# HBIM: to Know to Model the Complexity. Cases History on Italian Cultural Heritage

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ABSTRACT: Building Information Modelling (BIM) is a particularly suitable methodology to implement a multidisciplinary approach in dealing problems that involve a large amount of data. This condition is typical of cultural heritage buildings, that are intrinsically complex (due to construction phases, variability of materials, unusual architectural solutions). However, the complexity of existent buildings makes very difficult to reduce them to repetitive schemes, useful to set an ordinary BIM model. For this reason, currently the application of BIM to the cultural heritage field (properly called HBIM - Heritage Building Information Modelling) is still not sufficiently tuned and need further reflection and development. In this paper case studies are presented in which the processes of knowledge, modelling, and conservation are applied to some Italian cultural heritage buildings of small dimension. The discussed applications are mainly referred to seismic retrofitting interventions, that are particularly sensitive because they require a holistic approach involving the knowledge of the construction phases, construction techniques, production methods, and the ageing processes of the historical materials.

## 1 INTRODUCTION

Building Information Modeling (BIM) methodology accomplishes a unique reference system operating throughout the whole life cycle of the building by sharing information. Through this method, a model of either a single building or a buildings aggregate is implemented by collecting and correlating a large amount of geometric, historical, and diagnostic data. HBIM (Heritage Building Information Modeling), is the transposition of this concept of digitization to historic heritage buildings. HBIM is obviously a very useful methodology where buildings are the result of many constructive and evolutionary phases, material stratifications, architectural, and structural changes.

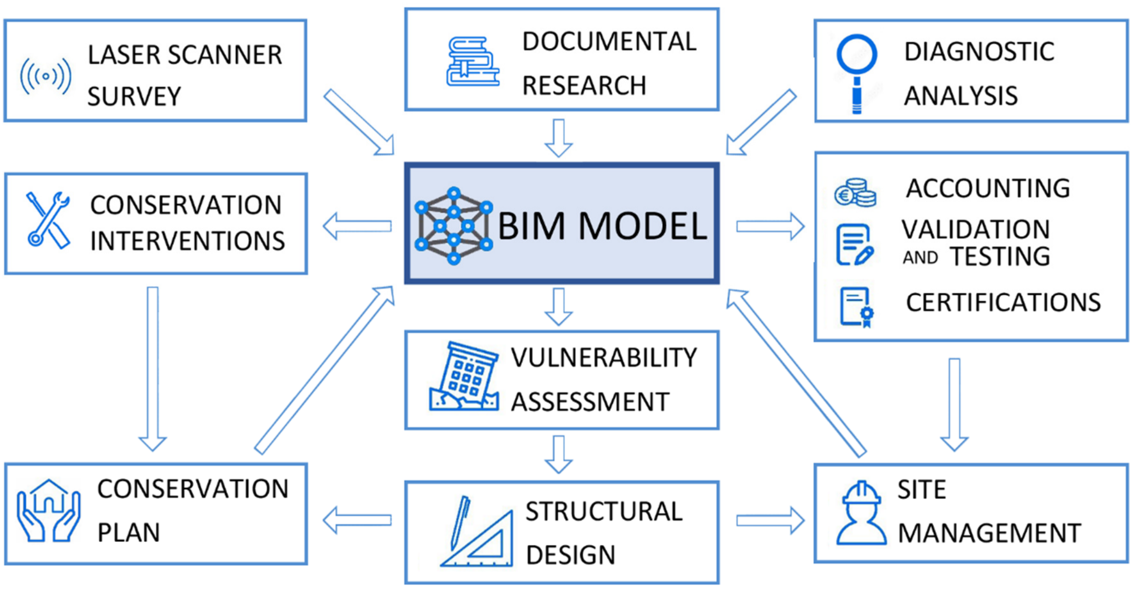
While BIM operating methods applied to new buildings are well-established, the HBIM process is still not mature. However, in recent years many research studies have been published about BIM theory and case studies. The main themes addressed are semantic interoperability (Della Torre & Pili 2020), accuracy of the geometric survey (Brumana et al. 2019), implementation of the conservation plan within the process (Oreni et al. 2017), and case studies of HBIM use for restoration of important buildings such as the Basilica of Collemaggio in L'Aquila (Brumana et al. 2017) or Masegra Castle in Sondrio (Di Giuda & Villa 2017).

