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Valentino Castle North Wing: A Study of a Documentation-Oriented HBIM Framework

By

Li Xiang

Supervisor:
Prof. Lorenzo Teppati Lose'
Prof. Fulvio Rinaudo

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Abstract

Valentino Castle, a UNESCO World Heritage site and the core educational venue for Politecnico di Torino's Architecture and Design department, is pivotal for research and studies in different domains. The field of architectural heritage conservation and research on Valentino Castle has developed a series of profound study results and comprehensive archival records. Facing these data complexity and environmental degradation, a digital documentation system is vital. It consolidates historical findings and supports the castle's upkeep strategies. Heritage Building Information Modeling (HBIM) stands out in cultural heritage preservation, merging geometric and semantic data for historical analysis, monitoring, and interventions. It boosts information management efficiency and responds to environmental shifts. However, HBIM's application in heritage projects needs better standardization and archival clarity.

Addressing the issues, this study delineates a methodological approach oriented towards archival HBIM, aimed at effective digital documentation and management of Valentino Castle via HBIM technology. In contrast to the prevalent HBIM workflows driven by heritage conservation and intervention - such as typical scan-to-BIM projects - this documentation-oriented HBIM workflow can reduce the impact of the metric survey phase. Instead, it utilizes a variety of pre-existing geometric data, including both detailed point clouds as well as traditional drawings, to expedite and simplify the construction of 3D geometric models, thereby facilitating more efficient management of heterogeneous data. Consequently, this approach avoids the exclusive reliance on high-fidelity point cloud acquisition or intricate geometric modeling, instead emphasizing the development of comprehensive documentation standards and the strengthening of information management infrastructures. The methodology is partitioned into four distinct phases, each following the previous in a logical sequence, thereby ensuring a seamless execution of the project. It begins by establishing a standardized research framework and workflow paradigm, providing a reference and comparison for specific project workflows to assess the completeness of the project framework and identify any omitted steps. Subsequently, detailed methods for geometric simplification modeling are formulated for different architectural elements, combining building construction knowledge with HBIM technology. The third, for the semantic and heterogeneous information of the north wing of Valentino Castle, the study introduces a four-tier information framework - Level 1: Building, Level 2: Zone, Level 3: Components A, Level 4: Components B - to manage the information of different types and objects within the project. It establishes external database and table management methods based on this framework. Lastly, the study evaluates the implementation efficiency of HBIM using the Free and Open Source Software (FOSS) platform to enhance information interoperability, thereby achieving a broader multi-disciplinary research environment.

The documentation-oriented HBIM system methodology proposed in this study has been implemented and validated in the north wing project of Valentino Castle, achieving preliminary HBIMD work. Moreover, this methodology provides methodological references for other architectural heritage documentation projects with similar objectives, promoting the digitalization process of architectural heritage projects.

Keywords:HBIM,HBIM Documentation(HBIMD), Scan-to-BIM, Information Modelling.

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List of Abbreviations

AEC: Architecture, Engineering and Construction industry

AIR: Asset information requirement

API: Application programming interface

AR: Augmented Reality

BCF: BIM Collaboration Format

BEP: BIM Execution Plan

BHIMM: Built Heritage Information Modelling and Management

CDE: Common Data Environment

CH: Cultural heritage

CIC: Construction Industry Council

CIDOC-CRM :International Committee for Documentation - Conceptual Reference Model

COBie: Construction Operations Building information exchange

DB: DataBase

DBMS:DataBase Management System

EIR: Exchange Information Requirements

FOSS: Free and Open-Source Software

FM: Facility Management

HBIM: Heritage Building Information Modeling

Historical Building Information Modeling

HBIMD: HBIM Documentation

HVAC: Heating, Ventilation and Air Conditioning

IFC: Industry Foundation classes

ISO: The International Organization for Standardization

LiDAR: Light Detection and Ranging

LoA: Level of accuracy

LoD: Level of Detail

LOD: Level of development

LoG: Level of Geometry

NURBS: non-Uniform Rational Basis Spline

OCR: Optical character recognition

OIR:Organisational Information Requirements

PIR: Project Information Requirements

PAS: Publicly Available Specifications

SaaS: Software-as-a-Service

SDK：Software development kit

SfM: Structure for Motion

UAV: Unmanned Aerial Vehicle

VBA: Visual Basic for Application

VR: Virtual Reality

Chapter 1 Introduction

1.1 Research background

Cultural heritage sites around the world are endangered by natural disasters, extreme weather or human negligence. In this urgent situation, the importance of CH documentation has been widely acknowledged. As early as 1908, the British counties/Shires established Royal Monuments Commissions and developed technical documents at various levels, from rules and guidelines to detailed technical specifications, to guide documentation and recording[1]. Since 1939, Italy has enacted the Law on the Protection of Works of Art and Historical and Cultural Property, and has developed a comprehensive protection system for CH over the past 80 years. In the international context, since the Venice Charter of 1964, various international organizations have issued charters, resolutions and statements that emphasize the importance of CH recording for conservation, management, evaluation, assessment of its structural condition, archiving, publication and research. Limited by the lack of technology, early CH records depended on physical archives and photos, which required more space and site conditions. At the same time, the huge amount of documents also caused difficulties in retrieval and transfer among different experts or stakeholders.

Since the 1990s, the records management of CH has evolved from physical documents to digital documents with the popularization and development of computer technology. Early digital documents were stored in independent file formats such as TXT, JPG, etc., and managed separately by folder, which greatly reduced the difficulty and space of file management. Meanwhile, in the Architecture, Engineering and Construction (AEC) industry, a new platform, Building Information Modeling (BIM), has been widely used. As a database platform, BIM performs well in geometry, project management, team collaboration, etc. in modern buildings, which can improve management efficiency and reduce costs. While BIM has been applied for a long time in the AEC field and has great potential for documentation in the CH field, its application to CH is much more recent. The concept of BIM for Heritage (HBIM) was first proposed by Murphy, as a strategy for applying BIM in the CH field[2]. Unlike the focus of BIM in new construction projects, which covers the whole life cycle from conceptual design to construction to operation, HBIM focuses more on information acquisition, high-level geometric modeling and asset management of heritage. For these reasons, HBIM is often defined as "reverse engineering"[3].

The introduction of new technologies with specific purposes and uses, such as HBIM and GIS, overcomes the limitations of traditional CH documentation[4]. Firstly, these technologies significantly reduce the storage cost of traditional documentation and improve the efficiency of documentation and recording. Secondly, the excellent file management mode enables the storage of new technology data, such as point cloud acquisition using scan-to-bim, or data in various formats in the form of external links. Thirdly, they can describe the precise geometric model and decay mapping, and scientifically establish the connection between geometric data and semantic data. Last but not least, they facilitate the knowledge transfer of rich models among different experts and users using IFC format[5]. Nowadays, all countries and regions in the world have issued laws and regulations related to HBIM Documentation(HBIMD), and various universities and research institutions have also conducted in-depth exploration and research on the norms, strategies and expanded applications of HBIM. Italy, with the UNI (Italian National Unification agency which represents Italian legislative activity at the International Standard Organization (ISO) and European Committee for Standardization (CEN))

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[1] Fowler P J. The Royal Commission on Historical Monuments (England)[J]. Antiquity, 1981, 55(214): 106-114.

[2] Murphy M, McGovern E, Pavia S. Historic building information modelling (HBIM)[J]. Structural Survey, 2009, 27(4): 311-327.

[3] Pepe M, Costantino D, Alfio V S, et al. Scan to BIM for the digital management and representation in 3D GIS environment of CH site[J]. Journal of CH, 2021, 50: 115-125.

[4] Pritchard D, Rigauts T, Ripanti F, et al. Study on quality in 3D digitisation of tangible CH[J]. Proceedings of the Joint International Event 9th ARQUEOLÓGICA, 2: 1-7.

[5] Colucci E, De Ruvo V, Lingua A, et al. HBIM-GIS integration: From IFC to cityGML standard for damaged cultural heritage in a multiscale 3D GIS[J]. Applied Sciences, 2020, 10(4): 1356.

11337:2017, part 4, which extends the ISO EN 19650 at the national level, has been the first country to introduce levels of development of HBIMD and open a discussion on the use of this methodology also applied to architectural heritage and restoration. In the UK context, Historic England published “BIM for Heritage” in 2017 to guide owners, end-users and professionals to develop Historic Building Information models[6]. Besides, Historic England published the “Metric Survey Specifications for CH” to provide a description of the services and standards required for the supply of various types of metric survey and BIM[7].

However, HBIMD also poses new challenges and gaps. On the one hand, the new management method demands new standards and strategies to eliminate ambiguities and errors in information, which requires professionals to have a thorough understanding of HBIM theoretical knowledge and operating methods. This requirement leads to extremely high labor costs for HBIMD. On the other hand, the process of HBIMD is quite complex. It not only involves modeling the geometric information of CH, but also managing various types of semantic information. Compared with the traditional documentation method, this results in the high cost of the initial phase of HBIMD, which often discourages managers and operatives. Fortunately, aware of these challenges and gaps, more and more professionals are trying to solve these problems in various ways, with ontology or with new methodological approaches.

1.2 Research scope and Delimitation

To efficiently manage the heterogeneous information of architectural heritage within the semantic structure of architecture, this study proposes a document-centric HBIM approach(HBIMD workflow). This method simplifies the acquisition and modeling of geometric information to a certain extent, reducing the impact of metric surveys and thus rapidly constructing 3D geometric models. It also implements the linking and management of CH information based on this simplified 3D model. The method has been improved and adapted based on the widely recognized overall HBIM approach, and as such, the specific definition of this study will be divided into four parts:

· Formulating the scope and content of HBIMD based on current laws and regulations and proposing a documentation-oriented HBIM workflow.

· Simplifying the geometric model as the core purpose of HBIMD, and verifying the scalability of the simplified model.

· Developing specific management methods for HBIMD.

· Implementing information transfer and interoperability methods for HBIMD.

The research will concentrate on the methodology and management framework of HBIMD construction, the management of specific information types, and the simplification of HBIM geometric models under the framework of semantic information. Areas such as point cloud acquisition, scan-to-bim, modeling strategies in geometric information are important but will not be the main focus of this study. The case for this research will be restricted to the northern wing of the Valentino Castle. The research on the HBIMD of Valentino Castle has been ongoing for many years and the related data and materials are very large and complex. Therefore, this research can be considered as an optimization and update of the HBIM archive management of Castle Valentino.

1.3 Literature review

Although the proposal of HBIM began in 2009, the potential of HBIM in CH has been widely concerned in the past ten years. Broadly, the concerns of HBIM are mainly divided into the following aspects:

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6 Antonopoulou, S.; Bryan, P. Historic England 2017 BIM for Heritage: Developing a Historic Building Information; Historic England: Swindon, UK, 2017.

7 Bryan P, Blake B, Bedford J, et al. Metric survey specifications for CH[M]. English Heritage(Historic England), 2013.

Since the proposal of HBIM in 2009, the potential of HBIM for CH has attracted wide attention in the past decade. Generally, the concerns of HBIM can be mainly categorized into the following aspects:

· The utilization of data derived from 3D metric survey products (mainly point clouds, etc.)[8], which can be further divided into different topics, such as multi-resolution surveys[9], automatic point cloud classification and segmentation[10], etc.

· 3D geometric modeling. This part mainly involves parameterization of complex elements[11], modeling of irregularities and structure deformations[12], and auto modeling from point-cloud[13].

· Semantic information management of CH.

· Interoperability of HBIM.

· Application of HBIM based on specific purposes, such as HBIM strategy and performance in pre-protection and daily monitoring.

As expected, the focus of the research presented here is documentation of HBIM, non-geometrical information management in HBIM and potential extended application. Therefore, the literature review will emphasize the 3rd, 4th, and 5th topics.

This part of the literature review summarizes the research on HBIMD in the last five years, and presents an alluvial diagram of the research content, to identify thematic connections among different research directions (**Figure 1**). An alluvial diagram is a visualization method that shows the relationships and changes among multidimensional data in a flowing form. Therefore, it is very useful to help extract the concerns and ideas about HBIMD in the current state-of-the-art. The Alluvial Diagram of this literature review considers a total of 5 dimensions: publication time, paper and author, core theme, specific key points, and proposed solutions. Moreover, the width of the flow region indicates the strength of the relationship or the amount of the data. The specific goals of this part are:

· Identify the theme and research topics of each author.

· Analyze the relationship among each research topic and solution method.

· Demonstrate trends in research topics and solutions over 5 years.

According to the literature review, academic research on HBIMD can be roughly divided into three themes: the first is framework of HBIM and the optimization of workflow, the second is interoperability, and the third point is applications based on specific purposes.

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[8] Jóźków G. Terrestrial laser scanning data compression using JPEG-2000[J]. PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 2017, 85(5): 293-305.

[9] Girelli V A, Borgatti L, Dellapasqua M, et al. Integration of geomatics techniques for digitizing highly relevant geological and CH sites: The case of San Leo (Italy)[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2017, 42: 281-286.

[10] Chizhova M, Gurianov A, Hess M, et al. Semantic segmentation of building elements using point cloud hashing[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2018, 42: 241-250.

[11] De Luca L, Véron P, Florenzano M. A generic formalism for the semantic modeling and representation of architectural elements[J]. The visual computer, 2007, 23(3): 181-205.

[12] Moyano J, Carreño E, Nieto-Julian J E, et al. Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project[J]. Automation in Construction, 2022, 143: 104551.

[13] Analysis and management of structural deformations through parametric models and HBIM workflow in architectural heritage[J]

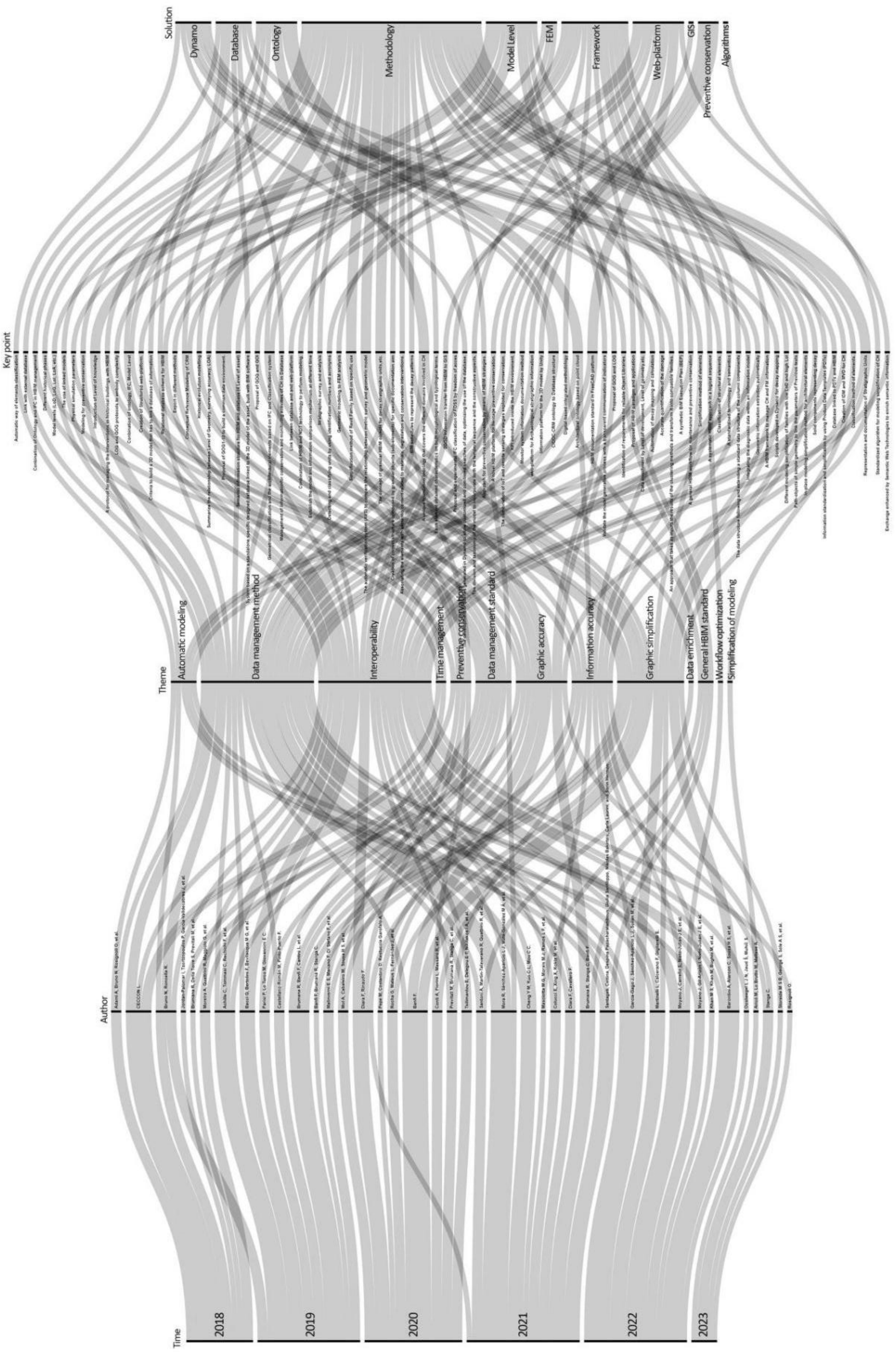

Figure 1 Alluvial Diagram of literature review

Unlike AEC projects, which have unique morphological and semantic information, BIM management standards and paradigms for CH are still an open issue. In 2017, Historic England[5] proposed BIM for heritage[5] to define the specifications of BIM for European architectural heritage. Based on this, Jordan-Palomar I, Tzortzopoulos P, García-Valldecabres J, et al.[14] proposed a protocol named BIMlegacy to specify the different stages in HBIM program. Bruno N, Roncella R.[15] developed an HBIM methodology to support HBIMD in various platforms: They divided architectural heritage information into 4 levels (Building, Zones, Architectural components A and B), and assigned different information to each level, to standardize the information transfer between the BIM platform and the database.

The credibility of the information is essential for HBIM management of architectural heritage, which depends on the level of the model. Model levels (LOD, LOI, etc.) were first applied to quantitatively define information in BIM for AEC. In 2017, UNI 11337-3-2017 presented the concept of model levels such as LoD-LoI for CH. Since then, Model Level has been extensively discussed in Multi-dimensional Representation with H-BIM[16]. Unlike concepts such as LoD-LoI designed for HBIM, another model level named LoK (sometimes LK) was offered by the Italian ''Technical Standards for Construction'' (Italian NTC 2009) as early as 2009. Bruno N, Roncella R.[17] suggested integrating LoD, LoI, LoK and other model levels into metadata, and established a systematic HBIM framework.

Besides the quantification of credibility, another advantage of the model hierarchy is that it can be used to represent the simplification of the geometric model. Castellano-Román M, Pinto-Puerto F.[18] proposed a holistic approach to heritage assessment and documentation, using detailed definitions of LOK to retain maximum geometric information. Brumana R, Della Torre S, Previtali M, et al.[19] proposed a parametric generation modeling process (GOG9-10) based on NURBS to obtain a model that describes complex geometry and matches relevant semantic information. In the last five years, research based on GOG1-10 has been more widely applied in geometric simplification, accuracy description, and quality control of models at different dimensions and scales[20,21]. Barontini A, Alarcon C, Sousa H S, et al.[22] continued to lower the level of the geometric model, but enhanced the management of semantic information. For example, the damage to the building surface would be created as a fixed-thickness volume to represent location and size, and to link semantic information.

The framework optimization and workflow optimization of HBIM can improve the efficiency of information management. However, another important issue is how to efficiently retrieve heritage

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[14] Jordan-Palomar I, Tzortzopoulos P, García-Valldecabres J, et al. Protocol to manage heritage-building interventions using heritage building information modelling (HBIM)[J]. Sustainability, 2018, 10(4): 908.

[15] Bruno N, Roncella R. HBIM for conservation: A new proposal for information modeling[J]. Remote Sensing, 2019, 11(15): 1751.

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[17] Bruno N, Roncella R. A restoration oriented HBIM system for cultural heritage documentation: The case study of Parma Cathedral[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2018, 42: 171-178.

[18] Castellano-Román M, Pinto-Puerto F. Dimensions and levels of knowledge in heritage building information modelling, HBIM: The model of the Charterhouse of Jerez (Cádiz, Spain)[J]. Digital Applications in Archaeology and Cultural Heritage, 2019, 14: e00110.

[19] Brumana R, Della Torre S, Previtali M, et al. Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): Surveying, preservation, site intervention—The Basilica di Collemaggio (L'Aquila)[J]. Applied geomatics, 2018, 10: 545-567.

[20] Banfi F, Brumana R, Stanga C. Extended reality and informative models for the architectural heritage: from scan-to-BIM process to virtual and augmented reality[J]. Virtual Archaeology Review, 2019, 10(21): 14 -30.

[21] Brumana R, Stanga C, Banfi F. Models and scales for quality control: Toward the definition of specifications (GOA-LOG) for the generation and re-use of HBIM object libraries in a Common Data Environment[J]. Applied geomatics, 2021: 1-29.

