society of Jesus church in Cusco, Perú. It is estimated that it was built in the mid-16th century, but it was severely damaged in the earthquake of 1650, so it had to be rebuilt in its entirety. It is a single nave chapel with barrel vaults and one little dome. The vaults and arches are made of brick masonry and the walls and columns are mainly made of andesite stone masonry. It also has a connection to other room where some bathrooms are located and has a closed span which leads to the main nave. At present, the chapel is open to the public as it is used as a museum and a place to sell handicrafts. Some pictures of the Loreto chapel are presented in Fig. 2.

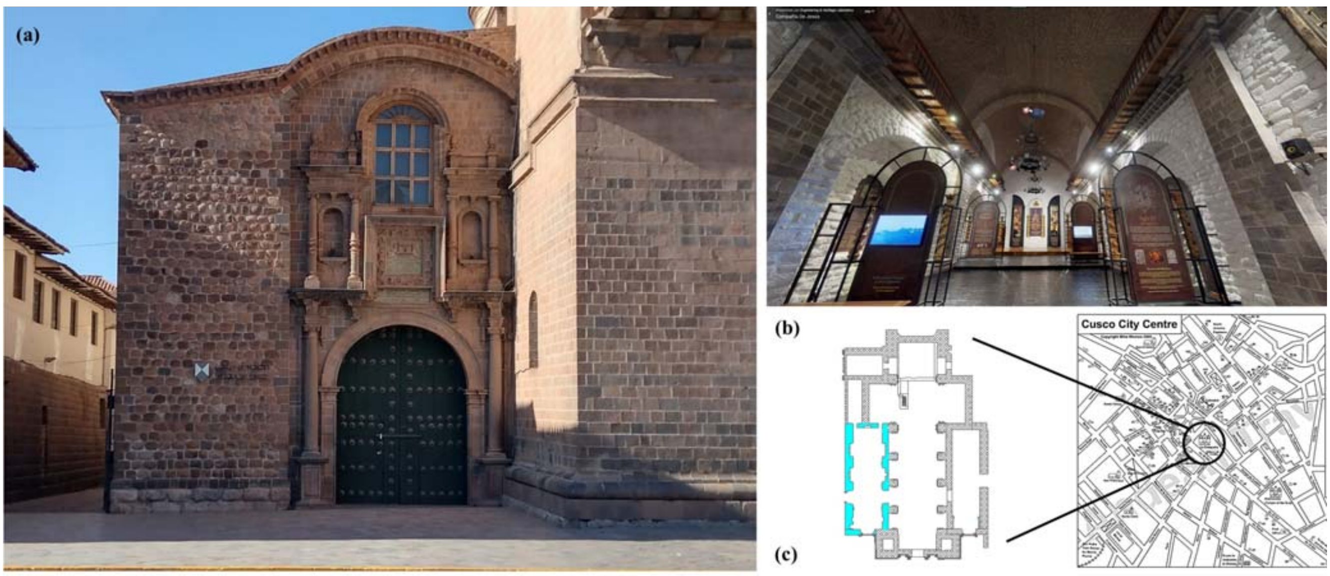

Fig. 2 Loreto chapel: (a) main façade, (b) interior, and (c) location

Data acquisition consisted of a set of non-destructive testing. For geometrical survey, Terrestrial Laser Scanning (TLS) and aerial photogrammetry were used. All the information was registered and filtered with Leica Cyclone [28] software for the

TLS survey and Agisoft Metashape [29] for the photogrammetry survey. Geomagic Design X [30] was used for unify the point clouds, and then was imported in Recap Pro for cleaning and visualization. Fig. 3 shows the final point cloud of the Loreto chapel.

Fig. 3 Point cloud of the Loreto chapel

Sonic testing and infrared thermography (IRT) were used to evaluate the state of conservation of the materials. Also, dynamic elastic modulus (E_D) was estimated for some walls with the sonic test information. Visual inspection also was carried out in order to register different structural pathologies (e.g. moisture stains, black spots, cracks, among others). Finally, Operational Modal Analysis (OMA) also was applied to characterize the dynamic behavior of the structure.

