BIM Modelling of Ancient Buildings

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Abstract. In the last years, new procedures on design and management of constructions, based on 3D standardised models of building elements, have been proposed. It's the case of Building Information Modelling (BIM) applications, that, differently from CAD ones, allow to work with libraries of 3D parametrical objects (smart objects) describing geometric, structural and material properties of building elements. This methodology is based on the Industry Foundation Classes (IFC) model, that represents a global standard for the building data exchange. Initially used for the design of new architectures, BIM methodology has been even more considered also for the management and the conservation of historical buildings, thanks to the possibilities of implementation of semantic information of 3D objects, guaranteed by the connection with the external database. At the same time, the lack of regular surfaces and standardised objects are relevant problems that nowadays strongly limit the use of BIM for Cultural Heritage (CH). Anyway, in recent times, the study of parameterised objects has opened new perspectives for BIM applications on historical buildings (HBIM). The present work shows the last achievements on this topic, focusing the problems derived from the application of BIM methodology to CH. In fact, the irregular shape of ancient architectural components, the wide variety of architectural languages that characterise historical buildings, the presence, sometimes, of different stratifications, are clear examples of the difficulties of implementing HBIM methodology for CH.

Keywords: HBIM · Cultural heritage · Archaeology · Geospatial DB Survey · 3D modelling

1 Introduction

The digital revolution that is affecting our era, with the huge amount of data that can be shared and/or exchanged anywhere and at any time, has also affected the building construction world with the advent of the Building Information Modelling (BIM). This term refers to a methodology or process through which it is possible to develop and manage digital representations of buildings, infrastructures and, more generally, built places. In fact, according to BIM methodology, it's possible to take in account not only the geometric information of building components but also information concerning

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their physical characteristics, functionalities and mutual relationships. Although BIM design has taken place in recent years, it had been conceptually proposed about 40 years ago (Eastman et al. 2008). One of the first examples was, in fact, the prototype of Charles M. Eastman who, in 1975, theorised a unique three-dimensional model to describe the construction elements, also useful for the estimation of quantities and materials, associated with an external database (Eastman 1976).

BIM software, available today on the market, favour the sharing of models and related information through the network, thus encouraging collaboration between the various actors involved in the life cycle of constructions. These applications were created for the design of new building (as-designed BIM), based on parametric elements connected to each other through a hierarchical structure of “smart objects” (Garagnani 2013).

Through BIM technology, the use of shared models among different professional figures, with different skills, allows obtaining continuously updated diachronic information (Garagnani et al. 2016). Therefore, this methodology is dedicated not only to the planning and design of an architectural or engineering work but also to its management, maintenance and monitoring (Volk et al. 2014).

Then, the application of this methodology to existing building assets (as-built BIM) has become of fundamental importance, adding information related not only to design but also to current conditions and structural changes over time (Huber et al. 2011). The use of the as-built BIM approach, therefore, represents a particular interesting solution for CH, to manage the information related to the individual 3D components of the monument (Saygi, Remondino, 2013). The BIM applications for historical architecture are much more complex because ancient buildings contain elements and materials having geometries that cannot be represented with standard software libraries (Logothetis et al. 2015). Furthermore, due to its history and to long life, CH tends to change over time as a result of the use, natural deterioration and collapse of structures. A BIM model of a historic building (HBIM model) could also contain dynamic information that, for example, thanks to sensors and control signals, could support the conservation of the structure. This application allows finding the presence of a possible structural problem, such as a collapse or a fracture. In this way, it’s possible to analyse the 3D model avoiding the physical exploration of the construction.

This paper deals with the evaluation of approaches that allow the creation of HBIM model of architectural heritage, starting from 3D laser scans and photogrammetric techniques, called ‘Scan to BIM’ (Baik 2017). HBIM methodology allows providing not only a visual description of the monument but also the implementation of a smart database of semantic information concerning its conditions, materials and history (Scianna et al. 2014). This information can be used, for example, to support the design of a possible restoration intervention, helping the operators involved in the subsequent management and monitoring phase. The possibilities offered by HBIM methodology are strongly linked to the correct decomposition of the structures, based on in-depth studies. It’s necessary, in fact, the creation of an abacus of the constructive elements.