[22] Barontini A, Alarcon C, Sousa H S, et al. Development and demonstration of an HBIM framework for the preventive conservation of cultural heritage[J]. International Journal of Architectural Heritage, 2022, 16(10): 1451-1473.

information. To address this problem, some BIM plug-ins in computer language were developed and used for information retrieval and management. Santoni A, Martín-Talaverano R, Quattrini R, et al.[23] developed and tested a Dynamo-based plugin that is used to associate the elements of the 3D model with construction phases, stratification ID or other parameters. Once the specific ID is selected, the program isolates the elements in a specific 3D view. Bruno N, Roncella R[16], mentioned earlier, wrote an ID-based plug-in for Revit in C language, which is a desktop database management tool for querying/adding, editing/viewing data about projects through a graphical interface.

Interdisciplinary collaboration is the core of HBIM, and interoperability is the core of linking different fields. The interoperability of BIM refers to the ability to share, exchange, collect and process the same data through a common set of exchange formats, using the same file formats and the same protocols[24]. The Industrial Foundation Classes (IFC) data model is an international standard data model for the construction industry. It adopts an object-based file format to promote interoperability in the architecture, engineering and construction industries, which is a commonly used collaborative format for building information. Classification scheme (e.g. Uniclass, Omniclass, etc.) is another standard format in the BIM environment, like a common language. In BIM, classification schemes allow people, software, and machines to share and use building component and object information efficiently and accurately. Therefore, discussions on the use of IFC and classification schemes are very extensive, such as modeling specifications based on IFC standards[25] and semantic information management based on classification scheme encoding[26]. However, the IFC classification and classification scheme were developed based on the AEC project and are not always so accurate for CH applications. Therefore, more and more research has begun to focus on the development of architectural heritage ontology for HBIM purposes. The earliest complete ontology for CH is CIDOC-CRM, which became the reference standard of ISO in 2006. Although there is a relatively complete ontology for CH, its classification scheme has not stopped developing, but there have been some new discussions in recent years. Parisi P, Lo Turco M, and Giovannini E C.[27] have developed an information organization framework based on existing ontological systems such as CIDOC-CRM (including CRMba, CRMGeo, etc.), which facilitates the linkage between BIM models and external databases. This initiative aims to foster the integration of disparate computational methodologies, addressing the semantic limitations inherent in BIM systems within the field of CH, thereby enhancing the efficacy of BIM applications in the conservation and management of CH. Further, Previtali M, Brumana R, Stanga C, et al.[28] developed a basic ontology of architectural heritage and an accurate ontology of vault system based on it.

A noteworthy point is that the semantic classification of CH remains to be further explored: currently, there is still no single and complete classification system covering all disciplines for CH conservation that is universally applicable to all CH.

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[23] Santoni A, Martín-Talaverano R, Quattrini R, et al. HBIM approach to implement the historical and constructive knowledge. The case of the Real Colegiata of San Isidoro (León, Spain)[J]. Virtual Archaeology Review, 2021, 12(24): 49-65.

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[25] Moreira A, Quattrini R, Maggiolo G, et al. HBIM methodology as a bridge between Italy and Argentina[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2018, 42: 715-722.

[26] Malinverni E S, Mariano F, Di Stefano F, et al. Modelling in hbim to document materials decay by a thematic mapping to manage the cultural heritage: The case of "chiesa della pietà" in fermo[J]. The international archives of the photogrammetry, remote sensing and spatial information sciences, 2019, 42: 777-784.

[27] Parisi P, Lo Turco M, Giovannini E C. The value of knowledge through H-BIM models: historic documentation with a semantic approach[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2019, 42: 581-588.

[28] Previtali M, Brumana R, Stanga C, et al. An ontology-based representation of vaulted system for HBIM[J]. Applied Sciences, 2020, 10(4): 1377.

Thanks to the rich common languages and frameworks provided by IFC and classification schemes, it has become much easier to integrate HBIM with other software tools and platforms. In the field of CH, GIS is often closely integrated with HBIM. Tsilimantou E et al.[29] proposed a systematic 2D/3D management framework to develop GIS thematic maps and HBIM. Similarly, external databases are also a data management solution. Adami A et al. discussed the establishment and the connection of an external database with HBIM when designing the system framework of HBIM. Subsequently, Bruno N and Roncella R.[14] optimized the structure of the external database and linked it with HBIM, ontology languages and other systems.

BIM-based informative solutions have been essential for documenting and analyzing historic sites and buildings in recent years, as they change the methodological approach of these steps. Cloud-bim platforms enhance data transparency and accessibility, not only for IFC files and related building SMART standards, but also for external semantic data linked to objects. Fassi et al.[30] developed a web-based system called BIM3DSG in 2016, which archives and manages all the information about the Milan Cathedral.

These HBIM platforms are either non-open-source or designed for a specific CH project, making them hard to apply to other CH projects. Therefore, the Polytechnic of Turin and Sapienza University of Rome conducted a conservation project of Domus Regia, Sacraria Martis et Opis, and tried to manage CH information through an open source BIM platform and verify its effectiveness. Diara F, Cavallero F.[31] used FreeCAD version(FOSS) to manage the data of the Domus Regia and then evaluated and shared HBIM models with BIMData cloud platform. They also tested the models in another environment specially developed for archaeological purposes. Meanwhile, Diara F, Rinaudo F[32]. developed a customized cloud-based HBIM platform, ARK-BIM, based on Cloud-BIM Solutions and BIM Data open source platform in 2021, which is more suitable for archaeological documents.

In addition to the exploration of HBIM, there are also some interesting extended topics and applications. Mol A, Cabaleiro M, Sousa H S, et al.[33] studied how HBIM can record the decay and damage of the timber roof of the Guimarães Castle. They compared the point cloud data, model data, and damaged orthogonal images from two periods, along with the data from non-destructive testing technology. (2014 vs. 2019) This method offers a useful template for monitoring data analysis and preventive conservation, but it also requires a lot of survey data(NDT data and point-cloud,etc.) and modeling time, which may not be very cost-effective. Khan M S, Khan M, Bughio M, et al.[34] examined the possibility of integrating HBIM and other technologies in CH facility management. Mora R, Sánchez-Aparicio L J, Maté-González M Á, et al.[35] suggested a comprehensive workflow for preventive conservation. They not only proposed information storage specifications, but also combined daily monitoring system data and other heritage information into a single web platform.

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[29] Tsilimantou E, Delegou E T, Nikitakos I A, et al. GIS and BIM as integrated digital environments for modeling and monitoring of historic buildings[J]. Applied Sciences, 2020, 10(3): 1078.

[30] Rechichi F, Mandelli A, Achille C, et al. Sharing high-resolution models and information on web: the web module of BIM3DSG system[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2016, 41: 703-710.

[31] Diara F, Cavallero F. From excavation data to HBIM environment and cloud sharing: the case study of Domus Regia, Sacraria Martis et Opis (Roman Forum, Rome-Italy)[J]. INTERNATIONAL ARCHIVES OF THE PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES, 2021, 46: 207-213.

[32] Diara F, Rinaudo F. ARK-BIM: Open-source cloud-based HBIM platform for archaeology[J]. Applied Sciences, 2021, 11(18): 8770.

[33] Mol A, Cabaleiro M, Sousa H S, et al. HBIM for storing life-cycle data regarding decay and damage in existing timber structures[J]. Automation in Construction, 2020, 117: 103262.

[34] Khan M S, Khan M, Bughio M, et al. An integrated hbim framework for the management of heritage buildings[J]. Buildings, 2022, 12(7): 964.

[35] Mora R, Sánchez-Aparicio L J, Maté-González M Á, et al. An historical building information modelling approach for the preventive conservation of historical constructions: Application to the Historical Library of Salamanca[J]. Automation in Construction, 2021, 121: 103449.

Current academic research on HBIM mainly focuses on point cloud acquisition, parametric modeling and other fields, while archive management is less studied. However, this field is not simple or unimportant. Based on these documents, the current challenges of HBIMD include: 1. The difficulty of querying and retrieving large amounts of HBIM data. 2. The complexity of establishing archives with sufficient depth and breadth. 3. The balance of semantic information and geometric information richness. 4. The lack of paradigm and standardization for archives establishment due to the uniqueness of heritage projects. 5. The poor interoperability between different fields and the difficulty of project management.

1.4 Research significance

1.4.1 Significance of HBIMD

CH encompasses a diverse array of information categories, including material ontology, related documentation, and extensive records. These elements are pivotal in ascertaining the veracity of CH. Sustainable, precise, and comprehensive documentation is instrumental in delineating and articulating the historical nuances of CH, as well as chronicling its historical interventions and preservation efforts. A principal benefit of HBIM systems lies in their enhanced capability to comprehend and steward CH. Primarily, HBIM platforms are adept at documentation information across varied formats, facilitating the corroboration and validation of data accuracy. In this context, point cloud data serves as a crucial source of geometric information for three-dimensional metric documentation. The Heritage Building Information Modeling (HBIM) system is capable of efficiently managing the acquisition and modeling of these geometric details, as well as the association with their corresponding semantic information. This not only facilitates the quantitative assessment of geometric precision but also enables the automation of the modeling process and the systematic linkage of semantic information, thereby enhancing the accuracy and efficiency of data processing[36].

Additionally, HBIM proposes an archival classification schema, aiding personnel in the dissection and governance of unstructured data and metadata, thereby yielding heightened precision in information and insights into CH authenticity. A further advantage of HBIM is its provision of a temporal reference framework, ensuring that informational records possess chronological context, which safeguards the temporal integrity of CH documentation. Lastly, the dynamic nature of HBIMD furnishes an optimal platform for the ongoing update of data, encompassing routine inspections and asset management.

In essence, HBIMD signifies the digitization of exhaustive informational content. The digital stewardship of data mitigates the workload of staff members and meticulously logs each phase of CH-related endeavors. This systematic approach simplifies the audit of file management and personnel errors, while also fostering a more methodical approach to information retrieval. Such benefits substantially elevate operational efficiency and curtail the fiscal outlay associated with CH interventions, rendering conservation efforts more sustainable and cost-effective. The HBIM information management platform delivers a systematic framework and structure for the storage of information. It also affords a more streamlined methodology for data input, retrieval, and extraction. Moreover, it diminishes the magnitude and bulk of physical information storage, alongside the associated costs of data preservation and maintenance, both monetary and labor-related.

Interoperability is the main concern of researchers in BIM-based workflows, despite the various dimensions and applications of HBIM. The industry foundation class (IFC) is a solution to the interoperability issue.[37]. IFC is an open and neutral standard that enables interoperability and

[36] Lorenzo T L, Diara F, Spadaro A, et al. From 3D Metric Survey To Hbim Model. Testing Of Different Scan2Bim Approaches For The Archaeological Documentation[J]. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2024, 48(2): 437-444.

[37] Sharafat A, Khan M S, Latif K, et al. BIM-based tunnel information modeling framework for visualization, management, and simulation of drill-and-blast tunneling projects[J]. Journal of Computing in Civil Engineering, 2021, 35(2): 04020068.

integration of information from different sources in BIM in a well-structured way. It allows the project to exchange 3D object data, including information, regardless of the software used by the project team. Based on the IFC standard, HBIM can link the data and records of the monitoring system of CH, which plays a huge role in asset management and preventive conservation of CH. Moreover, HBIM files can be applied to other software or platforms without losing information. For example, the application of web platforms can make the management of CH independent of a single software, and enable all stakeholders to participate in the CH program management.

In the gaming field, particularly in serious games, laser scanning and other metric survey technologies have garnered widespread attention for digital replication of real-world scenes. These technologies not only reduce the workload of game scene modeling but also significantly enhance the detail and realism of the scenes. Researchers such as Tschirschwitz F, Büyüksalih G, Kersten T P,et al[38]. have elaborated on the process of acquiring point cloud data through laser scanning and conducting 3D modeling, which has led to the development of virtual reality applications with strong interactivity and high immersion. Notably, the acquisition of point cloud data is not limited in architectural elements, which presents excellent prospects for collecting geometric and color information of various items, furnitures[39], and even human bodies[40].

1.4.2 Significance of optimizing HBIMD

HBIMD is the digitization of complex information from multiple disciplines and technologies, as described. It allows the optimization of the workflow and method of HBIMD, regardless of the discipline or technology breakthrough. The continuous iteration and optimization of HBIMD can reduce the skill requirements of operatives, improve the user's efficiency, and lower the cost of the program, thus providing more effective ways and strategies for CH protection. Therefore, it is very important to optimize the workflow and operation methods under the existing framework and specifications of HBIMD, combined with the current cutting-edge technology and theory, to improve the efficiency and value of HBIMD. Moreover, by proposing an association strategy that unifies semantic information and geometric information, and a simplified strategy for HBIMD, it can reduce the time cost and the difficulty of the documentation process and the operation of HBIMD. This provides a better foundation for the promotion and application of HBIMD.

After optimizing the workflow and modeling methods of HBIMD, and proposing a simplified strategy for HBIMD, the next step is to study the application and verification of the simplified model on the network platform. This way, the simplified model can be improved when needed, and the information can be modified and optimized through the website. This can enhance the flexibility of the simplified model.

1.5 Methodology

The scope of this research is the optimization method and extended application of the HBIMD for CH, as explained in chapter 1.2. The purpose is to try to propose solutions for the issues such as low operability, low efficiency, time consumption and the fusion between geometric and non-geometric information. The approach adopted for this research is Design Science Research (DSR). DSR focuses on solving practical problems with theoretical relevance and producing artefacts as an output[41]. The research was divided into five stages: identify the problem, define objectives, design the solution,

[38] Tschirschwitz F, Büyüksalih G, Kersten T P, et al. Virtualising an Ottoman Fortress–Laser scanning and 3D modelling for the development of an interactive, immersive virtual reality application[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2019, 42: 723-729.
[39] Bagnolo V, Argiolas R, Cuccu S, et al. Beyond HBIM: serious games and procedural modelling for heritage dissemination[J]. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2021, 46(4): 55-60.
[40] Parrilla E, Ballester A, Uriel J, et al. Capture and Automatic Production of Digital Humans in Real Motion with a Temporal 3D Scanner[J]. 2024.
[41] Holmström J, Ketokivi M, Hameri A P. Bridging practice and theory: A design science approach[J]. Decision sciences, 2009, 40(1): 65-87.

implement the solution and evaluate the solution, following the methodology proposed by Peffers, Tuunanen, Rothenberger, & Chatterjee[42]. **Figure 2** shows the research design adopted, which is iterative in nature.

(1) Identify the problem: The state of the art on HBIMD and implementation was studied, and the workflow, executable methods, relevant laws and regulations in HBIMD were summarized. These parts served as the basic framework of the research. Then the open issues and challenges in HBIMD were identified, including but not limited to workflow complexity, high cost, low interoperability, etc. Moreover, issues in specific fields, such as CH operation and maintenance, asset management, were also focused.

(2) Define objectives: Based on the summary of the problems, the causes of these problems were analyzed and categorized into the following aspects: workflow, modeling strategies, management methods, cross-domain applications, etc. Then the specific research objectives were defined.

(3) Design solution: Based on the workflow, operative methods, laws and regulations, etc in the literature review, the framework of HBIMD was established to provide guidance and prototype basis for the overall research progress.

(4) Implement solution: The north wing of castle valentino was selected as the case study for the implementation and application of the solution. The time of documentation was recorded to measure the efficiency of workflow optimization and model simplification. The feasibility of the HBIM file in the new model was tested when the model was deepened in the future to ensure the modifiability of the simplified model. The feasibility of applying optimized HBIMD on the FOSS platform was also implemented and tested, and the performance and accuracy of the deepened model compared to the simplified model were evaluated to ensure the sustainability of the simplified model.

(5) Evaluate solution: The feasibility, efficiency, and shortcomings of the solution were summarized and evaluated to ensure the sustainability and general applicability of the research.

[42] Peffers K, Tuunanen T, Rothenberger M A, et al. A design science research methodology for information systems research[J]. Journal of management information systems, 2007, 24(3): 45-77.

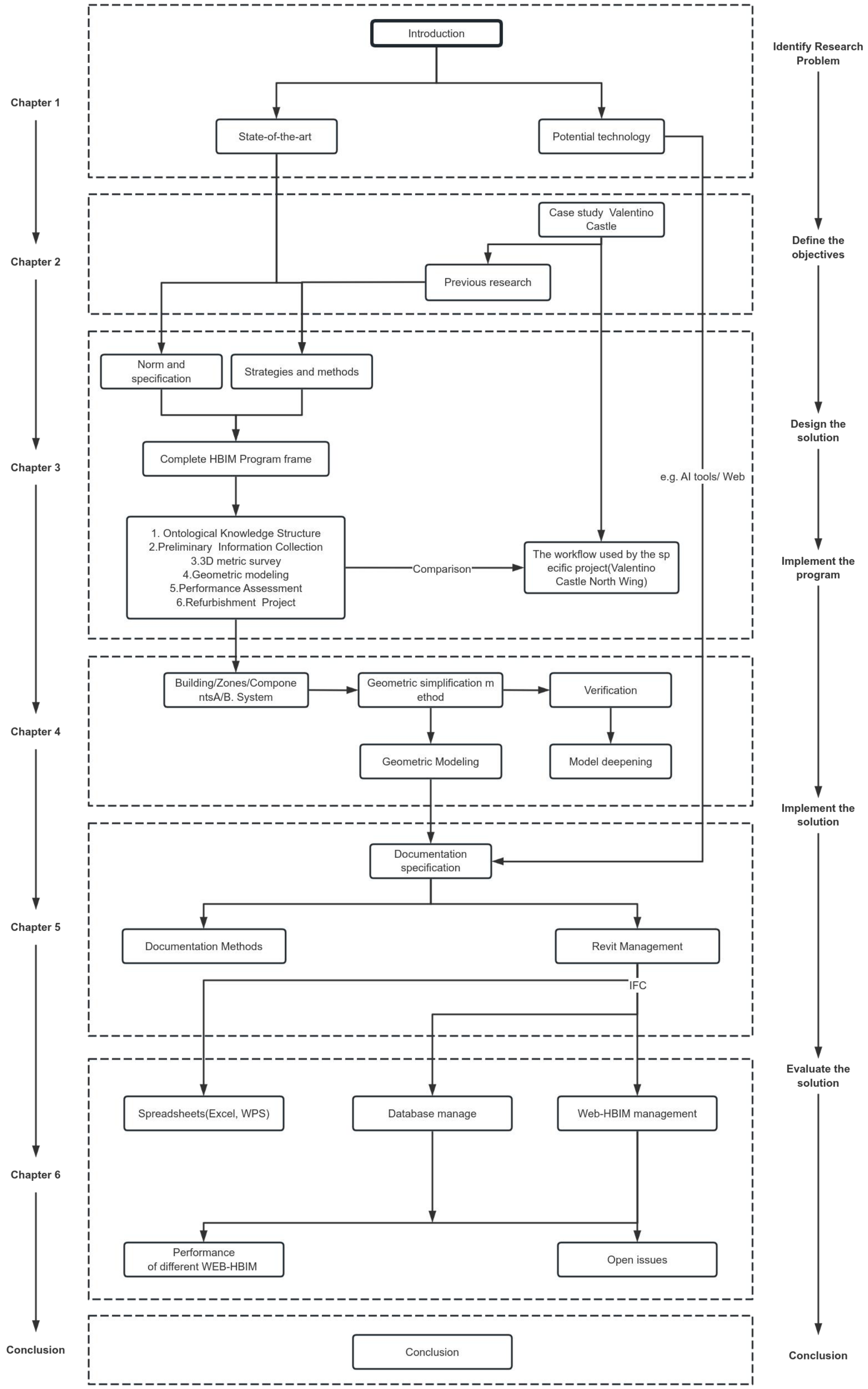

Figure 2 Research framework

Chpater 2 Case study: Valentino Castle

Studying and analysing heritage requires multi-disciplinary collaboration: experts and specialists from different fields share and interpret complex information and data about a heritage asset to understand its value and significance. Poor information (inaccurate, incomplete or uncoordinated) can lead to errors, which can harm the historic asset, its value and significance. Therefore, before developing the project plan, it is necessary to establish a basic understanding and cognitive framework of the target CH. The CH of this study is the Valentino Castle in Turin. It is not only the Faculty of Architecture of the Politecnico di Torino, but also a World Heritage Site: it has been on the UNESCO World Heritage List since 1997, as part of the "Le Residenze sabaude" (The Savoy residences) serial site[43].

Figure 3 Valentino Castle(Source: Bei Bao)

The description of the Castle will consist of three parts: The first part will present the historical chronology of Valentino Castle, aiming to understand the historical development of the castle, and to establish the time dimension of the project plan (historical events, historical intervention, degradation of materials, etc.). This will also help to comprehend the relationship between the specific object of research and the whole castle. The second part will conduct preliminary historical research on the target site and object, in order to define the research scope and depth. The third part will review the previous HBIM-related research on Valentino Castle, since this project is not the first of its kind. This will help to determine the purpose and scope of the research, and to utilize the previous research results (point cloud data in different periods, decay mapping, etc.).

2.1 Brief history of Valentino Castle

Valentino Castle is a famous Italian CH and the campus of the Department of Architecture and Design of Politecnico di Torino. It has a rich and complex history that involves different aspects, such as historical evolution, stylistic changes, decay and intervention, etc. To better understand the relationship between these aspects, chronology is a useful tool. Therefore, the historical summary of Valentino Castle will be presented in a timeline[44] (**Figure 4**).