IV. Scan-to-BIM Procedure

A. Geometric Modeling

The manual modeling process was carried out using the point cloud as reference in the Revit environment. All the walls were created using the native families of Revit, which correspond to the wall family. This was necessary to automatically attach the upper part of the walls to the roofs, which were created as roof families. For the latter, it was necessary to create a mass family to fit the point cloud, and then use the upper faces of this mass family as a reference for modeling. A constant thickness of 0.10 m was assigned to the roof families, which corresponds only to brick tiles. Near the little dome of the chapel, the roof's form adopts a particular curvature, so in order to fit the geometry to the point cloud, Dynamo programming was necessary. A code was developed in order to create a surface from patching a closed curve, and then use the surface to create the roof. Besides, the majority of the spans were created as generic void families using the extrusion and blend commands that Revit includes.

Aiming at transferring the loads from the circular shape of the dome drum to a rectangular shape with four supporting corners, a structural element called a pendentive is required. The modeling of this element was necessary in order to adequately represent the structure following the construction process. A Dynamo code was developed to create this element by assigning the dimensions of the quadrilateral in which the pendentive will be embedded, as well as the thickness of the pendentive. The results are the pendentive and the infills that go between the pendentive and the upper drum, which are usually made of a different material. A detail of these elements can be seen in Fig. 4.

Fig. 4 Detailed view of the pendentive, infills and dome of Loreto chapel

The creation of the vault system was the most time-consuming part of the geometric modeling. Due to its particular forms, it was necessary to develop a code in Dynamo to automatically create the vaults and infills. The approach used consisted of the creation of a parametric mass family based on 3D lines that serve as input for the Dynamo code (see Fig. 5). All the parameters such as width, length and height of the arches are controlled with the mass family's parameters to fit the point cloud and can be used for the three different vaults located at the Loreto chapel. Once all the parameters are established, the Dynamo code is run and all the 3D solid geometries are obtained.

The main advantage of this approach is that no external software is needed to create complex geometry. The whole process was carried out inside the Revit software with Dynamo plugin. The interaction between Revit and Dynamo interface is intuitive and allows the user to select various elements inside Revit, use them as input for the generation of new geometry inside Dynamo, and then import the new geometry into Revit as a family instance or as an imported SAT file. This last option was adopted for several complex geometries since the first method gave errors when trying to use it.

According to [25], the modeling process can achieve a GOG that depends on the modeling techniques used. This scale goes from 1 to 10, where the first eight values correspond to basic extrusion, sweep, blend, loft, reveal and revolve operations that are included in almost all 3D modeling software. The last GOGs 9 and 10 are based on the creation of NURBS surfaces from a 3D wireframe or a set of points respectively. To achieve these high GOGs, external free form modeling software is required to generate the NURBS surfaces (e.g., Mc Nell Rhino [31], Autodesk AutoCAD, Autodesk Inventor, Solidworks [32]).

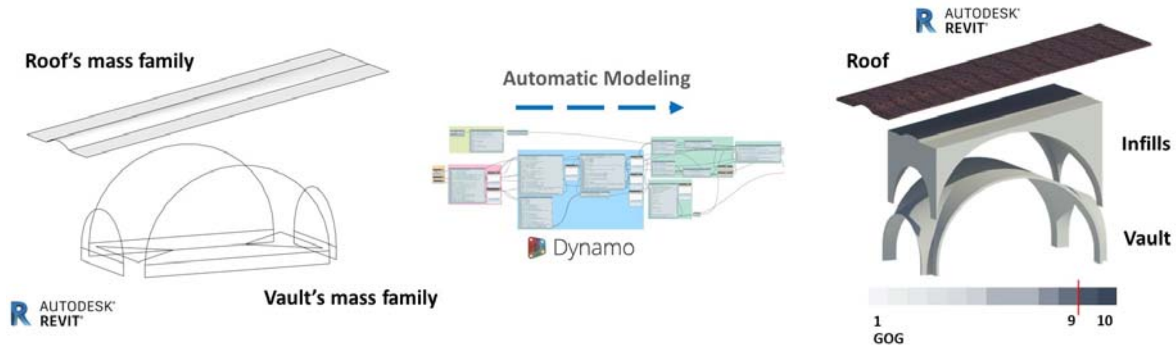

Fig. 5 Automatic modeling process of the vaults, infills and roofs of the Loreto chapel: from 3D wireframe to 3D solid geometries

