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

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ABSTRACT
This article presents a case study on the virtual modeling and reconstruction of Architectural Heritage building. The graphic and semantic information required determining the conservation status of the building, obtained from point clouds and historical and bibliographical data, are combined. The different components are modeled manually by using commercial Building Information Modeling (BIM) software, and used to create a library of parametric elements under the concept of Heritage Building Information Modeling (HBIM). This represents a solution for the 3D modeling of a wide range of buildings in the same style, due to the flexibility of the modeled elements that can change in shape and proportions, thus adapting to new requirements. Moreover, technical documentation and quantitative and qualitative information can be produced, allowing detailed analysis to be carried out in a remote and multidisciplinary way within the general framework of "Smart heritage".

KEYWORDS
3D; cultural heritage documentation; graphic/semantic information; HBIM; smart heritage

1. Introduction
Heritage is considered to be everything that has a universal value from the historical point of view through art or science, such as named monuments, buildings or landscapes, and can be divided into tangible or intangible (Simeone et al. 2014; Vecco 2010). In particular, architectural heritage is threatened by environmental conditions, structural instability, increased tourism, etc. (Ibañez et al. 2015).

Performing restoration or rehabilitation works on architectural heritage is often difficult. This is due to several problems, such as the lack of technical documentation and information about the status, shape or composition of the different elements (del Giudice and Osello 2013; Tomažević and Lutman 2007). Therefore, the collection, storage, and processing of all kinds of information about the buildings is required to determine their current state, defects, or pathologies, the architectural style and the different stages of their construction (Alsadik, Gerke, and Vosselman 2013).

Nowadays, a high level of automation can be achieved through the use of 3D scanning and photogrammetry technologies, which allow the collection and further processing of spatial data to be accelerated. In particular, laser scanners provide a large amount of three-dimensional data in a short time, under the form of millions of points (Figure 1A) (Gómez-García-Bermejo et al., 2013). Moreover, color data can also be incorporated by using digital cameras (Figure 1B) (Lerones et al. 2014). However, handling the said amount of data requires large computational resources.

In order for the point clouds to be useful, several steps should be taken, such as cleaning and filtering. Moreover, the processed point clouds could be incorporated into Building Information Modeling (BIM) platforms, which have emerged in recent years as a means to integrate building design. According to (Baik, Yaagoubi, and Boehm 2015; Logothetis, Delinasiou, and Stylianidis 2015), BIM methodology allows 3D models to be generated with such parametric information as specifications and technical drawings (2D), the geometric properties in a collaborative model (3D), constructive programming (4D), the definition of amounts and costs (5D), sustainability of the project (6D), and their life cycle (7D), thus turning a simple graphical representation into a virtual project with real
conditions (Azhar 2011). An example of the semantic organization and parameters of a given object can be seen (Figure 2). The properties of each constituent element can be modified by changing the numerical values in the table. Every object in a BIM environment has a particular parametric representation, so BIM platforms have the ability to import, manipulate, and manage graphical and non-graphical information, as well as the semantic data describing each element in the model (Cheng, Yang, and Yen 2015).

Often, when thinking about architecture, engineering or the construction industry, new construction, and projects are considered. For this reason, the libraries of the BIM platforms are geared primarily for the design of new buildings. The reconstruction of cultural-historical heritage has revealed some limitations of BIM, such as the unavailability of historical parametric object libraries and the lack of tools for managing complex and irregular shapes obtained from point clouds. Moreover, obtaining parametric 3D models of the building elements from the point clouds is often a time-consuming process. Therefore, once the 3D models are created, libraries of the modeled elements should be generated, thus encapsulating the concept of Heritage Building Information Modeling (HBIM). Thus, the design process of the actual model and a wide range of buildings in the same style will become simpler, clearer, and quicker.

Figure 1. (A) Georeferenced point could, \((X, Y, Z)\). (B) Georeferenced point could \([(X, Y, Z); (R, G, B)]\).
Source: Own figures.
1.1 Hbim

The HBIM concept was first used in Murphy, McGovern, and Pavia (2009), from the Dublin Institute of Technology. According to Dore et al. (2015) and Murphy, McGovern, and Pavia (2009, 2011), HBIM is a special library of BIM parametric objects that was created as a multidisciplinary and constantly evolving system. Generally, the HBIM library is built using the architectural historical documentation and the data obtained from the physical analysis of the building in question. The new components will allow 3D virtual models of any project with similar character and style to be generated, thus approaching a solution for reverse architecture.

