Methodology for an HBIM workflow focused on the representation of construction systems of built heritage

Abstract

Conservation and valorisation practices of built heritage can greatly benefit from Heritage Building Information Modelling (HBIM) workflows. The use of HBIM as an information management process is not fully established yet, also due to the focus on industrialised architecture typical of the most common BIM tools. Capitalising on the benefits of the BIM process in the field of built heritage requires pursuing a continuous trade-off between geometric accuracy, semantic richness and parametric behaviour. This research aims to present an HBIM workflow that, as compared to other, more specific pipelines, is general in scope to support the planning and implementation of maintenance and conservation activities of built heritage, emphasising the representation of the building construction systems. The workflow is structured in five phases (model planning, data collection, geometric survey, breakdown structure and HBIM modelling), recursive and flexible to influence one another and to adjust to the information available and the development of the work over time. Each phase of the workflow is presented with a general outline and a methodological insight to help operators in developing the HBIM process most suitable for specific cases. The results of the application of this methodology on a complex and massive historical building (The National Archaeological Museum of Naples – MANN) show that the workflow is both versatile and sufficiently flexible to accommodate a heterogeneous range of objectives while guiding experts to select and document the most appropriate course of action.

Keywords

HBIM, built heritage, conservation, 3D model, digitalization

1 Introduction

The term *Building Information Model* (BIM) defines a digital representation of the physical and functional characteristics of a built asset producing a shared source of knowledge about it and forming a reliable basis for decision-making [1,2]. BIM can also refer to the process of information management that said digital representation promotes [3].

The process is generally based on commercial BIM design tools, which are object-based parametric modelling systems where model objects are defined by rules and relationships among them, called *parameters*, that "simulate" the behaviour of corresponding construction elements [4]. Each object is associated with non-redundant geometric and alphanumeric information and documentation [5], to provide a robust data framework for collaboration among stakeholders [6]. To effectively support the series of activities involving a building though time, a BIM model should be carefully planned, selecting a specific set of model uses, which elicit a specific Level of Information Need, that describes the information to be exchanged for a given model at each work stage, setting its extent and granularity and helping to prevent the production of too much information [2,5].

The decision-making process regarding the conservation and valorisation of built heritage is based on multidisciplinary data, such as historical, diagnostic, bibliographic data [7,8]. Such process can greatly benefit from BIM workflows applied to historical buildings, commonly referred to as *Heritage BIM* (HBIM), in terms of information management, data permanence and accessibility [9], enhancing the dynamic integration of evolving data [10,11]. So far, HBIM has mainly focused on digital documentation, boosted by technological developments in three-dimensional data acquisition [12–14]. The use of BIM to support information management [2] for historical buildings, both in the operational phase and in the design and intervention phases, [15,16], has been explored in the definition of an Asset Information Model (i.e., a BIM model for the operational phase) specific for built heritage [9], and the development of a protocol for HBIM in heritage interventions [17], or the use of HBIM to support restoration [15,18].

To foster HBIM to support the planning and implementation of maintenance and conservation activities, models should enable the critical understanding of the building's construction system, acting as a hub for historical data, documents, surveys, etc. and as a guide to the modelling process [19].

An issue with construction systems in HBIM lies in the modelling logic of most common BIM tools, optimised to represent the behaviour of modern buildings, developed by architecture, engineering and construction (AEC) industries. In fact, following parametric modelling, BIM objects, that stand for the building's technical components, are organised in a structure of hierarchical relationships, specific for each BIM tool, according to pre-defined design rules. For example, window objects are related to wall objects, to represent their structural association. In some cases, this introduces simplifications based on constructive assumptions that are generally true for contemporary construction but may not easily harmonise with built heritage that is characterised by heterogeneity of materials and technologies.

Taking advantage of the benefits of the BIM parametric process when dealing with built heritage, ensuring that each model object can participate in the constructive simulation of the building, requires pursuing a continuous trade-off between geometric accuracy, semantic richness and parametric behaviour [20]. A model with very high geometric accuracy, representing out-of-plumb walls with minimal thickness variations, could make it difficult to exploit all the parametric functions of BIM tools, greatly limiting model functionality [3,21,22], while too simplified models could overlook building characteristics with significant historical, artistic or constructive value [23]; the guiding criteria of these compromises should always be the model uses. Moreover, the reliability of modelled information depends on the quantity and quality of collected data on the building and its integration in the model, which still represents a limit in the widespread application of HBIM [24].

2 Research aim

This research aims to present an HBIM workflow to support BIM processes for historic buildings.

Several pipelines tackle this issue. Researches such as Historic England [3,9] and Jordan-Palomar et al. [17] focus on the managing aspects, such as stakeholder involvement, regulation, intervention options, information collection and delivery, data standardisation. Quattrini et al. [25] concentrate on documentation, proposing a Scan-to-BIM approach for geometric representation and the subsequent semantic enrichment of architectural elements via ontology. Drawing attention to the depiction of complex architectural elements, that require an ad-hoc survey and modelling techniques, Brusaporci et al. [19] and Oreni et al. [24], present different methods for vaults and beams, depending on the level of detail to reach, up to the vault brick pattern. Restoration interventions based on BIM have arisen more specific issues. Brumana et al. [15], in the restoration of the Basilica di Collemaggio, defined BIM strategies tailored to the model uses, such as the creation of an inventory model of the stones of the ashar pillars, while also addressing more general topics, such as the assessment of modelling accuracy against geometric survey, the interoperability between BIM modelling software and structural simulation, the representation of decay patterns, the use of NURBS software to model complex geometry.

Santagati et al. [26], for the documentation of the St. John the Theologian Church in Nicosia, develops a dynamic pipeline from surveys and investigation to modelling to data integration, with a focus on decay. Biagini et al. [18] propose a detailed workflow for the restoration of the SS. Nome di Maria in Manua, centred on the relationship between geometric modelling and time development (3D and 4D dimensions) in the design and management of the interventions and construction site.

Taking into account also the available BIM methodologies commonly used in the AEC sector, most of them are directed to new or existing buildings with no historical connotation (**Errore. L'origine riferimento non è stata trovata.**).

In comparison with the described pipelines, the proposed HBIM workflow (Figure 1) channels the existing extensive research on the topic [6,20,27] to define a comprehensive, overall methodology. The workflow is general in scope and presents an overview on how to approach and develop the design and implementation of maintenance and conservation activities of built heritage, from planning to investigation up to specific modelling strategies. As its focus is on technical approaches for conservation and restoration, the workflow emphasises the representation of the building's construction systems.

Existing method	**Main topics of the existing method**	**Peculiarity of the proposed workflow**
AEC (UK) - BIM Protocol [28]	Developed for new buildings - focus on technical protocols and standardization (naming conventions, file/folder management, interoperability, etc.)	Specific for historic buildings and their model uses - broader approach on information management and model development
COBIM [21]	Developed for new buildings - focus on BIM requirements for models and objects	Specific for historic buildings and their model uses - general overview of an HBIM workflow (from data collection to management)
Singapore BIM Guide [29]	Developed for new buildings - focus on project implementation and collaboration - ease of use, practical examples	Specific for historic buildings and their model uses - general overview of an HBIM workflow (from data collection to management)

BIM for Heritage [3]	Focus on managing aspects (BIM strategy, information delivery, commissioning, infrastructure)	Focus on technical aspects (model planning and organization, data acquisition, model strategies)
BIMlegacy [17]	Focus on organization/workflow of interventions (stakeholder involvement, asset strategy, options, interventions, handover, management)	More general approach, flexible to encompass also other model uses (documentation, valorisation, etc.)
COTAC BIM4C [30–32]	Focus on organization/workflow – conservation parameters – case studies	More general approach – focus on technical aspects (model strategies)
Diagnosis-aided HBIMM [16]	Focus on diagnostics	Focus on technical aspects (representation of construction systems)

Table 1: Comparison of the main topic of existing BIM methodologies and the proposed HBIM workflow. The methodologies were selected for their relevance and affinity with the proposed BIM workflow; they are all general in scope for general use by the AEC sector. We excluded: proprietary guidelines or guidelines related to a given software; guidelines developed for a given region; guidelines with a specific focus on a stakeholder, a design phase, or a documentation phase (such as contracts or tenders). Among BIM methodologies not specific for historical buildings, the selection could be broader, but this kind of methodologies, although useful to define the proposed workflow, have a limited interest within the scope of this paper.