Although the modelling of historical architecture has been sufficiently explored by many scholars, its architectural and compositional variety, over time, requires and will still require considerable study work to define the methods of structuring models useful for applications not originally provided for BIM design. Hence to model historical buildings, a comparison with IFC standards (Laakso, Kiviniemi 2012) should be initially made to understand which elements are already included in IFC and which ones can be assimilated to those already present.

2 From BIM to HBIM

In the field of building design, the construction industry has increasingly focused on the use of digital models that go beyond the simple geometric representation of construction elements. Between them, the most complete and validated model is IFC which BIM methodology is based on. Considering the BIM approach applied to historic buildings, called HBIM as mentioned above, the advantages of this methodology would be many: remote control of external and internal parts of the architecture, planning of restoration operations, structural analysis, interactive 3D representations for cultural and educational uses. All this through a single final model. On the other hand, the complexity of historical buildings leads many problems on HBIM applications. It's necessary to take care of the different needs of this methodology, to focus all of the limits and the issues linked to HBIM applications:

- the necessity of a systematic standardisation of every part of the building, useful for the implementation of specific libraries dedicated to CH. These could be considered a particular example of Digital Libraries (Ioannides et al. 2017);
- the necessity of making a classification of the architectural elements, dividing the structure into categories at different hierarchical levels and creating a database for the inclusion of new libraries;
- the modelling and parametrisation of new smart objects that represent the architectural elements of historical buildings. In fact, the complexity of these structures needs an in-depth knowledge of historic construction techniques and advanced modelling skills.

During the experimentation carried out for different study cases, it's been possible to individuate a workflow for the creation of a complete HBIM model (Fig. 1):

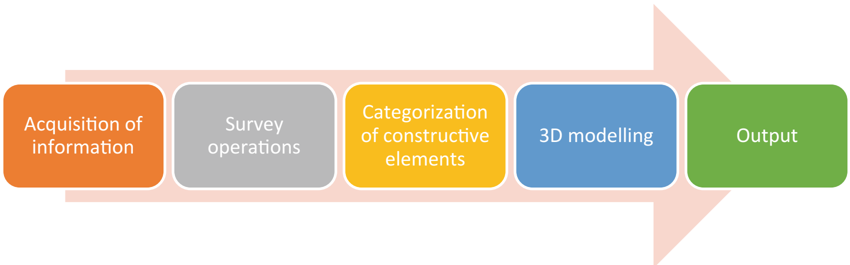

Fig. 1. The workflow for the creation of an HBIM model.

- acquisition of information;
- survey operations;

- categorisation of constructive elements;
- 3D modelling;
- output.

The first phase of acquisition of necessary information regarding each historical building is fundamental for the choice of the next survey operations and also for making a correct decomposition of the structure. Survey operations are necessary for the geometrical reconstruction of the point clouds, that, together with the decomposition of the structure in macro-categories, categories and subcategories of elements, are the basis for the construction of the 3D model. Even if the BIM was thought of as a multipurpose model, that should cover each building over its whole life cycle, and for supporting each kind of processing, the modelling phase depends on the choice of the output model required. In fact, different user needs require different model outputs, and, consequently, different modelling techniques.

In the following section of the paper some interesting issues encountered in the application of the workflow will be analysed:

- the difficulties encountered in the part of the workflow between survey operations and the generation of the 3D model;
- the complexity of the categorisation of constructive elements, necessary for the creation of a library of "smart objects" and the correct modelling of a building;
- the difficulties in modelling and parametrisation of single architectural elements connected with the output to realise.

3 From Survey Operations to General Model

Data collected using the most modern survey instruments and related techniques allow generating models that geometrically describe the building in a very accurate way. They are the starting point for the next modelling phase of the building. Some software and plug-ins, such as Agisoft Photoscan ®, Pix 4D mapper ®, Bentley Context Capture ® and FARO ® VirtuSurv, also allow the semi-automatic creation of 3D models passing through processing of point cloud. However, in all of these cases, the 3D meshes generated from point clouds hold only geometric information. Instead, to correctly create smart objects, it's necessary to store not only their whole geometry but also semantic information on materials properties (specifications). These information are required to describe the shape of a smart object and to consider its function and its relationship with other elements (relational system). Nowadays, the complete automatic generation of building elements from a point cloud is almost not possible. The point cloud can be assumed mostly as a spatial reference for the drawing of geometric parts of building elements whose semantic description can be associated with.