The components of the HBIM library have the opportunity to develop details stored behind the surface of the objects regarding their construction methods and materials (Dore et al. 2015; Quattrini and Baleani 2015). This provides a better reading of architecture thanks to the semantic organization. In addition, the components of this library can be used as patrimonial visualization models, and to produce such technical documentation as floor plans, elevations, section cuts, details, and perspectives in a semi-automated way. Historical analysis of the structure, energy simulations, calculating times and costs, as well as other functions, also become possible. All this provides the best way to manage the process of restoring the analyzed buildings. It also becomes possible to understand the heritage buildings that are not documented and
to know their materials and construction techniques, observe the pathologies, and assist maintenance and restoration efforts.

1.2. Complementary research

Several research works have combined point clouds and BIM software to meet the virtual modeling of architectural heritage. A set of instructions, rules, and algorithms are proposed in Dore and Murphy (2012), which are restricted to the use of a methodology that morphologically represents a unique architectural period, while several BIM-related programs are used to build 3D models that can be part of the future HBIM library.

Other authors, such as Baik et al. (2014, 2015) and Oreni et al. (2013) propose a series of steps to perform the reconstruction of a historical library of entire buildings from the use of point clouds. The inability of BIM programs to model irregular and complex surfaces is noted and the use of such specific software as Rhinoceros 3D or Bentley is proposed to model complex surfaces from the point clouds. Then, the solid objects obtained are exported to BIM software, where each element can have parametric information about the materials, conservation state etc. added, thus creating the HBIM library.

The work presented by Quattrini et al. (2015) defines the components to be modeled depending on their typology, hierarchy, and material. Each element is modeled directly on the point cloud without using cuts or sections. Reference lines are used to mark the distances in the point clouds. Regular surfaces are modeled with the Revit software tools. Complex surfaces are created in B-Rep and the results obtained are exported to Revit. Details about the constructive parameters used to model the different elements are not given.

Simple surfaces are modeled in Barazzetti et al. (2015) using tools and solid objects of Revit software, such as columns, walls, windows, etc. Then, the plug-in “NURBS” is used to represent the complex or organic surfaces and convert them to solid elements.

Finally, another approach for accurately modeling the buildings under study is presented in Murphy, McGovern, and Pavia (2011). A series of bibliographical studies representing proportions, rules, and patterns of the different elements are used for performing cuts and sections. However, these actions do not follow a logical order, thus making the precise modeling of the architectural components difficult.

To summarize, the presented approaches suffer from some relevant difficulties. In particular, when the modeling of architectural components is addressed on point clouds by using intermediate software, as in Baik et al. (2014), Barazzetti et al. (2015, 2014), Oreni et al. (2013), and Quattrini et al. (2015), there is no guarantee that the complete information extracted from the point cloud is preserved. This will lead to disadvantages such as the impossibility of having a global perspective on parameterized objects and corresponding point clouds. Moreover, the independent, separate modeling of the different objects would result in information loss from the viewpoint of conceiving a general perspective of the buildings.

For this reason, a case study based on the use of point clouds and the constructive patterns corresponding to the historical architectonic periods is presented in this article, which allows the simple and complex forms found from the analyzed heritage buildings to be modeled in situ. In addition, the process followed is considered an efficient solution for overcoming some limitations of BIM software, demonstrating that it is possible to model a complete heritage building.

1.3. Aim of the article

In this article, the conversion of laser or photogrammetric data into HBIM elements grouped in a library, adapted to the particular characteristics of historic buildings, is addressed. To this end, cuts, sections, views, grids, and reference lines are used, which follow the norms, rules, and constructive patterns analyzed in the bibliographic data corresponding to the actual historical architectonic periods. The aim is to create a fast and semi-automatic modeling of the objects from the use of point clouds within a real case study: a monument of the Spanish Romanesque period. However, similar ideas could be applied to buildings of any other period, provided that the said instruments are adapted to the corresponding construction method, technology, typology, and materials.

2. Process description

The process followed in the present case study consists of three main steps that are presented in Figure 3. Each step is analyzed in depth in the following subsections.

2.1 First step

This step concerns the collection of historical data, which we consider as non-graphic or semantic information, and the graphic or spatial information.

Our case study focuses on an 11th century Romanesque church. Therefore, a bibliographical study of the norms, rules, patterns, and architectural proportions of this construction period has been carried out. The work of Lorente & Francis (2007) describes the modules and proportions characterizing the plants and elevations
of the Romanesque period according to simple geometric shapes, such as triangles, squares, or circles. A comparison between the figurative plant concerning modules and proportions obtained from Lorente & Francis (2007) and the projection used in the current work is shown in Figure 4A. Moreover, the work of Kimball and Edgell (1918) helps us to understand the repetitive modules that will determine the measurement patterns, distances between sections and number of sections, etc. A comparison between the section on a system of repetitive modules obtained from Kimball and Edgell (1918) and the projection performed in the present work can be seen in Figure 4B. Furthermore, the work of Jackson (1920) is used to make a comparison between a prototype of a richly decorated arch with organic and figurative forms, and the arch used in the current work, as shown in Figure 4C.

