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ReUSO 2024

Documentazione, restauro e rigenerazione sostenibile del patrimonio costruito

a cura di
Alessio Cardaci, Francesca Picchio, Antonella Versaci

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SEZIONE 1

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letture storico-critiche, documentazione, rappresentazione,
valorizzazione del patrimonio costruito e paesaggistico
anche mediante il mondo digitale

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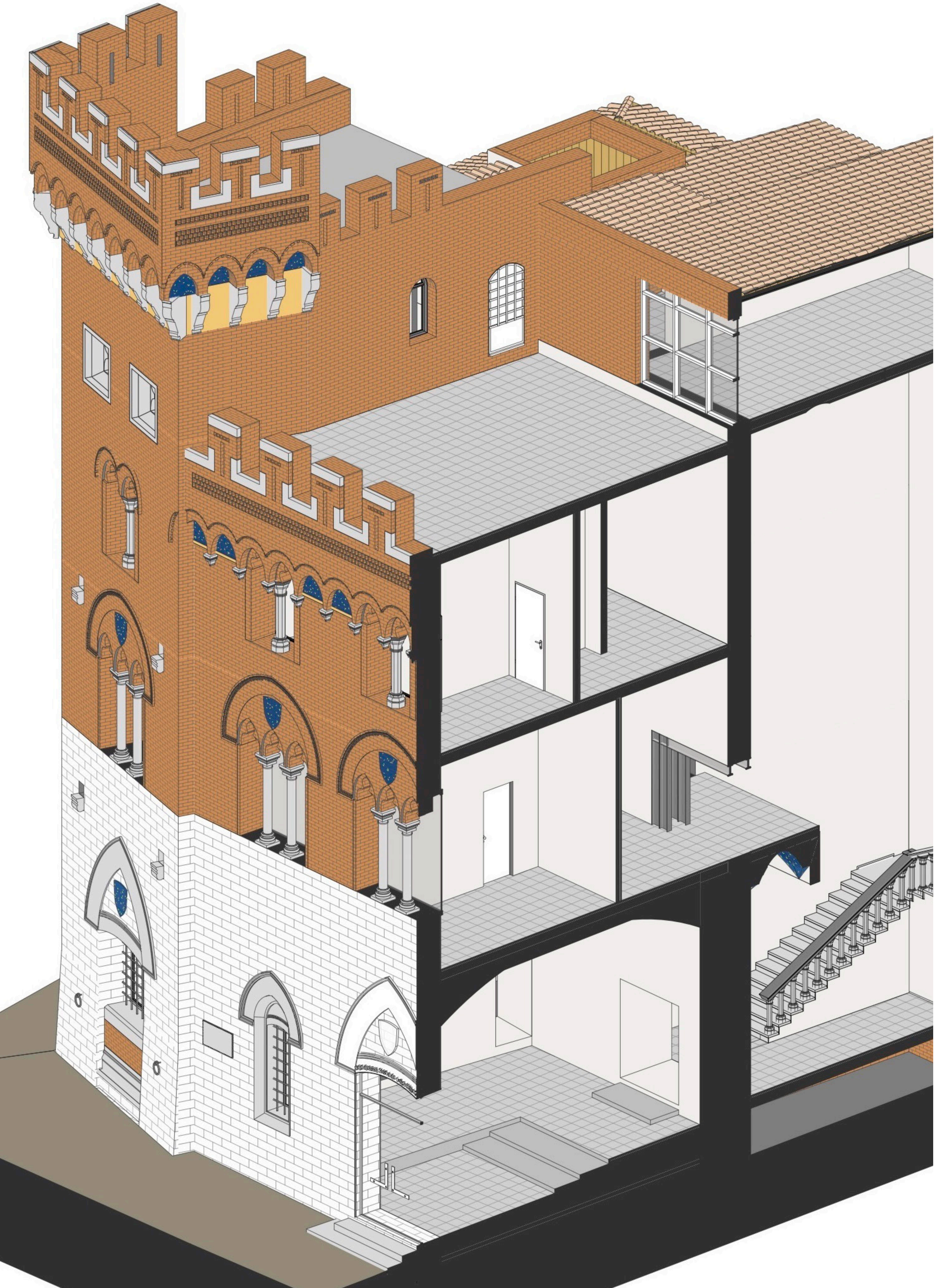

Exploded views of the H-BIM model , © Dell'Orca, D'Errico (on the left).

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REQUISITI DI SCAMBIO INFORMATIVO (EIR) NEGLI USI DEL BIM PER L'ANALISI STRUTTURALE DI EDIFICI STORICI: IL CASO STUDIO DI PALAZZO ALDOBRANDESCHI A GROSSETO

EXCHANGE INFORMATION REQUIREMENTS (EIR) IN BIM USES FOR THE STRUCTURAL ANALYSIS OF HISTORIC BUILDINGS: THE CASE STUDY OF ALDOBRANDESCHI PALACE IN GROSSETO

Carlo Biagini - University of Florence, Florence, Italy, e-mail: carlo.biagini@unifi.it
Andrea Bongini - University of Florence, Florence, Italy, e-mail: andrea.bongini@unifi.it
Daniele D'Errico - University of Florence, Florence, Italy
Gianmarco Dell'Orca - University of Florence, Italy, Italia

