



Article

Insight on HBIM for Conservation of Cultural Heritage: The Galleria dell'Accademia di Firenze

Silvia Monchetti ^{1,*}, Michele Betti ¹, Claudio Borri ¹, Claudia Gerola ², Carlotta Matta ² and Barbara Francalanci ²

¹ Department of Civil and Environmental Engineering, School of Engineering, University of Florence, 50139 Florence, Italy; michele.betti@unifi.it (M.B.); claudio.borri@unifi.it (C.B.)

² Galleria dell'Accademia di Firenze, Ministero Della Cultura, 50139 Florence, Italy; claudia.gerola@cultura.gov.it (C.G.); carlotta.matta@cultura.gov.it (C.M.); barbara.francalanci@cultura.gov.it (B.F.)

* Correspondence: silvia.monchetti@unifi.it

Abstract: The application of Building Information Modeling (BIM) on historic constructions is investigated in this paper by discussing, as a representative case study, the Galleria dell'Accademia di Firenze (Italy), thus showing as this tool can be used effectively for the management and maintenance activities of a historic museum. In fact, while BIM is already well-known as a powerful tool for the design and management of new buildings, its development in the field of historical construction is currently growing and attracting increasing interest in the scientific community. This paper proposes, in particular, an Information Model (IM) aimed to collect the structural information to be subsequently employed for numerical modeling of the building, thus representing the link between the real world and the computational models. The possibility to handle different types of information to be used for the management, maintenance, and modeling of existing constructions, as shown in this paper, encourages the popularization of this approach as an effective method to support cultural heritage (CH) conservation.

Keywords: museums; HBIM; 3D modelling; management; FE model; experimental data



Citation: Monchetti, S.; Betti, M.; Borri, C.; Gerola, C.; Matta, C.; Francalanci, B. Insight on HBIM for Conservation of Cultural Heritage: The Galleria dell'Accademia di Firenze. *Heritage* **2023**, *6*, 6949–6964. <https://doi.org/10.3390/heritage6110363>

Academic Editor: Ákos Török

Received: 13 July 2023

Revised: 12 October 2023

Accepted: 21 October 2023

Published: 25 October 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The conservation of cultural heritage (CH) requires, as a preliminary and mandatory step, the collection of different types of information: from the historical evolution of the construction and its (if any) restoration interventions to the experimental and monitoring data acquired over time [1–3]. The handling of this flow of information requires an effective Information Model (IM) capable of collecting different types of data, and possibly using 3D models. Indeed, recent advances in the development of 3D digitalization of CH offer the possibility to correlate heterogeneous information with their spatial referencing.

The purposes of this informative procedure are multiple, including, among others, structural, architectural, and system equipment management.

In this scenario, Building Information Modelling (BIM) is a process that is proposed as a solution for supporting scheduled maintenance and conservation activities [4]. It aims to create a 3D model by integrating the concept of a digital model with the level of knowledge [5]. Its diffusion in the field of new constructions and/or ordinary existing buildings is today well established (e.g., [6]), while its application to CH buildings is somewhat limited and still under study. However, as shown in [7–20], Historic Building Information Modelling (HBIM) can be considered a promising and effective tool for the conservation of historic assets due to its capability of handling and archiving all the different sources of information pertaining to a CH building.

As an example, Mora et al. [21] proposed an HBIM approach for the preventive conservation of CH buildings, presenting the case study of the Historical Library of the University

of Salamanca (Spain). The approach exploits the latest advances in 3D digitalization, inspection protocols, and monitoring networks. All the information is integrated with the HBIM environment by ad-hoc families and interoperable communication protocols that allow for obtaining a complete knowledge of the building conservation status. Considering the goal of their study, the authors adopt a low Level of Detail (LOD) with a high Level of Information (LOI).

To move towards the BIM implementation for historic buildings, Biagini et al. [22] developed an innovative approach to the construction management of historical building interventions by exploring the following issues: parametric modeling of the historical building together with the phases of the restoration works, and 3D graphic representation of safety procedures. The authors, through the discussion of the case study of a church seriously damaged during an earthquake, highlight the need to set up a clear and easy-to-use national framework related to the LOD for the appropriate use and expansion of HBIM methodology. An HBIM workflow specifically oriented to the identification and collection of the structural features of historical buildings has been recently presented by Cardinali et al. [23], discussing the case study of Palazzo Vecchio in Florence (Italy). The LOD is set to account for the goal of the HBIM approach. The parametric modeling of the building is specifically focused on determining its structural parameters, avoiding problems related to excessive details related to different issues or too detailed models.

Recently, the application of BIM in the field of CH has received interest not only for the conservation and maintenance at the scale of the building but also at the level of the structural element. This is the case with historic timber structures, as these elements can easily suffer damage over time. Mol et al. [24] investigated the case study of the timber structure of the roof of the key tower of the Castle of Guimarães (Spain) and the roof of the room of the Knight's Room in the Convent of Christ (Spain). Celli and Ottoni [25] examined the wooden hooping tie-rod encircling the dome of Santa Maria del Fiore in Florence (Italy). Both these studies propose the HBIM methodology as an operative tool for the maintenance over time of the wooden elements, focusing on the organization of data obtained from non-destructive testing and geometric surveying with the virtual software model within a 3D space.

The above-mentioned papers draw the lines for the development of the BIM methodology in the field of CH by identifying the elements/open issues that need to be addressed for HBIM to reach its full maturity (and popularity). Among them, two that can be highlighted are the organization of the database on non-geometric information and the passing information procedure from HBIM to numerical models. Bruno and Roncella 2019 [8] set the basis to solve the first issue, focusing attention on non-geometrical information management in HBIM by using, as a case study, the Cathedral of Parma (Italy). One of the first efforts to consider the second issue was proposed, e.g., in [26–30]. Additional improvements can still be introduced in terms of (i) dataset management, (ii) graphical user interface development specific to CH, (iii) storage and handling of monitoring data, and (iv) passing information to numerical models for structural and conservation purposes.

To face these challenges, and to draw some general results useful to enrich the state-of-the-art in terms of digitalization and conservation of CH, this paper takes advantage of a representative case study: the Galleria dell'Accademia di Firenze (Italy). The final goal is the design of a digital storage for the Galleria able, in a 3D model asset, to collect all the available information of the museum and to make them available for numerical modeling. This paper introduces the application of a methodology that, by using HBIM technology, allows for (i) the storage of different information about an existing building (geometric data, mechanical properties of the materials, construction phases, etc.), (ii) its numerical modeling, and (iii) the analysis of the structural health, through periodic comparison over time, with the identification of possible maintenance and intervention actions. To this aim, the paper is organized as follows. Section 2 introduces the methodology. Section 3 illustrates the representative case study, and Section 4 reports the implementation of data.

Section 5 summarizes and discusses the main results and, eventually, Section 5 concludes the paper.