This workflow is not linear, but its phases are recursive and flexible to influence one another and adjust to the information available and the development of the work over time. It is presented as a general outline, adapting to the activities to carry out on the building, its characteristics, model uses, BIM tools, etc.

An application of the workflow to develop the information model of the National Archaeological Museum of Naples is briefly described, to show its potential in optimising the management of the large amount of data that such a complex building entails.

3 Materials and Methods: proposed workflow

The workflow is structured in the following phases:

1. model planning, illustrating the information management aspects of HBIM;
2. data collection on the building, oriented towards integrating the gathered information in the HBIM model and using it to identify the building’s construction systems;

3. design and implementation of geometric survey processes specifically for HBIM;
4. definition of the breakdown structure of the building into construction elements to be modelled separately and identification of the Level of Information Need for each model object [5];
5. HBIM modelling process, aimed at conveying construction systems as accurately as possible within model use.

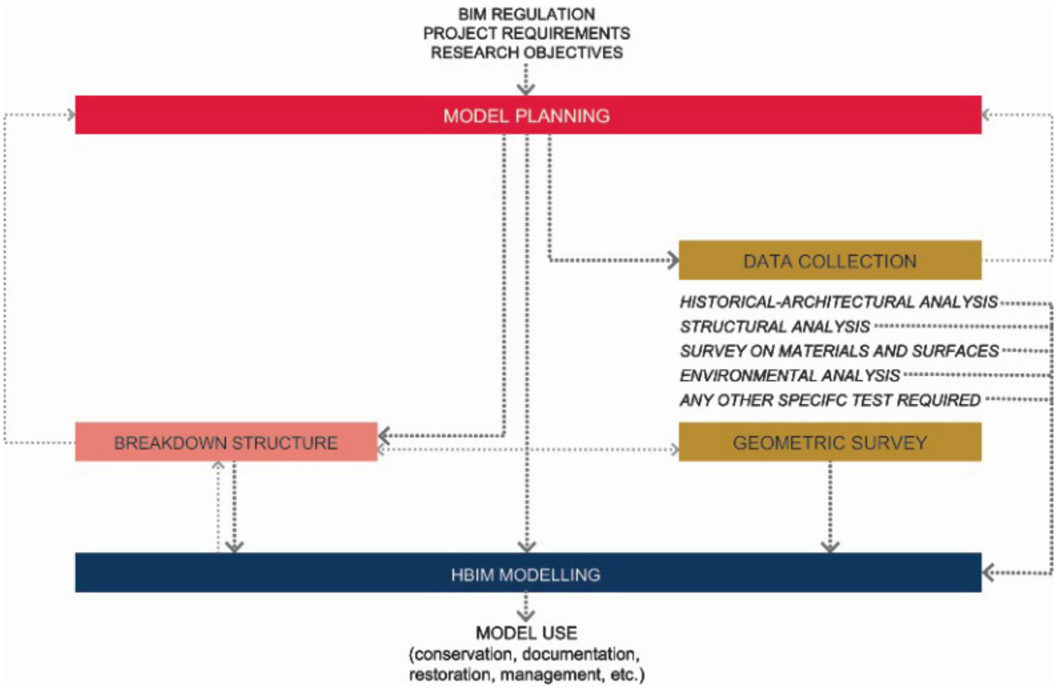

Figure 1: Schematic representation of the proposed workflow.

3.1 Model Planning

Within the framework of ISO 19650 [2] on organisation and digitalisation of information about buildings, BIM processes are structured by a series of documents defining requirements and model practices, also when applied to built heritage [9]. Describing this framework is out of the scope of the research; however, the HBIM workflow proposed is coherent with it and its first phase, model planning, is consistent with the technical section of the BIM Execution Plan (BEP), which states how the information management aspects of the model will be carried out [33]. Drafted by the appointed party of a BIM project, following the requirements of the appointee, BEP is a guide for the implementation of the workflow for all the actors in the process. The contents of BEP are not explicitly regulated; usually, it chronologically structures the activities; it describes and facilitates the exchange and coordination within a data-sharing environment; it defines the methods for producing and managing information (modelling strategies, data entry, etc.); it establishes the procedures for checking and verifying consistency; it specifies the roles and responsibilities of those involved [34]. Within BEP, model planning also establishes a collaborative data-sharing environment, the so-called Common Data Environment (CDE), that is a repository of files for collecting, organising and disseminating models and documents among the actors involved [2,35]. The CDE represents the agreed information source for a project; therefore, it should guarantee security, accessibility, traceability and version history for all the files. There are no specific characteristics for CDE, as long as these requirements are fulfilled; online solutions via the cloud are generally more feasible for collaboration. Depending on CDE functionalities, it should be possible to connect BIM models to external documents (images, reports, technical sheets, etc.), visualise and interrogate information, provide feedback, especially if a 3D viewer is available. Open and non-proprietary formats should be preferred to enhance accessibility, notably for public processes.

Model planning is the phase most intertwined with the others: while some topics, such as requirements, model uses and common protocols, can be defined in advance, others, like modelling strategies and data entry, depend on a comprehensive knowledge of the building and are affected by data collection and breakdown structure.

3.2 Data collection on the building

A thorough data collection is paramount for a solid understanding of a historical building, especially for an HBIM process aimed at representing the building's construction systems.

A global diagnostic survey programme involves a large number of complex investigations and sophisticated instrumental methods. Within the proposed workflow, the diagnostic program starts from a first document investigation and an image-documented survey to perform a visual analysis of the building structure, materials and state of conservation. Subsequently, the diagnostic analysis (depending on model uses) usually comprises five main areas, which can be specified in subsequent surveys [36,37]:

1. historical and architectural analysis
2. geometric survey (with a designated phase within the workflow, see § 3.3)
3. structural analysis
4. surveys on materials and surfaces
5. environmental analyses.

The historical and architectural analysis consists of onsite study and desktop research on bibliographical and archival documentation, maps and historical cartography and studies on similar and/or coeval buildings, and it constitutes a historical-critical guideline for the other analyses. All the data gathered and interpreted by experts should allow retracing the development of the building over time.

Based on the results of visual analysis, specific tests can be planned to investigate construction aspects or significant decay patterns of the building. Geophysical tests, ground-penetrating radar observations, endoscopic investigations, ultrasound surveys, as well as thermographic surveys, may be useful for identifying walls stratigraphy or for characterising the deteriorated portions of the masonry, to fill in a complete list of damages throughout the building.

To streamline the process, particular attention is paid to retrieving and organising data aimed at understanding the building's construction systems, such as shape and size of technical elements (especially when not visible from a geometric survey, e.g. the beam system of a wooden floor), construction nodes, etc.