BIM methodology applied to existing buildings is based on the Real-Based 3D modelling. It allows the building of a three-dimensional model representing the architectural object's characteristics with a high level of accuracy by processing the data collected during the survey phase. The process involves the construction of a digital model that is implemented with all the available information regarding the architectural object. Conventional design drawings, at different representational scales, can be extracted from it.

Nowadays operative complexities in the implementation of parametric modeling of a non-repetitive object with geometric irregularities (commonly present in existing buildings in general and in monumental buildings in particular), derive from the intrinsic characteristics of the currently used modeling software. Consequently, specific simplifications should be applied to the model. They can be considered design choices because they are based on decisions about the range of importance that the information can give back. Therefore, the complexity of the model depends substantially on the pre-established project target. From this perspective, a BIM Execution Plan (BEP)is given a key role. BEP is a document written by the operator (in agreement with the client) that defines and describes how to optimize the modeling process that refers to a specific application.

The systematic use of the HBIM methodology has to be established and defined from the earliest stages of the project and properly implemented throughout the development process of the project itself. The stages include the design phases, construction and site management, and the maintenance and conservation plan. More precisely, the HBIM methodology has to define goals, roles, and skills of the working group' members. The methodology must also define the steps to be implemented, the Level of Development (LOD), Level of Information (LOI), as well as all other useful information to build a shared modeling process.

Figure 1. Actions and information flow in the BIM process




It is commonly believed that the HBIM methodology can be applied in an efficient and cost-effective way only to large-scale projects. In this paper, the authors present their experience of applying the discussed methodology to small-scale projects. The models developed were implemented with metadata allowing for the pairing with other software. In this way, the model's interoperability (i.e., the capacity of two or more software to share and exchange information) is guaranteed. In all of the presented case studies, three-dimensional parametric relational databases have been obtained. The resultant databases return the precise geometry of the buildings, information about the historical development, and the workflow to be undertaken during the construction phase. These databases can be constantly updated and modified so that all the operators involved in the process can refer to them during all stages of the conservation project.

## 2 METHODOLOGY

The HBM methodology has to be applied from the preliminary stages of the project, from the acquisition of a specific level of knowledge of the building (Italian Structural Guidelines, 2011) and the design, to the "as-built" phases and the management of the conservation process.

### 2.1 *Survey and modeling*

In reference to the case studies of existing buildings, outputs of a traditional geometrical survey and laser-scanner survey can be implemented despite the use and application of HBIM methodology. This is the most effective approach because it minimizes measuring and representation errors. A laser-scanner survey provides redundant information that can be used in a second stage to extract useful indications to classify certain elements (e.g., identification of structures, non-load bearing walls, and decorative elements). Thus, the obtained model is a robust tool to implement and improve all subsequent study and design phases. The use of a 3D laser-scanner technology provides a considerable density of metric information which is useful for a correct and accurate three-dimensional modeling of the building. For these reasons, it can be considered an unavoidable starting point for the model, as well as an integral part of the methodology used in the analysis of a large dataset.

The HBIM of an existing building is a Real-Based type of modeling. The digital model of the real object is built through parametric elements based on the data coming from the survey and on-site investigations. For existing buildings, operators have to carry out simplifications of the reality in order to manage the complexities arising from the three-dimensional transposition of the survey and due to the many geometric irregularities, that could be present. The simplified criteria strongly depend on the aim of the intervention and have to be evaluated considering the importance of the information to be returned. For example, the parametric model used to carry out a seismic vulnerability assessment and those built to design a restoration intervention will contain different levels of information and will have different levels of metric tolerance.

However, independently from the model outputs, information provided by the geometrical survey has to be preserved. For this purpose, point clouds are integrated within the model in compatible file format (e.g., rcp for Autodesk Revit). This approach promotes modelling based on parametric elements rather than on a rigorous geometric precision without parameterization. In HBIM modeling, it is fundamental to consider the model as a digital representation of the reality that can be changed over time through the integration of data acquired during subsequent phases of knowledge gathering, design, and conservation processes.