2. Materials and Methods

In recent years, the increasing popularity of the BIM process applications has been connected to the advantages in building conservation management: (i) the implementation of 3D representation, (ii) the possibility to link different typologies of information, (iii) the parametrization of 3D objects, (iv) the integration of monitoring systems, and (v) the updating of the object information. As far as the existing buildings are concerned, the integration of a BIM process starts from the observation of the real object which, through the survey, modeling, and data acquisition, produces the digital model (Figure 1).



Figure 1. Flowchart of the BIM process [8].

However, as underlined in [8], the complexity and the assortment of the CH assets, and the amount of heterogeneous data, introduce some difficulties in the application of the reference standards both in terms of semantic classification and Level of Detail (LOD) (Figure 2). A first effort to connect the complex organization of the information in the field of CH conservation was performed in [31] by introducing some indication (Table 1) related to the historical evolution of the elements and their updating during the building life cycle. In this scenario, the definition of an ontological model related to the multi-disciplinary aspects involved in CH conservation becomes a promising tool for a comprehensive semantic classification [32,33], even though the formalization of shared knowledge about a historical construction is still an open issue [34]. In this paper, a first effort in this direction is proposed through the definition of an HBIM model which handles and integrates all the information and views required for the conservation and maintenance purposes of a historical museum, with specific attention to the data needed to set up a numerical model.

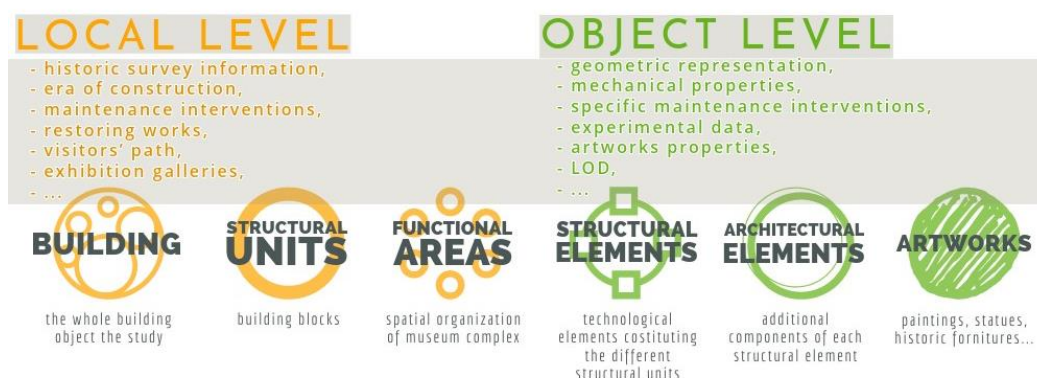


Figure 2. The proposed semantic level classification.

Table 1. LOD degrees according to the standard [31].

| LOD | | Characteristics |
|-------|--------------------|--|
| LOD A | symbolic object | Symbolic 2D or 3D representation. Not geometric representation. Qualitative and quantitative information are indicative. |
| LOD B | generic object | Generic geometric representation or generic placeholder. Qualitative and quantitative information are approximated. Defined geometric representation. |
| LOD C | defined object | Qualitative and quantitative information are generic and can be referred to similar entities. Detailed geometric representation. |
| LOD D | detailed object | Qualitative and quantitative information are specific for many defined similar products. Information related to specific construction systems and maintenance activities. Specific geometric representation. |
| LOD E | specific object | Qualitative and quantitative information are specific to a single system. Information related to construction, assembly, installation, and maintenance activities. As-built representation. |
| LOD F | constructed object | Qualitative and quantitative information are specific to the real product. Information about specific maintenance, management, repair, and substitution activities. |
| LOD G | updated object | Updated representation. Historical representation during the life cycle. Information about specific interventions carried out. |

This process involves a multi-disciplinary knowledge domain and heterogeneous data that need to be handled, shared, and updated. The objective is thus the definition of an HBIM which provides a reliable understanding of the conservation state of the building in terms of functional assets, system equipment, structural configuration and safety level, and the passage of information to computational models.

In this comprehensive scenario, this paper introduces an enriched methodology and novel results based on the outcomes presented in [35–37]. The adopted framework allows for the storage of information on historical masonry buildings, in particular, museum complexes, including geometrical surveys, semantic classification, and LOD definition. These characteristics are referred to in the specific case study, as well as their specific elements, and according to different time periods (i.e., evolution over centuries). The semantic level classification herein proposed considers the information data organized on two levels (Figure 2).

The first—named *local level*—is connected to the building itself, its structural units, and its functional area, and contains global information (e.g., historic survey data related to the era of construction, maintenance interventions, and restoring works).

The second—named *object level*—is strictly associated with the specific element (structural, architectural, and artworks) and includes its characteristics according to the LOD reached (e.g., geometric representation, mechanical properties, specific interventions, and experimental data).

According to this classification, the data generated by different experts are spatialized and referred to the building components. As a result, different typologies of data are associated with each level (Figure 3).

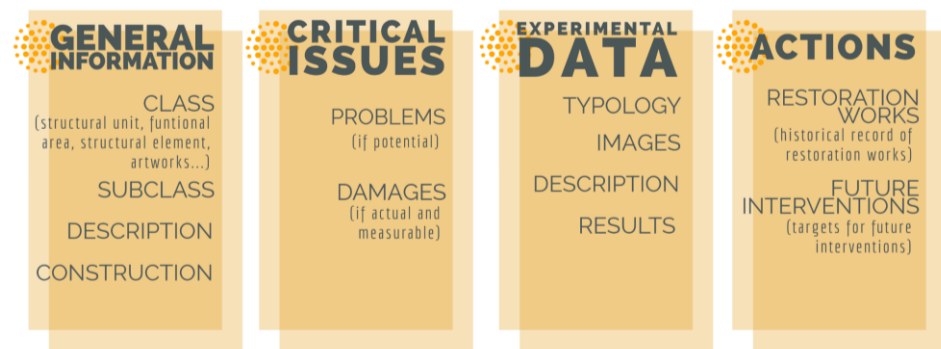


Figure 3. Summary of the information database.

The implementation of the HBIM methodology (Figure 4) requires the combination of two preliminary steps and four iterative stages. The approach starts with the identification of the real structure object of the study and next involves the definition of the specific objectives related to the modeling strategy's purpose.



Figure 4. HBIM procedure.

In particular, a building can be classified following different features (functional, structural, technological, among others) as well as at different LODs according to classification purposes [8]. These targets represent, as a matter of fact, an input of the modeling and affect the entire composition and organization of the HBIM. In this paper, the proposed HBIM methodology is focused on the structural aspects of the historical buildings, without neglecting the possibility of enriching the strategy with additional aspects regarding management of the museum complex.

The methodology introduces four main iterative steps, which need to be repeated in different time periods and when additional information becomes available: (i) data acquisition, (ii) semantic classification and modelling, (iii) data integration, and (iv) data transfer to a numerical model.