The above considerations have been tested also in a study case regarding the participation to the benchmark activity issued by the Italian Society of Photogrammetry and Topography (SIFET) concerning the "restitution of 3D/HBIM models from point clouds obtained with UAV surveys or terrestrial laser scanning" of the Fornace Penna (an historical industrial building located in Sicily).

Starting from the point cloud, it's been necessary to create a 3D model retracing the shape given from the cloud. In this case, only walls and pillars have been taken from existing libraries. In fact, walls and pillars can be easily adapted to the real ones thanks to the possibility of managing profiles and sections and by assigning materials.

New families of openings, ad-hoc created, have been parametrised to be adapted to the real ones and have been inserted into the library. The difficulty in parameterising the individual segments that make up an opening led to the creation of a family for each opening so that BIM appears less productive. In fact, the openings of the building showed very small differences in size, although they could look the same at first glance. Even for openings with collapsed elements, dedicated families have been created (Figs. 2, 3 and 4).

Fig. 2. Visualization of the BIM modelling of walls of the Fornace Penna over its point cloud.

Hence, this case study highlighted some problems that can be resumed in:

- the lack of specific libraries of smart objects for historic buildings as the great variety of architectural shape requires designers to create new libraries on a case-by-case basis;
- the existence of some limitations in modelling and parameterisation of certain constructive elements;
- the absence of a comprehensive classification of the construction elements of historic buildings supported by semantic data.

4 From the General Model to the Classification of Its Elements

One of the main features of the BIM software is the presence of a parametric objects library described in IFC standards. This kind of library helps very much architects and engineers during the design and the management of buildings. However, despite its vastness, the elements included in software libraries, as said before, not always meet the design and management needs, requiring the creation of specific components for each design case, especially in the case of CH. In fact, doesn't exist a complete

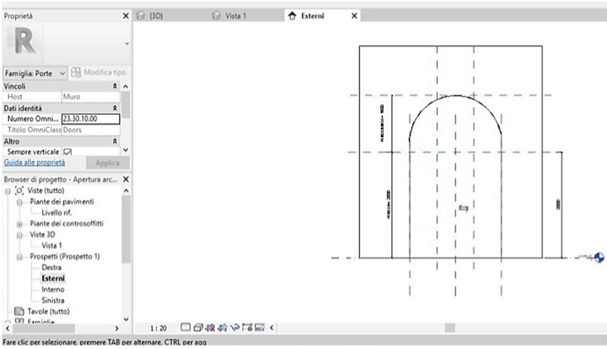

Fig. 3. An example of a parametrisation of an arc opening in BIM.

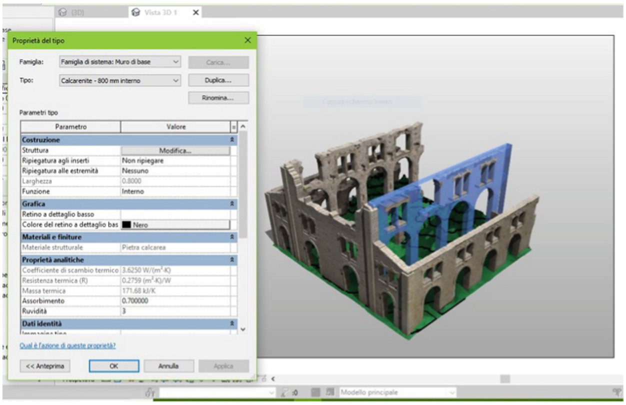

Fig. 4. Visualization of information about a selected element of the Fornace Penna BIM model.

database of ancient smart objects to use as a basis for modelling, that could give essential advantages of reducing times and costs during operations. However, this kind of library must meet specific requirements to be exploited in the same way as those already present within the software. Hence, modern software libraries propose, for new constructions, a very detailed categorisation of the components of the building organism. In Autodesk ® Revit or Graphisoft ® Archicad, for example, it's possible to find a distinction between architectural elements, structural elements and plant engineering. After this, it's possible to find a subdivision that identifies the classes of objects that allow access to the default library and then load the chosen components in the project.