[43] Decision 21 COM VIII.C Inscription: Residences of the Royal House of Savoy (Italy)

[44] Castello del Valentino. Faculty of Architecture Projects compared, edited by Sisto Giriodi, Lorenzo Mamino, Turin, Celid, 1988 and Il Castello del Valentino, edited by Costanza Roggero, Annalisa Dameri, Turin, Allemandi, 2007]

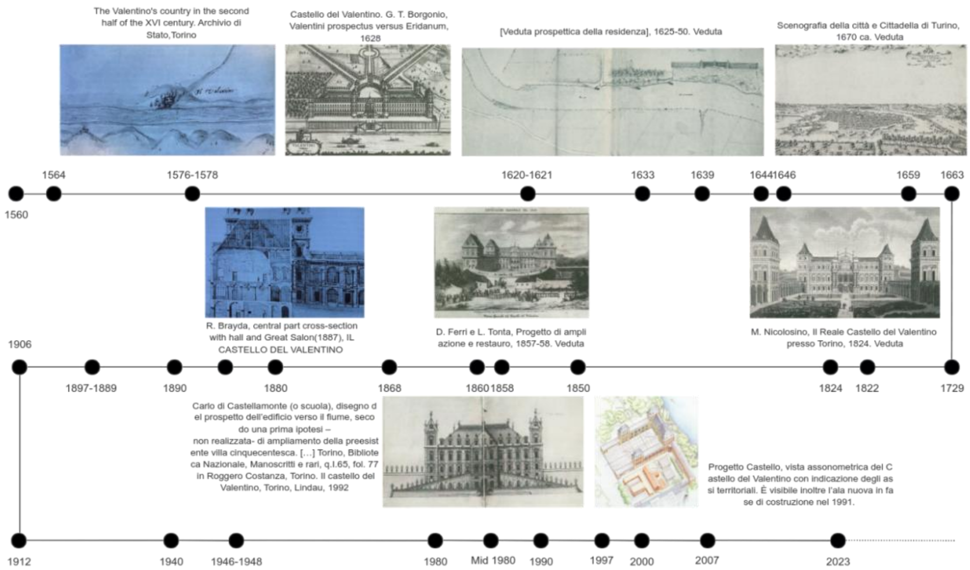

Figure 4 Timeline of Castle Valentino that includes part of the archival documentation collected during the research

In 1564, Emanuele Filiberto bought a riverside villa in the "Vallantinum" area from Renato Birago. This villa was the origin of Valentino Castle. From 1576 to 1578, the first major renovation of the villa occurred. The structure and layout of the building stayed largely the same: the villa extended along a single wing parallel to the Po river. A watchtower stood at the south end of the wing, while the north end had reception rooms, such as the decorated hall (now the Sala delle Colonne) and the Sala del Pallamaglio, located in a protruding part. Between 1620 and 1621, Christina the Princess and her husband Vittorio Amedeo Emanuele I requested the transformation of the riverside palace into a maison de plaisance. Carlo di Castellamonte's project added important extensions to the castle in the sixteenth century and gave it the actual architectural shape of the royal residence. The original project planned a building with a wing twice as large as the existing one at the time, parallel to the Po river, and bounded by two towers with a pavilion roof. Although it was never built, it set the basis for the later work.

In the new project, the square Cortile d'Onore became the center of the whole complex, along with the loggia, the staircase and the double-height Hall of Honor above the current hall of columns. They built the expansion of the factory symmetrically around this focal point. Square halls connected to each other were built adjacent to the main core of the building, following a modular principle. The wing parallel to the river was extended, the tower to the south of it was integrated into a larger structure and a new tower was erected to the north. They also built a new gabled roof in *lose*. Around 1633, they started building the Arcade Gallery. Sadly, the war in 1639 severely damaged the building, and they only finished the reconstruction work gradually by 1644. During this period of intervention, they built two arcades and two front towers. At the same time, they completed the interior design work for the south-facing and north-facing apartments. In the next two years (1645-1646), they connected the two pavilions facing the city of Turin by exedra semicircular terraced porticoes, which formed a large courtyard of the Grand Cortile d'Onore, described as en forme de théâtre. Amedeo di Castellamonte mainly led the whole project.

Starting from 1659, the Turin-facing façade underwent a year-long renovation after a decade, which involved building a series of false windows to reduce the effect of the steep roof slope. In 1663, Christina of France died, and the Valentino stopped being a ducal residence, giving its function to the Venaria Reale. For this reason, it did not receive any intervention except for maintenance until the end of the 17th century. Over time, the lack of a specific department to plan its function caused some problems with the use of the building. The first solution, proposed in 1729, was to use the northeast garden of the IL SALONE D'ONORE as the botanical garden of the Royal University. However, legal reasons delayed the functional changes of the building for 70 years. In fact, in that year, the then French government named the palace “National House” and assigned it to the Faculty of Veterinary Medicine, which stayed here until the Palais Valentino returned to the royal family. At the time of the reacquisition, the building had serious problems of static instability in the system of galleries, porticoes and the hemicycle. Therefore, in 1822, the Royal ordered the demolition of the semicircular system and, the next year, asked for its reconstruction on the same site in the same style, allowing the use of different but similar materials from the original.

Starting in 1824, the Valentino Palace became the barracks of the Compagnia del Genio Pontieri, which stayed there until 1850 when the state property acquired the Royal estate. In 1859, the Palace turned into an applied school for engineers and, thanks to the Casati Law, the “Regio Politecnico” in 1906. Moreover, the Valentino area hosted several exhibitions of industrial products from the beginning of the 19th century, the sixth of which occurred in 1857-1858. During this period, they also replaced the word “palace” with the word “castle”. In 1862, they made some changes to the layout of the castle: they switched and moved the main entrance from the front facing the Po river to the front facing the city. They demolished the semicircular building and built two terraced buildings in its place as extensions of the north and south wings, connected by iron gates.

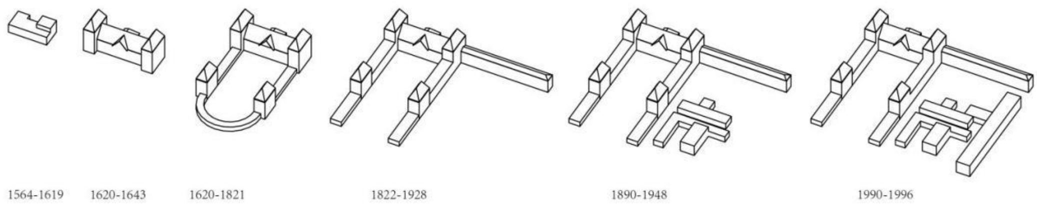

Figure 5 Chronological development of Castle Valentino
(The phases shown in the figure will be defined into the phases of HBIM)

From 1868 to 1880, they built a new wing named Manica Chevalley parallel to the Po, which they later integrated into the original structure of the castle. Then, from 1897 to 1899, they built the Chevalley wing to the west, near the entrance. After giving the castle spaces to the Polytechnic of Turin, founded in 1906, they renovated them to fit new functions: they built the mechanical workshop (1912-1913) and new classrooms (1946-1948). They also consolidated the structure, restored the decorations and facilities at the same time. In the mid-1980s, they started a series of renovations and maintenance on the Valentino castle. A project called “Progetto Castello”, initiated by the Politecnico di Torino, created new spaces for teaching activities and conservatively restored the monument. The restoration project ended in 2007 because of the huge size and scale of the building. In 1997, it became one of the UNESCO World Heritage Sites as one of the Savoy residences.

The castle has served multiple functions and undergone many changes over the years, making the Castello del Valentino a complex and intricate architecture. The Polytecnico di Torino, which owns the castle, divides it into four areas. Area A is the main body of the castle, with the Hall of Honor, the two main towers, the north and south towers, and the 19th century wings. Area B is the Chevalley wing along the Po River, and Area C is the Aloisio block built in 1890, which is the school's public service area. Area D is the new wing on the south side. The University of Turin also has the Botanical Garden on the north side of the castle.

2.2 Target site: North wing

The present study delineates the architectural features and historical significance of the northern wing of Valentino Castle. This section comprises the 19th-century annex situated between the principal and frontal towers, encompassing two levels above ground and a subterranean basement. Additionally, the frontal tower to the north, which includes two stories and an attic, and the terraced edifices at the extremity of the frontal tower, are integral components of this wing. The internal space of the northern tower primarily facilitates movement, equipped with contemporary staircases and elevators. The attic houses a wooden truss system beneath a pronouncedly inclined roof, which underwent restoration and analysis in 2016 as part of a conservation initiative[45]. The ground level of the 19th-century extension serves educational and administrative purposes. The original partitioning on the first floor was supplanted by a series of compartments framed in metal. Above the second story, a sleeper truss system supports the roof, now covered with prefabricated metallic panels in lieu of traditional tiling. The wing's northern aspect adjoins the corresponding tower, while its southern flank merges with the main tower. The northwest terrace, repurposed as office space, extends to form an external terrace at the first-floor level of the northern tower. The above-ground segments of the north wing, including the interior walls and suspended ceilings, have been refurbished with fresh white plaster, contrasting with the unoccupied basement that retains its original brickwork. The wing's southern facade is predominantly clad in light yellow plaster, interspersed with concrete elements. The northern extremity of the wing abuts the University of Turin's Botanical Garden. In contrast to the southern facade, the northern exterior presents exposed brickwork. The external materials and structural integrity of the north wing are well-preserved, with the southern facade exhibiting minimal foundational damage. The fenestration elements show signs of wear. The condition of the northern facade is comparatively deteriorated, with evident brick loss and damage exacerbated by increased vegetation and humidity. The interior state of the ground, first, and second levels is satisfactory.

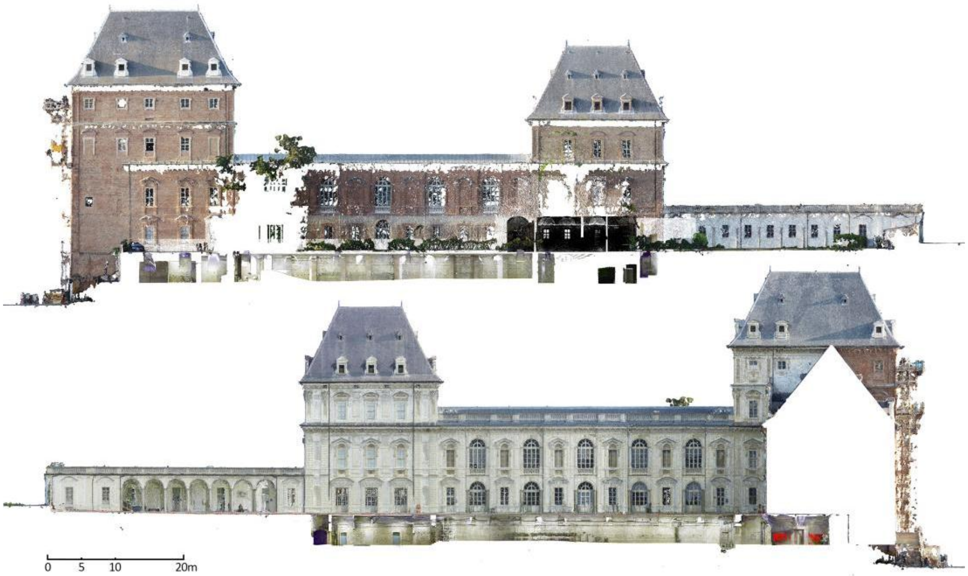

Figure 6 Othoimages of the north wing, exported from Point cloud (Above is the north facade, below is the south facade). The missing part of north facade is due to the vegetation

The interior of the north wing has undergone more alterations than the castle's primary eastern section, which retains much of its original decor and furnishings. While the majority of scholarly attention has been directed towards the main body of the castle, the north wing constitutes a significant segment of the Valentino Castle's heritage. Research pertaining to the north wing is extensive yet dispersed, necessitating consolidation. Given its current utilization as academic and administrative space, the north wing houses a plethora of intricate documents related to internal management. These records encompass asset management details and information on institutional activities and pedagogical logistics. Such documentation, derived from diverse sources, is invaluable for assessing the efficacy of the proposed Heritage Building Information Modeling Documentation (HBIMD).

[45] Bertolini-Cestari C, Invernizzi S, Marzi T, et al. Numerical survey, analysis and assessment of past interventions on historical timber structures: the roof of valentino castle[J]. Wiadomości Konserwatorskie, 2016 (45): 87-97.

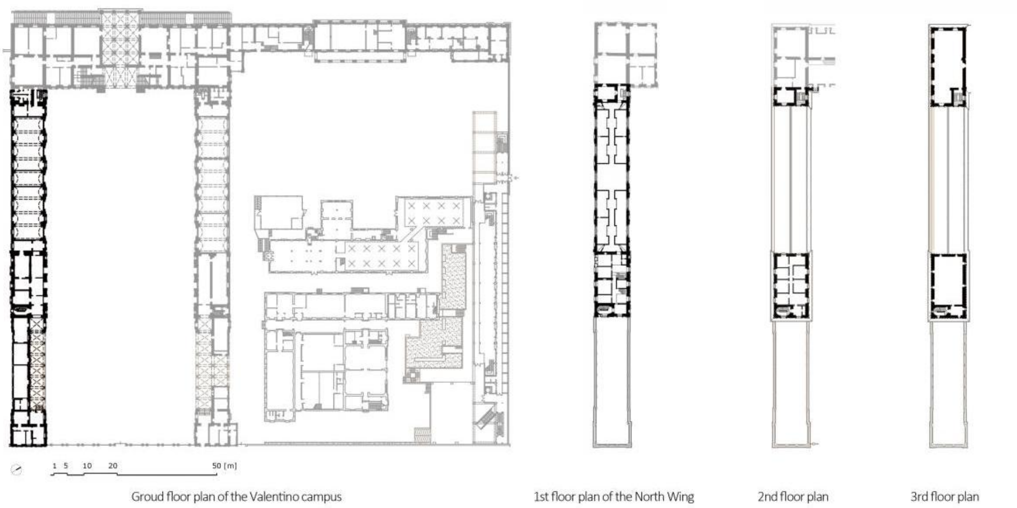

Figure 7 Ground floor plan of the Valentino campus, and 1st, 2nd, 3rd floor plans(North wing).

2.3 Previous researches and results

The Castle of Valentino is the campus of the Faculty of Architecture and Design of the Politecnico di Torino. It offers a unique case for students and professors of architecture. As a result, there has been considerable research and surveys in the past decades, which provide a solid foundation and a large number of original databases for this study.

This historic building has been undergoing a series of researches and renovations since the mid-1980s, in a project called "Progetto Castello". The Politecnico di Torino initiated this project, which aims to create new teaching spaces and preserve and restore the CH. They have collected and preserved a large amount of historical data in various drawings and texts during this period, and many data about the castle of Valentino come from this period. In the academic year 2005-2006, prof. Grazia Tucci and tutor Valentina Bonora[46] led about 60 students in Topography/Survey and Survey Methods/Survey Automation courses. They surveyed the facades and plan of the Valentino Castle, and measured and investigated the interior Frescos, such as the ortophoto of the vault. They proposed to carry out this work on a dedicated website, which can be the first project on the web platform's information management of Castle Valentino. In 2012, Costamagna E and Spanò A[47] proposed to adopt open standards and languages in the information documentation of Castle Valentino, and transform the GIS practice into a set of open standards and frameworks. They tested a framework for standardizing 3D metrology survey archives. They also suggested the potential of BIM application in Valentino Castle at the end of the thesis.

In 2015, Raineri P.[48] made an early proposal for creating the HBIMD of Valentino Castle. He proposed detailed methods for acquiring information and building models for HBIM files. But this proposal focused more on the geometric information of Valentino Castle, and less on the standards and methods of HBIMD. In 2016, Chiabrando F, Sammartano G, and Spanò A.[49] proposed a more specific

[46] Tucci G, Bonora V. Teaching geomaTics[C]//Atti, XXII CIPA Symposium, KIOTO. 2009.

[47] Chiabrando F, Sammartano G, Spanò A. Historical buildings models and their handling via 3D survey: From points clouds to user-oriented HBIM[J]. the international archives of the photogrammetry, remote sensing and spatial information sciences, 2016, 41: 633-640.

[48] L'APPROCCIO BIM (BUILDING INFORMATION MODELING) PER LA DOCUMENTAZIONE DELL'ARCHITETTURA STORICA : UNA PROPOSTA APPLICATIVA AL CASTELLO DEL VALENTINO

[49] Chiabrando F, Sammartano G, Spanò A. Historical buildings models and their handling via 3D survey: From points clouds to user-oriented HBIM[J]. the international archives of the photogrammetry, remote sensing and spatial information sciences, 2016, 41: 633-640.

method - building a comprehensive HBIM file management based on 3D survey (aerial and terrestrial photogrammetry, LiDAR and their integration). They proposed the methods of point clouds, and different manual and semi-automatic modeling methods for geometric models. From September 29th to October 5th, 2016, they did a new HBIM test on the courtyard of the Valentino Castle, to compare LoD and graphic detail (GraDe) with point cloud survey. For documentation, they linked information such as original drawings, historical papers, etc. to the BIM model through the URL database. And for sharing 3D models, they proposed a website called SketchtFab. It has a 3D model viewer based on the WebGL technology that can display 3D models on any mobile, desktop webpage or VR headset. But the website only allows the upload of textured mesh models using OBJ format. So it was not possible to upload the point clouds or the enriched Revit model.[50]

In 2018, the Politecnico di Torino held a workshop to help the blind touch and appreciate the Valentino Castle[51]. The professor and students talked about how blind people experience CH, and made 3D models and relief drawings for them. They also explored other ways to enhance blind people's perception. This work mentioned the role of HBIM in simplifying geometric models. It also gave a new idea for HBIM archives management - a CH management model for the blind and other special groups. In 2019, Gasbarri P. suggested a method to create an accessible web platform using GIS system and BIM modeling. The platform gathered information on the documentation, analysis and research done by Castello del Valentino for a long time, especially the information on the restorations done in the main floor of Castello del Valentino. The project aimed to make it easier to manage and access the data for planning future restoration works for the building. In 2021, Adamopoulos E, Colombero C, Comina C, and others provided a lot of photographic information on the current state of Valentino Castle by combining multiband photogrammetry, scanning and GPR for the facade survey of Valentino Castle. In 2023, Tanduo B, Teppati Lose L, Chiabrando F[52] tested the point cloud technology of Mobile Mapping Systems (MMSs) for the basement part of Valentino Castle. This added to the Valentino basement section, which also had the basement of the North Wing, and gave information on this part for the next management of the HBIMD.

These published studies show that the HBIM research on Valentino Castle is very thorough. But these studies mainly focus on the acquisition of point clouds or high-precision modeling, and not much on the application of HBIM in castle documentation. Also, because of software updates and management optimization, there is no summary and verification of past research.

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[50] Chiabrando F, Lo Turco M, Santagati C. Digital invasions: from point clouds to historical building object modeling (H-BOM) of a Unesco WHL site[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2017, 42: 171-178.
[51] Cristina A M, Annalisa D, Angela L, et al. Seeing Valentino Castle through the Hands: Heritage Building Accessibility for Visitors with Visual Impairments[J]. Modern Environmental Science and Engineering, 2018: 755.
[52] Tanduo B, Teppati Losè L, Chiabrando F. Documentation of Complex Environments in CH Sites. a Slam-Based Survey in the Castello del Valentino Basement[J]. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2023, 48: 489-496.