In the first iterative step—*data acquisition*—measurements and tests are used in order to collect as much information on the element and structure onsite condition as possible. Visual techniques, such as visual inspection, photogrammetry, and laser scanners, are commonly employed for geometrical survey and damage detection purposes. These techniques need to be combined with the experimental campaign definition in order to acquire information on the mechanical properties of the materials, the dynamic features of the building (as well as of its different structural units), and the restraint conditions provided by the soil–structure interaction and, if any, by the interaction with adjacent buildings.

In the second iterative step—*semantic classification and modeling*—the geometric survey is handled by following the semantic classification in the HBIM process. All the elements composing the building are modeled and associated with a unique identifier. The building,

therefore, appears as a container that consists of different structural units, functional areas, structural and architectural elements, and, in the case of museum complexes, artworks.

In the third iterative step—*data integration to HBIM*—all the elements composing the building are characterized based on the acquired information and the experimental test results with respect to a specific time phase. Consequently, the respective LOD can be associated. Note that, in the present paper, the LOD definition follows the classification provided by the standard [31] which defines 7 LODs indicated with capital letters A to G, as reported in Table 1, by introducing two specific levels (LOD F and LOD G) of development for restoration of CH sites.

In the fourth iterative step—*data transfer to FE model*—the structural information about the building is selected and transferred to a numerical model for structural analysis purposes.

The above steps are repeated each time further information becomes available, or an update of the experimental tests is carried out.

As a result of the integrated procedure, the system links the 3D model of a heritage construction by using commercial BIM software with an extensive information database. As shown in Figure 3, the information database consists of four typologies: (i) general information; (ii) critical issues; (iii) experimental data; and (iv) actions. These data are associated with the local database and the object level of the semantic classification.

More in detail:

- The “General Information” typology specifies the semantic level considered through the definition of the “class” and “subclass” according to Figure 2 and characterizes it with both general description and specific information about the construction phases.
- “Critical Issues” provides documentary evidence about problems (if any) and damages (if actual and measurable) related to the specific semantic level considered.
- “Experimental Data” collects the experimental campaigns available for each semantic level considered by providing images and information about the typologies of observations, their description, and the results.
- “Actions” summarizes the restoration works through the historical record of the interventions and plans future interventions and their targets.

This architecture aims to ensure multi-platform access and user-friendliness. The specific information is directly available within the BIM software as text content or accessed via a web URL.

3. Galleria dell’Accademia

The Galleria dell’Accademia di Firenze (GA-AFI) is a world-renowned museum, home to some of the most important painting and sculpture collections in the world, including Michelangelo’s sculptures, with the renowned David among them, and a rich collection of early Italian paintings. The foundation of the Galleria dates back to 1784, when the Grand Duke of Tuscany Pietro Leopoldo reorganized the Academy of Arts of Design in Florence, founded in 1563 by Cosimo I de’ Medici, in the modern Academy of Fine Arts. However, the turning point for the history of the museum was in August 1873, when Michelangelo’s David, for conservation issues, was moved from Piazza della Signoria to the GA-AFI. During these years, a project began by Architect Emilio De Fabris for the Tribuna, a new construction to complete the museum complex and to host Michelangelo’s David.

From a structural point of view, the GA-AFI is composed of an aggregate of pre-existing structures occupying the premises of the fourteenth-century Hospital of San Matteo and those of the convent of San Niccolò in Cafaggio, which are completely inserted in a wider urban context (Figure 5). After the construction of the Tribuna, the structural configuration of the museum has not been substantially changed, even though the building has continued to undergo maintenance and restoration works until now.



Figure 5. Galleria dell'Accademia di Firenze, orthophoto.

The historical documentation of the construction phases and the restoring works of the GA-AFI, as well as the results of the experimental campaign on masonry walls, allowed for the identification of the different structural units (SUs) that compose the museum (Figure 5). As highlighted in Figure 6, three main SUs can be identified: SU_01 (*Sala dei Gessi*), SU_02 (*Tribuna del David*), and SU_03 (*Galleria dei Prigioni* and *Sala del Colosso*).

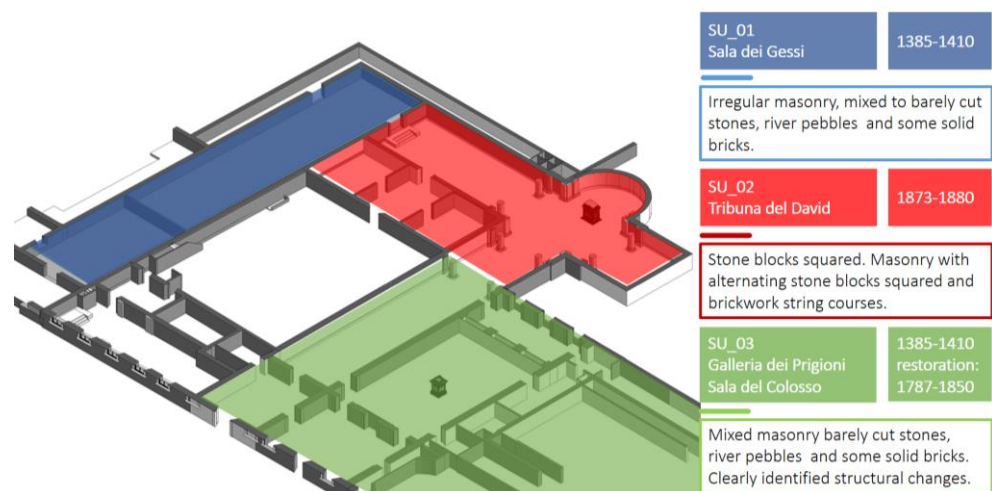


Figure 6. Structural units of Galleria dell'Accademia di Firenze.

SU_01 and SU_03 are part of the original (and oldest) buildings by occupying the premises, respectively, of the Hospital of San Matteo and the convent of San Niccolò in Cafaggio, whereas SU_02 was built between 1873 and 1880 as a new construction adjacent to the existing structures. Restoration works were carried out over time in all SUs, but the most extensive are those realized in SU_03 in order to adapt the old convent to the needs of the museum complex. The actual level of knowledge reached for the GA-AFI is the result of different studies performed over the decades aimed at acquiring information about the geometric and mechanical properties of the materials and the construction phases. In particular, the 3D metric survey of the whole museum of GA-AFI was provided by the Laboratory of Geomatics for the Environment and the Conservation of Cultural Heritage

(GECO) of the University of Florence in 2012. The chronological reconstruction of the restoration works is reported in [38] through the analyses of the archival documents of the “Soprintendenza BAPSAE di Firenze, Pistoia e Prato”.

The mechanical characterization of the masonries was the object of research activities performed in 2013 by the Department of Architecture of the University of Florence [39,40]. More recently, additional experimental campaigns were performed in the framework of a wider research project co-founded by the Tuscany Region and the Galleria dell’Accademia di Firenze with the aim of preserving the museum and the works of art inside [41,42]. As part of this research project—named DAVID (that is the Italian acronym of “Defense of cultural heritage and Assessment of Vulnerability through Innovative technologies and Devices”)—, this paper shows in the next section the definition of the HBIM model of the GA-AFI and points out as different information, experimental data, and numerical models can be grouped and visualized starting from a single information-based 3D model.