HBIM assumes that each building element foreseen by model planning should be modelled; however, it is not always possible or feasible to obtain construction information on all building elements. Therefore, the diagnostic analysis's results influence model planning and breakdown structure, to establish: which elements possess enough data to be modelled according to the required Level of Information Need; which elements do not have enough data, although that could be obtained with further investigations, and should be modelled in a simplified way, already planned to be subsequently detailed; which element do not have enough data and will therefore remain simplified.

Diagnostic analysis's results are also crucial to convey the reliability of the critical interpretation of each construction system and to trace its main sources [37–41]; for example, if a wall stratigraphy was assumed according to manuals on coeval architecture or traditional construction techniques, the document can be linked to the corresponding wall model object.

3.3 Design and implementation of the geometric survey

The geometric survey is the main basis for HBIM geometric modelling and also serves as the most accurate source of geometric information on the building (especially point clouds), since any model is, regardless of its complexity, inherently a simplification [42]. Currently, it is possible to generate very meticulous geometric surveys with limited costs. Depending on the object to be surveyed and existing data, different kinds of acquisition procedures and processing tools can be used [43]. If robust information on the geometric characteristics of the building is available, the activities focus on a measurement verification of this information and, if needed, data integration to attain the required survey accuracy. If such information is not available, the activities shift towards a complete georeferenced geometric survey of the exterior and interior of the building.

While traditional direct survey methods can be effective, it is recommended to apply or integrate, if possible, advanced survey methods such as photogrammetry and/or laser scanner with RGB information, able to produce a point cloud of the building, to enhance modelling. At the same time, very detailed point clouds can be large in file size, resource-demanding and difficult to manage. Numerous workflows explore compromises between data size and feasibility [18,20,44]. For example, the raw point cloud acquired can be decimated (reduced in file size) to a given level of detail. The survey operator could also perform a survey with a differentiated level of detail: for instance, a more detailed survey of the exterior (to capture decorations) as compared to the interior (to define spaces and wall thicknesses), or, for the sole exterior, an overall survey with coarser detail for general dimensions and a focus on specific areas (e.g. a strip of elevation that includes all the orders of windows and mouldings). Moreover, the whole point cloud file can be divided into portions of fixed file size, corresponding to building sections.

To select the best process, a clear scope of the geometrical survey effort, depending on model use [45], should be established, with a list of measurements to be taken, measurement's resolution, the required accuracy and file format for deliverables (Figure 2).

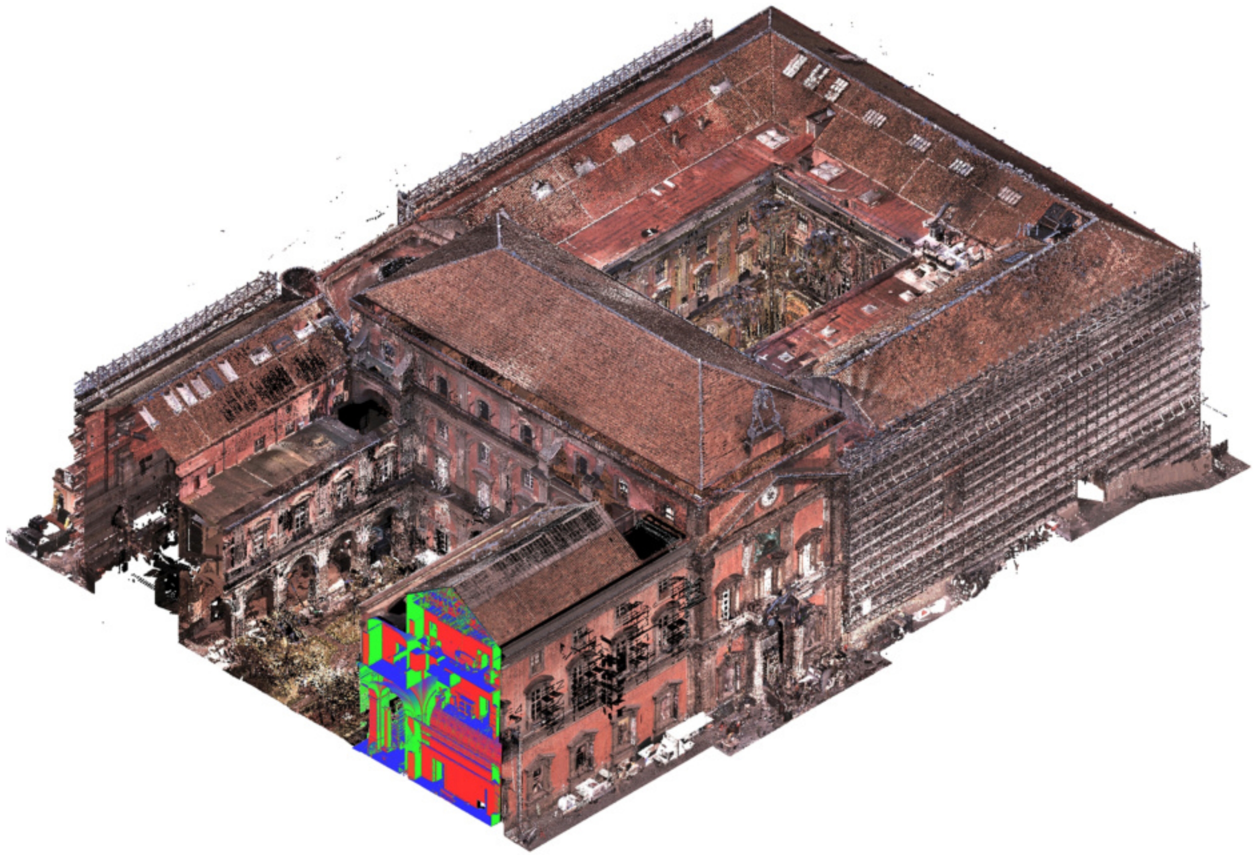

Figure 2: Point cloud from the laser scanner survey for the HBIM model of the National Archaeological Museum of Naples. The survey was carried out with a Leica ScanStation P50 – Long Range 3D Terrestrial Laser Scanner with an integrated camera, supported by Leica GS15 - GNSS and Leica Nova TS60 total station. The number of scans is 191. The software solutions used for post processing are Leica Cyclone and 3DReshaper.The laser scanner survey of the entire building was planned with an average scanning pitch of 10 ÷ 15 mm, while the detailed survey of friezes, cornices and other decorative elements was carried out with a more dense step. The presence of protrusions, pilasters, tympanums on the facades and the friezes that decorate the openings of windows and balconies, required a greater number of measurements from multiple angles to minimize the shaded areas.

3.4 Definition of the breakdown structure and Level of information Need

The breakdown structure of the building into construction elements, to be modelled as single objects, depends on the building's components and systems [26], but it is also influenced by the BIM tool chosen and its pre-set hierarchy and behavioural rules. A necessary trade-off requires selecting, for each building element identified, the model category that not only is most akin to its construction role but also allows for the most effective modelling of its technical characteristics.

For each model object, the Level of Information Need, composed of geometrical information (i.e. detail, dimensionality, location, appearance, parametric behaviour), alphanumerical information and documentation (i.e. external links of reports, analysis, manuals, specifications) is indicated

[5]. An overall Level of information Need, applied indistinctly to a whole historical building, is usually not recommended, but it has to be adapted to the construction elements identified.