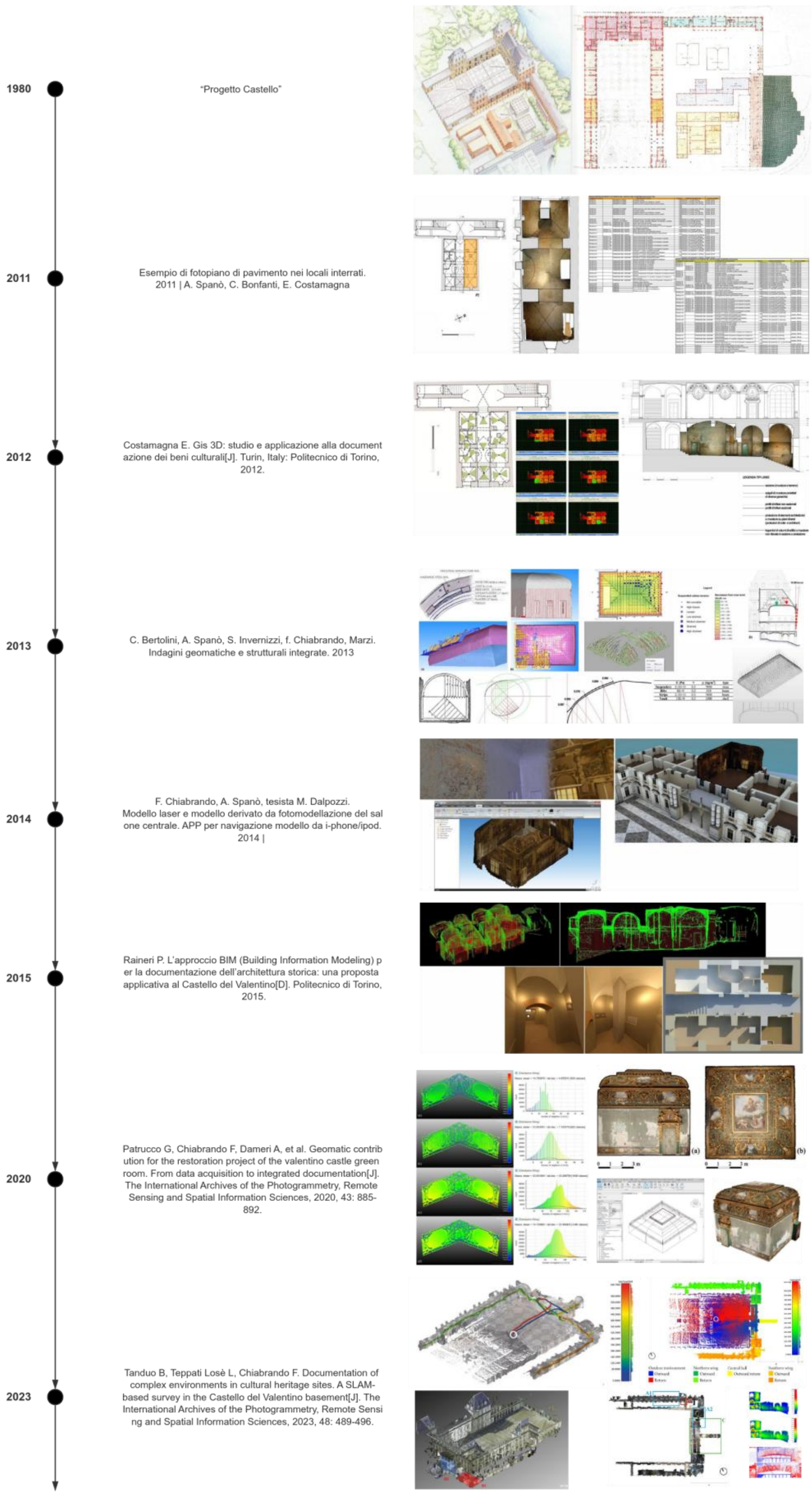

Figure 8 A timeline of some existing research results and achievements.(Some images and research information come from the Castello del Valentino website: https://castellodelvalentino.polito.it/?page_id=2337)

Chpater 3 Documentation-oriented HBIM workflow

Every HBIM project requires a well-defined framework as part of its strategic plan. In the context of CH, HBIM projects typically commence at a mid-point in the asset's life cycle[53]. This implies that the project framework necessitates not only the planning of CH restoration or protection projects but also the gathering and analysis of various historical information on CH to enhance understanding. It further requires a standard for each operation and execution of the project to avoid errors. Presently, numerous systematic scan-to-BIM frameworks have been proposed, which establish the strategic plan at the project's inception in great detail. However, unlike these conventional scan-to-BIM workflows, a documentation-oriented HBIM workflow does not concentrate on a specific conservation project. Therefore, it may not rely on high-quality point cloud acquisition or precise 3D modeling, but instead requires a methodology and standard for managing diverse information, as well as flexibility or compatibility for various potential projects.

The project established a documentation-oriented HBIM workflow for the north wing of the Valentino Castle, utilizing existing Scan-to-BIM frameworks. It defined the scope, depth, and method for preserving the current information of the North Wing Project. This chapter primarily discusses the framework and is divided into three parts. The first part addresses the various rules, laws, and standards required in the CH context. The second part involves the creation and explanation of the systematic scan-to-BIM workflow. This section aims to compare the scan-to-BIM workflow with the documentation-oriented workflow, and to better organize historical information (i.e., many past projects may have used the scan-to-BIM framework, so creating a comprehensive Scan-to-BIM framework can more effectively summarize this information). The third part entails the development of a complete documentation-oriented HBIM workflow, based on the second part.

3.1 Specification and protocols

3.1.1 UNESCO provisions for world heritage properties

Valentino Castle, recognized as a World Heritage Site within the Savoy Residence, adheres to certain protection and preservation rules typically established by UNESCO. The 1972 Convention on the Protection of Culture and World Heritage, serving as the organization's foundation, does not dictate the format or specific content of such a document. The methodology for report writing is left to the discretion of each Member Country. Consequently, the institution depends on other entities, such as the International Council on Monuments and Sites (ICOMOS), for CH management and follows its guidelines in documenting asset information. In fact, ICOMOS, through the Principles for the Recording of Monuments, Groups of Buildings and Sites (1996), outlines the rationale for recording heritage-related information, the responsibilities associated with recording, planning for content inclusion, and procedures for handling and disseminating the collected data.

3.1.2 The Italian regulation on the documentation of restoration

In addition to adhering to international charters and regulations pertaining to CH, it is paramount that the documentation of Valentino Castle, whether traditional or in HBIM, aligns with Italian laws and regulations. Gasbarri P. categorizes the national laws related to the documentation of CH into three distinct groups[54]:

The first category is ‘Le Carte del restauro' (The Charters of Restoration). This charter originated from the proposal by Camillo Boito at the Fifth Italian Congress of Engineers and Architects in Rome in 1883.

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[53] BIM for Heritage,Developing a Historic Building Information Model. 3rd ed. Historic England. England: Historic England, 2017. ISBN:978-1848024878

[54] Gasbarri P. I RESTAURI DEL CASTELLO DEL VALENTINO: PROPOSTE PER LA RACCOLTA, LA GESTIONE E LA CONSULTAZIONE DEI DOCUMENTI D'ARCHIVIO SU MODELLI GRAFICI DIGITALI INFORMATI= THE RESTORATIONS OF THE VALENTINO CASTLE: PROPOSALS FOR THE COLLECTION, THE MANAGEMENT AND THE CONSULTATION OF ARCHIVE DOCUMENTS ON INFORMED DIGITAL GRAPHIC MODELS[D]. Politecnico di Torino, 2019.

Over more than a century of development, the Charters of Restoration have been continually enriched and refined. In summary, the chapter mandates that the documentation of restoration and interventions is compulsory, and that a cognitive phase must precede the documentation to conduct the necessary survey and research on the target. Furthermore, each survey and research activity itself also needs to be documented. Each intervention must be accompanied by a report that, where applicable, includes: ① archival, bibliographic, and graphic surveys, ② surveys and technical drawings with an adequate Level of Detail (LOD), ③ potential use and availability, ④ photographs, ⑤ diagnostic analysis, and ⑥ motivation and aim. Ultimately, the collected data must be digitally stored and managed.

The second category is 'Il Codice dei beni culturali e del paesaggio' (The Code of CH and Landscape). This Code serves as a crucial reference for professionals involved in the conservation, restoration, and enhancement of Italian heritage. Enacted through Legislative Decree No. 42 on January 22, 2004, it legally defines CH and governs the power dynamics between countries and regions in the protection and management of CH. Additionally, it establishes rules for content related to cultural assets. Notably, this Code also directly regulates archives management at the Italian legal level. It considers the archives and documentation themselves as 'Cultural Assets' and stipulates provisions for their consultation and confidentiality protection in instances of inaccessible documents. However, it does not directly address the digitization of documents and data computerization.

The third category is 'Il Codice dei contratti pubblici, regolamenti e decreti ministeriali' (The Code of Public Contracts, Regulations, and Ministerial Decrees). In addition to the laws and regulations previously mentioned, this Code is significant as it governs procurement contracts within the public sector and between public and private entities. While the Code does not contain specific rules for compiling documentation for scientific reports on interventions and project reports, it does provide general provisions for the documentation required at each programmatic level of recovery interventions.

From the aforementioned laws and codes, it is evident that the rules and requirements for the documentation of CH have been well-established, and the necessity for digitization of documentation has been acknowledged.

3.1.3 Specification and protocols of HBIM

In a collaborative work process, often referred to as HBIM project management, the adoption of universally accepted standards and protocols is crucial. This ensures that the acquisition, management, and exchange of information adhere to strict discipline and limitations, thereby eliminating ambiguity and error. These standards and protocols encompass various aspects: project management standards, modeling methods, CAD standards, templates, metadata, and IFC specifications, among others. Structured according to the chronological order of the project, the HBIM project can be segmented into four key areas: workflow (which includes the specification and content of archives management), modeling, documentation, and data transfer and delivery.

Within the framework of ISO 19650, which pertains to the organization and digitization of building information, the BIM process comprises a series of documents that delineate requirements and model practices, which are equally applicable to built heritage. For the HBIM workflow, during the planning stage of this project, 'BIM for Heritage' and 'BIM for Heritage - Developing the Asset Information Model' presented by Historic England were primarily adopted. The former outlines the main content and workflow of HBIM, while the latter introduces the requirements of CH in asset management and organisational management. 'Metric Survey Specifications for CH', also published by Historic England, prescribes specifications for acquiring geometric information. The latest version of the 'AEC (UK) BIM Technology Protocol' (AEC (UK) 2015) aligns with the recommendations of PAS 1192-2:2013 (BSI 2013b) and offers comprehensive guidance for the development of BIM standards and procedures. The model of semantic information primarily focuses on the specifications and templates of the classification system. The consistent application of classification systems enables information about specific types of building components to be retrieved from large data sets and queried swiftly and efficiently. For instance, one of the principal roles of The Forum on Information Standards in Heritage (FISH) in the heritage sector is to foster interoperability and data exchange. One facet of this work involves the commissioning, maintenance, and development of a standardized vocabulary for departmental use. The vocabulary listed on the FISH terminology page spans from simple vocabularies to complex multi-level thesauri, and FISH collaborates with partners in the SENESCHAL project to provide primary vocabulary resources in the form of linked data. The standards and manuals considered are documented in HBIM in tabular form (**Table 1**) for future reference.

Existing method	Main used topics	Adopted content	Reference
AEC (UK) - BIM Protocol	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	AEC U K.[55]
COBIM	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)	Martinelli L, Calcerano F, Gigliarelli E.[56]
Singapore BIM Guide	Project implementation and collaboration	Specific for historic buildings and their model uses - general overview of an HBIM workflow (from data collection to management)	Kaneta T, Furusaka S, Tamura A, et al. [57]
BIM for Heritage	(BIM strategy, information delivery, commissioning, infrastructure)	Focus on technical aspects (model planning and organization, data acquisition, model strategies)	Antonopoulou S, Bryan P.[6]
BIMlegacy	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.)	Jordan-Palomar I, Tzortzopoulos P, García-Valldecabres J, et al.[58]
COTAC BIM4C	organization/workflow – conservation parameters –	More general approach – focus on technical aspects (model strategies)	Maxwell I. [59]
IFC protocol	Open international standard	The IFC format includes information about the geometry, materials, schedules, and quantities of building elements, as well as the spatial relationships between them.	Tang S, Shelden D R, Eastman C M, et al.[60]
Metric Survey Specifications for CH	Scan-to-BIM standard for pointcloud acquisition /CAD template	Management method of Point cloud	Bryan P, Blake B, Bedford J, et al.[7]
BIM for heritage-Developing the Asset Information Model	Technical aspects (model planning and organization, data acquisition, model strategies)	Strategic planning and preparative requirements	England H.

[55] AEC U K. AEC UK BIM Technology Protocol: Practical implementation of BIM for the UK Architectural[J]. Engineering and Construction (AEC) industry. London, 2015.
[56] Martinelli L, Calcerano F, Gigliarelli E. Methodology for an HBIM workflow focused on the representation of construction systems of built heritage[J]. Journal of Cultural Heritage, 2022, 55: 277-289.
[57] Overview of BIM implementation in Singapore and Japan[J]. Journal of Civil Engineering and Architecture, 2016, 10(12): 1305-1312.
[58] Jordan-Palomar I, Tzortzopoulos P, García-Valldecabres J, et al. Protocol to manage heritage-building interventions using heritage building information modelling (HBIM)[J]. Sustainability, 2018, 10(4): 908.
[59] Maxwell I. COTAC BIM4C integrating HBIM framework report[J]. COTAC: London, UK, 2016.
[60] Tang S, Shelden D R, Eastman C M, et al. BIM assisted Building Automation System information exchange using BACnet and IFC[J]. Automation in Construction, 2020, 110: 103049

Table 1 Specification and reference used in program(Restructed from Martinelli L, Calcerano F, Gigliarelli E.[56])

3.2 Complete HBIM Program frame

Numerous systematic and comprehensive HBIM frameworks based on Scan-to-BIM have been proposed[21,22]. For instance, the Diagnosis-Aided Historic Building Information Modeling and Management (DA-HBIMM) framework[61] was developed to address the challenges of intelligent knowledge acquisition, performance evaluation, and preventive conservation.

These frameworks share similar characteristics: they all commence with the establishment of a Common Data Environment (CDE), followed by the implementation of an accurate metric survey, point cloud processing, geometric modeling, and conclude with semantic enrichment. Consequently, they are ideally suited for conservation and restoration projects. The summarized systematic workflow is structured into the following phases:

Phase 1. Ontological Knowledge Structure: A program planning phase that illustrates the information management aspects and requirements of HBIM.

Phase 2. Preliminary Information Collection: Oriented towards integrating the gathered information into the HBIM model and using it to identify the building's construction systems.

Phase 3. 3D Metric Survey: Involves data acquisition and processing, and the design and implementation of geometric metric survey processes specifically for HBIM.

Phase 4. Geometric Modeling: Aimed at accurately conveying construction systems within model use.

Phase 5. Performance Assessment: A management phase of structural analysis and material analysis for daily inspection or preventive conservation.

Phase 6. Refurbishment Project: A phase for storing future interventions.

Phase 7. Deliverable: A special part for interoperability and exchange.

The establishment of a systematic workflow is essential. On one hand, the documentation-oriented HBIM workflow proposed in this project would be based on the systematic Scan-to-BIM framework. In essence, it is a simplification of the system Scan-to-BIM framework, which omits a precise metric survey and high-level geometric models, thereby enhancing HBIM management efficiency. On the other hand, a systematic HBIM framework can provide a common environment in a HBIM context to facilitate the summary and comparison of different previous projects.

[61] Bruno S, De Fino M, Fatiguso F. Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management[J]. Automation in Construction, 2018, 86: 256-276.

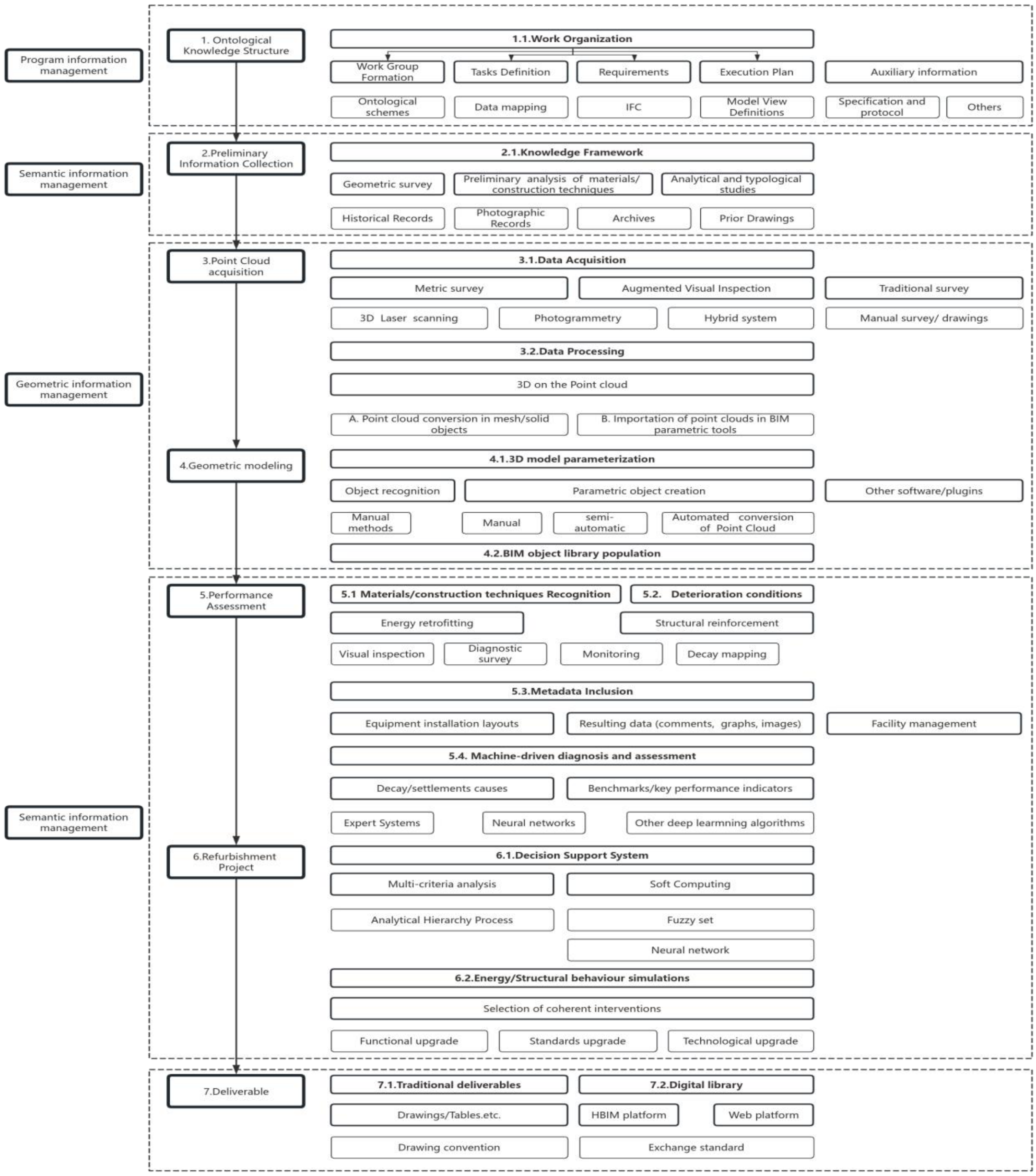


Figure 9 A complete frame paradigm adapted from Bruno S, De Fino M, Fatiguso F.[62]

3.2.1 Ontological Knowledge Structure and Preliminary Information Collection

The initial phase delineates the project preparation stage. Work organization encompasses professional tasks, and the establishment of competencies and responsibilities. During this stage, a comprehensive Building Execution Plan (BEP) should be specified and described to facilitate exchange and coordination within the data sharing environment. It defines the methods for generating and managing information, such as modeling strategy and data input. Concurrently, Organizational Information Requirements, Asset Information Requirements, and Program Information Requirements are considered the starting point to clarify project goals, contract conditions, and the organizational model. This aids in organizing the project team to achieve effective collaboration during the preliminary stage. The introduction of Level of Detail (LOD), Level of Information (LOI), and Level of Knowledge (LOK) serves as a quantitative standard to concretize the level of abstract semantic information. Well-defined specifications and protocols are viewed as constraints to eliminate inconsistencies and redundancies, and provide communication protocols. In the BEP, model planning also establishes a collaborative data sharing environment, known as the Common Data Environment (CDE). The CDE is a document repository used to collect, organize, and disseminate models and documents among the involved actors. It represents the agreed-upon source of information in the project and should guarantee the security, accessibility, traceability, and version history of all files. The complete BEP includes: 1. Time arrangement, 2. Roles and responsibilities, 3. Model use, 4. BIM tools, 5. Data formats and data exchange methods in CDE, 6. Naming conventions, 7. Coordination between established model alliance, and 8. Decomposition structure and information requirement level for each model element.

The second stage of the knowledge framework outlines a comprehensive information acquisition phase. Building Information Modeling (BIM) of existing or historic assets necessitates substantial initial information input. Organizational Information Requirements in HBIM projects should meticulously define the scope and deliverables of data collection activities, encompassing metric surveys, site surveys, desk-based assessments, and management of legacy information. For the procurement of Asset Information Model (AIM), Asset Information Requirements (AIRs) should specify how data and information are procured and integrated into the model (in accordance with PAS 1192-3:2014; BSI 2014b). The acquisition of comprehensive information serves not only to provide a robust information base for HBIMD but also to revise and iterate the project execution plan, with the objective of providing information for the detailed planning of a more systematic investigation. Moreover, the historical and architectural analysis includes field and desktop studies of bibliographic and archival documents, map and historical cartographic studies, and the study of similar and/or contemporaneous buildings, which collectively form a historically critical guide for subsequent analyses. All data collected and interpreted by experts should enable the tracing of the building's development.

3.2.2 Point Cloud acquisition（Metric survey）

The third phase outlines a comprehensive Scan-to-BIM approach. Geometric measurements form the primary basis for geometric modeling in HBIM and represent the most accurate source of geometric information about buildings, especially point clouds. Given that any model, irrespective of its complexity, is inherently a simplification, this phase, based on the Metric Survey Specifications for CH, describes the acquisition and pre-processing of point clouds using various techniques, as well as the supplementation of traditional surveys. Concurrently, during the HBIMD process, the point cloud data source, acquisition method, information of Point cloud accuracy, acquisition time, and pre-processing information should all be stored in the BIM platform in tabular form. This phase also includes an initial identification of decay interfaced with the metric data. Based on the results of the visual analysis, specific tests can be planned to investigate architectural aspects of the building or significant decay patterns. To select the optimal process, a clear scope of geometric measurement work should be established based on the model used, including the measurement list, measurement resolution, required accuracy, and file format of the deliverables. For instance, the acquired raw point cloud can be extracted (reducing file size) to a specified level of detail. The surveying operator can also perform measurements to varying degrees, such as measuring the interior (capturing decoration, defining spaces, and wall thicknesses) or, for the exterior alone, detailed measurements of overall dimensions and focusing on specific areas (e.g., including all windows and high belt of mold sequence). Furthermore, the entire point cloud file can be segmented into fixed file size parts, corresponding to the building parts.