So, the first problem to be faced for the creation of a standard library of elements belonging to the historical building heritage is precisely the breakdown of the building itself. This technique could allow achieving a global knowledge of the artefact. For example, it's possible to apply this technique to a Greek temple, a structure that can be considered as a symbol of historical architecture and which can also provide interesting methodological considerations (Fig. 5).

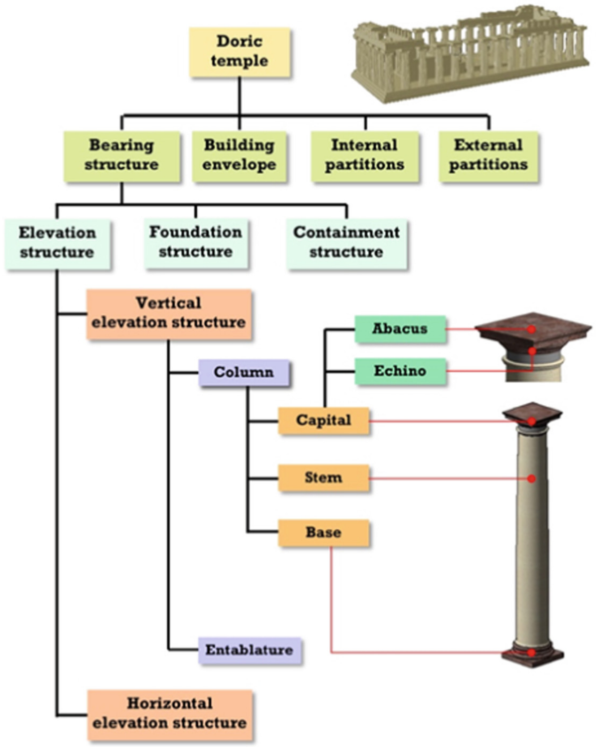

Fig. 5. Example of the breakdown of a Doric temple structure.

The decomposition to follow derives from the classification of the modern technological building system. So it's possible to divide the parts of a building into macro-categories, categories, micro-categories of elements and technical elements. The components constituting each piece of CH should be grouped and classified according to their function, also identifying a further internal subdivision. For example, the technical element "Column", which in turn is composed of other parts, can be found within the micro-category "vertical elevation structure". This last is part of the "Elevation structure" category, which in turn is contained in the macro-category "Bearing structure".

Thanks to this decomposition of the structure, it's possible to associate elements such as columns and lintels with the corresponding modern structural elements. So, they are insertable, through appropriate modelling, within the database, creating a new library of structural elements. For other components such as metopes and triglyphs, the association is not immediate, and it requires an in-depth study of the evolution of historical construction techniques. According to Vitruvius, for example, the triglyphs were used to cover the heads of the wooden beams in the first temples, the metopes instead had the function of filling the gaps between the beams. Furthermore, metopes were all different from each other, because they were also decorative elements used to tell stories. With the subsequent adoption of the stone elements, these parts remained, becoming canonical elements and completing part of the entablature (Washburn 1919; Jones 2002).

This example is useful for underline that the knowledge of the origins and functions of historical elements are fundamental for the association to smart objects already present in the software and for the application of the modelling techniques. It's also important to consider, during modelling, the way in which the elements should be inserted in the overall model and the task or role they have to play.

5 Modelling and Parametrising Objects

The stage of modelling is very delicate and complex. In particular, in the case of BIM, it is important to take care about of some fundamental aspects during the creation of objects belonging to a larger and articulated system.

As seen before, the correct use of HBIM methodology needs the analysis and the breakdown of the architectural structure, where every element should be implemented into a specific library of smart objects related to a particular architectural language.

Despite the proposals of some authors on the creation of a library of historical elements based on the manuscripts of Vitruvius and Palladio and on the books of architectural patterns of the Eighteenth Century, nowadays only a few things have been realised and only in relation to specific cases (Dore et al. 2015). In many historical buildings, besides, apart from differences caused by degrades or for subsequent alterations, it's possible to find differences between similar elements caused by their handmade production. This aspect greatly increases the difficulty of parameterisation of the geometrical elements that compose these buildings.