Since most of the model objects pertaining to a historical building fall outside customary BIM implementation methods, specific, often non-standard modelling strategies should be proposed, weighing their advantages and disadvantages to find the best simplification compromise to suit model uses. Both semantic enrichment and modelling strategies should accommodate the possibility, through further data collection, of obtaining more information and therefore allow for easy updating of the model.

This phase requires a specific field analysis supported by photographic documentation, sketches and field modelling tests, to anchor any consideration on the model to the actual building for immediate verification.

3.5 HBIM Modelling

HBIM modelling is at the core of the proposed workflow, capitalising on all previous phases to obtain a semantic representation of the construction system and technological characteristics of the building.

At present there is no specialised software and universally accepted guidelines for HBIM modelling phase [20]. Modelling of construction systems is based on a trade-off between geometric accuracy and construction reliability, taking the most advantage from the parametric behaviour of the chosen BIM tool and tolerating a controlled amount of simplification, for instance, discarding minor deformations and unevenness that would compromise the usability of the model [22,26].

Geometric complexity and uniqueness of historical building elements are other challenges of HBIM modelling, which is generally time-consuming, demanding tailored objects that cannot rely on existing object libraries [18]. Some of these challenges can be overcome by deepening the knowledge of the building: by understanding its geometrical and technical features, it is possible to define a correct modelling workflow, as similar as possible to the building element's construction workflow. This requires HBIM operators not only to be experts in BIM modelling but also to be built heritage experts, with extensive knowledge of the building and the conservation practices the model should support [20,46].

There are numerous procedures for modelling, depending on data collection. Generally, when the geometric survey results in a point cloud, a Scan-to-BIM approach is preferred (Figure 3):

even if not a standardised method [16], it implies the use of the point cloud, imported in the BIM tool, as a "scaffold" upon which BIM objects are directly modelled [14,20].

Figure 3: Point cloud superimposed on the HBIM model of the National Archaeological Museum of Naples, highlighting their high correspondence and the effectiveness of a Scan-to-BIM approach.

Currently, interesting experiments on automatic and semi-automatic modelling methods from point clouds are underway [14,44,47]; however, the recognition of historical construction objects is still scarce, because knowledge and critical interpretation of highly qualified operators is crucial. Therefore, manual modelling strategies are preferred.

Numerous researches overcome the geometric limitations of most BIM tools in dealing with complex, irregular surfaces by creating objects with other software, supporting Non-uniform rational B-spline (NURBS) or mesh, and then importing them in the BIM tool of choice [48–51]. This can be an effective strategy when dealing with non-simplifiable, non-ruled surfaces and when geometric accuracy is crucial for model use: however, imported objects can be restricted in their local editing capabilities and parametric behaviour. Moreover, when simplification of uneven features and decorations is admitted, most historical buildings' elements, following specific rules according to their architectural language, are composed of primitive geometries, combined to define elaborate forms that can generally be represented, with limitations, by BIM tools.

Therefore, this workflow proposes to model objects primarily as native parametric objects, or, when unfeasible, to model them with native non-parametric tools adapted to complex shapes; imported geometries are seen as a last resort.

Native parametric modelling is specific for each BIM tool. However, it usually involves the preliminary definition of an object class, or family, which describes a group of building elements as model objects with common characteristics, represented as some mixture of fixed and parametric geometry, and provides information and a set of relations to control the parameters by which object instances (i.e., single objects within the model) can be generated. BIM tools have a predefined number of base building object classes that predetermine what building elements (e.g. walls, roofs, floor, etc.) are and how they interact with other objects [4]. Different building elements can correspond to more or less flexible object classes.

For instance, the software Autodesk Revit (whose object classes are called "families") divides families into two main categories. System families are predefined in the software and available within a project file; they cannot be created or deleted. They are used to model main construction elements (such as walls, floors, ceilings and stairs), and present effective fixed built-in behaviours (for example, they can represent material and junctions correctly), albeit with limited variability. Component families (including most building components, windows, doors, columns, beams, HVAC elements, etc.), are created in a specific family editor, outside of the project file, and can be loaded into different models. Therefore, their flexibility is enhanced, because user-defined, highly customizable parametric rules can be applied to them, but they lack built-it, integrated behaviour.

Autodesk Revit also supports a subdivision of families into types (Figure 4), which specify the values of certain parameters of the family (e.g. in the case of a 'hinged door' family, doors with different widths may represent different types). Hierarchical aggregation of object elements can be “nested” into comprehensive families.

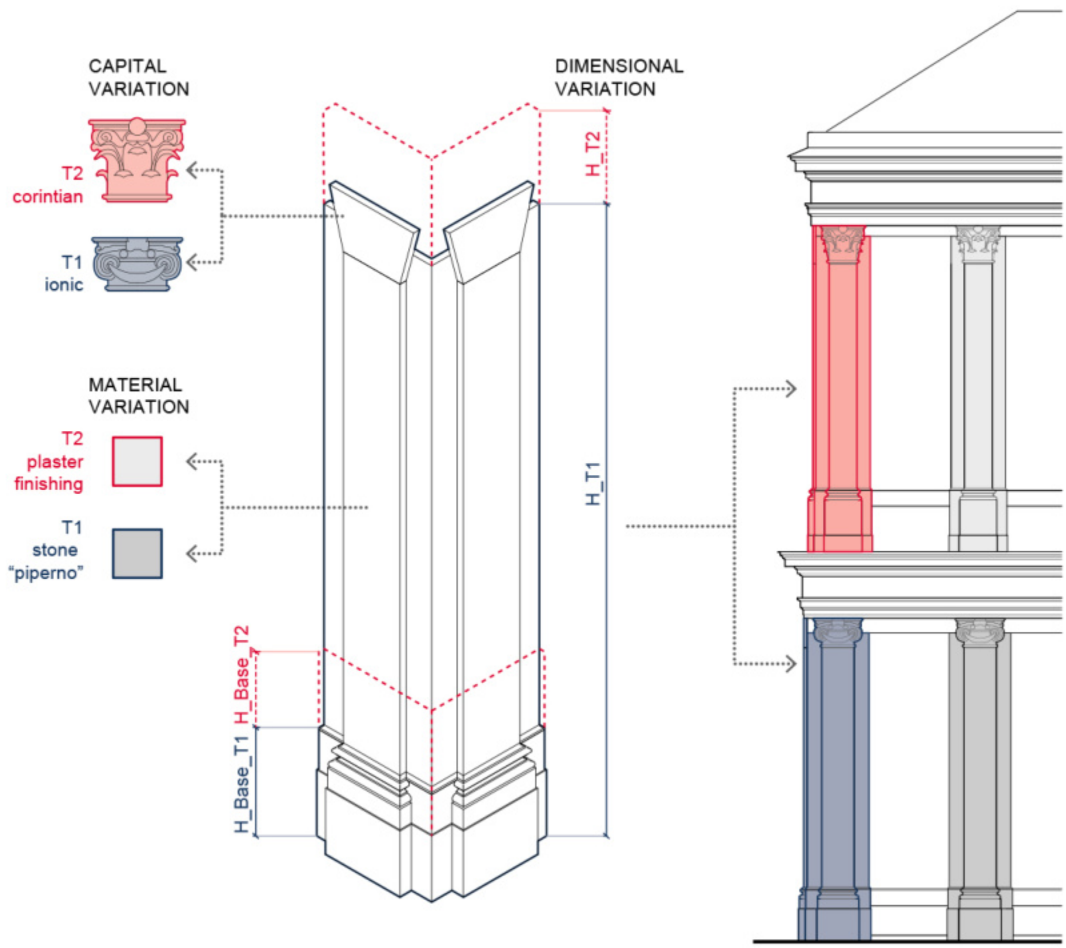

Figure 4:Parametric model of the lesenes of the National Archaeological Museum of Naples: the same object family is flexible to represent, using different types, the differences in materials, decoration and dimensions of the lesenes from the "piano nobile" (ground floor) and form the other floors.