3.3 Documentation-oriented workflow

Based on the comprehensive HBIM Scan-to-HBIM framework (see **3.2**), the following is the design of the documentation-oriented HBIM workflow:

Phase 1. Ontological Knowledge Structure: At this stage, the concept of "Ontological" is more focused on the philosophical domain, representing a specification of a "conceptualization," rather than the engineering artifacts defining vocabulary and language in the fields of computer science or artificial intelligence mentioned later in section 3.4.2, which includes "domain ontology" and "application ontology."[62] Hence, in this phase, in addition to obtaining Organizational Information Requirements (OIR), Asset Information Requirements (AIR), and Project Information Requirements (PIR) consistent with the Scan-to-BIM project, another focus is the standardization of information storage strategies for multi-platform and multidisciplinary groups. To satisfy this, a comprehensive information management strategy that combines the HBIM information management framework and CH ontology (CIDOC or IFC, etc.) needs to be proposed and used to standardize all aspects of information management, geometric modeling, and interoperability (see **3.3.2**).

Phase 2. Preliminary Information Collection: Unlike the Scan-to-BIM workflow, documentation-oriented information collection can be continuous, as it includes various types of architectural heritage-related information, such as historical geometric information (e.g., drawings, past point cloud scans, etc.), as well as past asset management information, facility management information, etc. (which may not be required in general Scan-to-BIM projects). Therefore, this stage needs to establish a standard information collection specification to clarify the collection method, information metadata, classification method, etc., in order to provide a rich semantic information for subsequent geometric information management (see **Chapter 4**).

Phase 3. Geometric Processing: Although an accurate metric survey is not always required for documentation-oriented HBIM, it is still advantageous to utilize existing point cloud or drawings and other modeling sources as much as possible. Therefore, a detailed analysis and processing of these geometric information sources is necessary. For existing point clouds, cleaning, registration, and fusion are essential. For past drawings or manuscripts, they need to be scanned, digitized, and converted into clear CAD files or PDFs. Furthermore, the metadata of these modeling sources and the operations performed in the preprocessing stage should be properly recorded to ensure that future workers can understand the credibility of the geometric model (see **Chapter 4**).

Phase 4. Geometric Modeling: In documentation-oriented HBIM, high geometric level and high-precision modeling are not the main goals, but rather the semantic information and its correct matching with three-dimensional objects. Therefore, this stage adopts a reasonable 3D simplification strategy to ensure the proper storage of semantic information while maintaining the modifiability of the geometric model. This stage is explained in detail in Chapter 5.

Phase 5. Semantic Information Enrichment: In the documentation of CH (especially in the HBIMD of the north wing of the Valentino Castle), the information involved can be categorized into four types: architectural information, heritage information, asset information, and project information. To effectively manage these complex and intertwined information, this stage specifies how different types of information are handled in the HBIM platform, which is elaborated in Chapter 6.

Phase 6. Interoperability: The types of information involved in documentation are very complex, as are the groups of stakeholders, experts, etc. This not only increases the difficulty and complexity of archiving projects but also poses challenges for accessing and updating information for different purposes. Therefore, in order to efficiently transfer information among different people and organizations without causing information loss and misunderstanding, possible methods and standards for information transfer and external management need to be formulated in advance, such as spreadsheet patterns, external databases, or network platform applications.

[62] Colucci E. Geospatial Ontology to support the Documentation of Minor Historical Centres[J]. 2022.

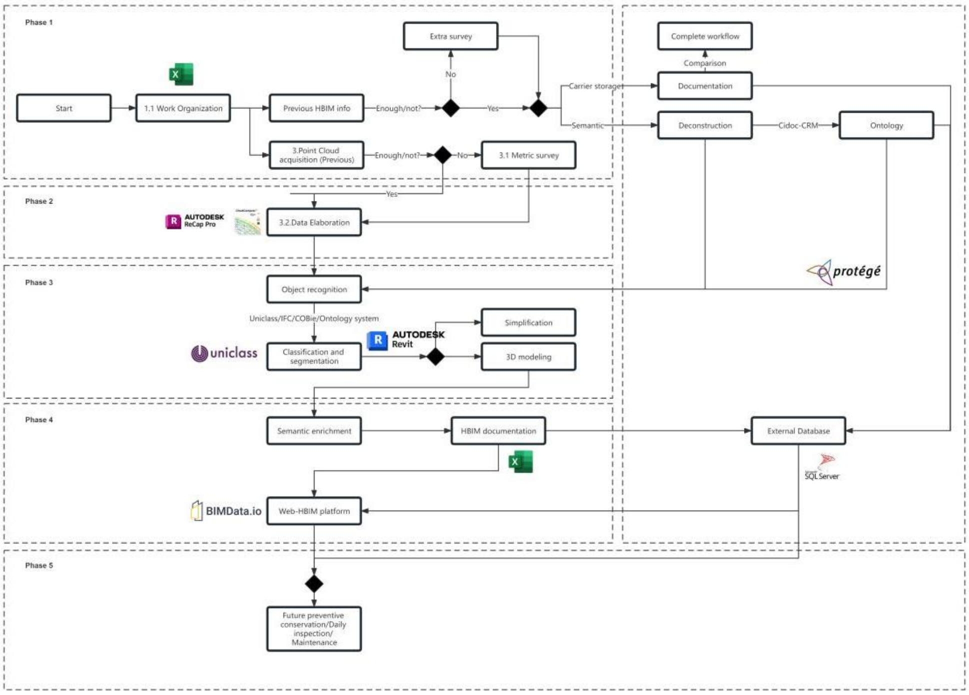


Figure 10 The HBIMD workflow in this project

Figure 10 illustrates the application method of this workflow and the management platforms and methods involved in it. **Table 2** shows the software used for different types of information to guide the steps in subsequent work.

Information Types		Delivery Team	
		Software agreed	**Version / Build**
Modeling	PointCloud	Autodesk Recap	2024
		CloudCompare	2.12
	2D model	Autodesk CAD	2024
	3D model	Autodesk Revit	2024
Analysis	Structural Analysis	PRO_SAP	Free Version
	Ontology	Protégé	5.6.3
	Material Analysis	WUFI	6.5.3
	Component simulation and building simulation	WUFI	6.5.3
Manage	Room data sheet	Microsoft Excel/WPS	2024
	Survey	Microsoft Excel/WPS/PDF	2024
	Animation file	Lumion	11
	Request for information	Microsoft Excel/WPS	2024
	Report	Microsoft Excel/WPS	2024
	Schedule of accommodation	Microsoft Excel/WPS	2024
	Schedule	Microsoft Excel/WPS	2024
	Snagging list	Microsoft Excel/WPS	2024
	Specification	Microsoft Excel/WPS	2024
	Bill of quantities	Microsoft Excel/WPS	2024
	Calculation	Microsoft Excel/WPS	2024
	Combined model	Autodesk Revit	2024

	Correspondence	What'sApp/Email	/
	Cost plan	Microsoft Excel/WPS	/
	Geographic information model	ArcGIS pro	2023
	Method statement	Microsoft Excel/WPS	2024
	Model renditions/Information exchange file/File note/Drawing rendition/Clash rendition/Health and safety/Programme	/	/
Expanded Application	Visualisation	/	/
	Web platform	BIMData/Dalux	/
	Database	Microsoft SQL server	2022

Table 2 Schedule of Software Use in HBIMD project(partial)

3.4 Information framework and ontology

HBIM provides a platform for the management of CH knowledge. However, the structure and interpretation of this knowledge require standardization. In other words, the documentation of architectural CH through HBIM cannot be separated from the establishment of a basic(the domain of which is CH) ontology. This ontology strengthens the alignment and matching of respective ontologies across different fields[63].

This plan proposes a dual-track information storage method for the documentation-oriented workflow. For information storage, the program designs a system that can accommodate both the HBIM structure and the structure of an external database. The HBIM system, based on the work of Bruno N and Roncella R[14], connects three-dimensional geometric models with external relational databases to interpret multidisciplinary data. Each object is assigned a unique identification code (ID) that links it to a specific BIM model, ensuring the connection between the 3D model and the database. Furthermore, the system structure will serve as the foundation for geometric simplification.

Additionally, the plan designs a universal basic ontology system for CH information, drawing on the work of Previtali M, Brumana R, Stanga C, et al[27]. This system can establish relationships between architectural entities, spaces, events, assets, and other CH information.

3.4.1 HBIM information System: Database Design, Surveying and Modeling Metadata

As outlined by Bruno N and Roncella R, a semantic classification system has been devised. This system organizes information related to architectural heritage, drawing on the performance requirements approach as detailed in UNI 10838:1999 and UNI 8290:1981. The system is structured into four levels: building, zones, architectural component A, and architectural component B.

Level 1. Building: This level encompasses the entire building and processes data related to it, such as archives containing comprehensive information like historical events, photographs, and details about past interventions and conservation projects.

Level 2. Zones: A building can be conceptualized as a collection of rooms and spaces. Thus, this level is utilized to describe parts of the building that possess unique characteristics or identifiable volumes. It can also be employed to detail the facilities, equipment, and assets within these rooms or spaces.

Level 3. Architectural Components A: This is a subclass of technical elements compatible with a representation scale of 1:100–1:50. It is used to describe building components and elements. HBIM can

[63] Karshenas S, Niknam M. Ontology-based building information modeling[M]//Computing in Civil Engineering (2013). 2013: 476-483.

also be viewed as a documentation-oriented model that targets levels of geometric modeling simplification (refer to section 5.1.2).

Level 4. Architectural Components B: This level pertains to architectural components and elements with higher modeling details (representation scale 1:20-1:10). It can be used for more refined component semantic segmentation, accounting for different materials, decay and damage, or providing more geometric information.

One of the key advantages of this classification is its ability to align geometric and semantic information in HBIM with the external database information structure, as each building element has a graphical representation in the 3D model and a corresponding description in the database. For each level, there are three main categories of associated data: investigation metadata, modeling metadata, and descriptive data. This is crucial because, while the documentation-oriented workflow does not depend on high-precision models, it does necessitate extensive data management and collection. As such, all actions and operations during any documentation process must be meticulously recorded and described to ensure users understand the quality, methods, instrumentation, accuracy, and validation of the modeling or documentation. Therefore, the accurate recording of metadata is of utmost importance. Descriptive data are systematically organized to cater to the needs of various disciplines, including but not limited to pre-conservation, conservation restoration, and any monitoring information.

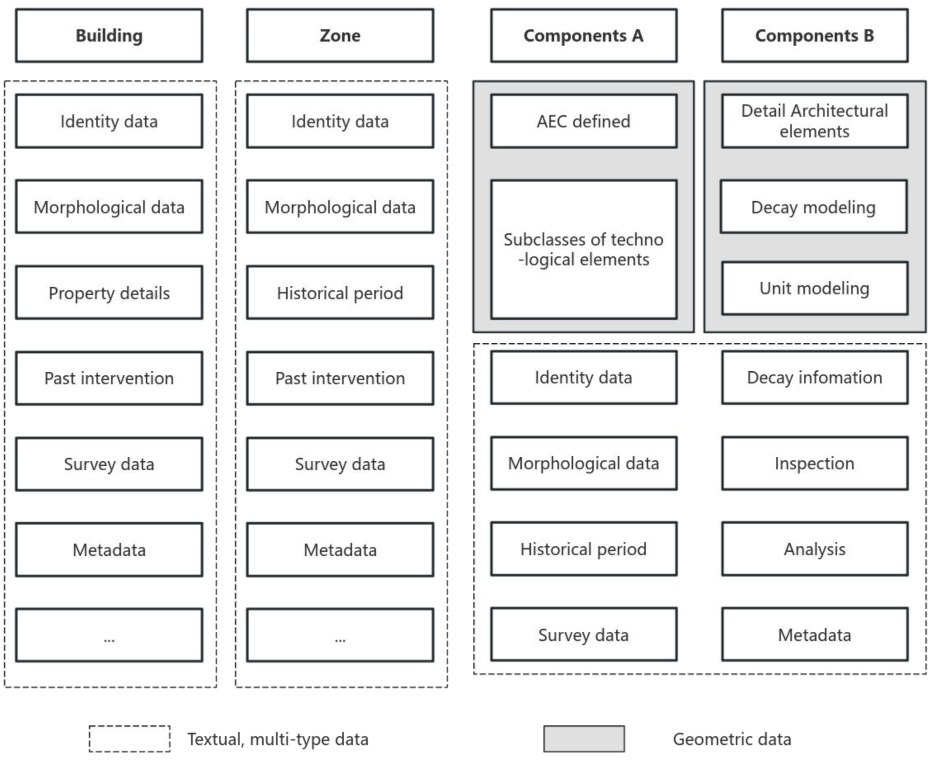


Figure 11 Summary of the data entered in the database, grouped by levels of detail.

Although there are inclusion or parallel relationships between four different semantic levels, depending on the information processing method, this strategy defines the four levels as BIM entities in the database to link the BIM 3D model and database information. These four hierarchical entities form a main relational table. The main table can be bound to separate tables that store other subdivided information grouped by information types. This data structure can ensure the flexibility of the database, and can also create separate tables for new information in any field and realize linkages and bindings with existing databases. Additionally, the linkage between the main table and each appendix can also be achieved in various ways (see **7.1-7.2**).

Based on the information structure optimization by Bruno and Roncella, a template database that included tables and precompiled data seeds was created. This template can be used for North wing of Valentino Castle related to the BIM model of recovery and maintenance. Moreover, the link between the BIM model and the database can be realized using VPL, Revit's built-in DB manager module or the database plug-in for Revit (see **Section 7.2**).

3.4.2 Foundation ontology design

The HBIM information system allows for the consideration of the relationship between 3D models and semantic information within HBIMD, while also connecting the HBIM platform and database. However, for some potential interdisciplinary research, the descriptive semantic information in HBIM is unreadable or non-interoperable. Additionally, BIM data represented by Industry Foundation Classes (IFC) often lacks the flexibility for efficient data sharing. Therefore, developing ontologies in the field of cultural heritage is crucial.

In the domain of HBIM documentation for architectural heritage, the definition of ontology is typically derived from computer science and knowledge graphs, rather than the philosophical domain: it refers to the formalized description of concepts, entities, and their relationships within the architectural heritage domain, used for knowledge representation and data sharing in HBIM documentation. Simultaneously, it expresses the knowledge graph in the documentation process—a standardized description of concepts, terms, and their interrelationships, constructing the basic knowledge system of the domain. Its purpose is to facilitate users and readers in understanding the knowledge system and structure of the documentation, thereby better integrating and sharing data, managing knowledge, and enhancing research capabilities.

Constructing an independent ontology based on a specific research domain from scratch is challenging. Therefore, this study adopts the "foundational" ontology proposed by Previtali et al., and additionally defines new classes within this foundational ontology to represent the different levels proposed in section 3.4.1. The "foundational" ontology can be extended by various domains to develop their specific ontologies, making it suitable for HBIM workflows aimed at documentation.HBIM

In the documentation-oriented HBIM project, this "Foundation" ontology employs seven elements to provide conceptual knowledge for buildings, which can serve as a foundation for developing domain-specific ontology. The ontology developed suggests concepts that can be readily integrated with concepts in ifcOWL.

· Building
· Architectural components(A, B)
· Room（zone）
· Space（zone）
· Level
· Phase
· Survey
· Actor

Among these seven elements, buildings, rooms and spaces, and architectural elements (including A and B) have some relation to the four levels in the HBIM Information system, but they are not fully aligned. Furthermore, this "Foundation" ontology includes an additional survey to ensure the accuracy and reliability of HBIMD information. This "Foundation" ontology also maintains consistency with the existing CH ontology CIDOC-CRM. **Figure 12** illustrates the main concepts and relationships contained in the "Foundation" ontology implemented in RDF/OWL language. In this framework, each domain creates its own domain ontology by adding domain-related attributes and relationships to the "Foundation" elements.

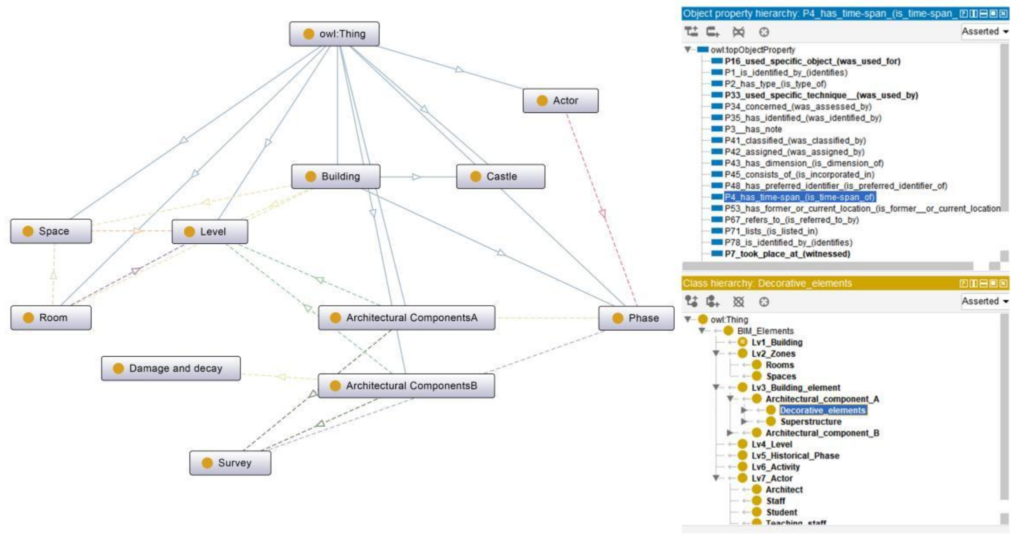


Figure 12 General view of the "foundation" ontology used to share a general view of the building among different domains involved in the historical building information modelling (HBIM) process.[28]

The software platform used is Protégé, an ontology editor and knowledge management system developed at Stanford University. It can build large-scale visual ontology models with various representation formats, which helps to understand the connections between components and concepts.

Based on the Stanford seven-step method for ontology construction[64], and the aforementioned "foundational" ontology, constructing the ontology for this project in Protégé is relatively straightforward:

First, create a new ontology model and add new classes according to the foundational ontology proposed by Previtali. Then, in the Object Properties tab, add predefined new object properties through "Add Sub-properties" and define the domain and range of these properties. Next, in the Data Properties tab, add various attribute data and enrich the domain and range of these attributes. After constructing the conceptual framework of the ontology, and upon completion of the HBIM model, create the entity objects from the HBIM model into Individuals. Finally, use Reasoning to validate and derive new results.

[64] Noy N F, McGuinness D L. Ontology development 101: A guide to creating your first ontology[J]. 2001.

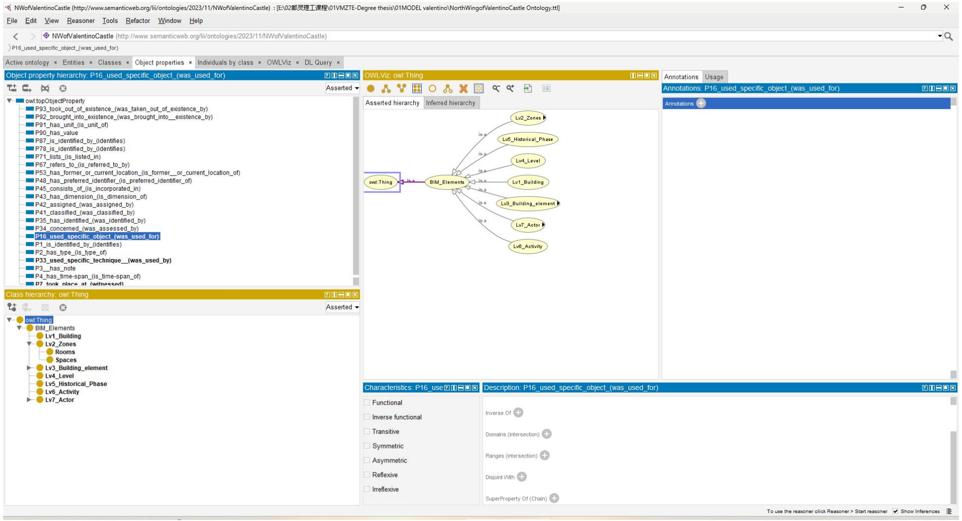


Figure 13 Protégé interface - The establishment of foudation ontology

Besides, a correspondence between the HBIM element and ontology semantics is built in the BIM environment. Revit Dynamo provides the interactive interface in the study, where users can browse the semantic information reserved in the ontology database and the 3D model in BIM platform at the same time (**Figure 14**).

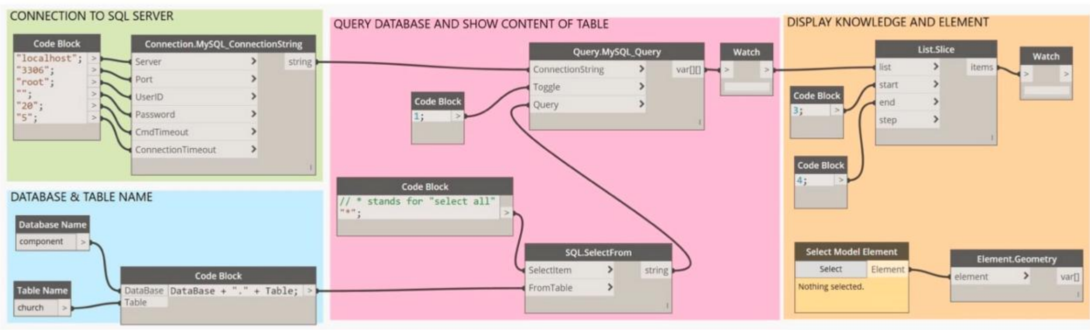


Figure 14 The connection of HBIM elements and ontological knowledge based on Revit Dynamo, where the corresponding knowledge of the element selected in Revit can be displayed in the "watch" window.