4. Implementation of HBIM Data

The HBIM model of the GA-AFI was built starting from the results presented in [35–37]. By using 2D drawings and point cloud data, the 3D model of the museum can be visualized inside the commercial software Autodesk Revit, in which different views guide the user to identify a specific semantic level (from the structural units to the structural elements) which composes the museum, add/edit/view both textual information and files and link them to the objects of the model, query the model and the database, view past conservation works and plan new conservation activities.

These operations, which the user can perform, are available for the different classes of objects.

On the basis of the structure of the database reported in Figure 3, Figure 7 shows the classes, and related subclasses, that compose the semantic classification of GA-AFI. In particular, the classes are structural units (SUs), functional areas (FAs), structural elements (SEs), architectural elements (AEs), and artworks (Aws).

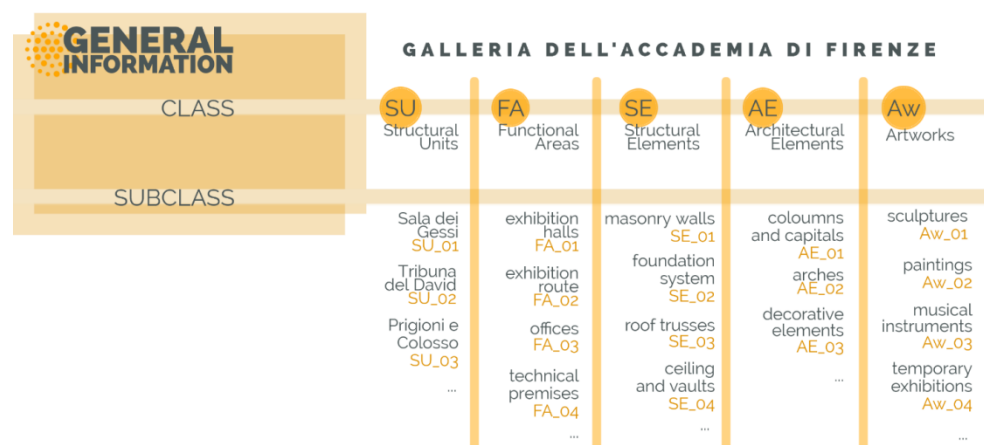


Figure 7. General information related to the GA-AFI database.

The first class, SUs, reflects the structural organization of the building and involves the portions characterized by a unitary structural behavior with respect to horizontal and vertical loads. Note that, for historical constructions, which GA-AFI does, the division of SUs can involve other ownerships. An example is provided by SU_01 (see Figure 8), where the Plaster Cast Gallery of the Galleria dell’Accademia di Firenze occupies only a portion of the ground floor of the structural unit, and the other parts are owned by Accademia delle Belle Arti di Firenze, an institutional art academy.



Figure 8. General information related to the GA-AFI database.

The second class, FAs, reflects the spatial organization of the museum complex.

The third and fourth classes, SEs and AEs, represent the structural and architectural elements, respectively. They are defined based on whether (SEs) or not (AEs) they are capable of withstanding the loads acting.

Eventually, the fifth class, Aws, includes the works of art kept inside the museum complex.

The collected information related to these classes for CH conservation purposes is characterized by great heterogeneity. In this application, the focus is on structural aspects even though the database is repeatable and scalable to also meet other specific needs. In the following, specific details are reported to characterize some representative subclasses of the structural units (SUs), structural elements (SEs), and artworks (Aws) classes. Note that each class addresses information referring to the specific object in its entirety by associating data about the survey, the experimental campaigns, and modeling, including the following: information about the construction and the main restoration works, identification of the critical issues (problems and/or damages), results, and description of experimental data and hypothesis for future interventions. The LOD depends on the specific object, on its relevance, and on the acquired level of knowledge. It is related to a specific time, and it can be increased when additional information becomes available.

The capabilities of the developed HBIM are introduced by using as reference the SU_02: the Tribuna del David (see Figures 9 and 10). Within this SU, a representative masonry wall (SE_01) and a sculpture (Aw_01) are selected in order to underline that the information about these objects can enrich the computational model for structural safety assessment purposes of the building itself and of the artworks kept inside. Note that the information management of the different semantic objects in the BIM model is commonly governed by the underlying database. It contains object features, parametric constraints that handle the object's properties, and any attribute that can be attached to the model. These attributes are configured by the user; new ones can be defined to link all the desired information to the elements (texts, number, files, images, etc.). Nevertheless, in commercial BIM software such as the one employed in this study (Autodesk Revit), it is hard to manage the relational complexity of information that characterizes CH requirements, both in terms of time dimension management (4D), and connection to computational structural modeling. In order to overcome these limitations, in addition to the information inserted by using the Revit interface, external links are defined in order to connect all the available resources through the HBIM model. In this way, all features available to the user for building knowledge are contained in the model through a faithful representation of reality. In addition to the categories of information already implemented in the Revit environment, for each of the classes herein introduced, additional categories are defined: (i) general information, (ii) historical documentation, (iii) images, (iv) computational model, and (v) experimental data.

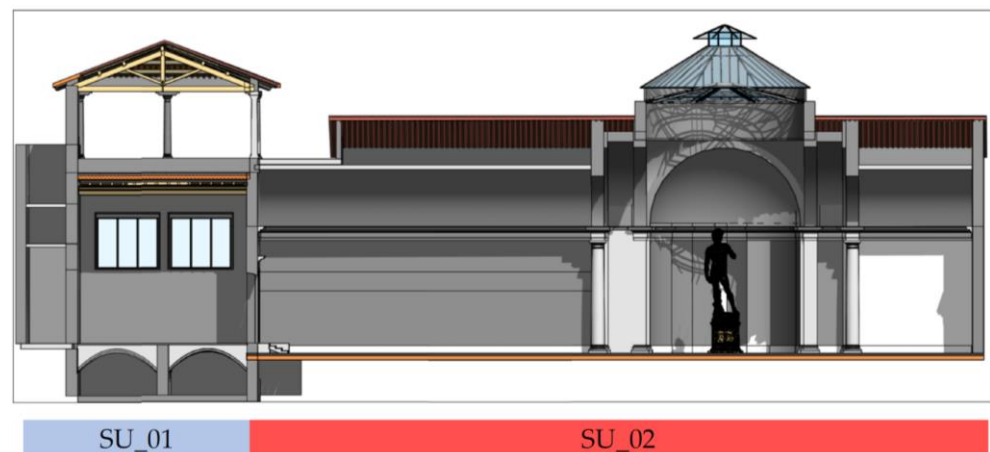


Figure 9. Cross section of SU_01 (*Sala dei Gessi*) and longitudinal section of SU_02 (*Tribuna del David*)—from left to right.



Figure 10. Longitudinal section of SU_03 (*Galleria dei Prigioni*) and cross-section of SU_02 (*Tribuna del David*)—from left to right.

Examples of access to data from external links are provided in Figures 11 and 12. Figures 13 and 14 report the information about a masonry wall by adding information to the material definition already present in the software.