This workflow proposes to use system families (or their equivalent in other BIM tools), whenever applicable, because, although not very flexible, their constructive behaviour is highly optimised: for example, they usually support materials' stratigraphy and resolve intersections between construction elements (walls and floors, stairs and floors, etc.). For all other objects, well-structured parametric component families and types, specific for the individual building and adaptable to local variations, should be created using geometric definitions, associated information and behavioural rules, with nesting of partial families, if needed. The use of a vocabulary of 2D shapes, derived from the point cloud and historical manuals, can support the modelling and aggregation of primitive geometries; parameters can identify modularity and invariants. This hierarchisation, if well planned, besides being useful for model management, allows to structure the model as an articulated architectural and construction system, providing a detailed identification, classification and representation of building language, proportions, modularity, construction typologies, their analogies and variations [46]: a process to enhance knowledge, not only documentation.

Properties assigned to each model object support the integration of alphanumerical information and documentation derived from data collection, according to the Level of Information Need. However, the properties' dataset is limited in accommodating heterogeneous, variable information and has reduced data management capabilities (Figure 5). Therefore, a coherent input strategy should define how and which information should be directly assigned to model objects as a single property value, assigned as a link to an external report, sheet, drawing, etc. in the CDE or organized in folders within the CDE, but without direct links to model objects.

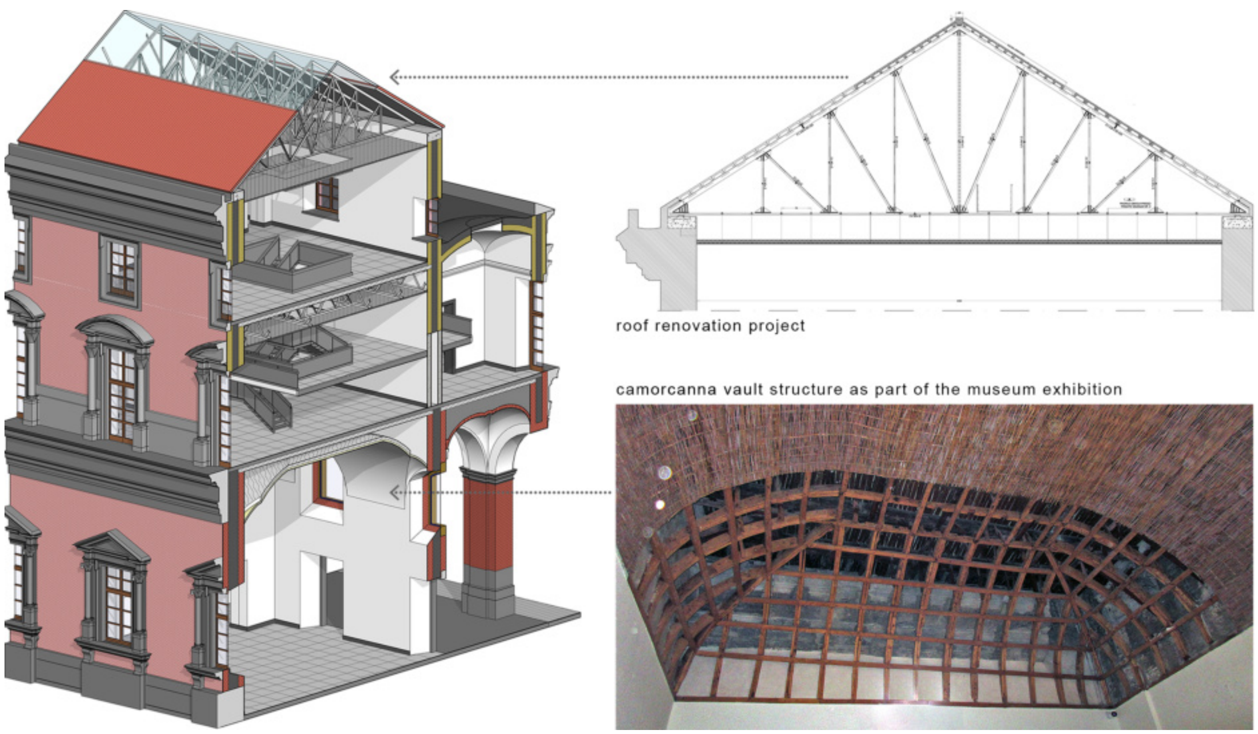

Figure 5: Section axonometric view of the HBIM model of the National Archaeological Museum of Naples, with an example of the external documentation linked to the corresponding model objects.

3.6 Results - discussion

To show the practical implications of the proposed workflow, we present its application to the HBIM model of the National Archaeological Museum of Naples, among the most prominent examples of 18th century Bourbon architecture. The construction originated as the royal stables in 1537, but was immediately interrupted to be resumed in 1610 to erect a Baroque-style building with a two-storey central body and symmetrical one-storey wings, dedicated to the university “Palazzo degli Studi”. From 1777, the building was subjected to a long series of renovation works and extension plans by F. Fuga and P. Schiantarelli, while architectural style and decoration were simplified up to the current imposing Neoclassical image. In 1821, the building was completed in its current form, with the construction of a second and third storey above the lateral wings, and it was converted into a museum in 1816, with the extensive archaeological collection of the Bourbon and private collections enriched with findings from excavations in Campania and Southern Italy throughout the 19th century [52].

So far, modelling concentrated on the southwest wing of the building, but will be extended to the whole museum in the next phases, and has been developed with Autodesk Revit BIM authoring tool. The model provides an information system of the building, to handle the museum complex for owners, managers and operators, by organising the conservation and day-to-day maintenance interventions it constantly undergoes and supporting tender and contract processes while ensuring the permanence, consultation and implementation of data (Figure 6).

The use of the workflow on this regular, 18th-19th century architecture highlights its efficiency in supporting a complex case study with significant managing demands, a rich documentation and data collection to be funnelled in the model and an in-detail modelling phase, involving the architectural analysis and representation of both constructive systems and decoration. Nonetheless, the workflow is general in scope and highly flexible, therefore suitable for all sorts of historical buildings from different historical periods, with peculiar characteristics (structural variation, geometric disturbance, heterogeneity, decay, etc.) by adapting it to model uses: the focus being principally on the reliable representation of constructive systems. For instance, depending on the main goal of the work, different tools can be employed: as suggested, even if not ideal, imported shapes from specific 3D modeller can be imported if geometric accuracy is paramount (see § 3.5), or the model can be optimised for interoperability with structural simulation software, or decay patterns can be represented in the model or linked as external reports in the CDE. In each case, the phases of the workflow remain the same.

Figure 6: Perspective section view of the HBIM model of the southwest wing of the National Archaeological Museum of Naples from the courtyard.

Starting with model planning, the workflow sought the involvement of building managers and operators, to initiate a robust collaboration to define objectives and procedures through questionnaires, meetings, etc. A synthetic BIM Execution Plan (BEP) was developed defining:

1. Time scheduling
2. Roles and responsibilities
3. Model uses
4. BIM tools
5. Data formats and data exchange methods within a CDE
6. Naming conventions
7. Coordination among the established federation of models
8. Breakdown structure and Level of Information Need for each model element.