It is worth noting that, although this study has conducted preliminary research and modeling on ontology, the exploration in this field is continuously evolving. Therefore, it is essential to keep updating and exploring this method to ensure the rationality and efficiency of the ontology.

3.4.3 Geometric modeling

The fourth stage delineates the geometric modeling of HBIM. HBIM modeling is a core component of this workflow, leveraging all preceding phases to obtain a semantic representation of building systems and technical characteristics. The current methods of parameterization are classified as follows: a) Conversion of point clouds into mesh/solid objects, b) Import of point clouds into BIM parametric tools, c) Automated conversion of point clouds into parametric objects, and d) Manual modeling from traditional methods. However, regardless of the modeling method employed, certain information loss and errors are inevitable. Therefore, this workflow stipulates that the modeler's information, modeling methods, and verification results of the model and point cloud information should be recorded in the shared parameters of the components for verification and future work.

Moreover, for projects with low model accuracy requirements, there currently exists no specialized software or recognized simplified guide for HBIM modeling. Consequently, this project is based on the Level of Knowledge (LOK) proposed by Castellano-Román M, Pinto-Puerto F, and is combined with the ontological framework of CH to establish a set of simplified rules and methods for geometric modeling. The purpose of this is to quantify the extent of modeling simplification. This part will be elaborated upon in detail in **Chapter 4**.

3.4.4 Performance Assessment,Refurbishment Project

Phase 5, Performance Evaluation, generates semantically enriched knowledge of the BIM model with the objective of evaluating residual performance. Consequently, the acquisition of structural information, material information, and damage information are consolidated in this section and recorded in their respective components in the form of shared parameters. Concurrently, the implementation following HBIM is archived, such as non-destructive tests, daily monitoring, and daily maintenance information, which are also preserved in BIM in the form of spreadsheets or pictures. Additionally, the defined IFC format and COBie format ensure the interoperability of performance information. Phase 6, the Conservation Project, involves selecting and detailing the most coherent interventions and responding to the required functional, standard, or technical upgrades, following an accurate diagnosis and performance assessment.

Conclusion

This chapter describes a comprehensive programmatic framework that combines multidisciplinary and multi-purpose use, as well as the paths within this framework that were adopted in the project for the northern wing of the castle. Unfortunately, this complete procedural framework is not an ideal framework that is absolutely correct and covers all relevant professions and fields. The purpose of its existence is to help heritage conservation personnel clarify the purpose and content of their work.

Chapter 4 Strategic planning for project implementation

This chapter presents the implementation of strategic planning in the documentation-oriented HBIM workflow for the north wing of the Valentino Castle. It covers the formulation and management of information requirements, the preliminary information collection and induction methods, and the processing of three-dimensional modeling sources. The aim is to create a solid foundation for the subsequent geometric modeling and health information management and operation.

4.1 Strategic planning for HBIM modeling

The complete program framework can provide a reference for specific project implementation, and also enable the archiving operator to clearly understand which part of the framework the archives and documents being processed belong to. The peculiarity of the north wing project is that it is not a project for conservation or restoration, but a project for establishing HBIMD directly. In other words, the project would skip the phases of geometric information acquisition and damage information acquisition, and instead rely on previous results and research. Therefore, it is crucial to record metadata such as the source of any information so that it can be used as a basis for accuracy at the time of adoption.

4.1.1 Information Requirements

Information requirements define what information needs to be recorded and the strategy for documentation. BS EN ISO 19650-1:2018 (BSI 2019a) provides definitions of Organizational Information Requirements, Asset Information Requirements, and Project Information Requirement.

Organizational Information Requirements (OIR) are mainly intended to define the information that an organization needs to answer or inform high-level strategic objectives, rather than asset-level or project-specific objectives. OIR can be defined at multiple levels of the organizational hierarchy and are based on a wide range of organizational activities whose purpose is to enable requirements to be communicated throughout the organization and information flow to inform decisions. These needs may be required for various decisions, which may include: policy decisions; portfolio planning; regulatory obligations; strategic asset management; strategic business operations. Asset Information Requirements (AIR) should provide the basis for the commercial, management and technical aspects of asset information production and management and should include standards, methods and procedures to be implemented by the delivery team. Project Information Requirement (PIR) should explain the information required to answer or inform the appointing party/client of high-level strategic objectives that may be relevant to the design and delivery of each project. The PIR should consider the life cycle requirements of the project, including project management and asset management processes. At the same time, those parts of the complete project framework adopted by the project will be stored in the PIR in the form of diagrams and text.

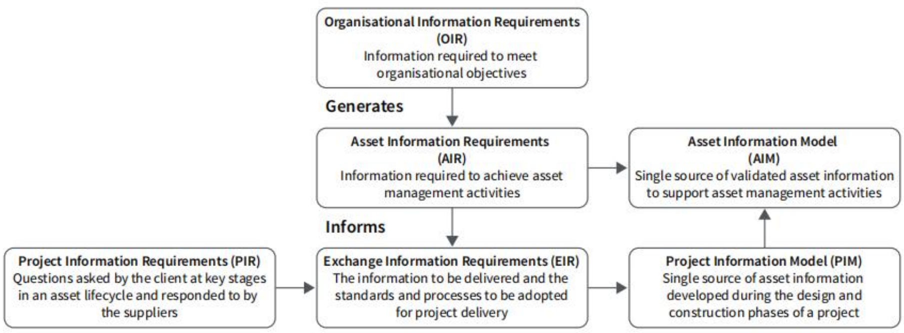


Figure 15 BIM information requirements and the resulting information models（Source: BIM for heritage[5]）

The spreadsheet templates (XLSX) for OIR, PIR, and AIR published by the Construction Industry Council 2021 are used in the project (see **Appendix A/B/C**). These documents have been prepared to enable all delivery team members to understand the information requirements of the appointing party/client organization and work within a consistent environment and ensure that information is delivered and verified in accordance with the identified requirements. The project must support the aggregation of this information required by all parties. Since the project's information requirements spreadsheets are predefined and not developed through scheduled meetings and questionnaires, the content and structure of the templates can be modified to ensure iteration and updating of the project.

4.1.2 Common data environments(CDEs)

The CDE is an agreed source of information for any given project or asset, for collecting, managing and disseminating each information container through a managed process (BS EN ISO 19650-1:2018; BSI 2019a). It is a digital workspace that provides a central repository of information about an asset that enables improved collaboration between project and asset stakeholders, reduces duplication and mitigates the risk of errors.

Before using the HBIM software and database, a suitable CDE is needed to provide a more efficient environment for collecting and storing the preliminary information. In this solution, Dalux BOX is adopted. Dalux BOX is a customizable data sharing environment that enables data and models to be shared and viewed through suitable 2D and 3D viewers. The platform also allows the creation and sharing of public annotations, markups, comments, and reports that can be attached to any object and document. (Dalux BOX will be introduced and explained in **Chapter 7**).

4.2 Preliminary Information Collection

4.2.1 Preliminary Information Collection

As described in Chapter 2, the Valentino Castle is an extraordinary architectural CH that has witnessed the passage of time and accumulated a large amount of information. Therefore, for a documentation-oriented HBIM project that does not rely on geometric models, preliminary information collection is a challenging task. To improve the efficiency of information collection and enhance the collaboration among teams, a framework for information collection was developed and the information collection and analysis process was divided into three steps.

1.Information Sources[65]

· Transfer of information and data from existing projects, archives or research.

· Recognising or relabeling an existing data and information store, such as GIS, Database.

· Collection of new or updated information and data from surveys and new research.

First, the project specified the sources from which the information would be collected. On one hand, there are existing research results and documents about Valentino Castle, including but not limited to books, documents, research, and reports on existing protection and restoration work. At the same time, from these existing results, the project extracted existing geographical databases and point cloud information to serve as the basis for geometric modeling and semantic information management. On the other hand, to ensure a basic understanding of the heritage objects and the current status of the castle's north wing, the project conducted a 3-day site survey to understand possible changes in information between the last conservation intervention and today, such as additional renovations, damage, etc.

[65] England H. BIM for Heritage Developing the Asset Information Model[J]. Historic England: York, UK, 2019.

2.Category of information[66]

· Archaeological and historical data

Aiming towards archaeological investigations, understanding of the historical context of the building and determining the morphology of the building's fabric and function over time. They are within the scope of archaeologists, architectural historians, listing authorities, museums and public dissemination.

· Geometry

Aiming to record, survey and visualise the exact shape and characteristics of the building's fabric on its current state. Geometry is an important element for many stakeholders but is the major element in the scope of architects, structural engineers and in general for the construction sector.

· Pathology

Aiming to discover and survey any potential damage or decay of the fabric of the historic building over time, being it material decay or structural deterioration. Those who work in the conservation industry are the major stakeholders that benefit from pathology data, but it can be useful also for stakeholders interested in the archaeologic and historic analysis of the building.

· Performance data

Aiming to understand and analyse the current status of the building's operability and performance on its various aspects, such as energy performance, thermal performance, users' comfort, systems' performance, safety and security performance. Performance data is in the core interests of architects, MEP engineers, lighting and acoustic engineers, energy auditors and other building scientists. It is worth noting that the classification of information is clear, but the same original information may contain different types of information. Therefore, the same original information may be stored repeatedly in folders of different information categories, to ensure that no information is missed when extracting the required information.

3. Information classified by storage[67]

· Documentation,

· Alphanumerical information,

· Geometrical information.

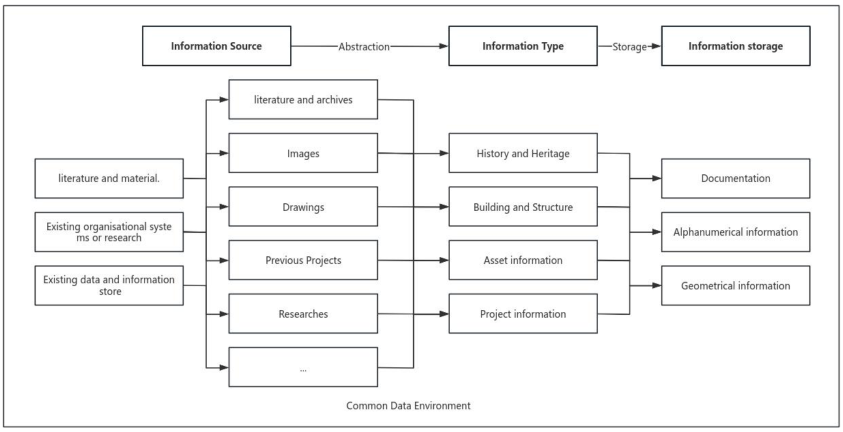


Figure 16 Preliminary Information Collection

[66] Khalil A, Stravoravdis S, Backes D. Categorisation of building data in the digital documentation of heritage buildings[J]. Applied Geomatics, 2021, 13: 29-54

[67] Cheng J C P, Zhang J, Kwok H H L, et al. Thermal performance improvement for residential heritage building preservation based on digital twins[J]. Journal of Building Engineering, 2024, 82: 108283.

All information needs to be labeled and stored in an appropriate way so that it can be used for subsequent geometric modeling and semantic enrichment.

4.2.2 Method of Preliminary Information Collection

Faced with a large amount of historical documents and past asset information of Castle Valentino, such as historical books, research papers, scanned paintings, and digital files, collecting and documenting information is very time-consuming. Since a large amount of information comes from physical books and scanned documents, this is unfavorable for information retrieval because the current search method cannot extract text from images. Therefore, this project uses both manual retrieval and AI query to improve the efficiency of information sorting. For digital documents (such as PDF, TXT format, etc.), while linking these documents to Revit files, this project uses artificial intelligence tools to extract key information. Humata is an AI-driven chatbot designed to help users manage and understand files efficiently. A dialog box will be generated when the documents to be sorted (in PDF format) are uploaded to the website. Then commands can be presented in the dialog box. Artificial intelligence automatically analyzes the document structure and framework and generates answers based on instructions and needs. Therefore, the extraction and summary of information will greatly reduce the time of information retrieval. (**Figure 17**) Currently, the free function of the website only supports retrieval and preliminary summary of a single document, and cannot query multiple documents at the same time. Another open issue is that the questions asked need to match the keywords of the article as precisely as possible, otherwise the AI cannot answer accurately. This will pose a possible problem: When you are not familiar with the article, you may not be able to ask for useful information accurately.

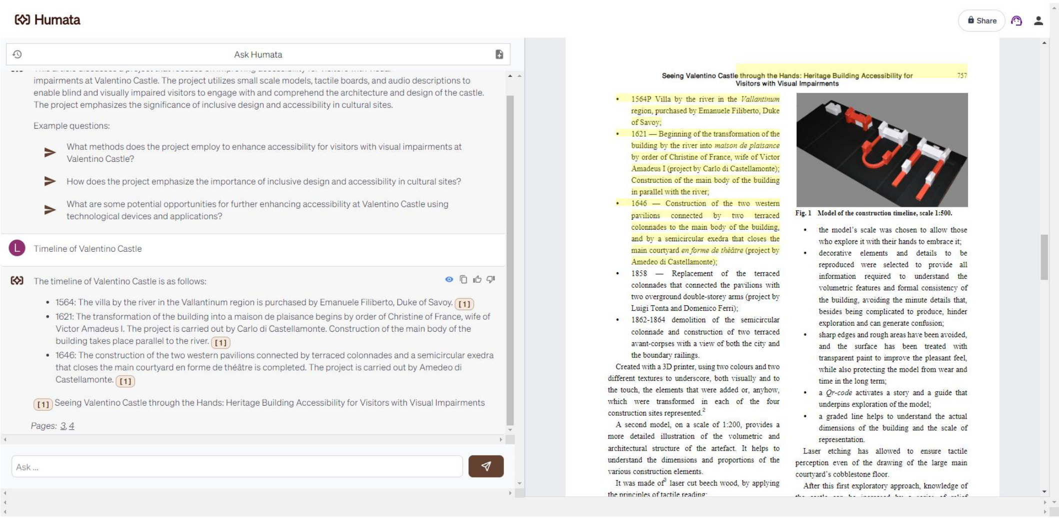


Figure 17 Humata AI's interface: automatic retrieval and summary of Valentino timeline(the right is the original document)

For physical documents and archives, the free Optical Character Recognition (OCR) platform is a good option. Currently, many OCRs have developed different functions such as printed text recognition, handwritten text recognition, and historical text recognition, which can convert uneditable images into editable text information and enhance the feasibility of retrieval. (https://www.onlineocr.net/)

4.3 Geometric processing

4.3.1 Point Cloud

Since this project did not plan a point cloud acquisition phase, it collected past point cloud information for modeling. Therefore, to ensure the accuracy of modeling, the storage of point cloud information is divided into two parts: first, the management of the original data, because the original data are not subsampled and are quite heavy, and some point cloud files are not georeferenced, so all original files need to be managed so that if there is a problem with the preprocessed point cloud file, it can be traced back to the original file or instrument.

Point Cloud				Instrument	
Name	**Object**	**Type of survey**	**Date**	**Name**	**Basic Info**
Castello_Valentino_UAV	Overall Castle External data	UAV	October 2018	Phantom 4 pro	CMOS 1'', 20 MP.
TLS_LIDAR_Castello_COURT	Courtyard	TLS	July 2018	Faro Focus X330	Range: 0,6m - 330m Measurement speed (pts/sec): 122,000 / 244,000 / 488,000 / 976,000 Ranging error1: ±2mm Field of view (vertical/horizontal): 300° / 360°
RTC_Castello_TLS_Underground	North underground floor	TLS	November 2022	Leica RTC 360	Maximum Scanning Range: 0.3 meters to 130 meters / Measurement Speed: Up to 2,000,000 points per second / Distance Accuracy: 1 mm + 10 ppm
...	...	...	...	...	...

Table 3 Table of some important point cloud file and instrument information

The second point is the preprocessing of Point Cloud. In this study, the preprocessing phase of point cloud data employed CloudCompare software, chosen for several key reasons: Firstly, CloudCompare, as an open-source and free software, provides users with a cost-free data processing option; secondly, the software demonstrates exceptional stability and high computational efficiency in the comparison, registration, and analysis of large-scale point cloud data; lastly, CloudCompare supports the import and export functions for various instruments and data formats, reflecting its good interoperability. In this project, CloudCompare was utilized to perform local fusion, registration, and cleaning of numerous point cloud datasets. Subsequently, the coordinate origin was updated in Autodesk Recap. However, due to the large number of point cloud files processed, delays occurred during project handling. Therefore, it was necessary to divide the point cloud data into multiple Recap files to ensure smooth data reading. Finally, these Recap files were imported into Revit and realigned.(**Figure 18**)

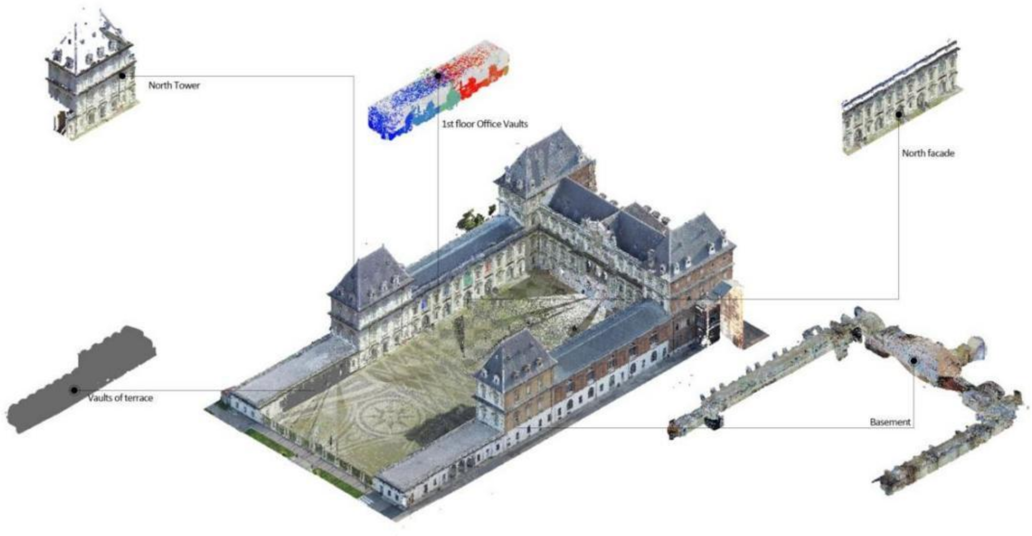


Figure 18 Fusion of multi-Pointcloud

4.3.2 Processing from other sources

After checking the final point cloud file, some problems were found: the roof truss structure and information in some rooms were missing from the point cloud file; and the local point cloud of the north facade was occluded by vegetation. To address these issues, a simple visual inspection and manual mapping task were performed to obtain the missing geometric information. Photographs were also taken to refine the geometric modeling, and the problems and solutions were recorded in the associated metadata.

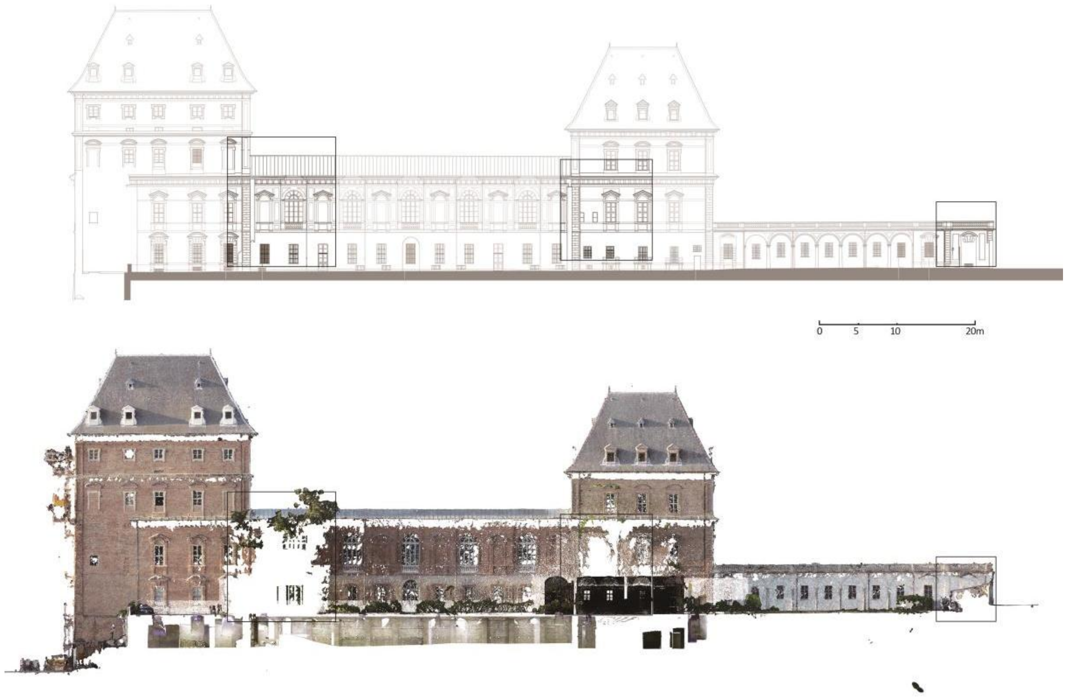


Figure 19 The missing point clouds in the north elevation were supplemented by the scanned drawing information.