Abstract: The digitalization process of cultural heritage is crucial for preservation and enhancement of historic buildings. This study focused on Exchange Information Requirements (EIR) for H-BIM modelling of Aldobrandeschi Palace in Grosseto (Italy), aiming structural analysis of the historic building and entailing the use of BIM authoring software (Autodesk Revit) and FEA structural software (DIANA). The research carried out several phases, starting with historical analysis and geometric survey, integrating internal measuring with laser device and capturing external geospatial data through photogrammetric procedures. The authoring modelling of architectural and structural discipline was performed to optimize interoperability with the specific structural analysis software, posing various challenges and requiring innovative solutions to improve the data exchange between the two different software. The structural model was undergone to seismic analysis following guidelines for calculating the structural integrity of monumental historic buildings in masonry, leveraging information from the BIM model. The outcome is a digital model providing a wealth of information for managing, conserving, and restoring the historic building. Specifically, the digital model can serve as database for restoration projects and structural analysis of the historic building. Moreover, this work intends to offer a contribution to promote collaboration among actors of different disciplines involved and improve the mutual understanding of interoperability issues.

Keywords: H-BIM, Interoperability, IFC, Finite Element Analysis, Aldobrandeschi Palace.

1. Introduction

The Building Information Modelling (BIM) methodology has reached a high level of diffusion in the international context, and it has brought about a need for seamless integration between BIM software and structural analysis tools. Although this, BIM still has limitations in this field, in particular when we talk about historical buildings characterized by complex and irregular geometries. The difficulties in using modeling software are combined with the lack of a complete interoperability between the different solutions adopted by the various actors. Interoperability that can enable architects, engineers, and construction professionals to utilize the advantages offered by each technology, including improved collaboration, reduced errors, and enhanced decision-making.

In the AECO sector in fact, information management still largely relies on proprietary software, hindering collaboration and data sharing among supply chain stakeholders. However, interoperability is crucial for BIM methodology and is also supported by buildingSMART's efforts to standardize language use. Digital modeling has advanced from simple geometric shapes to object-based modeling, focusing on virtual product creation and process simulation. BIM objects contain not only geometric data but also attributes, rules, and other relevant information to define their behavior at different stages of project simulation. As a result, BIM model exchange files will hold more comprehensive data than vector graphics files, requiring readable formats for various software systems and operators.

The application of BIM for historic buildings has emerged as a promising approach to streamline documentation, preservation, and maintenance processes. BIM modelling process begins with an in-depth architectural survey that gathers geospatial, material, and technical data, as well as semantic values highlighting their historical significance. This research phase can yield vast amounts of diverse information (archival documents, drawings, photographs, reports, etc.), which greatly impacts design decisions for restoration and conservation projects. By analyzing these sources alongside geometric surveys and other instrumental investigations, we can clarify the building's morpho-typological evolution. All collected data will be made available in open formats to enable sharing with other stakeholders involved in preserving the built heritage.

This paper focuses on the digitalization of the historical Aldobrandeschi Palace in Grosseto, (fig. 1) currently designating as Provincial Administration Hall, by utilizing H-BIM modeling in Autodesk Revit software to create a model that is both faithful and detailed for the architectural discipline, as well as optimized and simplified for export into DIANA FEA software for structural analysis. The study addresses the issue of interoperability between the two software, finding innovative solutions to overcome the challenges encountered during the project's development. Beyond preserving cultural heritage, digitalization enables the creation of an interactive information library that can be used by various construction disciplines, speeding up study and design processes. Moreover, this process facilitates coordination among professionals involved in managing historical building information, ensuring greater efficiency and reducing time and resource waste.

2. From architectural modelling to structural simulation

BIM applied to new or existing buildings have already established procedures for creating information models starting from the documentation developed during the different phases of the building process [1]. Instead, when BIM methodology is applied to historical buildings there are some critical aspects. Creating a model of a historic building, known as H-BIM [2], goes beyond simply reproducing geometric shapes; it is necessary first of all to recover all the documentation available and carry out an archive research, aimed at the recognition of the semantic values of every built components necessary for subsequent protection, preservation, and enhancement actions [3]. Furthermore, it's crucial to choose the most suitable methods for creating parametric models, starting from existing documentation (CAD-to-BIM) or various digital survey types (scan-to-BIM). This way, digital models help simplify reality's complexity, building databases that foster management system development. These models can represent information based on specific parameters, improving representation, management, and Cultural Heritage documentation efficiency [4]. Despite these efforts, the process remains complex, particularly in scan-to-BIM workflows, which frequently encounter challenges due to degradation and difficulties in identifying the technical parameters of historic elements and materials. While automation is improving for data collection and pre-processing workflow, the most critical aspect remains the modeling methods used [4]. It is necessary to introduce a level of simplification of the information model respect to the point cloud model, that is, a modelling uncertainty, which must be appropriately specified from the beginning of the process. To evaluate the geometric quality of the model, it is helpful defining a "modeling tolerance", intended as the precision level at which the model approximates the geometric data obtained through building scans, as reported, for example, by the USIBD Level of Accuracy (LOA) Specification Guide [5]. This can vary for different model components.

Fig. 1 - Picture of the Palazzo Aldobrandeschi, Grosseto (I).

BIM software designed for AECO often lacks tools for modeling complex historic buildings with multiple complexities, such as geometric, material, historical, and construction aspects. To overcome traditional time-consuming modeling techniques, researchers have proposed alternative approaches for various goals. These methods can be categorized into three main groups [6]: reverse modeling, direct modeling, and generative modeling. Reverse modeling involves generating a 3D polygonal mesh from processed point cloud data. Direct modeling involves extracting profiles from the point cloud and using them as references to create complex surfaces, often using NURBS (non-uniform rational B-spline) techniques. Generative modeling uses geometric operation algorithms developed in visual scripting environments, relying on specific input parameters to generate a model.