The informative models are characterized by data, information, and contents that are at the same time digital, relational (parametric), structural, and reworkable. During the transition from a less defined level of development (LOD), to a better defined one (e.g., from LOD A "symbolic object" to LOD E "specific object"), the data contained in the model have to be considered consolidated with respect to the previous level of completion yet lacking in information with respect to the next level.

Currently, the Italian standards in this field define specific scales based on the operational scope of the project. Ad hoc classes have been further specified for the restoration of historically designated buildings. The standard (UNI 11337-4) specifies that the levels from LOD A to LOD E are not significant in the context of restoration and conservation. They can be used properly only for the simplifications of the specialized models. Therefore, it is necessary as a minimum to achieve LOD F (the as-built object), to provide a verified virtualization of the actual state of the construction. LOD G (the updated object), can be used to consider the model implemented with the management and maintenance interventions.

The standard (UNI 11337 -5) defines roles, requirements, and flows of the digitization process, as well as the levels of analysis of information interference among structural, architectonic, and MEP needed to build disciplinary models. Generally, models can be structured according to different fields of competence (e.g., architectural, structural, mechanical, etc.), without reciprocal inconsistency. However, for interventions on cultural heritage sites, the coordination of data, information, and geometries is fundamental. Consequently, the interference analysis plays a fundamental role, especially in the design phase.

### 2.2 *Diagnostic results and outputs of documental research*

The acquisition of an appropriate level of knowledge is a necessary premise for the effective conservation of a historical building. A holistic approach has to be applied in the cultural heritage field. It involves a process passing through the knowledge of construction phases, of production methods, and of other physical and chemical mechanisms that cause aging and degradation of materials (Armanasco & Foppoli 2014). The integration within the same model of all the information collected from survey, inspection, and documentary research phases allows for the achievement of a detailed overview on the historical evolution of the building, including possible additions, demolitions, reconstructions, and other changes. Consequently, building components corresponding to different construction phases can be identified. In addition, one can gain a more comprehensive understanding of the load paths that help establish processes during the design phases. Specific strategies, such as the implementation of data coming from the crack pattern survey of the building or from other diagnostic investigations, can then be applied to modeling software in order to increase efficiency during this process. In this way, many descriptive parameters (i.e., the ones relevant for the crack identification), can be associated with the parametric elements.

The most relevant potentiality of the HBIM process is its possibility to be continuously updated and improved over time according to the available information, from the diagnostic investigation – preliminary to the on-site intervention – to the whole life-cycle of the building. As the level of knowledge of the building increases, the amount of information embedded within the model also increases by adding documents and information in the Shared Data Environment (ACDat).

The above aspects were addressed by the authors to model the Maritime Station at Trieste, a historical building dating back to 1912, that in the past decades has been altered by many interventions. HBIM modeling has allowed the classification of structural elements by assigning to each of them codes and parameters based on construction phases, material properties, and construction techniques. In addition, structural damage phenomena detected during the visual inspection have also been integrated into the model. In Figure 2 point clouds of Maritime Station of Trieste and the HBIM model achieved from them are reported.

The available historical documentation was classified and embedded within ACDat by setting a univocal link between the parametric element and document where parametric information was found. Historical information was later integrated by results of the diagnostic investigation that was performed in order to achieve an adequate level of knowledge (LC), according to the Italian codes (Italian Structural Code 2018 & Italian Structural Instructions, 2019).

### 2.3 *Design and Site Control*

The application of the HBIM process to the design phase is quite similar to the current use of BIM methodology in the new construction field. However, several peculiarities can be highlighted. The most relevant is the requirement to implement all elements of design within a model representing the building's actual status. Inevitably, the actual status imposes many more constraints. The level of definition of the details depends on the design phase (preliminary, working drawings and construction documents), and it has to consider the interferences derived from the interaction among existing elements (structural, architectural, etc.).