Conclusion

This chapter mainly describes the main processes in the planning stage, with the aim of providing a sufficient information basis for subsequent modeling and documentation work. However, the operation of information acquisition still depends on the skilled operation of the operator, which may compromise the credibility and accuracy of the information itself. At the same time, with the rapid development of AI technology, the potential of many image AI technologies and word processing AI technologies has not been fully explored. Therefore, how to collect and obtain preliminary information more efficiently is still a research area that cannot be overlooked.

Chapter 5 Geometric simplification method

HBIMD involves surveying and analyzing the geometric data of CH buildings. State-of-the-art point cloud acquisition technology and high-precision modeling methods are preferable but not always necessary. The most important aspects of HBIMD are a reliable documentation framework, a coherent modeling strategy, and a precise information management. A realistic representation may not require a high-resolution point cloud or a detailed model, especially if they lack sufficient heritage knowledge or fail to meet the project requirements. Overly detailed models without a plan may be resource-intensive. Therefore, reducing the geometric data is acceptable for projects that need semantic information management, preventive conservation, and other fields more than high-precision models. However, data reduction should adhere to certain standards and specifications to ensure data credibility and compatibility, and to facilitate future model refinement.

The main objective of the project was the documentation for the management of the north wing and did not require high-precision models to represent architectural features. The project developed a simplified method for the geometric model to reduce the time of the modeling phase effectively.

1. Identification and classification of HBIM objects. The integration of the HBIM information structure (see **3.4.2**), the classification system, and the architectural elements classification enables the accurate representation of the building structural components, the heritage building elements, and their associated semantic information.

2. Modeling simplification operation and record. This includes the quantification method of simplification, the metadata records, and the modeling procedures of various components and objects.

3. Model accuracy verification and refinement possibility.

5.1 Strategy of the simplification

5.1.1 Classification system

Semantically classifying and identifying the building elements, their relationships and hierarchies is the first step in creating an HBIM model. This facilitates organizing object libraries and family types (Revit family types), managing material and project information, and transferring and interoperating data. This project applies the classification system based on the Italian regulations (UNI 10838:1999 and UNI 8290:1981), which follow the requirements-performance approach[13] to construction technology. This approach relates the performance of an object to the multiple requirements it must meet. The European classification system mainly uses Uniclass2015, while the North American one mainly uses Omniclass. OmniClass provides more detail for some architectural domains, but less for others such as landscaping. Uniclass is less detailed than OmniClass in some areas, but it covers construction, civil engineering, landscaping, transportation, utilities, and process engineering more uniformly and consistently across the table. Based on the level of development (LOD) specification published by BIM Forum, this project establishes a semantic classification framework that incorporates some commonalities between Uniclass and Omniclass.

The semantic classification consists of four levels (see **3.4**).Levels 1 and 2 define the association of semantic information, while levels 3 and 4 define the geometry of the element. This semantic classification acts as both the basic framework of the database and the reference for geometry model simplification:

level 1 is the building, describing the overall information of the building;

level 2 is the zone, describing the type and information of the space or room;

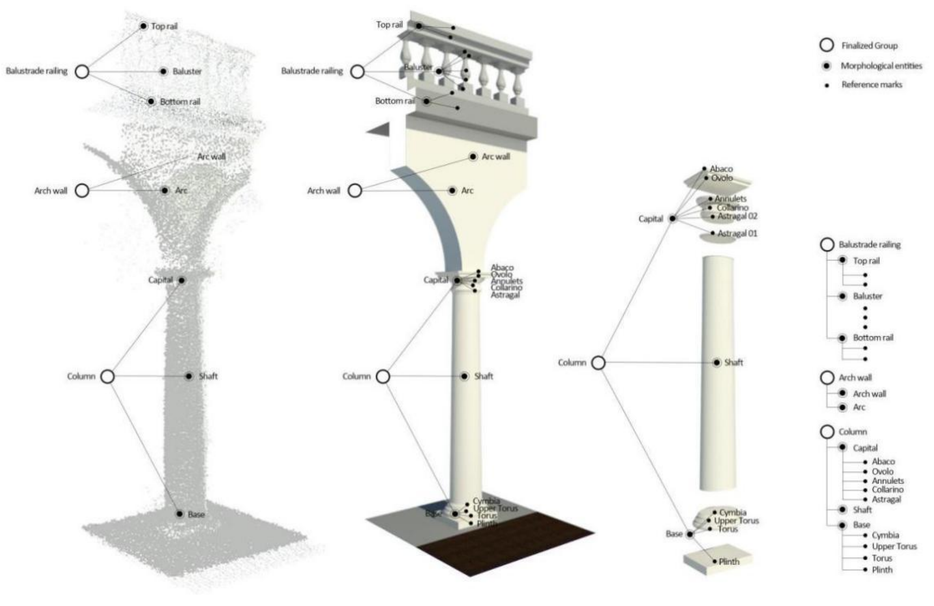
Level 3 is Building Component A, describing the specific components of the building identifiable in the AEC field (doors, windows, columns, etc.). For instance, in this project, the window surround is a specific decorative element assigned to exterior wall specialties, covering all elements in the project by the code of the classification system.

Level 4 is Building Component B, defining the further details of the element. These may include elements not defined in the AEC project, such as lintels, arches or deterioration in the window surround. Therefore, building component B does not have an independent Uniclass/Omniclass number, but belongs to building component A of the previous level.

5.1.2 Identification of the architectural elements

Uniclass/Omniclass classification systems include the content of Building Component A, which may suffice for managing project assets and transmitting information. However, without further identification of Building Component A, the building information may be insufficient and the model simplification may be erroneous. Distinguishing intentional simplifications from modeling errors is important for ensuring model modifiability. Livio De Luca et al.[68] propose three levels of semantic description for building elements: final groups, morphological units and reference features. For example, a column is a final group, which can be divided into three morphological units: capital, shaft, and base. Each morphological unit can have multiple reference features. For instance, a capital consists of abacus, ovolo, annulets, collarino, and astragal.

To clarify the relationship between the historical elements in Building Component B and their corresponding Building Component A, the project developed a database of the classification system of the Valentino Castle. The database, stored in CSV format, can be updated and queried. The final group in the semantic description of building elements is Building Component A, which represents the functions of various elements collectively. The morphological units and reference features that compose it are Building Component B, which are simplified during the modeling process. The text descriptions stored in the shared parameters of the model indicate the degree of simplification of the component.



[68] De Luca L, Busayarat C, Stefani C, et al. A semantic-based platform for the digital analysis of architectural heritage[J]. Computers & Graphics, 2011, 35(2): 227-241.

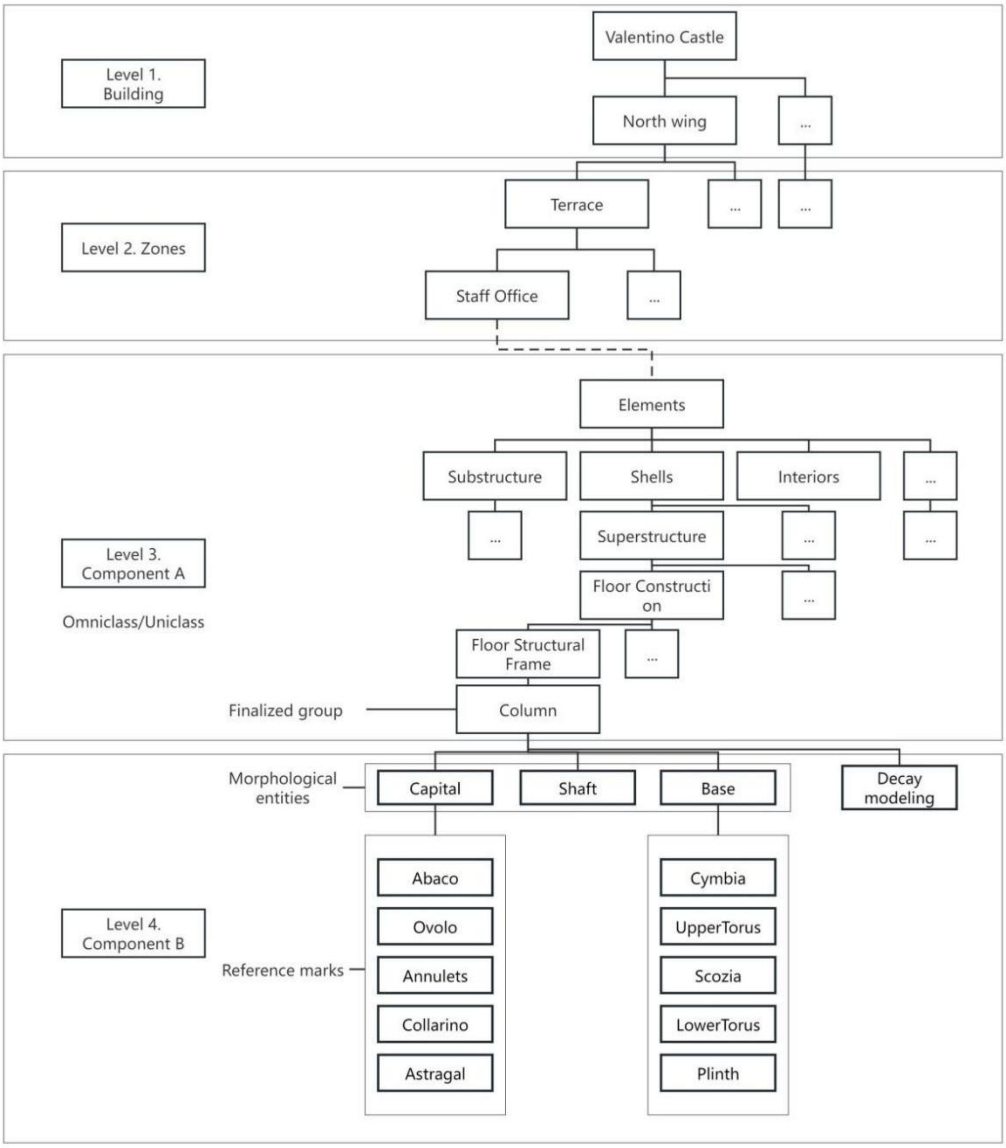


Figure 20 3D graph for the semantic description of the part of the terrace (Ontology) and Classification strategy of a column in the Valentino Castle Project.

In order to ensure the authoritativeness of the identification names of the historical elements in building component B, the book of Hopkins O.69 was consulted in this project.

[69] Hopkins O. Reading Architecture Second Edition: A Visual Lexicon[M]. Laurence King Publishing, 2023.

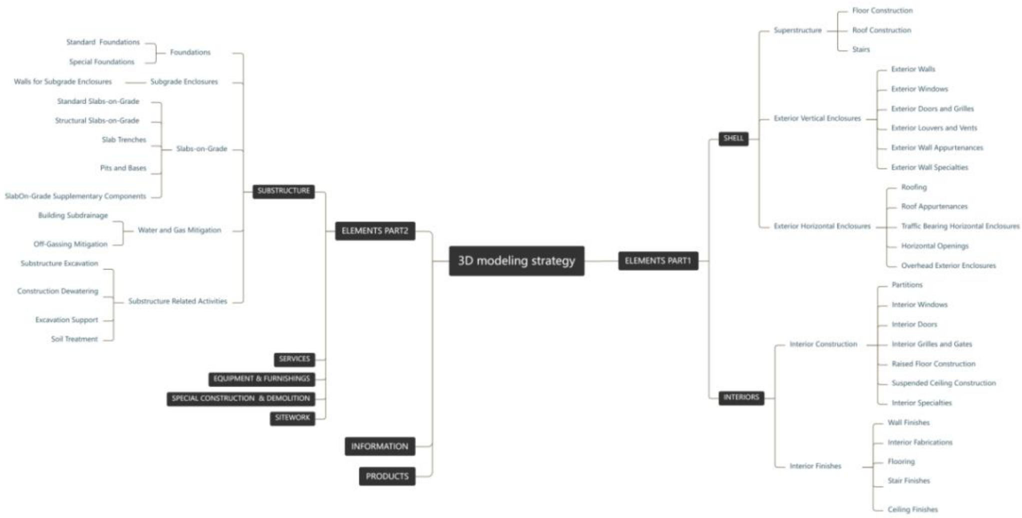


Figure 21 Complete framework of classification system(According to the LOD specification, it is designed to have six levels, the first five of which can be overridden by Omniclass/Uniclass, and the sixth level representing the elements in 4.1.2)

5.1.3 Level of Development and Level of Knowledge

The Level of Development (LOD) in AEC projects indicates how fully and reliably the project team members consider an element's specifications, geometry, and additional information when they use the model. International standards define two indicators: LOD (from 100 to 500) and LOG (from 1 to 3), where LOG stands for Level of Geometry. However, Italian law combines LOG (geometry) and LOI (Level of Information) to define LOD (from A to G). The concept of LOD may be confusing for HBIM, where CH already exists. Castellano-Román M and Pinto-Puerto F.[17] proposed LOK (Level of Knowledge) to reflect the object's information richness, including the element's geometry, degree of classification, material information, deterioration information, etc. This project uses LOK to distinguish between LOD in AEC projects and LOD in CH, and follows the Italian specifications for its rules and classification. It sets LOK=(LOI+LOD)/2. An element's LOK may not exactly match the drawing's accuracy, depending on the information it contains.

LOG (Level of Geometry) describes the accuracy of an element's geometry model. LOG reflects any decrease in accuracy due to errors or simplification. This project adds an additional point to the published LOG definition: LOG200 defines the creation of element A, as described in **4.1.1**. The shared parameters define the numerical parameters of LOK (Level of Knowledge), LOG, and LOI (Level of Information). They also provide additional descriptions to clarify why the accuracy decreases.

LOI (Level of Information) expresses the level of information in an element. The quality and quantity of the information determine the element's trustworthiness, which affects future intervention and protection. Chapter 6 explains this part in more detail.

The model used several geometric approximations and simplifications of objects with both geometric and informational parameters. We used the AsBuild plug-in to compare the point cloud and the model analytically and measure the deviation. We recorded this value as the Level of Accuracy.

Level	LOK 100	LOK 200	LOK 300	LOK 400	LOK 500
Phase	Identification	Protection and dissemination	Advanced research	Conservation and intervention	Comprehensive management
Description	Graphic codification,simbolic or accurate, but not categorized. Basic characterization. Georeferenced location and orientation	Basic structures and constructive evolution modelling.Legal protection documentation and estrategic planning. Graphical support for dissemination.	Complex structures modelling. Advanced material characterization and desciplinary diagnosis	Conservation and intervention projects. Criteria and procedures definition	periodic programs of research, preventive conservation, use and dissemination. Periodic investment plan.
Geometry	The geometry of the structure is not known and is supposed from analogies or images	The geometry of the structure is known from 2D surveys or original drawings.	The geometry of the structure is known from 2D surveys or original drawings	The geometry of the structure is known from 3D complete and certified survey.with adequate accuracy to the representation scale	Accurate expression of damage and deformation
Structure	The structure and the construction technique of the element is not known and supposed from analogies	Construction details are based on a simulated design carried out according to the construction practice	Construction details are known from an in-situ analysis or are partially available from constructive designs	Construction details are known from an accurate in-situ analysis o rare available from original constructive designs	Accurate representation of any components and objects
Material	Materials are not known and supposed from images or from view	Materials are known but their properties are not available neither from constructive designs nor from testcertifcates	Information on the mechanical properties of the materials is available on the basis of either the original design drawings or original test certificates, or appropriate in-situ tests	Information on the mechanical properties of the materials is available on the basis of the original design drawings or certificates, or by in-situ accurate tests	Accurate representation of material units
Level	**LOG 100**	**LOG 200**	**LOG 300**	**LOG 400**	**LOG 500**
Modeling sourse	Conceptual model, Historical reports, archives	Appropriate geometry,3D survey, data acquisition	Precise geometry, Scan-to-BIM model object	BIM uses conservation plan	Conservation site
Scale	1:1000/1:2000	1:1000/1:500	1:200	1:100	1:50
Usage	Basic structures	Components A-morphological entitie	ComponentsB-reference marks	Decay and Deformation	As-built
Description	Geometric representation of primitives. Show component presence and represent approximate massing and location	Morphological characteristics of subclasses-building components are represented by morphological entities	The model is built according to the depth of building component B, indicating reference marks.	Accurate expression of damage and deformation	Expression of building units, subdivision of materials, expression of accessories

Table 4 Definition of LOK,LOG

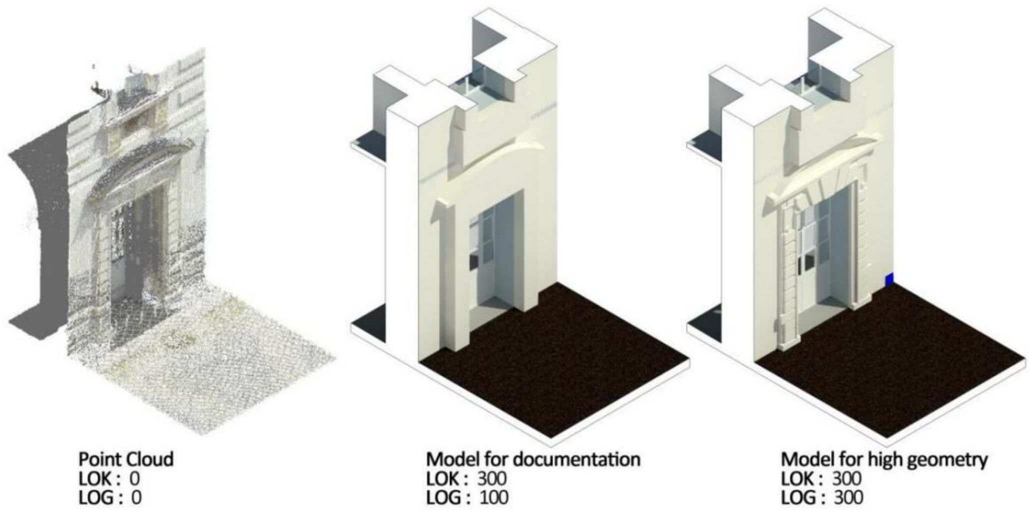


Figure 22 Point Cloud to HBIM models for different aims

5.2 Modeling Strategy in Revit

After defining the simplification strategy, the modeling process begins. Different modeling methods are applied to architectural elements and objects with various functions and geometric shapes, to achieve simplified modeling more efficiently. Most of the object modeling relies on processed point clouds (see **4.3**): point clouds collected by different devices are merged using Cloudcompare, exported in E57 format, and processed in RecapPRO for point cloud extraction and segmentation. Then, the data is imported using the Revit@Autodesk tool written by BIM.

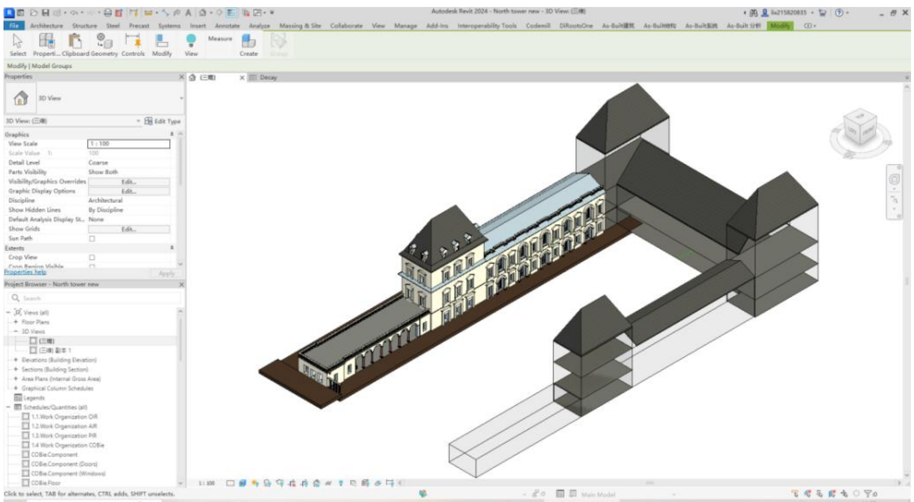


Figure 23 Revit geometric model of Valentino North Wing

There are four types of geometric modeling(**Figure 24**). The first type consists of structural components of the north wing. These components are essential parts of the structure, such as floors, columns, walls, and vaults,etc, forming the main framework of rooms and spaces. The second type includes decorative architectural elements, most of which have unique shapes and definitions. Together, these two types of elements constitute the core of geometric modeling. The challenge in modeling these lies in correctly simplifying geometric shapes to avoid introducing excessive geometric errors or losing important information.

The third type is the modeling of decay and damage. Decay and damage are essentially changes in the geometric attributes of building components or elements. However, it can be very difficult to express the damage accurately in geometric modeling. Therefore, the challenge in this type is to express the damage independently and simply, and to represent the relationship between the damage and the corresponding components correctly. The fourth type is the expression of rooms and areas. The difficulty of this type lies in two aspects: one is the simplified modeling of rooms with complex structures, and the other is how to link the room information in Revit with the proper expression of the database structure.