Trovatelli et al. [7] use generative modelling for the construction of a masonry vault which is then combined with a simplified version of the facade. Barazzetti et al. [8] try to maintain the irregularities typical of historical buildings by combining simpler geometries, created directly within the BIM authoring software, with more complex geometries created through NURBS in external software.

To make information modeling effective and efficient in managing historic assets, it is crucial to clearly define the modeling purposes and BIM uses upfront, ensuring they align with the client's (public or private) exchange information requirements. A comprehensive BIM execution plan (BEP) should then outline an operational workflow that integrates geometric modeling phases, alphanumeric data implementation phases, and subsequent validation steps to verify model accuracy (LOA) and completeness.

When our BIM use is aimed at structural analysis of a historic building, it is important to determine the used construction technique. It can be observed that, unlike reinforced concrete or steel, the exportation of masonry building models from BIM authoring software into FEA software does not take place through two-dimensional elements (frame and shell) but through volumetric elements. It is therefore important to know well the processes of exporting and importing the geometries executed by the authoring software, as well as the difference between the various MVD of the IFC scheme supported. Structural software also requires geometry without intersections or overlaps between parts. Leonardi et al. [9], for example, use an algorithm developed in Python to translate an IFC model of an aggregate of historic masonry buildings into a structural model useful for structural analysis.

3. Modelling approach for a lean and seamless exchange data workflow

The implementation strategy for the H-BIM modelling was articulated in several stages (fig. 2). Initially, it was necessary to achieve an in-depth knowledge of the work context by examining historical, cultural, regulatory and data-related issues. This included collecting on-site data through targeted inspections. In particular to integrate the available geometric survey of the building and enhance its understanding,

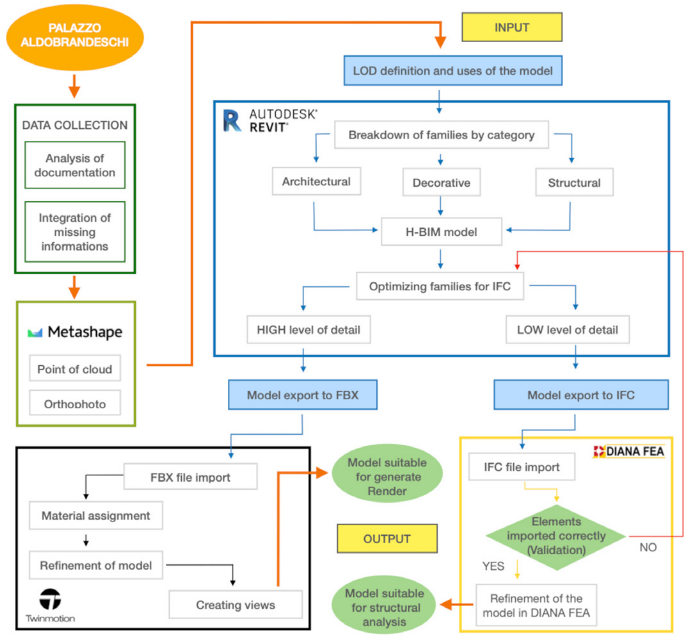


Fig. 2 - BIM modelling workflow.

photogrammetric techniques were used to generate orthophotos and point clouds. DSLR camera was selected for this purpose. This method involves processing image information taken on-site to create an accurate and detailed three-dimensional representation of the different objects. To achieve this, shots must meet specific criteria: capturing the building from various angles, achieving at least 60-70% overlap between them, and maintaining high resolution without deformation or distortion. This ensures that key points in each photo are precise and can be reliably interpreted by the software used for photogrammetric processing.

The second phase of our project entailed creating a single model encompassing all architectural, structural, and decorative details. This process involved modeling over 60 families, with several being enriched with specific parameters to facilitate modeling and streamline the export process to IFC (Industry Foundation Classes) for generating a lightweight model suitable for structural analysis software. When working on historical buildings with non-standard elements constructed with handmade techniques or altered over time, it is necessary to conduct an in-depth study of each element's connections with adjacent structural components to create a model that accurately performs the original structure and is compatible with other software or platforms. Furthermore, exchange requirements had to refer not only to the creation of a detailed architectural shape faithful to the original one, but also to the best modelling procedures to achieve a lighter version of the model for exporting into structural analysis software, that needs filtered information related to shape, material, and constraints [10].

To ensure accurate structural analysis, the entire model was divided into smaller parts using a structural logic, enabling a detailed examination of the mechanical behavior under loads and stresses. To avoid an overwhelming computation with unnecessary details such as decorations or non-critical elements, only relevant information was isolated for the structural analysis. In this project, innovative solutions were employed to overcome some of the challenges encountered, leading to the successful completion of the complex task. Besides classifying various masonry types found in the building, we adhered to guidelines for information production in BIM provided by the State Property Agency (Agenzia del Demanio). The coding system follows a basic framework consisting of five fields:

LevelOfDetail - FunctionType - FunctionSubtype - Description - SequentialNumber

The level of detail is represented by a number between 0 and 2, with increasing levels providing more comprehensive information about the material. For instance, Level 1 includes physical and thermal properties beyond those in Level 0, while Level 2 incorporates all characteristics from previous levels plus manufacturer information. Function type and subtype selection should be made from options listed in the guidelines table, while the description field highlights the most crucial characteristic for this case study, which is material type. In categorizing masonry types, we employed the IQM (Masonry Quality Index) method, classifying each type based on site-observed parameters. The IQM assessment enables determining a wall's strength by evaluating its physical and morphological characteristics using a numerical value between 0 and 10. To evaluate IQM, various geometric parameters and construction methods can be considered [11]. However, to ensure simplicity and practicality, we only considered seven parameters: good quality mortar, effective contact between elements, wedges; transverse interlocking, presence of through stones, strong elements with squared shape, large, strong elements relative to wall thickness, presence of horizontal courses, and good quality of strong elements. It is possible to estimate the mechanical characteristics of the masonry through the numerical correlations proposed by Borri and De Maria [12]. These correlations are based on associating IQM values with different masonry categories and their respective mechanical properties. These masonry categories have been used to define the description field.

The third phase focused on optimizing interoperability with other software applications, specifically DIANA FEA for finite element analysis and Twinmotion for rendering representation purposes. Achieving compatibility between these two programs posed significant challenges, necessitating unconventional modeling approaches and innovative solutions to overcome obstacles encountered during the modelling development. This approach enabled seamless integration of architectural and structural data, allowing for comprehensive analysis and assessment of the building's structural integrity and seismic resilience.

4. Case study: Aldobrandeschi Palace

The first step of the study involves gathering information. It begins with the urban framing of the building and goes on by analyzing historical data, concluding this initial phase of the study with the integration of data through site inspections and surveys.

Aldobrandeschi Palace is located in the historic town of Grosseto, in the central part traversed by the decumanus axis of via Carducci. It is currently the headquarter of the Province Administration and overlooks the eastern front of Dante Alighieri square. From historical evidences, it appears that the building was originally the residence of the Aldobrandeschi family and later the office of the Podestà. The construction of the southern part of the building date back to 11th and 13th centuries during the first urban expansion, while the other part was built together with the "Nuova Curia" in the early 16th century.

At the end of the 19th century, the Provincial Council decided to demolish the existing buildings and en-

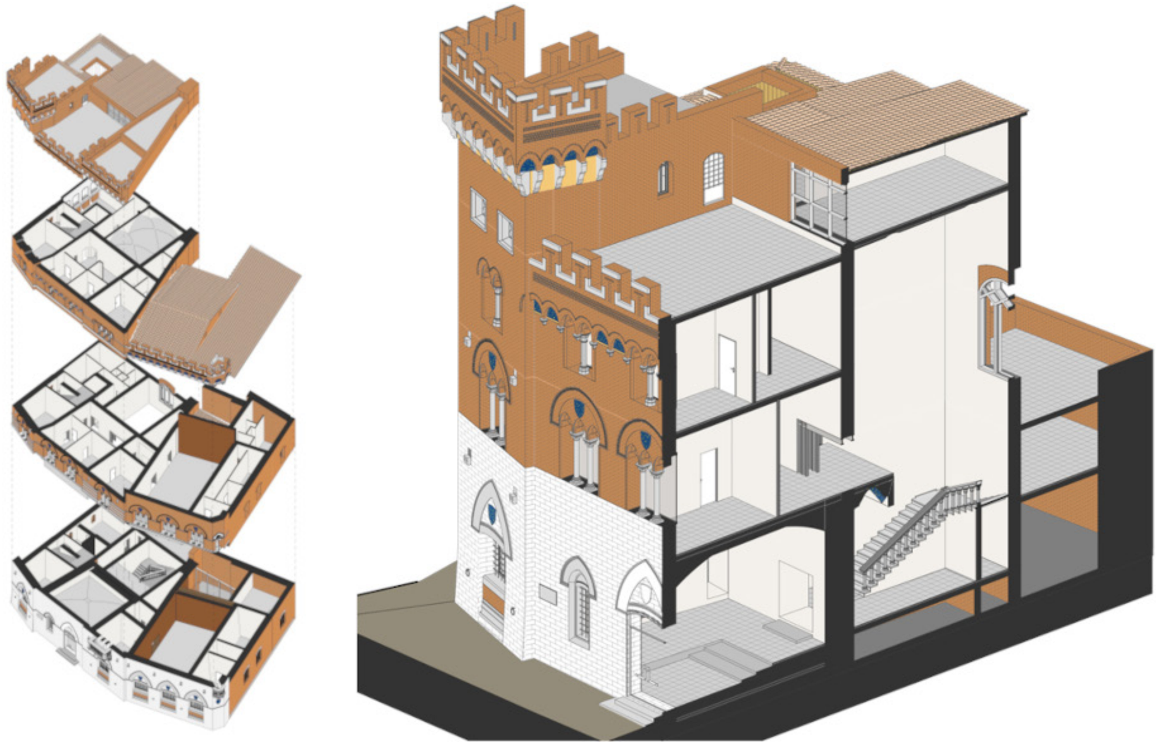


Fig. 3 - Exploded views of the H-BIM model (Dell'Orca, D'Errico).

trust the drafting of the new building project to the architect Lorenzo Porciatti and the engineer Ciriaco Salvadori. The demolitions began in the autumn of 1899, and construction work commenced on April 5, 1900. The new palace was officially inaugurated on May 31, 1903. More recently, a significant renovation of the building took place in 1985: on the ground floor, it mainly involved the demolition, on the right side of the entrance, of walls forming a long passage and some offices, to create a single space of considerable size and height. The demolitions did not affect the main load-bearing walls, on which a new mixed steel and reinforced concrete slab was then installed. There have been no further interventions on the structure, nor significant architectural changes after this works.