The predominant model use identified related to the support of conservation and maintenance interventions, which directed modelling towards the representation of construction systems.

Paramount to this use was the development of a cloud-based CDE, whose aim is not only to enhance collaboration during the HBIM modelling phase among team members but, mostly, to provide owners and managers with a cohesive environment where the HBIM model and all the structured and unstructured information gathered during data collection and produced during building management, linked to it, is deposited and organized and can be effectively consulted and updated. For this reason, the CDE features include a robust 3D viewer, a file repository of 100 Gb, ease of use and the possibility to enrich HBIM objects with supplementary properties.

As an example, alphanumeric information and documentation on the historical development of the building as a whole, that could not be directly integrated into the HBIM model in Revit software, has been externally linked to it in the CDE as a pdf report, to enhance accessibility. For single model elements, links to specific external resources in the CDE were included as object properties: technical analyses on masonry, images or documents to support construction hypotheses, material analyses, etc.

Within the CDE, naming conventions strengthen a consistent, unified approach to the identification and management of elements across datasets. PAS 1192 [53] and ISO 19650 [2] offered an effective method to name and organise files and folders, according to an alphanumeric string composed of single fields, representing file's properties (e.g. project, type, classification, etc.), joined by the "-" hyphen character, so that the name itself provides information without the file being opened. For model objects within BIM models, current classification systems, such as Omniclass and Uniformat [54,55], were unsuitable to describe the historical building components; therefore, a similar alphanumeric string, whose single fields illustrate the component's features, was developed for the building, based on Di Giuda et al. [56].

Data collection focused on the analysis of the building's construction systems and their transformation over time. Available documentation on recent works, although fundamental to trace the building's evolution and operation, is unstructured and therefore fragmentary, increasing complexity in data acquisition and organisation and highlighting the need for a coherent building information system.

Bibliographic research from cartographic and photographic documents, such as the design renovation plans of Ferdinando Fuga in 1778, of Pompeo Schiantarelli in 1785 and of Pietro Bianchi in 1834 [57–59], allowed a reliable representation of the building's masonry system. Integrated with information on the historical context and the coeval technical building methods derived from architecture manuals and specified with numerous building inspections, the analysis enabled the comprehension of the functioning and articulation of the main technological elements, such as walls' stratigraphy, vaults, floors, roofs and mouldings. Inspections had to face and sometimes collide with continuous restoration and maintenance activities, visitors' flows, exhibition set-ups; at the same time, ongoing works requiring invasive interventions unveiled materials and structures and enhanced the verification of constructive hypotheses that would have needed specific instrumental diagnostic analyses. For instance, a tuff wall layer was identified under plaster thanks to the inspection of a building's section under renovation and literature indicated the use of rubble masonry for walls of the thickness present in the building, suggesting typical layer thicknesses and material specificities. This information, combined with metadata displaying its source, guided wall objects' modelling (Figure 7).

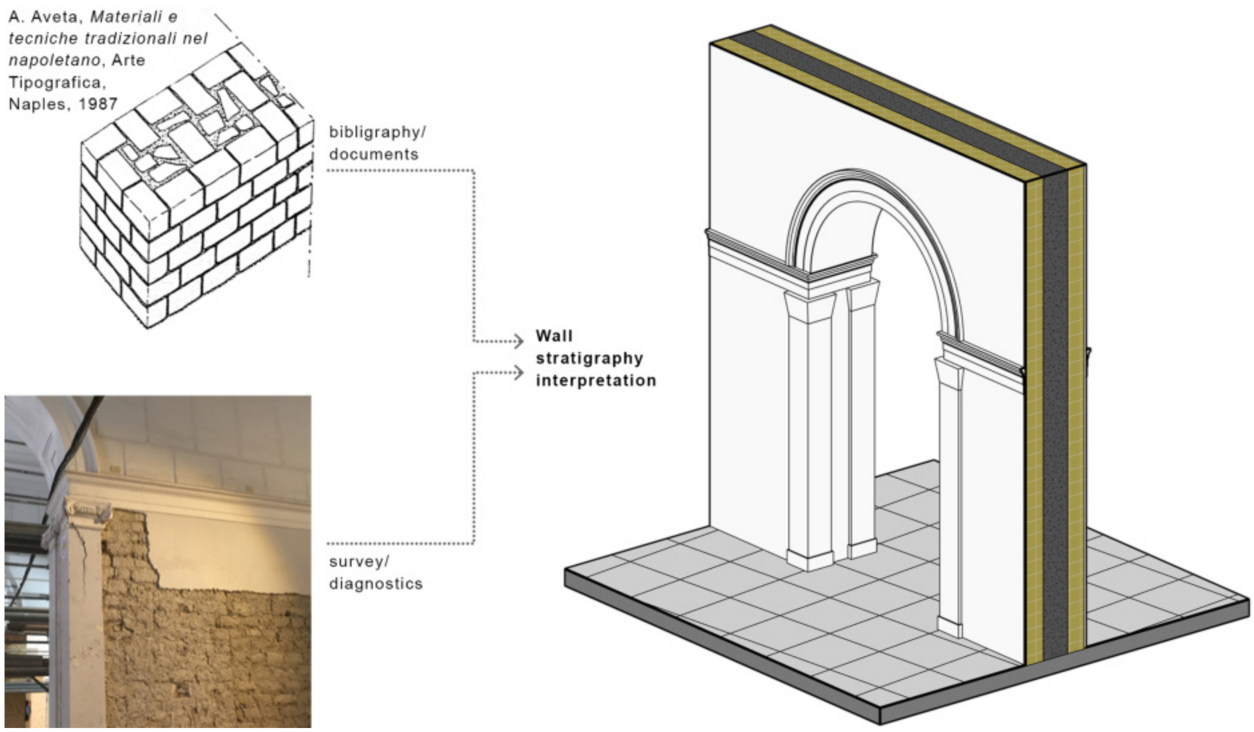

Figure 7: HBIM model of the interior tuff wall of the building, with reference to the sources (surveys and manuals) of the hypotheses on constructive systems.

A geometric survey of the exterior and interior of the building was carried out using photogrammetric and laser scanning techniques. The survey was performed with a Leica ScanStation P50 – Long Range 3D Terrestrial Laser Scanner with an integrated camera supported by Leica GS15 - GNSS and Leica Nova TS60 total station. The software solutions used for post-processing are Leica Cyclone and 3DReshaper. The number of scans is 191, with as many measuring stations distributed along the perimeter of the building at ground level and elevated with telescopic poles or on surrounding structures. The scanning step was between 6.2 mm at 10 m to 0.8 mm at 10m. The scans, complete with radiometric measurements and RGB information, covered all the external surfaces of the building including courtyards and the internal surfaces of the southwest wing.

To reduce information waste and optimise modelling, two point clouds were developed from the scans. The overall point cloud of the building, georeferenced, cleaned and processed at a lower resolution (decimated to 2 cm) includes the entire external envelope and roofs and was used for general measures. The point cloud of the southwest wing, georeferenced, cleaned and processed at a high resolution, includes all the external envelope and roofs and all the interiors and was the main reference to geometric modelling, imported in the BIM tool used. This point cloud was further segmented into portions for detailed modelling of single objects also by different operators (Figure 2).