In particular, Figure 11 shows the procedure for accessing the information on the historical evolution of SU_02 with the external link used to archive it in a shared online repository, while Figure 12 shows the images of previous archived interventions.

Figure 13 illustrates how, by selecting one of the walls of the SU_02 (the one highlighted with the arrow), it is possible to retrieve information about the type of wall texture, including the values of the mechanical parameters that characterize it. The used structure is derived from Autodesk Revit. From the interface shown in Figure 13, it is possible to access the visualization of Figure 14, where the experimental details of the wall texture are reported.

These data are specifically included in the HBIM in order to collect all the information (in terms of the type and mechanical characteristics of the masonries) needed for the realization of the numerical model. In its current state of implementation, the HBIM model includes all available experimental data and offers the possibility of future implementations for what has not been investigated to date. For walls that have not been investigated, estimated reference values based on the standard have been included.

As far as the computational models are concerned, Figure 15 shows, as an example, one of the numerical models available for the *Tribuna* and Michelangelo's *David*. In particular, the user can refer to the results of the experimental data to critically analyze the input and the output of the numerical model and, if necessary, to make corrections, observations, and updated analyses.

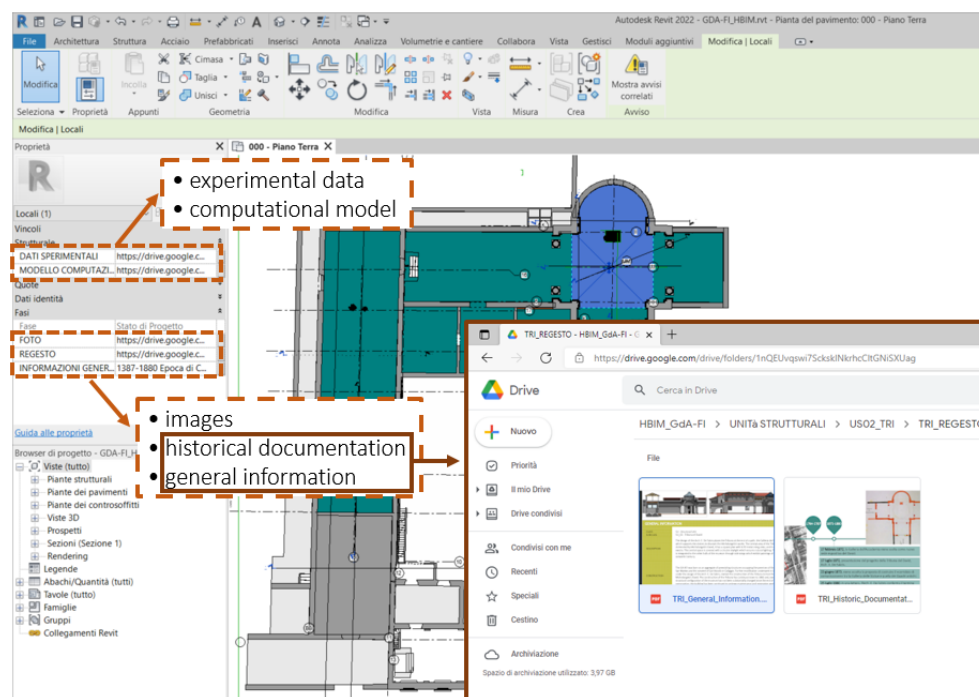


Figure 11. SU_02, detail of external links about historical documentation and general information.

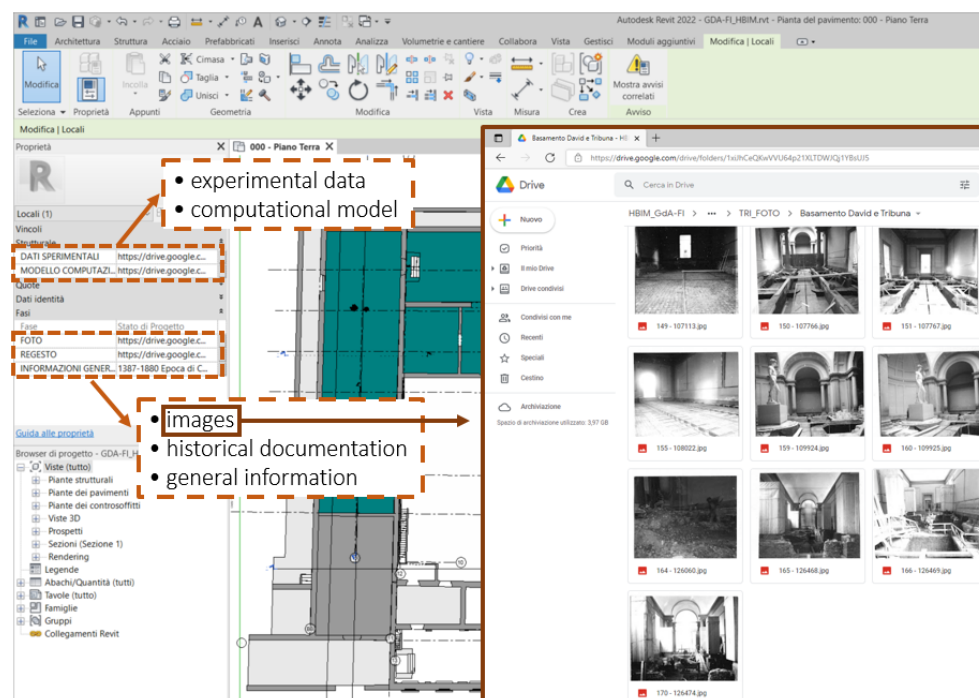


Figure 12. SU_02, detail of external links about archive images.

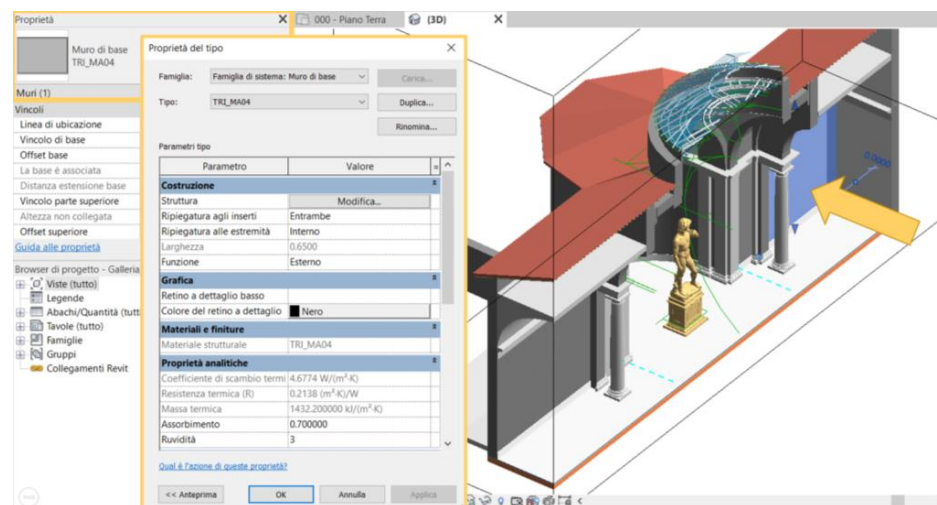


Figure 13. SE_01 subclass, masonry wall TRI_MA04 selection.