4.1. Historic documentation and geospatial data acquisition

The research focused on projects and technical documents from the time to lead an historical-critical analysis of the various phases of modification of load-bearing walls and other structural elements. Original plans from the 1901 restoration design and the major successive renovations were found in various places and historical archives. These include hand-drawn plans, elevations, sections, and details of floors [13], as well as notebooks with precise measurements of decorative façade elements or stair calculations [14]. By cross-referencing these drawings with more modern paper ones (such as 2D digital drawings of the last renovation works), the history evolution of horizontal and vertical partitions was traced. This was helpful for both traditional on-site surveying and for defining construction and decorative details in the final phases of BIM modeling. In addition, over 600 camera shots were processed to accurately reconstruct the building's external façades. The images were imported and processed using Agisoft Metashape to generate a dense point cloud, useful for accurately modeling the high-quality architectural decorations located in inaccessible areas such as the cornices at the top of the main external façade.

As mentioned in the previous chapters, in order to obtain an acceptable accuracy of the model, the process has followed the "heritage workflow" proposed by USIBD guidelines. The CSI Uniformat classification has been used to classify and evaluate all built elements, such as LOA30 for exterior walls (B2010), interior partition (C1010) and floor construction (B1010), and LOA20 for exterior windows (B2020) and doors (B2050).

4.2. Modelling customized procedures

Walls. The masonry structure has been modeled extracting information by geometric survey. Many walls, particularly the older ones, have an irregular shape and for this reason, where necessary, instead of using the standard procedures for wall creation, custom local models were employed to reproduce the geometric anomalies of the real masonry element in both plan and section.

Floors. In this case, the graphic plans and notes on the construction details of the 20th-century restorations were crucial, as they provided information on the thickness and construction materials of the floors. All individual components of each floor were modeled to make the detailed model as complete as possible, even if not essential for the structural analysis (fig. 4). The exact representation of this building component is crucial for the structural model's correct operation. During the import phase, all components displayed no geometry problems. However, there were challenges in correctly aligning the floors, which affected their precise depiction in the BIM software, as this impacts their connection with the masonry in the structural design. Specifically, in a traditional architectural model made with Revit, various methods can be used to draw a floor in a certain area to be identified as a level's horizontal closure. Yet, the structural software necessitates high precision in the design of this element, which can only be achieved through the use of a specific command.

Double cross vault. One of the most challenging problems of object modeling is undoubtedly represented by the vaults. In particular, there are two types: a pavilion vault and a double cross vault. The double cross vault, with its irregular plan and sharp angles, proved particularly problematic in a structural analysis software during the meshing process, potentially leading to various representation issues and inconsistencies. Given these difficulties, it was not possible to use parametric void families (to subsequently subtract the excess volume from the floor). Instead, the solution was to model the vault's structural section using a local model. Within this model, solid masses and voids were created to represent the intersection of the barrel vaults. The definition of voids was carried out with great precision, as any small incongruity in the geometry of the arches composing the vault caused mesh distortion and subsequent analysis failure (fig. 4).

Façade doors and windows. For the door and window objects on the façade, which feature diverse decorations, a parameter has been set that prevents the exportation of these decorative elements in IFC, keeping only the holes of the window (fig. 5). However, for certain types of doors and windows characterized by complex decorations, it was not possible. Therefore, they were modeled as voids in the masonry, associating with the host (the masonry wall) and maintaining the connection between them during the export process. A new object parameter was defined and set as an instance, associated with two reference dimensions. The first dimension tied the void to its correct and real position in the wall, while the second one was used to link the void to a fictitious position in space. Selecting the latter the void will neither be displayed on the building nor exported, as it was set only for visible elements in project views. In summary, the "decoration" parameter, depending on project needs and the input choice set, adjustable via a "Yes/No export" command, alters the position of the void in space and makes it either visible or invisible in the IFC export file.

Columns. For the column objects, the optimization process focused on simplifying the geometry, as the existing details and complex shapes would have imposed a high computational load during subsequent structural analyses. In this case, the parameter used for other families, which prevented exporting the geometry in IFC, was not applicable. To address this issue, the level of detail of the family was modified. Specifically, to import the same family with a customized level of detail, the visibility of the family was adjusted so that it appeared complete and realistic at a high level of detail and simplified and essential at a low level of detail (fig. 6). The modeling phase involved creating two distinct objects within the same family and with the same spatial coordinates, differing only in their visibility settings based on the level of detail considered, thus avoiding overlaps between the two elements. The final result is a column