As can be seen, the methodology used in this investigation for the generation of the vault system is very similar to the GOG 9 proposed in [25]: a set of outer and inner curves are used to generate surfaces which are then assigned a constant thickness. The difference is that the entire modeling process is performed in the Dynamo interface and does not require the use of any external free form modeling software.

Finally, the architectural details were modeled based on parametric families of generic models. The process consisted of defining the sections and values to be parameterized and then creating the families based on extrusion, blend, sweep and revolve operations. An isometric view of the HBIM model of the Loreto chapel is shown in Fig. 6.

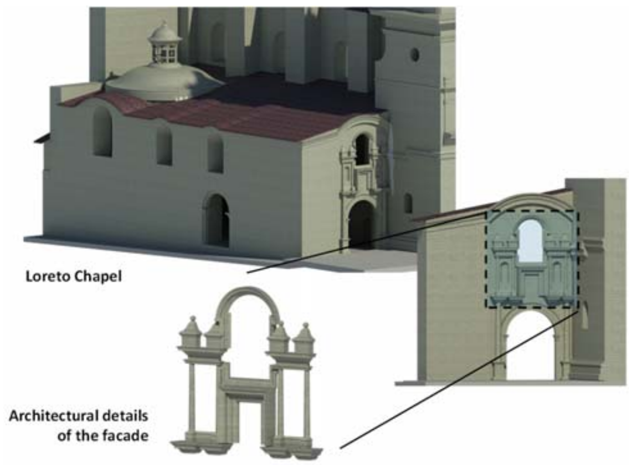

Fig. 6 Isometric view of the HBIM model of the Loreto chapel

B. Structural Documentation

The non-destructive tests performed on the structure (e.g. sonic tests, OMA, IRT) involve information that needs to be attached to the HBIM model, either because it is necessary to identify the areas in which they were performed or because they indicate particular properties of certain areas of the structure. As mentioned in [33], BIM tools provide a comprehensive understanding of the structure and help optimize maintenance, preservation and information management processes, thanks to their ability to integrate and manage both geometric and non-geometric information in a virtual model. In this sense, the need to integrate diagnostic information within the HBIM model is imperative today to carry out documentation, conservation and restoration projects of heritage structures. In order to carry out this task, the time and complexity involved in creating physical elements within the model that represent the structural pathologies must be taken into account. References [20] and [21] have shown that it is possible to create elements and assign visual properties within BIM software for damage mapping. To do this they use adaptive components that adapt to the different curvatures and complex solid shapes that exist in heritage structures. A similar approach is used in this research, with the difference that Dynamo is used for the creation and visualization of the pathologies. A reference plane is created parallel to the surface where the pathology will be projected. Then, the shape of the pathology is drawn as a closed planar curve on the reference plane, and a Dynamo code is run that takes care of projecting the 2D curve on the surface and creates the pathology as a generic element family with a very thin thickness. The advantage of this method is that it allows to project planar drawings on curved surfaces such as vaults and domes, or even on more complex elements such as cornices in a user-friendly way, as can be seen in Fig. 7.

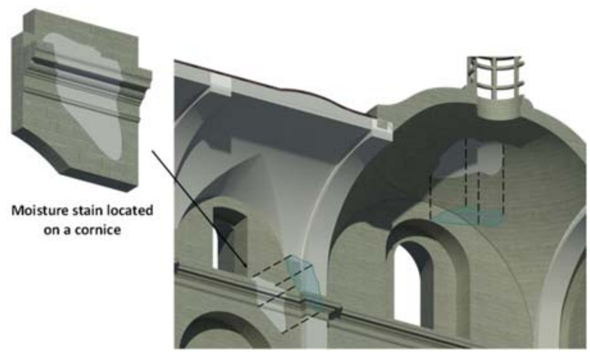

Fig. 7 Physical representation of pathologies within the HBIM model

Once the pathologies have been added to the model, non-geometric information such as pathology type or severity must be added so that they can then be classified and different colors can be assigned to each based on their nature. Since this is an initial version of the model, generic names and colors have been used for each type of pathology. However, in order to standardize the results, it is planned to use the classification developed within the HeritageCare project [23] in future work, in which the types of pathologies are divided into classes, sub-classes and sub-sub-classes, as well as having specific colors to represent each of them.