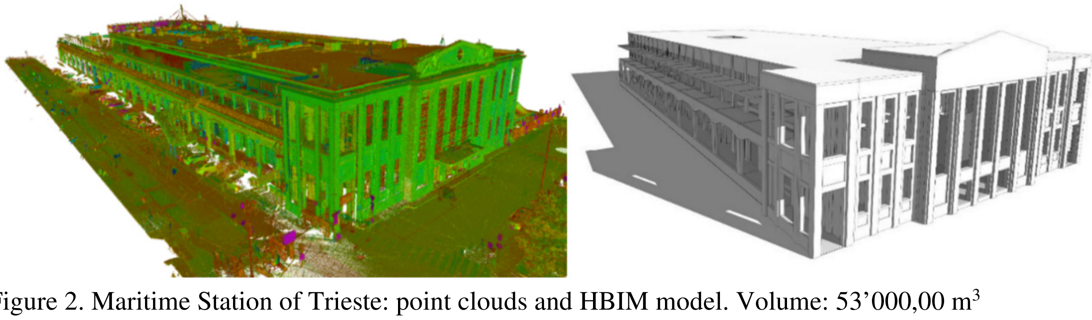


Figure 2. Maritime Station of Trieste: point clouds and HBIM model. Volume: 53'000,00 $m^3$

The overlapping between point clouds and the model is fundamental to digitize more complex architectures. In this manner, any interference can be easily managed including where elements are modelled in a simplified way. This approach is very useful, particularly in the preliminary planning phases that are characterized by a less detailed design level.

The most demanding aspect of HBIM is the elements parametrization and their precise articulation of each part of a building. Any on-site variation of the project can be implemented in the model in such a way that interferences are rapidly evaluated. This allows the control of the whole project procedure and of the possible consequences on other elements or systems.

Moreover, the management of the economical aspect of the project is carried out through plug-ins allowing interaction between the model, calculations, and accounting software. The calculation entry is associated to a material, an element or an assembly of parametric elements allowing for continuous updating during the project development and hence, an immediate costs / benefits analysis of the design choices. The HBIM model during the construction document design phase is a useful tool to support project management in drawing up of a building's accounting documents. At the end of this phase, there is complete coherence between the project and the current building interventions, thus achieving an updated "as built" condition of the construction.

### 2.4 *Conservation plan*

The conservation plan for a listed building is the planning of activities aiming at protection, conservation, and valorization of the cultural heritage according to a dynamic-systemic strategy. The adopted strategy is significantly different than an ordinary maintenance plan which is mainly based on two concepts that are applicable only to modern buildings: the life cycle of the technological elements and repairs after failure.

The use of the HBIM approach to the intervention provides efficient support to establish and manage the conservation plan. Indeed, the computerized system that records information continuously allows one to have a real-time knowledge of the actual conservation state of the building.

In order to draft a conservation plan, the preliminary phase requires analyzing the building's spaces and its elements. A univocal alphanumeric code has to be successively assigned to each modelled BIM element that can be considered homogeneous for materials, constructive techniques, and exposure of conditions to anthropogenic and environmental inputs. After the implementation of a conservation plan, the HBIM model can be managed in two different ways: by creating (and eventually by exporting) abacuses with the codified elements and their attributes (where codified elements are visualized), or by directly querying the model through a simple viewer. In this way continuous and interoperable information on the necessary preventive maintenance operations (including times and resources), are available for building managers. At the end of a specific maintenance action, the database has to be updated to preserve the history of the operations that have been carried out.

To make the process we describe effective, it is necessary to properly establish HBIM modelling from the first stage. This means assigning to parametric elements and families the correct parameters and to take into account both their maintenance and conservative features.

## 3 CASE HISTORIES

The methodology described in the previous paragraphs was used by the authors in many large-scale and small-scale projects including the Maritime Station of Trieste (Vol. 53.000 m3), shown in Figure 2. The strategies were developed in order to have a fluid and effective process even for buildings belonging to "minor" cultural heritage. This is crucial for the conservation of built patrimony because of its uniqueness and historical significance in Italy. Above all, this typology of building is relevant from a numerical point of view.

The strategies presented below regard specific case studies. They include the San Vittore Mauro church at Poschiavo in Switzerland (Vol. 3.000 m3), the Grana-Pievani Palace at Tirano (Lombardy) (Vol. 2.400 m3), and the Odescalchi Palace, at Berbenno (Lombardy) (Vol. 2.900 m3). Both of the palaces in Italy are located close to the Swiss border.