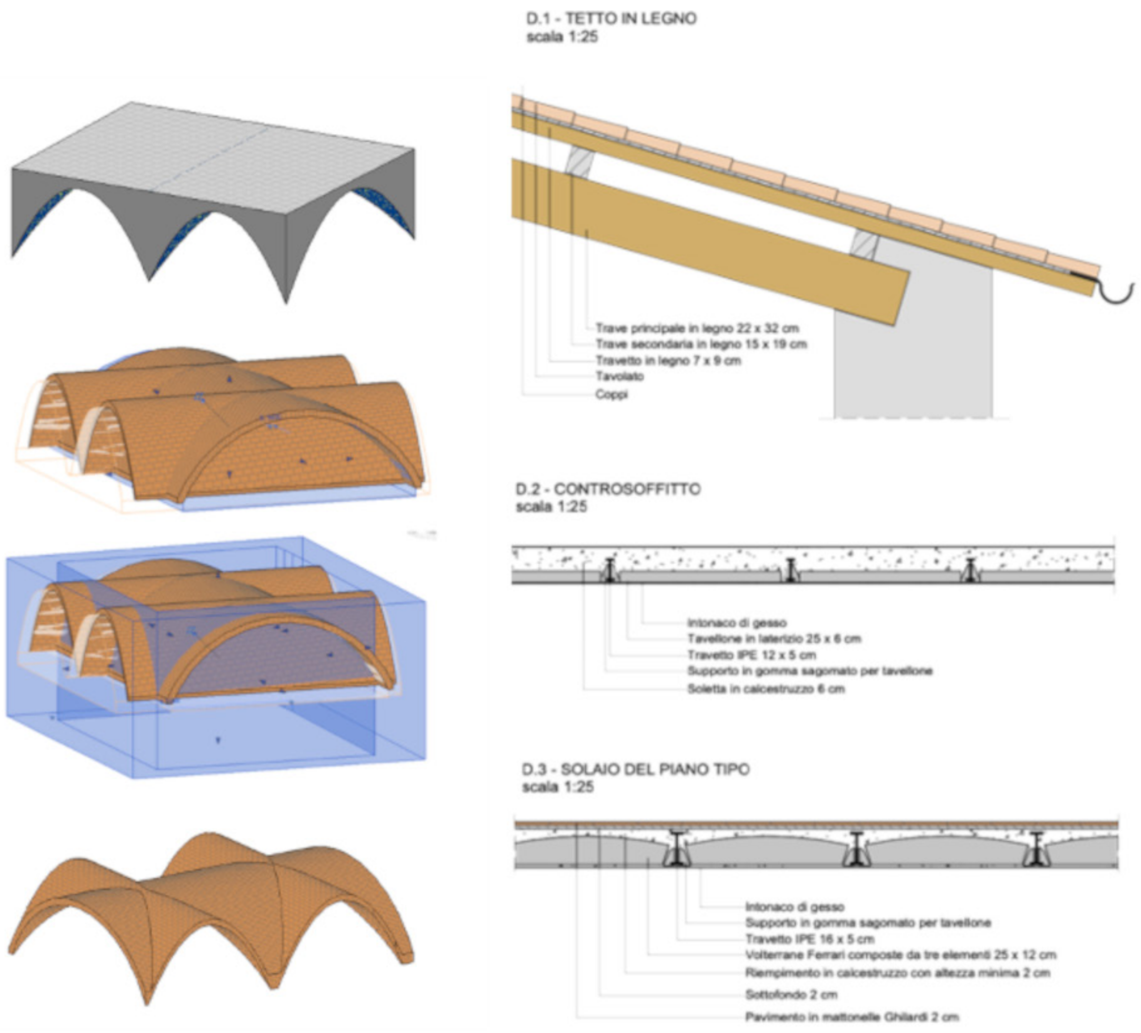


Fig. 4 - Floors and vault generation.

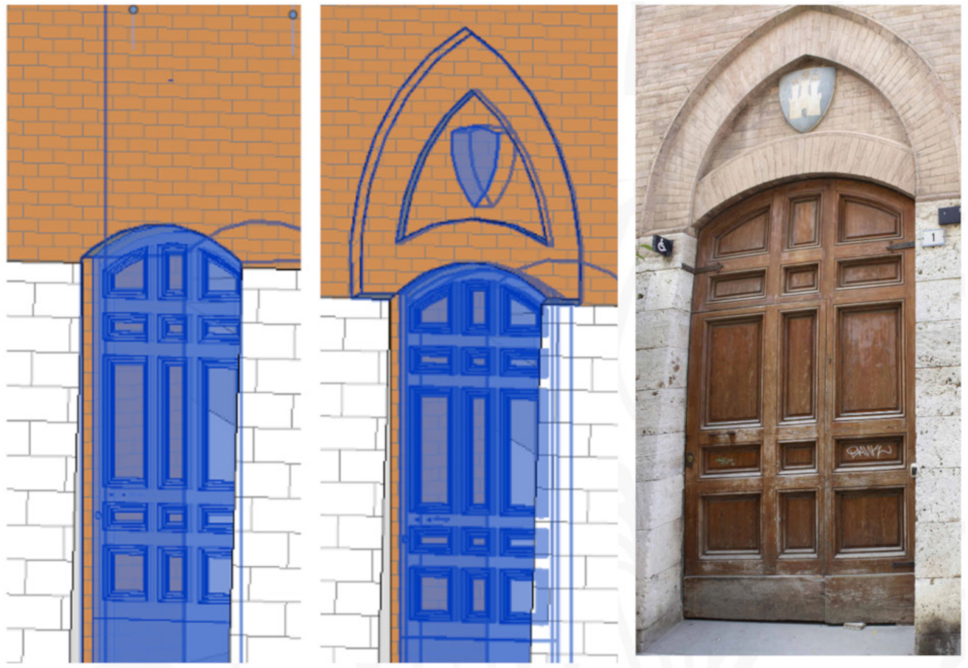


Fig. 5 - Doors in the facade.

composed of all its geometric parts at a high level of detail and a simplified column represented by a basic shape at a low level of detail.