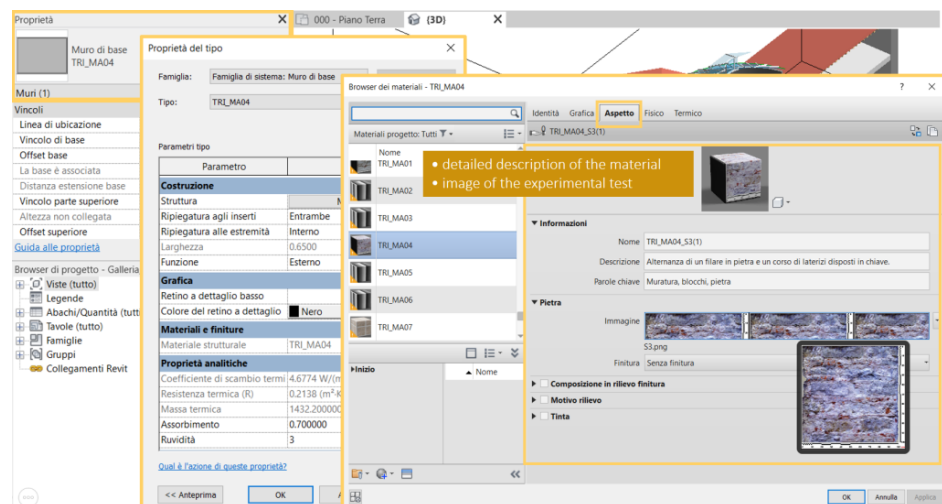


Figure 14. SE_01 subclass, masonry wall TRI_MA04 material properties.

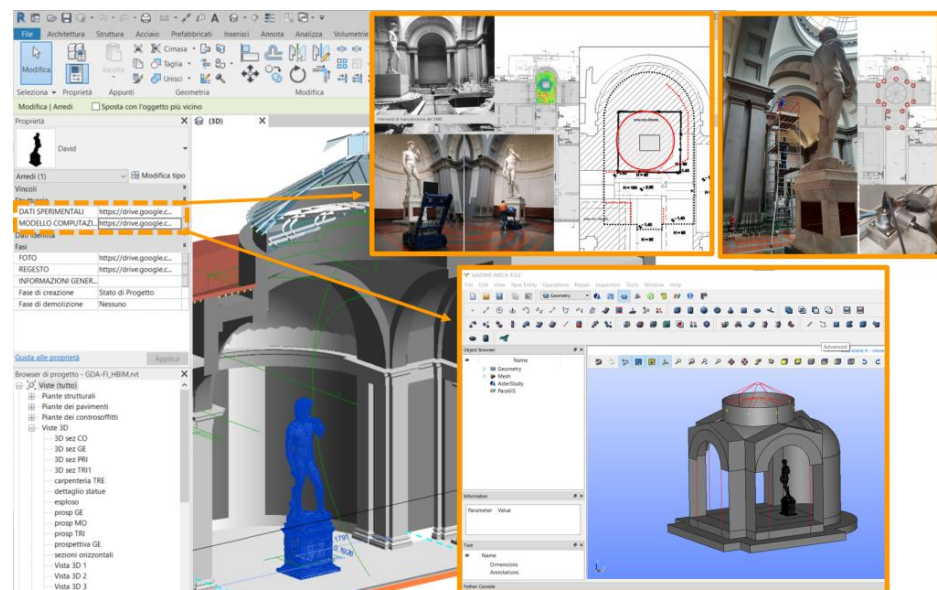


Figure 15. Aw_01 subclass, Michelangelo's David—experimental campaigns and computational model.

The numerical models were built using a finite element (FE) code, and, specifically, the FE code Code_Aster [37] was considered an open-source platform for FE modeling that allows for handling a plethora of neutral geometrical format inputs. The choice of an open-source code aims to provide a tool easily accessible without a specific license.

5. Discussion

The implemented HBIM is the result of the cooperation with the technical office of the GA-AFI in order to integrate their needs in terms of documentation, ordinary management, and planned conservation activities. To meet these requirements, the system has involved the creation of different 3D models (informative and computational) which, even though they describe an abstraction and simplification of reality, represent a powerful tool to collect all the information and documents necessary for the management and safety assessment of a historical museum complex. Indeed, the development of 3D models represents a fundamental step in the conservation of historical buildings, but whatever numerical modeling is needed unavoidably contains sources of error that produce the discrepancy between reality and the model output. The advantages of collecting all the information of a building in a single database are multiple:

- the data can be gradually integrated and updated with further investigations without losing track of past interventions during the whole lifecycle of the structure;
- the digitized information is directly associated with the specific local or object, according to the semantic classification, and checked from their toolbar;
- periodic comparisons over time on the structure of the onsite condition are eased;
- all the subjects involved in the management and conservation activities of the GA-AFI (surveyors, modelers, restorers, and owners/institution) can benefit from the complete documentation of the asset with a unique point of access and can validate/integrate information at any time;
- the data can be organized according to the specific requirements of the GA-AFI to check and extract specific information from the local to object level.

The reiteration of these activities moves toward the planned conservation strategy with the objective of guaranteeing minimum intervention. Note that, along these lines, the regulatory requirements are pushing towards the progressive adoption of BIM standards by making the use of commercial or open-source BIM software the standard in the management of both new and existing structures.

The implemented HBIM, although tested on a specific case study, demonstrates its feasibility to other building typologies due to the featuring of a wide variety of characteristics in terms of spatial complexity, constructive techniques, and related information in the structural units that compose it. The proposed semantic classification, from the local level (building, structural units, functional areas) to the object level (structural elements, architectural elements, artworks), aims to be effective for integration into other museum complexes. It allows for combining information about the historical construction evolution of the buildings with information about management and maintenance interventions as well as specific details related to the works of art and their interaction with the structure. Each structural unit, via a web URL, is associated with a numerical model able to perform static and seismic vulnerability assessment. These models are developed starting from the BIM model to the Code_Aster open-source platform for FE modeling purposes. Note that, among a large variety of FE software, the choice of an open-source code just aims to promote the cooperation of the subjects involved in the management and conservation activities of the GA-AFI, by providing a tool accessible to all without a specific license. Moreover, the Code Aster open-source platform handles geometrical inputs that are provided by external sources, which is the case for neutral format files (BREP, STEP, IGES, etc.), to generate the FE mesh. The connection between these two models was built in a flexible environment, Rhinoceros, where, thanks to the Python programming language-based interface, a link between informative and computational modeling was tested. The direct integration between the BIM model and the computational one will be investigated

in the next steps of the research. Particular attention will be devoted to the possibility of importing IFC standard format files through the identification of the structural objects that compose the building.