Another key aspect is the way the graphic or spatial information data is collected. Laser scanners can provide a point cloud that spatially demonstrates the visible parts of the (internal and external) surfaces of a building. The process of working with a laser scanner is divided into three main stages. First, the general work plan is conceived (Figure 5A), and the scanning locations are selected on this plan. Then the fieldwork, i.e., collecting scanner and/or topographic data, is carried out in Figure 5B and Figure 5C). Finally, the scanner is placed at the defined locations, according to the plan, to prevent hidden areas or shadows in the point clouds (Figure 5D), and data are then collected.
2.2 Second step

In this step, data from the previous step are analyzed and organized for feeding into the BIM environment. In particular, the point clouds obtained from a number of positions of the scanning device have to be registered and merged. To do this, a certain overlapping between adjacent point clouds (i.e., 20–30%) is required. Of course, the set of point clouds should cover the entire building. Moreover, the registration of the point clouds is commonly performed by using an Iterative Closest Point (ICP)-based algorithm (Besl and McKay 1992). This is an optimization method that starts at a first, rough approach of the transformation, and drives one point cloud towards the other. Frequently, the initial alignment is user-aided by selecting characteristics in the common overlapping area (in our case, we have used Polyworks software). Then, the transformation parameters are refined through the decrease in a mean square cost function, which measures the distance between the two point clouds at the overlapping regions. Refinement is iteratively repeated toward an optimum, until convergence is reached.

Subsequently, so that the raw point cloud can be usable, a series of steps, such as cleaning and filtering, are performed. Cleaning and filtering are carried out using specific point cloud handling software (such as Polyworks). This is generally a user-aided process, because some high-level interpretation of the scene may be required (e.g., cleaning

Figure 4. (A) Figurative plant about modules and proportions. (B) Section about a system of repetitive modules. (C) Prototype of a richly decorated arch, typical of the Romanesque entrances.

Source: (A) adapted from Lorente and Francisco (2007); (B) adapted from Kimball and Edgell (1918); (C) adapted from Jackson (1920).
points from trees, people, or outliers in the scene). Finally, the obtained cloud will be indexed to the BIM environment. Moreover, in this second step, the information obtained from the historical documents, images, construction methods, and dimensional data are analyzed and organized. The entire set of data is compared against the technical and historical construction details of the different architectural periods, in order to complement the specific records of the processed point cloud. This feedback between the spatial and semantic data allows the complexity of the modeling process required by the HBIM library to be reduced.

2.3 Third step

Finally, the data can be imported and stored in the BIM environment, and the accurate and efficient modeling of the different architectural components can be addressed. The modeled components are then incorporated into the HBIM library and represent the 3D model of the building. Moreover, analyzed buildings or monuments often suffer from different pathologies or deformations derived from the passage of time or structural problems, such as sloping walls, cracks or missing items. Point clouds provide the actual shape and spaces of the buildings, which is important for achieving an accurate modeling of each component.

In order to address the accurate modeling of the architectural objects, the elements are first classified into regular and irregular surfaces. The classification criterion is given by the complexity of the shape, evaluated upon the amount and type of details. On the one hand, such elements as capitals, archivolts, and ornaments, which have many details, will be assumed to be irregular or organic surfaces. On the other hand, such simple or uniform elements as columns, walls, windows, and doors will be assumed to be regular surfaces.

Thanks to the graphic information of the point clouds and the knowledge of the rules and constructive patterns of

Figure 5. (A) General scanning work plan. (B) and (C) Scanner positioning. (D) Simulation of hidden areas.
the architectural period the building belongs to, a design of multiple views, cuts, and sections made on the point cloud is created. The information obtained from these actions will allow the actual monument to be modeled.

In our case, the analyzed building belongs to the Romanesque architectural period. First, the point cloud representing the monument is inscribed in a section box (Figure 6A), i.e., a conceptual tool that delimits the 3D model used to carry out the different cuts. To be precise, the cuts are made on the point cloud in longitudinal and transversal directions, following the divisive concept of the current architectural period. These cuts will be the head, body, and foot (Figure 6B) of the monument, and will serve to show the composition and internal layout of the building, as well as to generate an estimate of the dimensions of the various elements and surfaces.