The laser-scanner survey was carried out in four steps. 1) a topographic survey performed by total station and GNSS satellite antennas, 2) laser-scanning, 3) aerial photogrammetry by drone (both of them on-site operations), and 4) post-processing (carried out at the technical office off-site). In the case of San Vittore Mauro church in Poschiavo a preliminary topographic survey was carried out by setting the Total Station survey equipment and receivers in base-rover configuration. Consequently, a points network of known coordinates (topographic polygonal), was achieved and used to link data coming from the laser-scanner and drone surveys. Once the preparatory phases were completed, a three-dimensional terrestrial laser scanner survey was carried out to acquire all building surfaces. In the post-processing phase, all scan positions were aligned and converted into a single Cartesian coordinate system. The most recent software improvements allow to record data on-site and transfer them in real time via Wi-Fi to a tablet. In this way, they can be visualized and verified directly during the survey phase.

Building parts that were not directly detectable by terrestrial laser scanner, such as the roofs' exterior surface, were acquired by using drone photogrammetry. Thus, a three-dimensional acquisition and a complete description of the whole building could be performed by combining different techniques. Scans were performed considering an 30% overlapping of the surfaces in order to provide statistical relevance to the global alignment. So, it was possible to relate data coming from the interior of the church with those of the area located between the roof and the vault through an algorithm cloud-to-cloud able to recognize analogous geometries in subsequent scans. A representative view achieved by laser-scanner points cloud is shown in Figure 3.

From point clouds obtained through the geometrical survey, the longitudinal section of the church was extracted. It properly describes the architectural and structural complexity of the construction and contributes to the consequent complexity of BIM modeling.

Figure 3. San Vittore Mauro Church at Poschiavo: view achieved by laser-scanner points cloud

The methodological experimentation carried out by the authors for the Grana-Pievani Palace in Tirano ("MigliorArTi" project) provides a consistent example of the application of the HBIM methodology within a strategy aimed at reducing seismic risk. The activities include a historical analysis (knowledge-based), conservation, and valorization of cultural heritage. This project was funded by the Cariplo Foundation through its project "Cultural Heritage at Risk." The submitted proposal took into account the use of the HBIM methodology as an operative model to be extended to the historical buildings in the entire Lombardy region.

The model was set from a geometric point of view and later integrated with all information taken by the structural analysis and by the consequent activity of assessment vulnerability and design in compliance with the building code (Italian Structural Guidelines, 2011). One of the most unique aspects of this HBIM model is the presence of a huge number of irregular load bearing elements. After the evaluation of many approaches concerning the level of accuracy of the model, a threshold of geometrical simplification was defined. Only in this manner it was possible to implement parametric elements with the needed information and characteristics.

For Palazzo Odescalchi at Berbenno a similar project for seismic improvement, structural, and functional retrofitting was carried out. HBIM modeling of the building provided a broad database of architectural and structural information inferred by the in-depth, on-site diagnostic analysis. At the same time, a detailed material and decay analysis of the external surfaces was performed. The resultant mapping was implemented in the model by generating specific parametric elements corresponding to the detected decays and specifying their type, location, area, and severity. The material and decay mapping implemented in HBIM model of Odescalchi Manor is reported in Figure 4. From this analysis, the kinds of interventions and their sequence could be better strategized by the design team.