6. Conclusive Remarks

In this paper, the implementation of an HBIM approach was introduced with the aim of improving the processes connected to the maintenance, conservation, and restoration efforts of cultural heritage. In particular, by using the case study of the Galleria dell'Accademia di Firenze (Italy), the main goal of the work was to investigate the possibility of providing a specific tool in order to organize and coordinate the whole museum complex documentation, including historical data about the construction and restoration phases, the time management, the coordinating of the functional areas, the storage of experimental campaigns, and the definition of computational models. The developed case study laid the groundwork for investigating two open issues, namely the organization of the database based on non-geometric information and the passing data from HBIM to FE models. In particular, an information database was tested and the integration between an HBIM software (i.e., Revit) and FEM software (i.e., Code_Aster) was investigated as a solution to guarantee an adaptable approach for museum complexes and other CH buildings to meet the requirements in terms of management, maintenance, and conservation. The procedure allows, on the one hand, for the use of the system objects already integrated in the Revit software to add general information on specific objects (e.g., period of construction, restoring works, mechanical properties, LOD) and, on the other hand, provides more flexibility by using external links for specific documents and computational models. This solution guarantees an adaptable approach to meet the specific requirements and objectives that characterize the specific CH museum. The results proposed in this paper set the basis for the future developments of the system which, from a structural point of view, will focus on:

- the automatic updating of the material properties of structural elements from HBIM to computational models. Indeed, currently, the user can refer to the results of the experimental data to critically analyze the input and the output of the numerical model, but the eventual changes are not automated;
- the integration of the HBIM with the monitoring data system by developing appropriate plug-ins and interfaces to organize, store, analyze, and easily query the observations over time;
- the possibility to handle robust computational models, whose inputs will be updated on the base of experimental data.

In particular, the periodic analyses of the computational models and their integration in the information modeling of HBIM will allow for defining the priority of action regarding restoration works both on the structure and the works of art inside. In this scenario, informative modeling becomes crucial in the process of management and conservation of CH, thus representing a reference for continuously updating the different sources of data necessary for supporting the stakeholders in management and conservation projects.

Author Contributions: Conceptualization, S.M., M.B., C.B., C.G., B.F. and C.M.; methodology, S.M., M.B. and C.B.; investigation, S.M., M.B., C.G., B.F. and C.M.; resources, S.M., M.B., C.B., C.G., B.F. and C.M.; data curation, S.M. and B.F.; writing—original draft preparation, S.M.; writing—review and editing, S.M. and M.B.; visualization, S.M.; supervision, M.B. and C.B.; funding acquisition, M.B., C.B., C.G. and C.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Tuscany Region and the Galleria dell'Accademia di Firenze.

Data Availability Statement: Data availability is not applicable to this article as no new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Dall'Asta, A.; Leoni, G.; Meschini, A.; Petrucci, E.; Zona, A. Integrated approach for seismic vulnerability analysis of historic massive defensive structures. *J. Cult. Herit.* **2019**, *35*, 86–98. [\[CrossRef\]](#)
2. Orlando, M.; Betti, M.; Spinelli, P. Assessment of structural behaviour and seismic retrofitting for an Italian monumental masonry building. *J. Build. Eng.* **2020**, *29*, 101115. [\[CrossRef\]](#)
3. Betti, M.; Bonora, V.; Galano, L.; Pellis, E.; Tucci, G.; Vignoli, A. An Integrated Geometric and Material Survey for the Conservation of Heritage Masonry Structures. *Heritage* **2021**, *4*, 585–611. [\[CrossRef\]](#)
4. Arayici, Y. Towards building information modelling for existing structures. *Struct. Surv.* **2008**, *26*, 210–222. [\[CrossRef\]](#)
5. Volk, R.; Stenge, J.; Schultmann, F. Building Information Modeling (BIM) for existing buildings—literature review and future needs. *Autom. Constr.* **2014**, *38*, 109–127. [\[CrossRef\]](#)
6. NBIMS-US V3; National BIM Standard—United States Version 3. National Institute of Building Sciences: Washington, DC, USA, 2015.
7. Murphy, M.; McGovern, E.; Pavia, S. Historic building information modelling (HBIM). *Struct. Surv.* **2009**, *27*, 311–327. [\[CrossRef\]](#)
8. Bruno, N.; Roncella, R. HBIM for Conservation: A New Proposal for Information Modeling. *Remote Sens.* **2019**, *11*, 1751. [\[CrossRef\]](#)
9. Jordàn Palomar, I.; Garcia Valldecabres, J.; Tzortzopoulos, P.; Pellicer, E. An online platform to unify and synchronise heritage architecture information. *Autom. Constr.* **2020**, *110*, 103008. [\[CrossRef\]](#)
10. Mojano, J.; Carreno, E.; Nieto-Julian, J.E.; Gil-Arizon, I.; Bruno, S. Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project. *Autom. Constr.* **2022**, *143*, 104551. [\[CrossRef\]](#)
11. De Falco, A.; Gaglio, F.; Giuliani, F.; Martino, M. A BIM-Based Model for Heritage Conservation and Structural Diagnostics: The City Walls of Pisa. In *The Future of Heritage Science and Technologies*. Florence Heri-Tech 2022. *Lecture Notes in Mechanical Engineering*; Furferi, R., Governi, L., Volpe, Y., Gherardini, F., Seymour, K., Eds.; Springer: Cham, Switzerland, 2022.
12. Bruno, S.; De Fino, M.; Fatiguso, F. Historic Building Information Modelling: Performance assessment for diagnosis-aided information modelling and management. *Autom. Constr.* **2018**, *86*, 256–276. [\[CrossRef\]](#)
13. Di Stefano, F.; Gorreja, A.; Malinverni, E.S.; Mariotti, C. Knowledge modeling for heritage conservation process: From survey to HBIM implementation. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2020**, *44*, 19–26. [\[CrossRef\]](#)
14. Bagnolo, V.; Argiolas, R.; Cuccu, A. Digital survey and algorithmic modeling in HBIM. Towards a library of complex construction elements. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 25–31. [\[CrossRef\]](#)
15. Dore, C.; Murphy, M.; McCarthy, S.; Brechin, F.; Casidy, C.; Dirix, E. Structural simulations and conservation analysis—historic building information model (HBIM). *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *40*, 351–357. [\[CrossRef\]](#)
16. Ferretti, U.; Quattrini, R.; D'Alessio, M. A Comprehensive HBIM to XR Framework for Museum Management and User Experience in Ducal Palace at Urbino. *Heritage* **2022**, *5*, 1551–1571. [\[CrossRef\]](#)
17. Attenni, M. Informative Models for Architectural Heritage. *Heritage* **2019**, *2*, 2067–2089. [\[CrossRef\]](#)
18. Vieira, M.M.; Ribeiro, G.; Paulo, R.; Bessa, M.; Sousa, F.R.; Moreira, E.; Mesquita, E. Strategy for HBIM implementation using high-resolution 3D architectural documentation based on laser scanning and photogrammetry of the José de Alencar theatre. *Digit. Appl. Archaeol. Cult. Herit.* **2023**, *30*, e00287. [\[CrossRef\]](#)
19. De Luca, L.; Driscu, T.; Peyrols, E.; Labrosse, D.; Berthelot, M. A complete methodology for the virtual assembling of dismantled historic buildings. *Int. J. Interact. Des. Manuf.* **2014**, *8*, 265–276. [\[CrossRef\]](#)
20. Moyano, J.; Gil-Arizon, I.; Nieto-Julian, J.E.; Marín-García, D. Analysis and management of structural deformations through parametric models and HBIM workflow in architectural heritage. *J. Build. Eng.* **2022**, *45*, 103274. [\[CrossRef\]](#)
21. Mora, R.; Sanchez-Aparicio, L.J.; Mate-Gonzalez, M.A.; García-Alvare, J.; Sanchez-Aparicio, M.; Gonzalez-Aguilera, D. An historical building information modelling approach for the preventive conservation of historical constructions: Application to the Historical Library of Salamanca. *Autom. Constr.* **2021**, *121*, 103449. [\[CrossRef\]](#)
22. Biagini, C.; Capone, P.; Donato, V.; Facchini, N. Towards the BIM implementation for historical building restoration sites. *Autom. Constr.* **2016**, *71*, 74–96. [\[CrossRef\]](#)
23. Cardinali, V.; Ciuffreda, A.L.; Coli, M.; De Stefano, M.; Meli, F.; Tanganelli, M.; Trovatielli, F. An Oriented H-BIM Approach for the Seismic Assessment of Cultural Heritage Buildings: Palazzo Vecchio in Florence. *Buildings* **2023**, *13*, 913. [\[CrossRef\]](#)
24. Mol, A.; Cabaleiro, M.; Sousa, H.S.; Branco, J.M. HBIM for storing life-cycle data regarding decay and damage in existing timber structures. *Autom. Constr.* **2020**, *117*, 103262. [\[CrossRef\]](#)
25. Celli, S.; Ottoni, F. An informative tool for the preservation of the wooden encircling tie rod of the dome of Santa Maria del Fiore, in Florence. In Proceedings of the Joint International Event 9th ARQUEOLÓGICA 2.0 & 3rd GEORES, Valencia, Spain, 26–28 April 2021. [\[CrossRef\]](#)
26. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul. Model. Pract. Theory* **2015**, *57*, 71–87. [\[CrossRef\]](#)