Subsequently, a set of grids is created on the planimetry (Figure 7). These grids are finite surfaces seen as straight lines, arcs or multi-segments at a given level. These grids, which cross through the middle of the point border regions, are responsible for marking the outline of the cloud surfaces. Moreover, each line serves as a reference to extract the current distances.

The resulting views of the point clouds, which the BIM platforms usually divide into North, South, East, and West, will be used as a profile to delimit the use of levels at different model heights (Figure 8A). These levels are finite horizontal planes that constitute a reference for determining the vertical distances between one point and another. Following the constructive logic of the abovementioned architectural period, and according to Schuermans et al. (2007), the levels will be placed on the basis of the materials that were used, these materials being the masonry or ashlar stone that are styled, parallelepipedic blocks. The approximate size of the stones may range from 40 to 200 cm in length, 30–60 cm in height and 4.5–35 cm in thickness (Figure 8B). Moreover, on each plane obtained automatically through the use of the abovementioned levels, the grids previously created (or new ones) are used for marking the cloud.

Once the said actions have been completed, the section planes are manually traced out on the major plant provided by the point cloud (Figure 9A). The planes cross the center of the structural or supporting elements that compose the building (walls, pillars, columns, arches, and vaults in the case of the constructive logic of a Romanesque monument). This strategy allows the deformations that affect the elements or the morphological profiles to be reflected more accurately and clearly (Figure 9B). Then, vertical grids are traced on each section to perform the same function described previously. New levels at additional heights can also be used, if necessary, to verify each component more accurately.

After completing this procedure, thanks to the levels, dimensions and grids, the point cloud will be represented by closed, sized polygons, thus allowing the cloud to be used as a guide for modeling the different architectural components.

When the geometry of a given surface is uniform and simple according to its appearance in view, section or elevation, the modeling will be performed using the basic tools of BIM environments. In addition, the parameters of the objects already in the BIM internal library, such as walls, windows, doors, or columns (Figure 2), will be modified and adjusted to best describe the current component of the building. Moreover, the modified objects can be readily put in place on the project following the grid lines, levels and cloud sections.

On the other hand, when the geometry of a surface is irregular or complex, the modeling mainly starts with the sketch of vertical and horizontal reference planes on a 2D work plane (Figure 10A). These planes allow lines and geometries used to generate the profiles of the architectural component to be drawn. In order to accurately model each profile, the images representing the frames and proportions of the current element will be inserted, and the perimeter of the shape will be drawn on these images using the model lines (Figure 10B).

Subsequently, now in a 3D work environment, the use of reference lines is the key to generating the 3D virtual model (Figure 10C). These reference lines are actually useful for drawing the profile of any element. Reference points will be plotted on the reference lines, and it is these points which are responsible for linking the 2D profiles to the reference lines. Then, the BIM modeling tools, such as extrude, revolve, union, path union, empties, solid sweep, and void forms, are used for creating the solid geometry of each designed element. At the end of this action, the parameters concerning size, materials, textures, real images, and historical data of each obtained element are created (Figure 10D).

The elements modeled this way simulate the building in 3D. These elements are then incorporated into the design of an HBIM library. This library will be connected to the database of the different elements, thus giving the opportunity to change the shape of the architectural components by tuning the corresponding parameters, which represents a solution for recurring 3D modeling of a wide range of buildings in the same style without having to start from scratch.
The implementation of this new HBIM library requires the level of detail and simplification of the objects to be considered, so that each parametric element will be suitable for conservation or restoration projects or model construction. The Standardized Level of Development (LOD) protocol of the American Institute of Architecture (AIA) will be used in this article (BIM FORUM, 2016).

The concept of this HBIM library is to be used as a complement to existing BIM software platforms within a general framework of “Smart heritage”. In order to make the existence of interoperability between different BIM software platforms possible, BuildingSMART has developed a common data structure called Industry Foundation Classes (IFC), which deals with the

**Figure 6.** (A) Longitudinal section of the point cloud. The section box is highlighted with a red dashed line. (B) Church Foot.
maintenance and exchange of relevant data between different software applications (Ochmann et al. 2014).

3. Results

The described process has been applied to the church of "Santa María la Real de Mave", a monument of the Northern Spanish Romanesque period (Figure 11A). This church is located within the monastery of Santa Maria, in the village of Santa María de Mave (Aguilar de Campoo, Palencia, Spain) (Figure 11B).