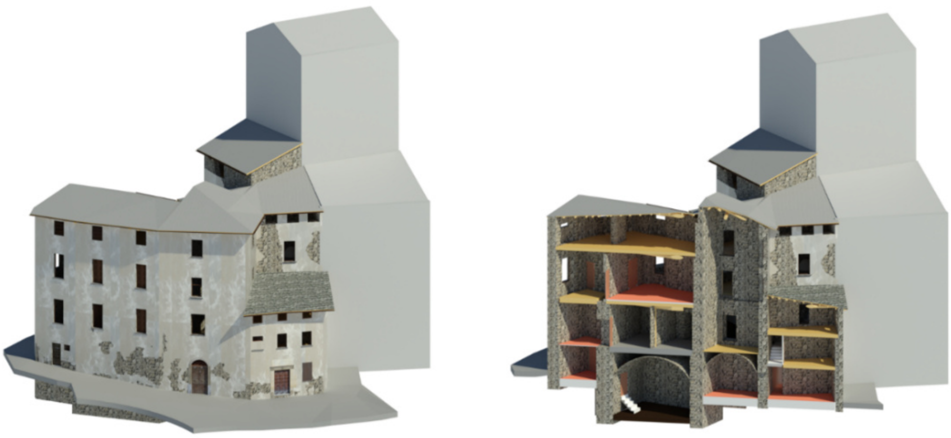


Figure 4. Odescalchi Manor, at Berbenno: material and decay mapping implemented in HBIM model

Another relevant aspect to be taken into account is the fact that the HBIM method allows one us to minimize the frequency of interferences characterized by non-regular and non-uniform elements and structures that are often found in the restoration of historical buildings. For example, in the roof of the Grana Pievani (represented in

Figure 5) Palace with each wood element consisting of a different cross-sectional form and dimension. In the model, the detected decay phenomenon was assigned to the corresponding structural elements in order to design each single strengthening element in its effective position. For the purpose of characterizing the intervention, the modelled elements were highly detailed by assigning all available technological and geometrical information, part of a broader strategy of information to be utilized during the construction phase. Reinforcement plates, metallic ties or wooden strengthening planks were modelled and having as a “host” the strengthened structural element where they would be placed. In this way, the connection of each design element to each existing structural element was correctly inferred.

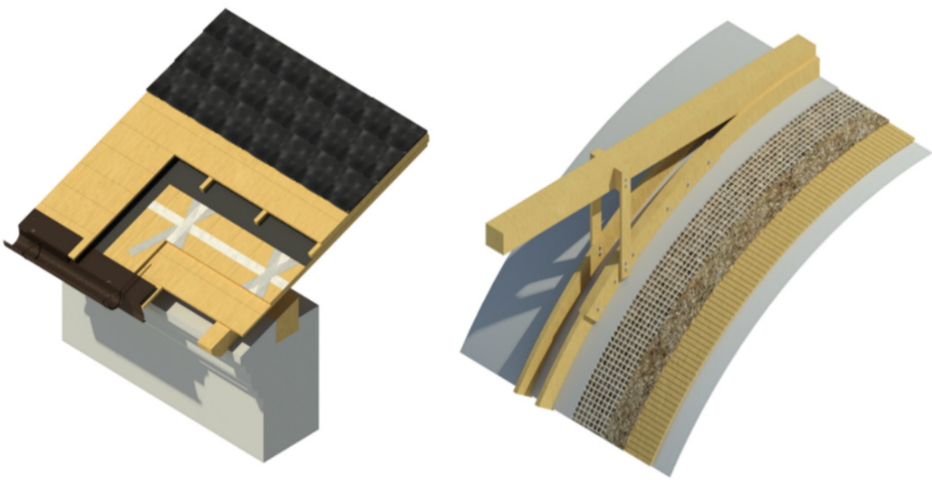


Figure 5. Grana-Pievani Manor, in Tirano: constructive details represented in HBIM model

## 4 CONCLUSIONS

The case studies presented in this paper discuss the HBIM methodology applied to buildings with volumes around 3.000 $m^3$ and are aimed to demonstrate that, in spite of the common view, HBIM is efficient and convenient also for the application to small scale buildings. This methodology proved to be very useful to classify the information with regards to geometrical and mechanical characteristics, the status of decay, and to assist during the design process in all its stages, including information gathering and drafting the "as-built" situation, on-site management of the eventual restoration works, and finally for managing the process of future conservation of the building. The scope of HBIM efficacy extends from the first phases of gathering knowledge about a specific object of study to the last phases of its management and conservation.

Future research entails an in-depth reflection on the part of the scientific community in order to develop adequate approaches, tools, and standards when dealing with cultural heritage buildings. Further development points toward a shared model in the professional community on the detailed issues that are specific for a correct approach to the conservation of existing buildings in areas that include the management of peculiar and not repetitive elements, the decay analysis, the vulnerability assessment, and the conservation plan.

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