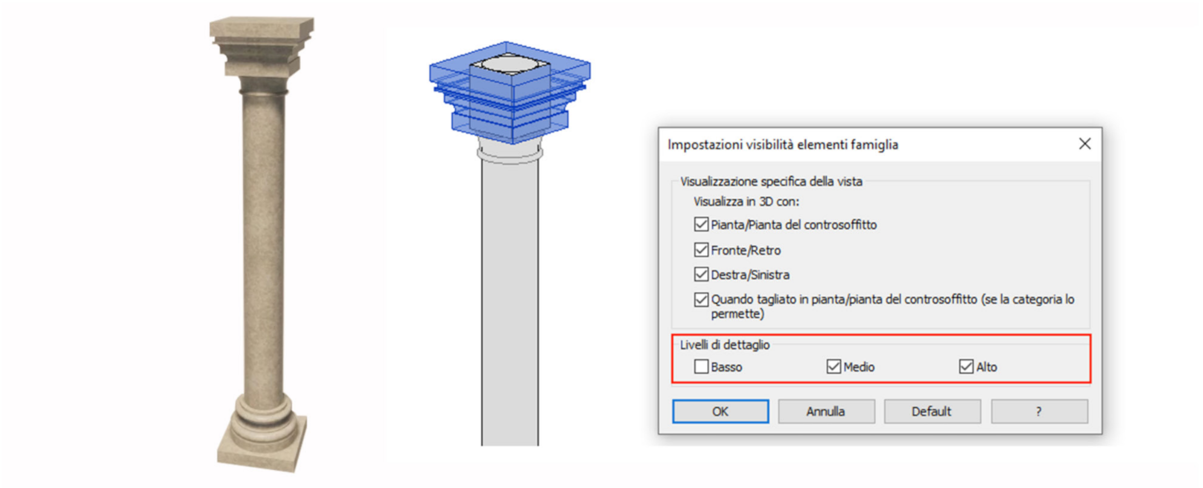
4.3 Model export

In BIM modeling, a specific goal is always set regarding the final use of the resulting model, enabling its application in a particular sector of AECO. In this study, although most efforts focused on interoperability with structural software, we aimed to create a BIM model that could also be applied in other BIM Uses. To achieve this, we utilized Revit 2023's options for exporting IFC files, which is a standard format facilitating information sharing across different software platforms. These configuration options include defining IFC properties, category mapping, object selection, view choice, and level of detail management. The definition of IFC properties allows for including detailed information about each model element, such as its location, size, and performance. "Category mapping" enables associating Revit categories with IFC categories, while "object selection" enables excluding unnecessary elements. "View choice" and "level of detail management" enable tailoring the export to requested visualization requirements. For this work, we based our configuration on the "IFC 2x3 GSA Concept Design BIM 2010" model (fig. 7).

4.4 Importing the simplified model into DIANA FEA and meshing

Regarding the analysis of masonry buildings, DIANA FEA proves to be a highly advantageous tool compared to other structural analysis software. This is due to its ability to accurately model the geometric and mechanical characteristics of these structures, which present various complications from a structural analysis perspective, such as the presence of rigid joints and variations in shear strength depending on the direction of the loads. Additionally, for modeling nonlinear structures, as in this work, using DIANA FEA allows consideration of both geometric and material nonlinearities. During the transition from a 3D model in Revit to the DIANA FEA software for masonry buildings, some incompatibilities may arise. The issues can vary depending on the versions of the software used. This work considers Revit 2023 and DIANA FEA version 10.3. Once the structure IFC file is imported, in the absence of a direct plug-in between the two software programs to enable bidirectional modeling of the geometry, changes to the imported elements can only be made using DIANA FEA itself. This becomes a significant problem for complex buildings like the one under study, as small modeling errors are common. To address this problem, external IFC readers can be used to convert individual elements for modification into a file compatible with DIANA FEA in the "File > Import CAD file..." section (.stp;.step; .igs; .iges; .dwg; .dxf).

Along with the simplified geometry of the building, information regarding materials, particularly masonry and flooring, was also imported. For convenience, the information exchanged with Revit included naming conventions and the identification of material assignments on individual elements, while the mechanical properties of the elements were added directly in the structural software. There were some minor compatibility issues with visualization in DIANA FEA using optimization tools. After these issues were resolved, loads were added and the mesh was executed (with a grid size of 0.2 m). At this point, all static and dynamic structural analyses were performed according to the guidelines for structural analysis of historic monumental buildings and compared with calculations executed using traditional methods, yielding minimal discrepancies in results. This confirmed the validity of the entire study and process.



Impostazioni visibilità elementi famiglia

Visualizzazione specifica della vista

Visualizza in 3D con:

☑ Pianta/Pianta del controsoffitto

☑ Fronte/Retro

☑ Destra/Sinistra

☑ Quando tagliato in pianta/pianta del controsoffitto (se la categoria lo permette)

Livelli di dettaglio

☐ Basso ☑ Medio ☑ Alto

Fig. 6 - Column family.