Anyway, the implementation of different databases, based each one on different architectural languages and containing a hierarchic categorisation of elements, could allow creating an HBIM model in a good level of detail (LoD).

Furthermore, according to BIM, it's important to consider that the same architectural elements could be reproduced with different modelling techniques. Even if BIM born to cover all the aspects and phases of the construction sector, the choice of the best method depends on the final use that has led the model creation. For example, in Revit, an element finalised only to 3D representation or metric calculation can be freely modelled with no limits to surface configurations. Instead, an element finalised to structural analysis (e.g. a pillar), to obtain an association with the analytical model, is obliged to be constrained on both ends to other structural elements (like beams) and to follow a regular path.

The example of modelling here proposed uses a typical column of a Doric temple. In the exposed case it's been used the creation of nested families. They are families containing other families to better manage the parameterisation of the various parts of the objects. With the help of the Book of architectural patterns "the Classical Order of Architecture" by Robert Chitham (Chitham 1984), the column was divided into small parts. The dimensions of each piece have been related to a base unit located in the diameter of the column itself (Aubin, 2013). A key element was the use of profile families containing a two-dimensional closed circuit. In this case, the drawing of the sections of the elements that composed the column has been used. These were then inserted from time to time in a “pillar” family where extruding, path sweeping and solid revolutions were applied. In this way, the typical behaviour of a pillar has been associated with the column, in order to create an analytical model useful for a possible automatic structural analysis (Figs. 6 and 7).

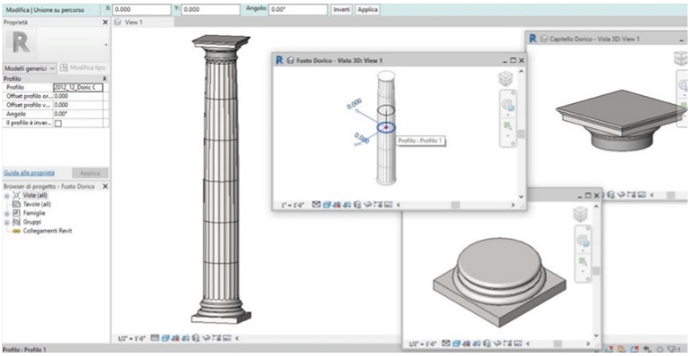

Fig. 6. Nested family “column” containing three families: capital, shaft and base. Each family includes profile families.

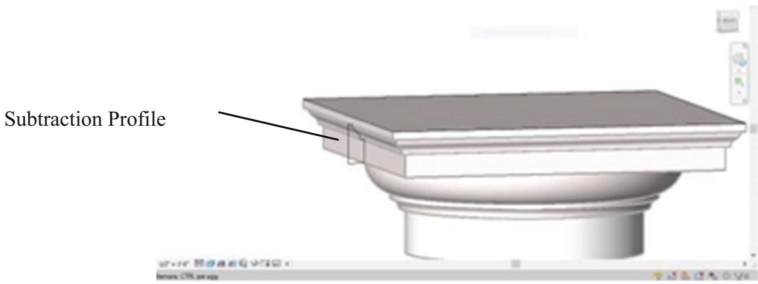

Fig. 7. Modelling and parametrisation of a Doric capital using a profile family in BIM.

The comprehension of the modelling techniques of the column has been very important for the application to a real case, starting from a point cloud obtained during survey operations. Software in facts allows the extraction of different profiles, obtained from point cloud sections.

In this way, the modelled object can be adapted to the real one by varying the base parameter and updating the profile families with the measurements obtained from the survey. This technique allows also representing any degraded elements acting directly on the nested families with solid operations. However, as the case study shows, it’s necessary to have a deep knowledge of the modelling techniques that the software makes available. The same techniques also vary depending on the constructive element to represent (Figs. 8 and 9).

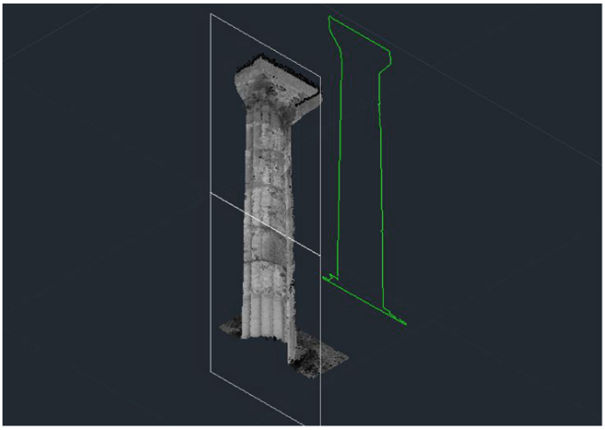

Fig. 8. Section of the column extracted from the point cloud.