All data collection highlighted the precision and high standards of “regola dell’arte” followed by the construction: proportion and modularity of construction elements are notably accurate, walls’ sections are extremely regular and out-of-square edges exceptional. Decorations, based on a complex combination of simple geometries, present a remarkable match between corresponding parts to different elements. These considerations on technical accuracy and architectural language informed breakdown structure and object modelling and were reflected in families and types’ organisation.

The breakdown structure of the building into its constituent construction elements, and the identification of alphanumeric information and documentation to associate them with, encourages the analysis of each element’s role in its broader context; hence, it was developed through dedicated field surveys.

The classification criteria used adapted the BIM tool taxonomic system, conceived to describe modern architecture, to a historical building, in harmony with the used naming convention for model elements. It also followed the principle of avoiding information waste, defining the minimum number of model objects and classes corresponding to building elements according to model uses, planning in advance which information should be modelled as object and which should be given as property, while foreseeing strategies to implement the Level of Information Need in the future, if needed. For example, floors were identified as a single object for each storey, because the geometric distinction of the finish was not influential, whilst information on the finish was provided through properties of the rooms, which is a more effective data organization for maintenance purposes.

Properties were defined to implement information on each object to support maintenance and conservation activities, such as structural and thermal characteristics of the building materials, construction period, etc. Some objects were planned to have a different geometric detail according to visualisation objectives.

Breakdown structure and HBIM modelling phase aimed to implement the BIM tool's hierarchy of categories, families and types to effectively represent the building's construction system and better describe its Neoclassical architectural language, based on modularity and rhythmic repetition of technical and decorative elements. Categories were selected to enhance the constructive behaviour of objects, particularly when direct correspondence was not available: vaults, not directly recognized as such in the BIM tool used, were modelled as "roofs" because this category grants an accurate representation of their shape and stratigraphy; lesenes and pilasters as architectural columns, which ensure their correct connection with the wall; mouldings as wall sweeps. System families were preferred whenever possible and component families were developed through parametric modelling, to optimise constructive behaviour as well. Families and types' organisation reflects the building's architectural syntax, for example, the subtle variation between the façade of the ground floor ("piano nobile") and other floors: the lesenes of the two floors belong to the same family, with different types highlighting the differences in materials, decoration and dimensions (Figure 4); profiles families for mouldings and decoration were developed by integrating the same basic motifs and reusing them throughout the model. Within this organisation, parameters were used: to describe stylistic or technical variations (type parameters); to accommodate local inaccuracies, transformations or decay of individual objects (instance parameters); to represent uncertainties that could be solved with further investigation, to simplify their subsequent update (for example, the height of the structural level of floors).

As all corresponding elements are connected, the process allowed for the parallel study of several aspects of modelling: material definition, based on typology studies, was performed separately and automatically applied to affected elements, to be updated in case of potential diagnostic analysis. Naming conventions, coupled with metadata, (i.e. data describing other data), helped to track the critical hypotheses on construction systems and architectural language. Metadata were integrated as a text property assigned to each object, describing the reliability of construction assumptions, the possible gaps in information and the potential need for further investigation.

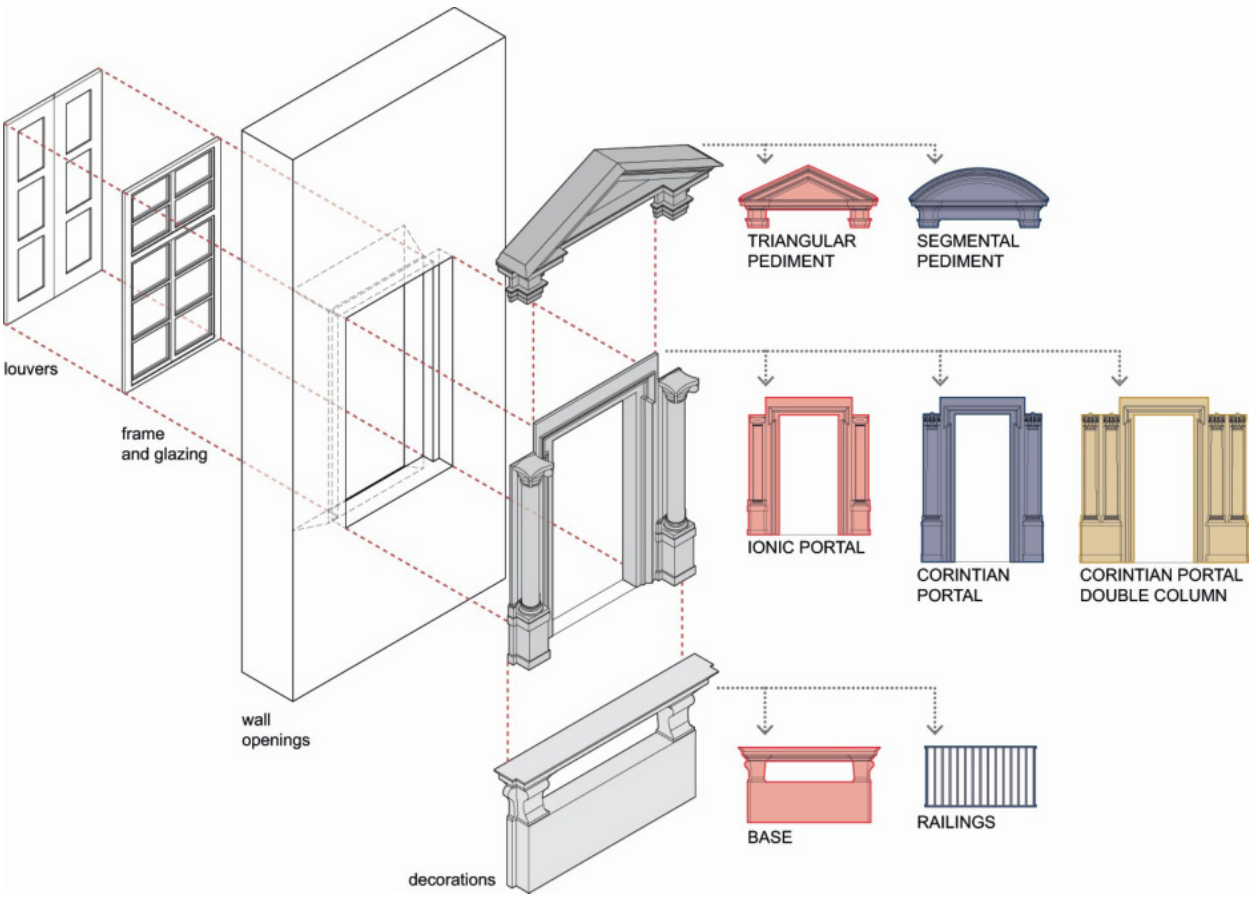

Figure 8: Schematic organization of the HBIM nested component family representing the articulated modular system of the windows of the National Archaeological Museum of Naples. By aggregating different objects according to specific formal rules, it is possible to obtain family types of all the windows in the building.

Windows well represent the modelling strategy, as they are typified components belonging to an articulated modular system, with specific formal rules. They were modelled as component families, disaggregated into: base, columns-trabeation, pediments and then nested to configure each floor’s specific aedicules, with variable pediment and capital for ground floor and first floor, or with doubled columns for the central window on the portal (Figure 8). Dimensions of objects and profiles are parametric, to describe typological and local variations.

Walls modelling involved the identification and organization of masonry types according to thickness, stratigraphy and materials, derived from inspection and description of coeval architecture in the literature [60–75]. External masonry highlighted the variations in the use of materials between the ground floor and the upper floors, and the representation of decorations (mouldings, friezes) in its formal and constructive characteristics (Figure 9).