In order to obtain damage maps based on the pathologies reported in the HBIM model, visualization filters and a Dynamo code were used to display elements of different colors based on the type of pathology: moisture stains, structural cracks, mould stains, detachments, black spots, swelling of the plaster and bird droppings. Fig. 8 represents the damage map of the Loreto chapel façade. It can be seen that there is a different quality of stone masonry in the same wall. This is probably due to restoration works carried out in the past. Besides, there are some mould stains mainly located above the door's top cornice, probably due to the accumulation of rainwater and lack of cleanliness. This structure has no severe cracks, except one located in an architectural column of the façade. Likewise, there are also black stains due to dust and water, mainly on the cornices of the façade.

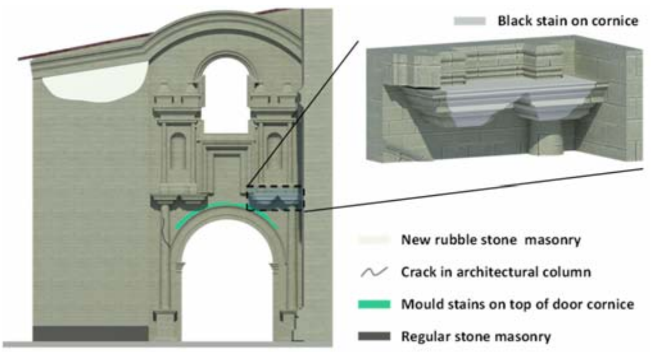

Fig. 8 Damage map of the Loreto chapel façade

It is important to visualize the state of conservation of the structural elements of a structure, especially if restoration and maintenance processes are to be carried out. Having damage plans that can be easily obtained and can be updated just by changing some parameters is of great relevance, and the BIM environment makes this possible. By means of project parameters, parameters such as the state of conservation of the structural elements were assigned, classifying them as good, regular and bad. Likewise, non-destructive testing location parameters such as sonic testing and OMA testing were also assigned, making it easy to locate the areas where the tests were performed. Then, using visualization filters, damage and test location maps were created, as can be seen in Fig. 9.

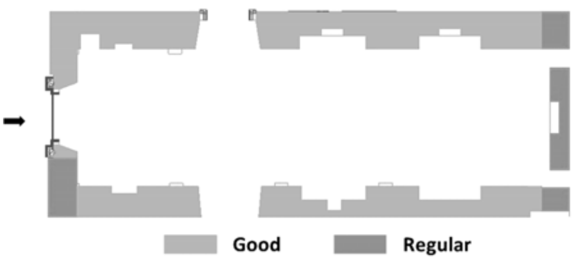

Fig. 9 Layout of the state of conservation of the walls of the Loreto chapel

V. Conclusions

The potential of the HBIM methodology for the management of heritage structures is highly dependent on the modeling techniques and information management implemented. In this sense, the present research shows the application of a modeling approach within the HBIM methodology. The case study is a 16th century stone masonry chapel located in Cusco, Peru. A three-stage modeling process has been followed, going from the point cloud obtained by TLS and aerial photogrammetry to the creation of an HBIM model in Revit software and the corresponding documentation of the information collected on site. It is possible to obtain models with an acceptable LOD and LOI for the 3D representation of heritage structures, not only with geometric information, but also with diagnostic information such as structural pathologies and the state of conservation of the elements. As several works have already demonstrated [5], [14], [33], the next step is to properly manage the information within the model, relating external databases, creating plugins for BIM software that allow better interaction and unification of information, in addition to generating a more user-friendly experience for the virtual documentation and management of heritage structures.

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