The said building dates from the first half of the 11th century (Wikipedia, 2015). Its current appearance is the combination of its constructive history and the reforms carried out in the 16th and 17th centuries (Romanico norte, 2015; Arquivoltas, 2015; Arte guias, 2015). The current neoclassic cloister was built during this last period. The church has a basilica plant, divided into three naves, with three articulated aisles topped by a triple head of semicircular apses. The flashlight tower is crowned with pendentives and a polygonal dome. The basilica plant and its distribution can be seen in Figure 12. Three pairs of cruciform pillars with semi-columns adjoining on every front, with the exception of the side arches, delimit the three longitudinal sections of the naves and arms of the transept. The central nave is covered by a barrel vault, and is separated into three sections by pointed arches.

Obtaining graphic information on the dimensions, proportions, shape, and state of the church of "Santa María la Real de Mave" can be an overwhelming process, due to the paucity of public data about this monument. To solve this problem, the workflow presented in this article has been followed, combining point clouds and historical sources.
The entire church was covered by 31 scans taken from an average distance of 20 m, to a 4 mm standard deviation accuracy (Figure 13A). The result was a cloud of more than 11 million points. Specifically, 18 scans were taken from the inside (Figure 13B) (7.5 million points) and 13 scans from the outside (Figure 13C) (3.5 million points). A Leica HDS3000 3D “Time-of-flight” scanner was used for data collection. In addition, a Canon PowerShot G6 digital camera (7.1 megapixels) was used to collect a total of 135 photographs that represent the actual appearance of the church.

Autodesk® Revit® 2015 software has been used to model the building. This software is an efficient BIM platform suitable for accurately modeling both regular and irregular surfaces, and the geometric anomalies of the different elements. According to Baik et al. (2014), this software has a number of advantages. In

Figure 8. East view of the point cloud with ashlar levels. (B) Approximate stone size.
particular, it allows a quick creation and change of the 3D model, and also generates construction documents with a high level of quality and flexibility. In fact, Revit provides us all the necessary tools to implement the case study.

It is worth noting that, according to (Help Autodesk REVIT 2015 2017), Families are the elements on which the Revit structure is based. A "Family" is a group of elements with a common set of parameters and a related graphic representation. Different elements belonging to a particular family, with different values of some (or all) of their parameters, are called a “Family Type”. In turn, the families created from a “Family Template” with a set of similar parameters are included in a higher-level entity called “Category”.

The families can be classified according to their source in System families, Loadable families, and In-place families. System families are predefined and internal elements of each Project Template (.rte)

Figure 9. (A) section planes are traced out on the major plant provided by the point cloud. (B) Longitudinal section with the inclinations of the walls marked in red. Inclination is less than 1% in all cases therefore there is no danger of collapse.
that has been selected to start a new project (.rtv) in Revit. Loadable families are created and modified in external (.rfa) files and imported, or loaded into (.rtv) projects. In-place families are unique elements that are used to model a particular element that will not be reused. These types of families cannot be inserted into other Projects.

The virtual model of the church has been built using two kinds of “Revit Families,” System families and Loadable families. Revit Families allow us to work with components located in the program library to model surfaces with simple geometries, while System families are used because they allow us to export or import the exclusive and specific components, modeled or custom made, in an external file.

The walls have been assumed to be regular surfaces, and have been modeled using the “Architecture” Revit tool. This tool allows a “Family wall” to be created, that already exists in the Revit internal library, to represent the requested surface. Mainly, the Basic Wall has been selected. This family presents, by default, a series of standard parameters (Construction, Graphics, Materials and Finishes, Analytical Properties, and Identity Data). A number of modifications have been made to these parameters in order to adapt the wall to the current project.

In the “Construction” parameter, the thickness and material type have been changed. In the “Graphics” parameter, the fill-in color has been changed. The default “Materials and Finishes” parameter

![Figure 10.](image-url)
changes when modifying the propriety of materials and finishes, in the “Construction” parameter. In the “Analytical Properties” parameter, the properties and coefficients change automatically when making changes to thickness and material type. Finally, for the parameter “Identity Data” has been added images from real views of the church. A representative example can be seen in Figure 2.

Moreover, vaults and arches, which are important parametric objects for church architecture, have also been assumed as regular surfaces. The arches have been modeled with the same “Family wall” used for the church walls, but using a lower thickness value in the “Construction” parameter. The set of arches is shown in Figure 14A. In turn, the vaults have been modeled using the “Architecture” Revit tool for creating a “Family Roof”. Once the Basic Roof type is selected, the types of parameters to be modified will be the same as in the above mentioned “Family wall”. The set of vaults and their modified parameters are shown in Figure 14B. It is also worth noting that walls, arches and vaults have been built as “System Families”.