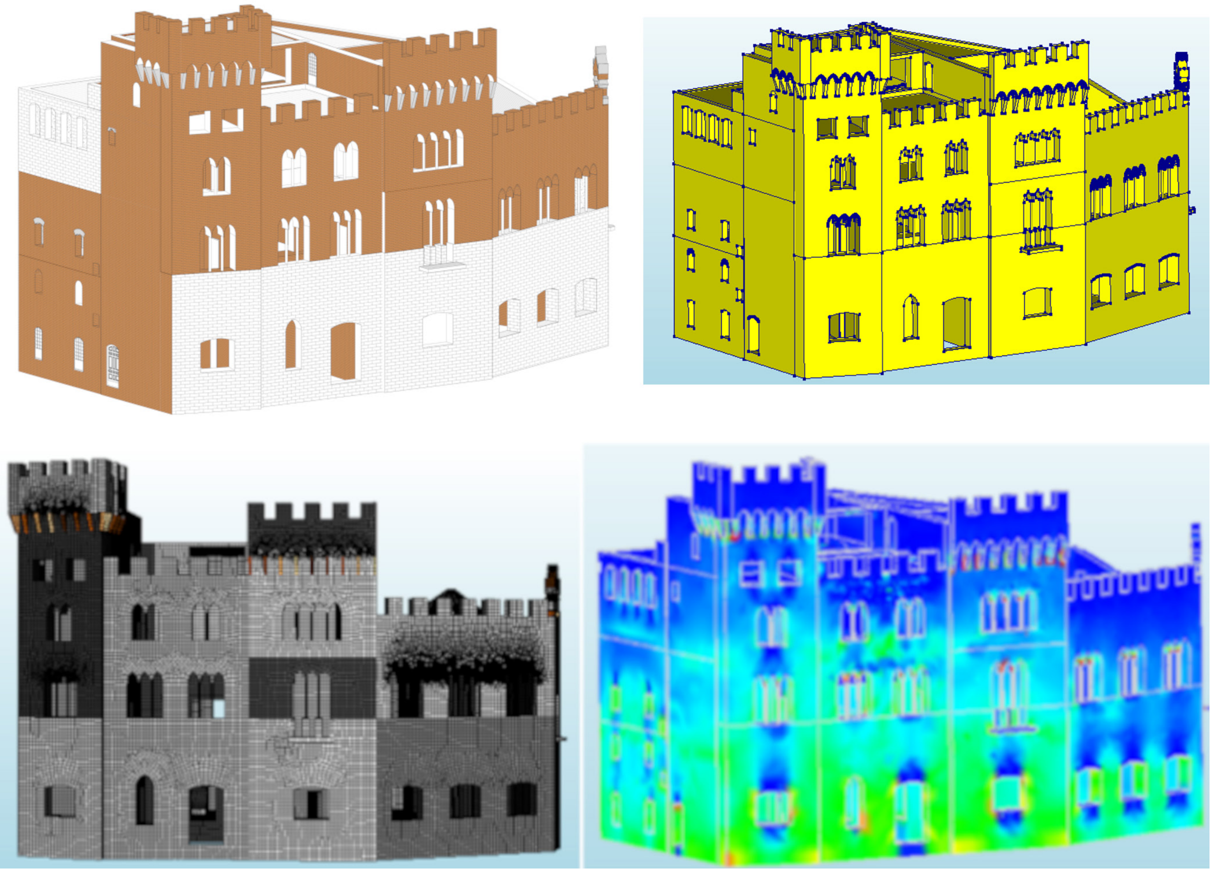


Fig. 7 - Model evolution, from modeling to simulation. a) H-BIM in a low level of detail. b) IFC model. c) Mashed model for structural analysis in DIANA FEA. d) Structural analysis results. (Dell'Orca, D'Errico).

4.5. Exporting into Twinmotion software

Finally, the detailed building renders were created using the Twinmotion graphic rendering software to achieve visualizations and realistic views of the building. The export operation from Revit to Twinmotion was relatively straightforward. The rendering software uses the .fbx format, which can be directly created from the Revit screen export command. It is important to note, however, that this procedure is limited to the most recent versions of the BIM software. For older versions, a specific extension needs to be downloaded directly from the Twinmotion website (fig. 8).

5. Conclusions

The digitization of Aldobrandeschi Palace has opened up new possibilities for tackling the complex problems associated with the conservation and management of historic buildings. This work was aimed at defining the exchange information requirements for a streamlined data workflow in a BIM Use for structural analysis.

In particular, the current software overview dedicated to the structural analysis presents a different maturity level between solutions, which involve the calculation of framed structures with prevalent linear elastic behavior (typical of buildings in concrete or steel structures), and those relating to masonry structures with assessment of shear resistance in a non-linear field. In the first case, completely reliable and consistent solutions with BIM-based workflows are already available. On the contrary for masonry structures (typical of historic buildings) it is necessary to preliminarily define rigorous modelling strategies and procedures, which allow a "lean" workflow in data exchange between BIM authoring software and structural analysis one [15].

Through a careful archive research, an on-site direct surveys and digital photogrammetry of Aldobrandeschi Palace, a highly detailed 3D model of the building could be authored. It combined an in-depth collection of historical and building data and information, defining specific modelling procedures to create an H-BIM model, that accurately reflects its architectural and structural features, but also ready and compliant with the subsequent information exchange with the structural analysis software. The model was then exported in IFC format for structural analysis with DIANA FEA, ensuring precision and reliability.

The adoption of these procedures for achieving H-BIM offered significant benefits in optimizing the masonry structural model, interoperable data exchange and computational time during FEA. At the same time, a high quality of architectural modeling was guaranteed (that's important dealing with cultural heritage) without any loss of the required level of accuracy (LOA), even in the geometric detail of the decorative elements, which can be alternatively selected on the basis of subsequent uses of the model: analysis structural or rendering for photorealistic visualization.

Fig. 8 - Render by Twinmotion software (Dell'Orca, D'Errico).

The modeling procedures developed in this study will become part of a BIM-guide of best practices for H-BIM modeling aimed at structural analysis of cultural heritage.

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