27. Croce, P.; Landi, F.; Puccini, B.; Martino, M.; Maneo, A. Parametric HBIM Procedure for the Structural Evaluation of Heritage Masonry Buildings. *Buildings* **2022**, *12*, 194. [CrossRef]
28. Castellazzi, G.; Lo Presti, N.; D'Altri, A.M.; de Miranda, S. Cloud2FEM: A finite element mesh generator based on point clouds of existing/historical structures. *SoftwareX* **2022**, *18*, 10109. [CrossRef]
29. Lucidi, A.; Giordano, E.; Clementi, F.; Quattrini, R. Point cloud exploitation for structural modeling and analysis: A reliable workflow. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, *43*, 891–898. [CrossRef]
30. Abbate, E.; Invernizzi, S.; Spanò, A. HBIM parametric modelling from clouds to perform structural analyses based on finite elements: A case study on a parabolic concrete vault. *Appl. Geomat.* **2022**, *14*, 79–96. [CrossRef]
31. International Organization for Standardization (ISO). ISO 11337:2017. Available online: <http://store.uni.com/catalogo/index.php/uni-11337-4-2017.html> (accessed on 30 January 2022).
32. ISO 12491; Information and Documentation—A Reference Ontology for the Interchange of Cultural Heritage Information. International Organization for Standardization (ISO): Geneva, Switzerland, 2014.
33. Messaoudi, T.; Véron, P.; Halin, G.; De Luca, L. An ontological model for the reality-based 3D annotation of heritage building conservation state. *J. Cult. Herit.* **2018**, *29*, 100–112. [CrossRef]
34. Croce, V.; Caroti, G.; De Luca, L.; Jacquot, K.; Piemonte, A.; Véron, P. From the Semantic Point Cloud to Heritage-Building Information Modeling: A Semiautomatic Approach Exploiting Machine Learning. *Remote Sens.* **2021**, *13*, 461. [CrossRef]
35. Tucci, G.; Betti, M.; Conti, A.; Corongiu, M.; Fiorini, L.; Matta, C.; Kovacevic, V.C.; Borri, C.; Hollberg, C. BIM for museums: An integrated approach from the building to the collections. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 1089–1096. [CrossRef]
36. Tucci, G.; Conti, A.; Fiorini, L.; Corongiu, M.; Valdambri, N. M-BIM: A new tool for the Galleria dell'Accademia di Firenze. *Virtual Archaeol. Rev.* **2019**, *10*, 40–55. [CrossRef]
37. Kovacevic, V.C.; Conti, A.; Borri, C.; Tucci, G.; Hollberg, C.; Matta, C.; Fiorini, L.; Betti, M.; Pintucchi, B. An integrated computational approach for heritage monumental museums. In Proceedings of the 7th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Crete, Greece, 24–26 June 2019. [CrossRef]
38. Mignani, D. *Applicazione Della Direttiva Della Presidenza del Consiglio dei Ministri del 12/10/2007 per la Valutazione e Riduzione del Rischio Sismico del Patrimonio Culturale—Approfondimento Della Ricerca Storica Delle Fasi Costruttive e dei Lavori Eseguiti Nella Galleria Dell'accademia di Firenze*; Ministero per i beni e le Attività Culturali: Rome, Italy, 2010; pp. 1–46. (In Italian)
39. De Stefano, M.; Cristofaro, M.T. The Complex of the Galleria dell'Accademia of Florence: Keeping in safety. *Procedia Struct. Integr.* **2020**, *29*, 71–78. [CrossRef]
40. Giorgianni, G. *Valutazione del Rischio Sismico nel Complesso Della Galleria Dell'accademia di Firenze*; Altralinea: Firenze, Italy, 2018.
41. Miccinesi, L.; Beni, A.; Monchetti, S.; Betti, M.; Borri, C.; Pieraccini, M. Ground Penetrating Radar Survey of the floor of the Accademia Gallery (Florence, Italy). *Remote Sens.* **2021**, *13*, 1273. [CrossRef]
42. Monchetti, S.; Bartoli, G.; Betti, M.; Borri, C.; Gerola, C.; Giachetti, A.; Hollberg, C.; Kovacevic, V.C.; Matta, C.; Zini, G. In-Situ Measurements for the Structural Monitoring of Galleria dell'Accademia di Firenze (Italy): Preliminary Results of the Tribuna. In *Experimental Vibration Analysis for Civil Engineering Structures. Lecture Notes in Civil Engineering*; Wu, Z., Nagayama, T., Dang, J., Astroza, R., Eds.; Springer: Cham, Switzerland, 2023; Volume 224. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.