Moreover, reproducing the rich ornamentation of the Romanesque Architecture is hard work. Therefore, the ornaments of the main entrance and the cruciform columns have been considered irregular surfaces and

Figure 11. (A) South facade of the Santa María la Real de Mave Romanesque church. (B) Location of the monument. Source: (A) Adapted from http://www.flickr.com/photos/rabiespierre/tags/klaster/. (B) Adapted from http://www.bing.com/maps/.

Figure 12. Basilical plant divided into three naves. The main entrance and the bell tower are developed on the foot. The section of the three articulated naves and the flashlight-tower are developed on the body. Finally, a triple semicircular apse is found on the headboard.
have been modeled externally by creating “Loadable families,” thanks to the use of the aided procedure described in the previous section. These elements may be reused in future projects with a similar architecture.

“Family Entrance” model has been created externally and is part of the “Generic Model” category of the virtual model. In addition, the “Family Entrance” contains several types, such as Archivolt, Capital Base, Main Base, Capital, Front Column, Capital Cornices, Entrance Wall, and Window.

The archivolt that enhances the main front has been divided into several individual arches that are considered as sub-types of the Arc type. The construction sequence of an arc mainly begins upon the creation of a new family template called “Metric Generic Model face-based,” that will allow work to be done on a 2D work plane. Then, the reference planes are sketched, and the perimeter of the shape is drawn on these planes using the model lines (Figure 15A). Once the object profile is diagrammed, a series of parameters will be created so the geometry of this profile works correctly in the next step.

The created parameters are: “Restrictions,” whose properties represent the geometric dimensions of the diagrammed profile; and “Dimensions” and “IFC Parameters,” whose Modulo property allows the value property of the other parameters to be modified or scaled (see Figure 15D).

Subsequently, in a 3D work environment called “Metric Generic Model Adaptive,” the reference
lines are used to draw the arc profile (Figure 15B). Then, at the end of this reference line, the reference points responsible for linking the 2D profile to the current working environment are plotted. Next, the tools mentioned in Section 2.3 for creating the solid geometry of each designed element are used (Figure 15C).

“IFC Parameters” and “Identity Data” parameters were created for the elements “Restrictions,” “Materials and Finishing,” and “Dimensions”. The properties and operation of these parameters are similar to those described above. The differences lie in the value given to each property. Other differences correspond to the “Materials and Finishing” parameter, which represents the 3D object, and the designation of an image type in “Identity Data” (Figure 15E).

The capital has been modeled in three sections. The first section refers to the sub-type “capital base,” which is modeled as a cylinder. The other two sections refer to the leaf sub-types that decorate the capital base. The leaves have been modeled in 3D, using the reference lines and several reference points, to give the curved shape to the different levels of the model, as can be seen in Figure 16A.

The whole main entrance modeled in the project, with all its components, can be seen in Figure 16B. Each component profile has been designed according to the size and shape extracted from the point cloud.

Furthermore, the “Cruciform Column Family” has been modeled externally too, and is part of the “Generic Model” category. The object types within this family are classified into Column Base, Terraced Column Base, Capital Terraced Column, Column Centre, and Terraced Column. Figure 17A shows one of the cruciform columns. The
representation of the types and sub-types that conforms the modeled families is shown in Figure 17B. A longitudinal section of the church showing the cruciform columns can be seen in Figure 17C.

In this context, and according to the obtained results, the capital has been modeled to demonstrate the three main (LODs) used in heritage rehabilitation and maintenance projects. These (LODs) are: LoD 200 (generic models); LoD 300 + 350 ( executive planning). The levels are displayed in Revit as “Low, Medium, and Fine”. Each level is suitable for the designated use, as can be seen in Figure 18.

Once the components have been modeled, they could be used as comparison objects with information about their actual size, derived from the point cloud. In addition, these components could also be used to automatically produce technical documentation, such as floor plans, elevations, section cuts, details, and perspectives. An example of a longitudinal cut carried out on the model is shown in Figure 19A, and an example of a cross-section can be seen in Figure 19B.

4. Conclusions and future lines

In this article, a case study has been presented on the use of point clouds and the constructive patterns for creating a BIM model of a heritage building, serving as an example for simplifying the work of architects, engineers, builders and other professionals involved in architectural heritage.

The laser scanner is a suitable surveying instrument that allows a dense point cloud of the buildings to be acquired. The collected data, after proper digital processing, can be introduced into BIM systems regardless of whether these systems are primarily based on simplified parametric models more suited to modern architecture or industrial elements. Ideally, BIM platforms would allow architectural
components to be built automatically from point clouds. However, in practice, human intervention is required to a certain extent, in order to model the different elements.