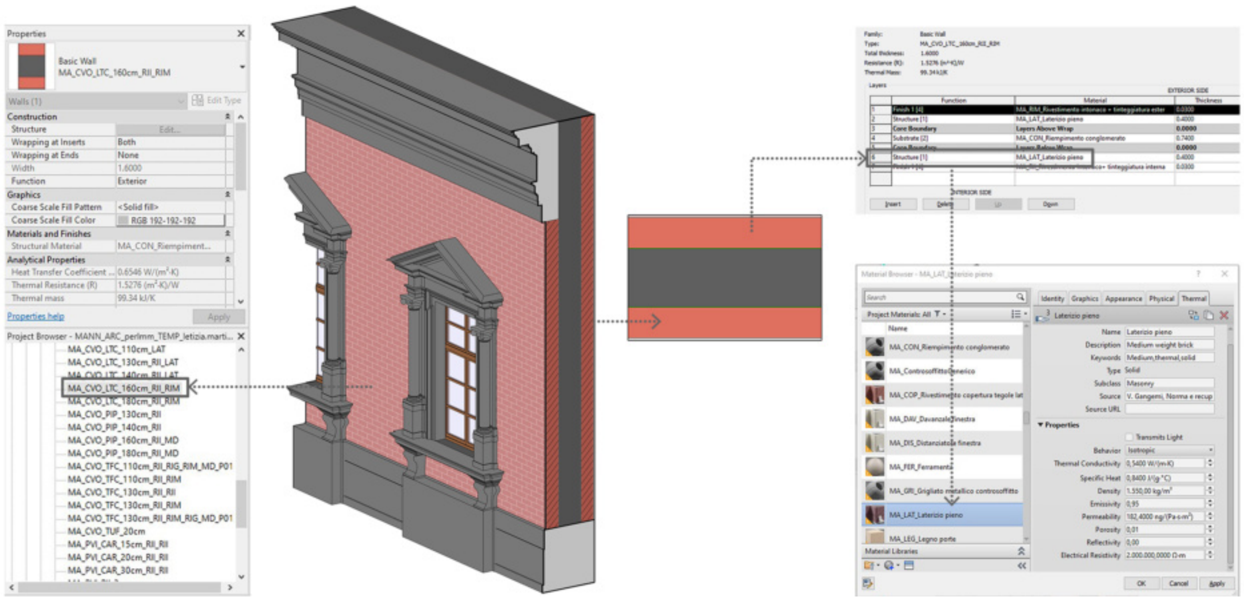

Figure 9: Hierarchical levels of the constructive information (stratigraphy, materials, etc.) embedded in the HBIM model of the walls of the National Archaeological Museum of Naples.

Floors' modelling was guided by data collection, because they are covered by vaults and not directly visible. The presence of wooden floors and information on typical beams and slab thickness, dimensions and joists, has been deduced from coeval construction systems, but more data, specific to the building, is expected. Therefore, the structural system was modelled separately as a simplified object, consistent with the available data, with parametric height and anchoring, to facilitate the future detailed modelling of beams and joists system with correct dimensions and wall junctions. The finishing floor was modelled as an extensive object with stratigraphy, for the entire level, intersecting the internal vertical walls: the correct relationship between vertical and horizontal elements is granted by the implementation of material priorities, a feature of the BIM tool used to natively simulate the intersection of structural and non-structural elements.

As the BIM tool does not contemplate dedicated strategies for vault modelling, adaptive component families called “conceptual masses”, representing abstract shapes, were developed for each typology of vault to reproduce the intrados surface. These masses are highly parametric objects, locally adapting to the vaults' shape by using control points to define their edges and dimensional parameters, and to control their geometry and relationships among parts. Constructive objects with specific stratigraphy were generated on the masses surface to represent the different technical solutions of vaults (reed and plaster ceiling, light vaults - "camorcanna") in the building; beam system structure has been modelled as a separate object, to be further detailed pending investigations (Figure 10).

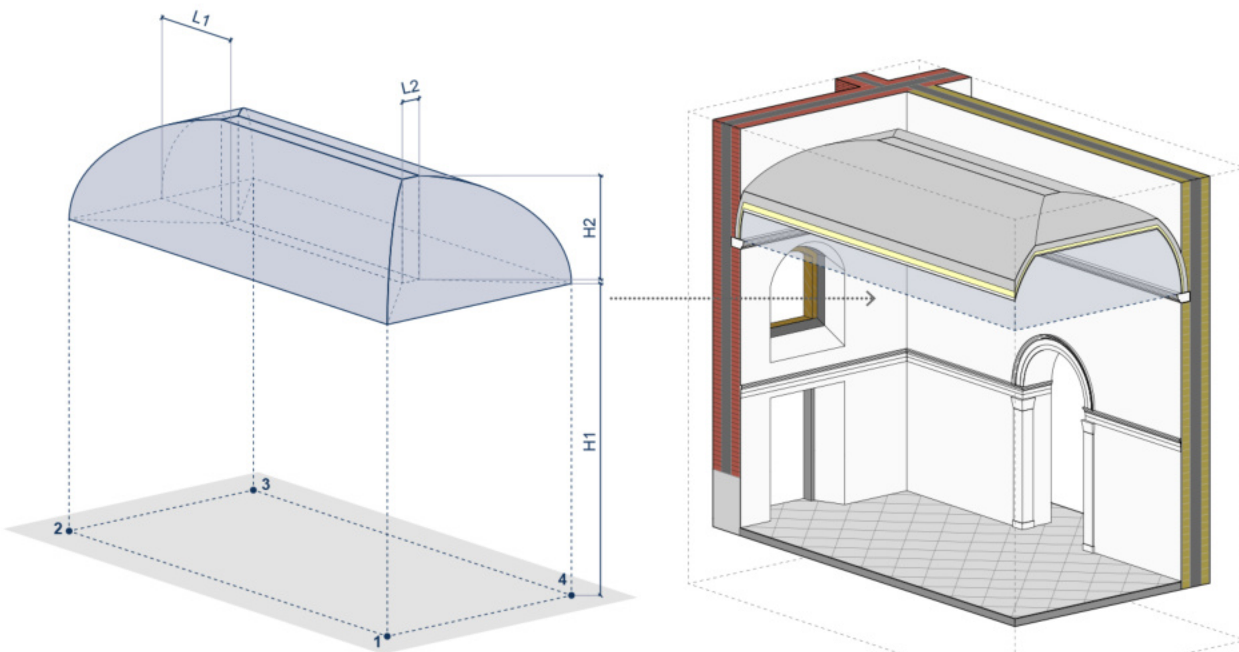

Figure 10: Relationship between the parametric "conceptual mass" representing the abstract shape of a vault and its corresponding constructive object, with a specific stratigraphy and its materials.

4 Conclusions

The research presents an HBIM workflow to support conservation and maintenance activities on historical buildings, with a focus on the simulation of building construction systems. The workflow is sufficiently flexible to accommodate a heterogeneous range of objectives while guiding experts to establish a trade-off between data accuracy and the parametric potential of BIM tools. The application of the workflow to a complex building, with great decorative richness and structural variety, confirmed its versatility.

Future developments include the implementation of management for building maintenance and the support to tenders on building interventions using BIM. The development of Internet of Things (IoT) systems and diagnostics to provide dynamic information could also be integrated into the workflow. Parametric model objects representative of an architectural period (such as windows) or highly flexible to adapt to many conditions (such as vaults' masses) can become part of a library of HBIM families.

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