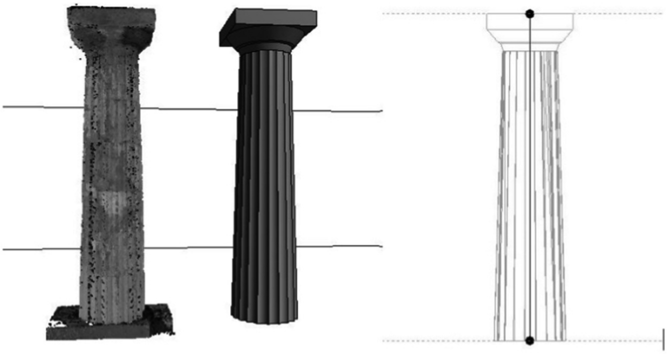

Fig. 9. Point cloud, HBIM model and analytic model of the column.

Considering the previous case of the Fornace Penna, the construction of the model was also finalised to develop a structural analysis of the building. This requirement needed to take care especially of connections between walls opportunely inserting the external static constraints. Furthermore, as described before, the choice of the correct modelling methods for the creation of arcs, windows and pillars, highlighting the differences between different kinds of stones, was a fundamental aspect for making a correct structural analysis of the building. About this aspect, it's necessary to clarify that the level of definition that characterises the HBIM model isn't compliant with

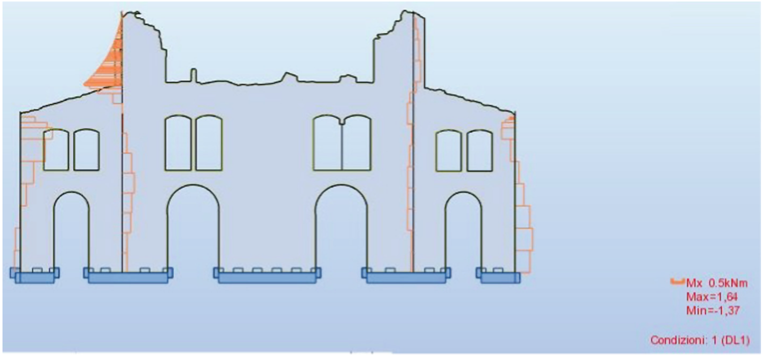

Fig. 10. A structural analysis result of a Fornace Penna facade from the BIM model.

monitoring infinitesimal movements of structures. Anyway, HBIM representation is useful for preventing imminent collapses and for planning restoration works (Fig. 10).

More difficulties appear, then, in the case of more complex elements and with more particular shapes; this aspect necessarily requires the use of custom elements to be defined case by case.

6 Conclusions

This paper investigates some critical issues in the making of HBIM representations of CH. The HBIM process is seen, here, as a set of procedures that starts from the collection of data up to the final creation of a complex 3D model of the building full of semantic information. After a definition of the reasons and the advantages that motivate an approach of this kind to the historic architecture, some technical problems have been presented in relation with some study cases. Indeed, while the survey stage is today enough advanced thanks to available technology, the modelling stage of the HBIM process is still problematic and not well defined. Most of the problems are related to the uniqueness of each existing building and/or its components. This uniqueness is due to the handmade production of the historical construction elements, the presence of degradation, the irregular shape of some constructive elements and decorations, and the vast variety of architectural languages on CH. Each of these features makes difficult the realisation of a standard library of CH smart parametric objects.

Moreover, the construction of these libraries needs a standard classification of the parts of historical buildings, but this operation isn't always simple for the reasons indicated before. The categorisation of the components of an ancient building requires an exploration of the old construction techniques to allow an association between their behaviour and the corresponding function of the structural elements formerly inside the BIM software. So, the diffusion of HBIM methodology needs still more technical insights that will be explored in future works.

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