The monument analyzed in this work, Santa María la Real de Mave, is an 11th century Romanesque church. The building has been completely modeled and each architectural component has been parameterized. The components of the “Family Entrance” may be adapted to other monuments belonging to the same period and architectural style, thanks to their flexibility. For this reason, this family has been incorporated into the HBIM library.

The virtual models obtained in this way can be used to carry out structural, energetic, luminous and temporal analysis, as well as to interpret the different construction elements and the missing elements.

Future research would focus on the development of a tab (toolbar) for Revit software that allows new BIM models to be generated from other historical buildings using the families created in the actual case. This tab would include quick access to heritage families and useful tools for creating, for example, different kinds of element arrays. To do this, either the corresponding Revit API SDK, or tools that facilitate these developments (such as Dynamo open source software), can be applied, thus expanding the digital world where researchers can interact on architectural heritage anytime, anywhere and with any device.

The library created in this work is available through the link www.eii.uva.es/%7Eeduzal/Hbim. We hope that this material will be useful for researchers in cultural heritage and will be completed through future interventions.

Figure 16. (A) Construction sequence of one of the leaves that decorate the capital and the obtained result. (B) Final result of the “Family Entrance” modeling.
Figure 17. (A) Cruciform column. (B) Types and sub-types that make up the modeled families. (C) Longitudinal section, where the cruciform pillars with semi-columns and barrel vaults separated by arches that cover the central nave.

Figure 18. Example of the different levels of development.
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Figure 19. (A) Longitudinal section of the church. (B) Cross section of the church. Some dimensions are shown in both sections.
References

About Families. Help Autodesk REVIT 2015. http://help.autodesk.com/view/REVIT/2015/ENU/?guid=GUID-6DDC1D52-E847-4835-8F9A-466531E5FD29 (accessed February 3, 2017).

Alsdik, B., M. Gerke, and G. Vosselman. 2013. Automated camera network design for 3D modeling of cultural heritage objects. Journal of Cultural Heritage 14 (6):515–26. doi:10.1016/j.culher.2012.11.007.

Azhar, S. 2011. Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. Leadership and Management in Engineering 11 (3):241–52. doi:10.1061/(ASCE)LM.1943-5630.0000127.

Baik, A., A. Alitany, J. Boehm, and S. Robson. 2014. Jeddah Historical Building Information Modelling” JHBIM”. Object Library. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2 (5):41. doi:10.5194/isprsannals-II-5-41-2014.

Baik, A., R. Yaagoubi, and J. Boehm. 2015. Integration of Jeddah Historical BIM and 3D GIS for Documentation and Restoration of Historical Monument. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 40 (5):29. doi:10.5194/isprsarchives-XL-5-W7-29-2015.

Barazzetti, L., F. Banfi, R. Brumana, G. Gusmeroli, D. Oreni, M. Previtali, . . . G. Schiانتarelli. 2015. BIM from laser clouds and finite element analysis: Combining structural analysis and geometric complexity. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 40 (5):345. doi:10.5194/isprsarchives-XL-5-W4-345-2015.

Besl, P. J., and N. D. McKay. 1992. A method for registration of 3D shapes. IEEE Transactions on Pattern Analysis and Machine Intelligence 14 (2):239–56. doi:10.1109/34.121791.

Cheng, H. M., W. B. Yang, and Y. N. Yen. 2015. BIM applied in historical building documentation and refurbishing. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 40 (5):85. doi:10.5194/isprsarchives-XL-5-W7-85-2015.

Del Giudice, M., and A. Oselo. 2013. BIM for cultural heritage. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 40:225–29. doi:10.5194/isprsarchives-XL-5-W5-225-2013.

Dore, C., and Murphy, M. 2012. Integration of HBIM and 3D GIS for Digital Heritage Modelling. Digital Documentation, 22–23 October, 2012, Edinburgh, Scotland.

Dore, C., M. Murphy, S. McCarthy, F. Brechin, C. Casidy, and E. Dirix. 2015. Structural simulations and conservation analysis-Historic building information model (HBIM). The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 40 (5):351. doi:10.5194/isprsarchives-XL-5-W4-351-2015.

Gómez-Garcia-Bermejo, J., E. Zalama, and R. Feliz. 2013. Automated registration of 3D scans using geometric features and normalized color data. Computer-Aided Civil and Infrastructure Engineering 28 (2):98–111. doi:10.1111/mice.2013.28.issue-2.

Ibáñez, A. J. P., J. M. M. Bernal, M. J. C. De Diego, and F. J. A. Sánchez. 2015. Expert system for predicting buildings service life under ISO 31000 standard. Application in architectural heritage. Journal of Cultural Heritage.

Jackson, T. G. 1920. Byzantine and Romanesque architecture (Vol. 1). London: University Press, 205–57.

Kimball, F., & Edgell, G. H. (1918). A history of architecture. New York: Harper & Brothers Publishers, 217–75.

Lerones, P. M., J. Llamas, J. Gómez-Garcia-Bermejo, E. Zalama, and J. C. Oli. 2014. Using 3D digital models for the virtual restoration of polychrome in interesting cultural sites. Journal of Cultural Heritage 15 (2):196–98. doi:10.1016/j.culher.2013.03.009.

Level of Development Specification. 2016. BIM FORUM, p. 11-13. https://bimforum.org/lod/ (accessed February 04, 2017).

Logothetis, S., A. Delinasiou, and E. Styliandis. 2015. Building Information Modelling for Cultural Heritage: A review. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2 (5):177. doi:10.5194/isprsannals-II-5-W3-177-2015.

Lorente, J. F. E., & Francisco, J. (2007). La metrología y sus consecuencias en los edificios de la Alta Edad Media Española. III: El Primer Románico en España. Artigrama: Revista del Departamento de Historia del Arte de la Universidad de Zaragoza, 22(4):423–72.

Memoria Histórica del Monasterio de Santa María de Mave. Románico Norte. http://www.romaniconorte.es/conte nido/index.asp?ddoc=1082 (accessed November 25, 2015).

Monasterio de Santa María de Mave. Wikipedia. http://es. wikipedia.org/wiki/Monasterio_de_Santa_Mar%C3%ADa_de_Mave (accessed November 25, 2015).

Murphy, M., E. McGovern, and S. Pavia. 2009. Historic building information modelling (HBIM). Structural Survey 27 (4):311–27. doi:10.1002/206308090110951801.

Murphy, M., E. McGovern, and S. Pavia. 2011. Historic building information modelling—adding intelligence to laser and image based surveys. ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 38161–7.

Ochmann, S., Vock, R., Wessel, R., Leander Evers, H., Nergård, H., & Törklind, P. 2014. Documenting the Changing State of Built Architecture – Software prototype v1. Durable Architectural Knowledge (DURAARK), Software prototype,1:20–23.

Oreni, D., R. Brumana, S. Della Torre, F. Banfi, and M. Previtali. 2014. Survey turned into HBIM: The restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L’Aquila). ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2 (5):267. doi:10.5194/isprsan nals-II-5-267-2014.

Oreni, D., R. Brumana, A. Georgopoulos, and B. Cuca. 2013. HBIM for conservation and management of built heritage: Towards a library of vaults and wooden bean floors. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences 5:W1.

Quattrini, R., and E. Baleani. 2015. Theoretical background and historical analysis for 3D reconstruction model. Villa Thiene at Cicogna. Journal of Cultural Heritage 16 (1):119–25. doi:10.1016/j.culher.2014.01.009.

Quattrini, R., E. S. Malinverni, P. Clini, R. Nespeca, and E. Orlietti. 2015. From TLS to HBIM. High quality semantically-aware 3D modeling of complex architecture. The International Archives of Photogrammetry, Remote Sensing
and Spatial Information Sciences 40 (5):367. doi:10.5194/isprsarchives-XL-5-W4-367-2015.

Santa María de Mave. Arte guías. http://www.arteguias.com/monasterio/santamariamave.htm (accessed November 25, 2015a).
Santa María de Mave. Arquivoltas. http://www.arquivoltas.com/8-palencia/02-Mave01.htm (accessed November 25, 2015b).

Schueremans, L., K. Van Balen, K. Brosens, D. Van Gemert, and P. Smars. 2007. Church of Saint-James at Leuven: Structural assessment and consolidation measures. International Journal of Architectural Heritage 1 (1):82–107. doi:10.1080/15583050601126137.

Simeone, D., Cursi, S., Toldo, I., & Carrara, G. 2014. BIM and knowledge management for building heritage. In Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture, 23–25 October, 2014, Los Angeles, California.
Tomaževič, M., and M. Lutman. 2007. Heritage masonry buildings in urban settlements and the requirements of Eurocodes: Experience of Slovenia. International Journal of Architectural Heritage 1 (1):108–30. doi:10.1080/15583050601126186.
Vecco, M. 2010. A definition of cultural heritage: From the tangible to the intangible. Journal of Cultural Heritage 11 (3):321–24. doi:10.1016/j.culher.2010.01.006.