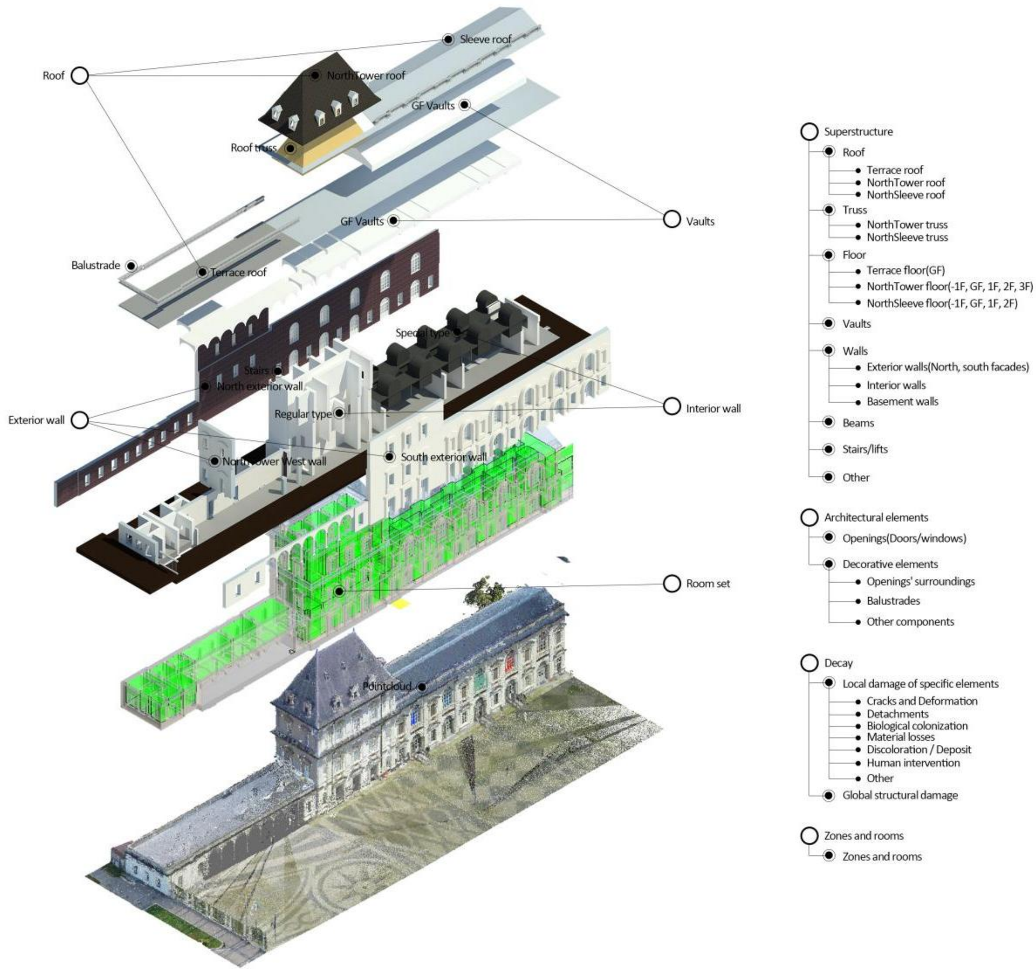


Figure 24 Explosion diagram of different types of architectural elements' geometric modeling in HBIM

Therefore, after identifying these four basic types of modeling, this study conducted an evaluation of the architectural elements of the north wing at the initial stage of geometric modeling. By summarizing the different types of architectural elements and analyzing their modeling challenges, the study developed corresponding geometric modeling methods for each type of architectural element.

5.2.1 Structural elements modeling

In the North wing of the castle, the construction of floors and walls was automatically generated from point cloud data using the Faro As-built architecture plugin. The core functionality of this plugin is based on a series of algorithms that can identify horizontal planes and lines formed by dense point cloud clusters within the point cloud, thereby detecting information about floors and walls. Subsequently, the plugin employs advanced mathematical models such as the RANSAC algorithm to extract geometric features representing architectural structures, such as corners, edges, and surfaces, from the marked point clouds. Once these geometric features are identified, the plugin generates a series of feature vectors that detail the features' positions, directions, and sizes. Finally, based on these feature vectors, the plugin precisely fits predefined geometric shapes to the point cloud data, thus constructing accurate models of walls and floors.

The specific construction method for walls and floors follows four steps as depicted in **Figure 25**:

· Data Import and Processing: Initially, point cloud data captured by laser scanners are imported into the FARO As-Built software. The software processes these data to identify the contours and surfaces of structures such as walls and floors. This process may involve operations like filtering, denoising, and data optimization, aimed at enhancing the accuracy of the final model.

· Feature Recognition and Model Generation: The software analyzes the point cloud data through algorithms to identify planes and lines that represent the boundaries of walls and floors. Based on these identified features, the software then automatically generates corresponding wall and floor elements within CAD or BIM models.

· Model Verification and Optimization: The generated model is overlaid with the original point cloud data for comparison to verify the model's accuracy. If necessary, manual adjustments can be made to the model to further improve its precision.

· Semantic Enrichment: The modeling method incorporates parameters and source information describing wall characteristics, as well as assembly parameters and material attributes of the walls. Additionally, the model is linked with relevant historical and measurement photographs to enrich its semantic information.

During the modeling process, structural units such as bricks and mortar within the walls and floors are omitted and instead documented in photographs and text. It also disregards any deviations from the ideal surface, such as deformations or identifiable rigid body movements.

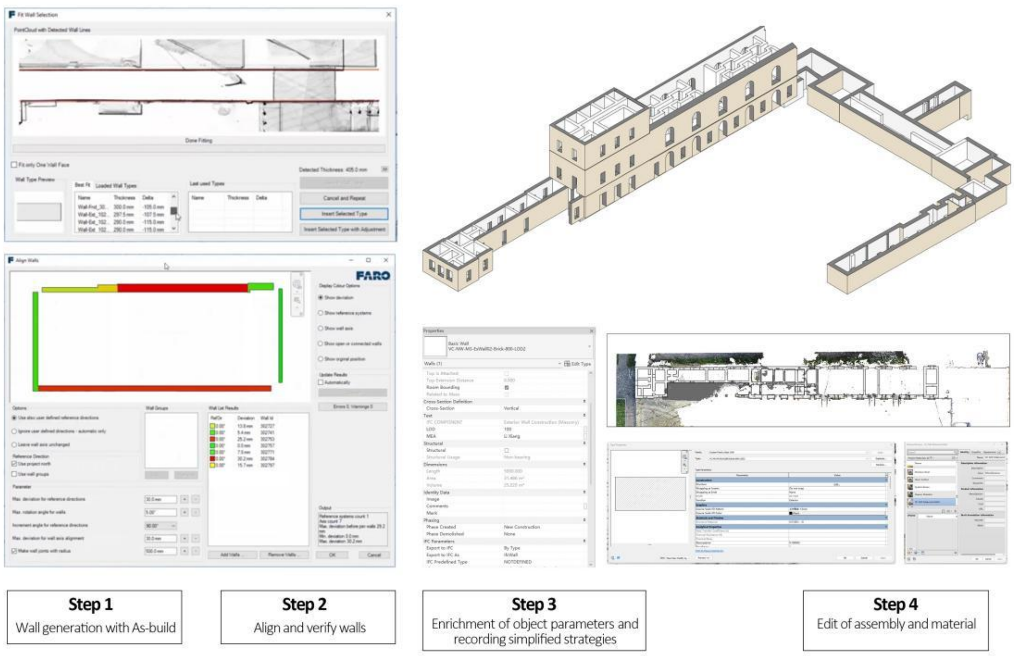


Figure 25 A semi-automated modelling approach for the walls and floors(As-Built™ for Autodesk Revit®)

This research tested four modeling approaches for curved surfaces such as vaults. The first method was to create the vaults in Rhino and then import them into Revit(see Approach1 in **Figure 26**). This method produced the most accurate vaults among all the tested methods, but it had a drawback: the vaults could not be joined to the wall, so the relationship between the vaults and the context was not detailed. Another issue was that the vaults created by this method were one-off, which meant that they could not be edited or modified in Revit.

The second method was adaptive family(see Approach2.1 in **Figure 26**): 1) Create a Generic Family. 2) Load Family into the Project and Create Instance (Pick the as-built generated boundary or structural intersections as the host for the vault family). 3) Cut the vault with the Instance. This method allowed the vaults to be modified and adapted for different rooms and projects. However, the modeling of adaptive families often failed when a Boolean operation intersected two volumes, which was easy in the first method. Another modeling method in Revit is In-place components(see Approach2.2 in **Figure 26**). 1) Create a basic 3D volume by extruding a 2D shape. 2) Remove and cut the volume by Void Forms. This modeling method is the simplest when faced with vaults with simple morphological characteristics. The type and characteristics of the vaults can be quickly expressed. However, this approach also has several disadvantages which cannot be ignored. The first is that vaults built in this way are the least accurate. Second, vaults with similar shapes cannot be obtained directly by copying and pasting, but need to be adjusted in each entity by modify the 2D shape manually. This also increases the workload.

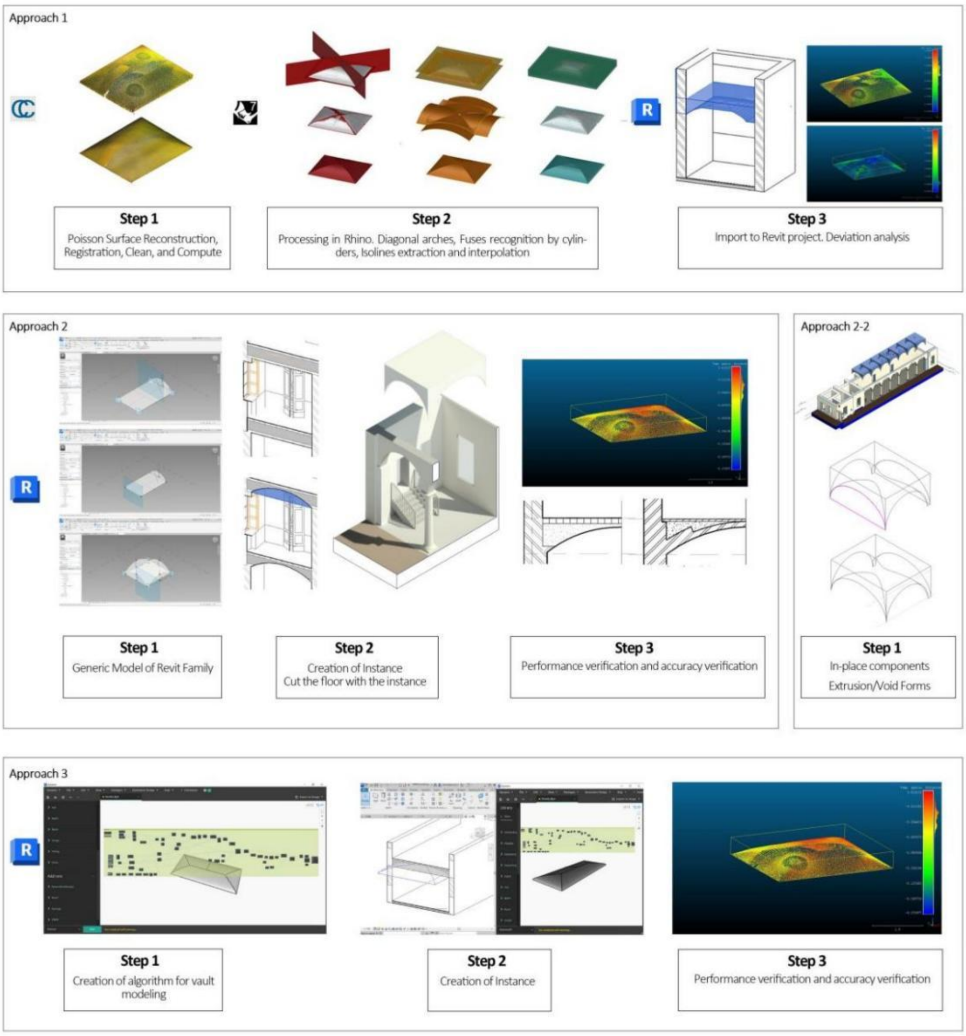


Figure 26 Three modeling approaches for curved vaults

The last strategy was visual programming, through Dynamo(see Approach3 in **Figure 26**). This method enabled the vaults to be adjusted and modified like the second method. But this method was not very accurate, and the vaults could not join the floor or wall correctly. It should be noted that this method also had a problem that could not be overlooked. The vaults created by Dynamo could not be kept in the view, which meant that Dynamo had to run beforehand to display the vaults correctly.

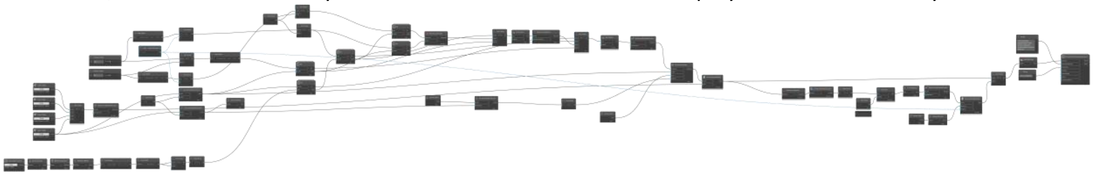


Figure 27 Dynamo algorithm for vault modeling with the fourth approach

Modeling the timber roof trusses of the north wing is challenging because of the irregular geometries and complex connection systems. However, the available point cloud could not capture the roof truss system, so the roof truss system of the north wing was only represented as an in-place component to mark its location and absence of modeling, with LOG 0(**Figure 27**). The same strategy is also applied to the modeling of the staircase, which means that the staircase cannot be accurately represented in the plan view. However, the important semantic information can still be stored in the component's attributes. The roof of the north tower could not use a similar solid. This was because the wall of the dormer window needed to be accurately represented in the plane of the second floor. Therefore, the modeling of the roof system used the conventional roof-dormer window modeling method.

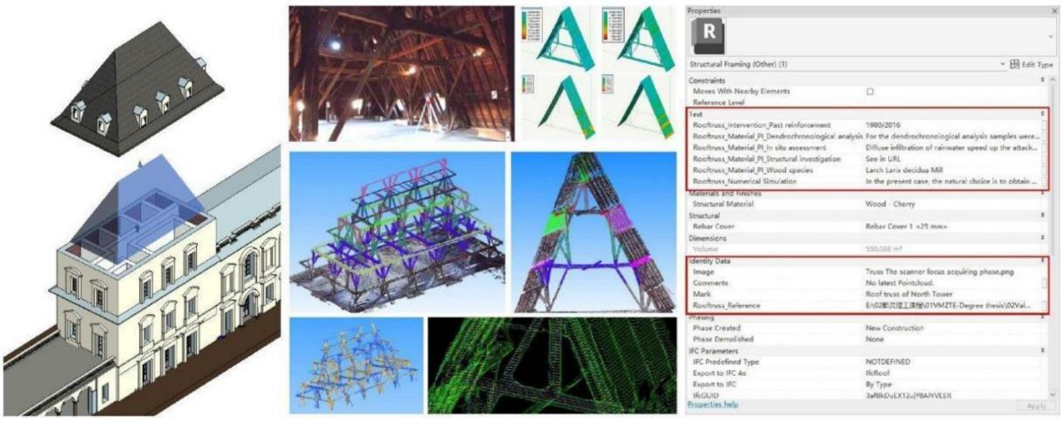


Figure 28 (Left) Simplified roof trusses model using In-place component (Middle) Information and data from previous studies[24](Right)Parameters in Revit

After completing the structural elements' modeling, the building's internal structure has been preliminarily expressed. By comparing the cross-sections obtained from **Figure 28**'s point cloud data with those of HBIM, we found that the precision of HBIM modeling is limited: ① The point cloud cross-sections reveal many missing internal information. ② The structure in the HBIM model cannot be accurately expressed. These issues mainly arise from: First, the lack of point cloud data leads to incomplete information about internal components. Second, the simplification of modeling leads to discrepancies with the actual situation. Therefore, our strategy is: To address the missing information in the point cloud data, we chose to read traditional drawings (DWG format) for internal information and supplemented HBIM modeling through on-site manual measurements. Additionally, we recorded the sources of modeling information and the simplification expressions in the attributes to emphasize the model's low precision.

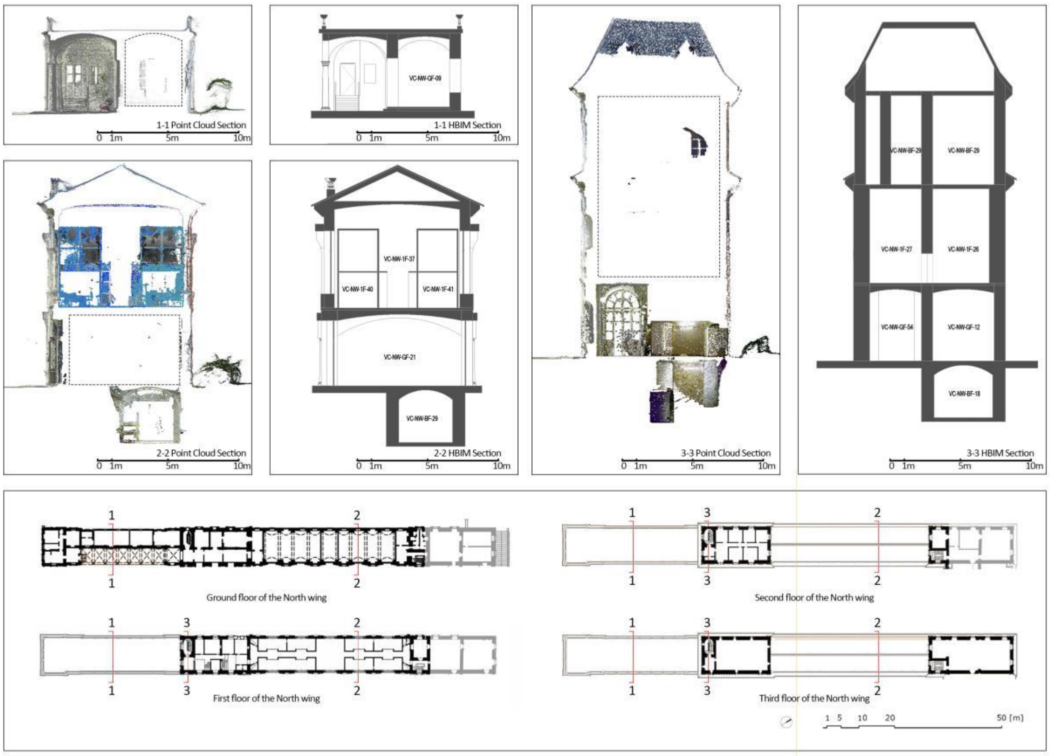


Figure 29 Comparison of sections between different point clouds and the simplified HBIM model

5.2.2 Architectural elements

One of the most important architectural elements of the building facade is the doors and windows and their decorative surroundings. The modeling of the doors and windows is based on semi-automatic modeling using point clouds. Since the geometric accuracy of the door and window components in this project was not high, each type of door and window only needed to be built once, and then the parameters were adjusted according to the specific characteristics of each element to ensure that it fit each instance. The specific modeling was done using the door creation function of the FARO As-built plugin, which generated the basic shapes of the doors and windows from the x-ray orthography in the family editor.

Next, we focus on the intricate structure of ornamentation around the exterior windows and doors (**Figure 29**). We use in-place components to create a simplified model of these decorations, and we set their type to wall to ensure that they are correctly recognized in the IFC format. We also save the identification of the decorative architectural elements and the hierarchical structure between the whole and its parts in the exported orthographic photographic image (Step 1-2). The simplified model stretches the outer contour of the orthogonal image to the maximum thickness of the component (step 3). We store the semantic information of the orthogonal image and modeling in the constructed parameters (step 4) to provide semantic hierarchy guidance for subsequent parametric refinement (step 5).

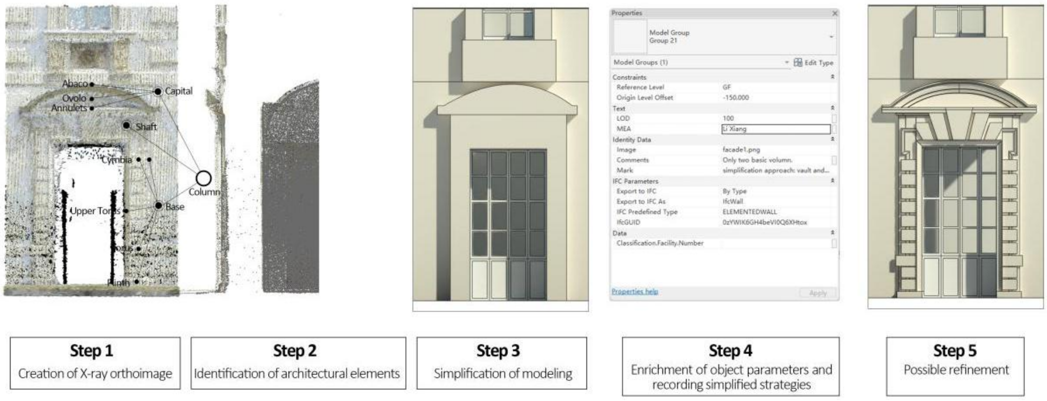


Figure 30 A simplified modelling approach for the door and its surroundings

The modeling of the pillars is similar to the decoration around the doors and windows, using an in-place model. The basic features of the three sections of the column (capital, shaft, and base) are retained, and only the basic volume and geometry are used, but the more refined structure is omitted. After investigation, the most common column on the north wing facade is this(**Figure 30**).

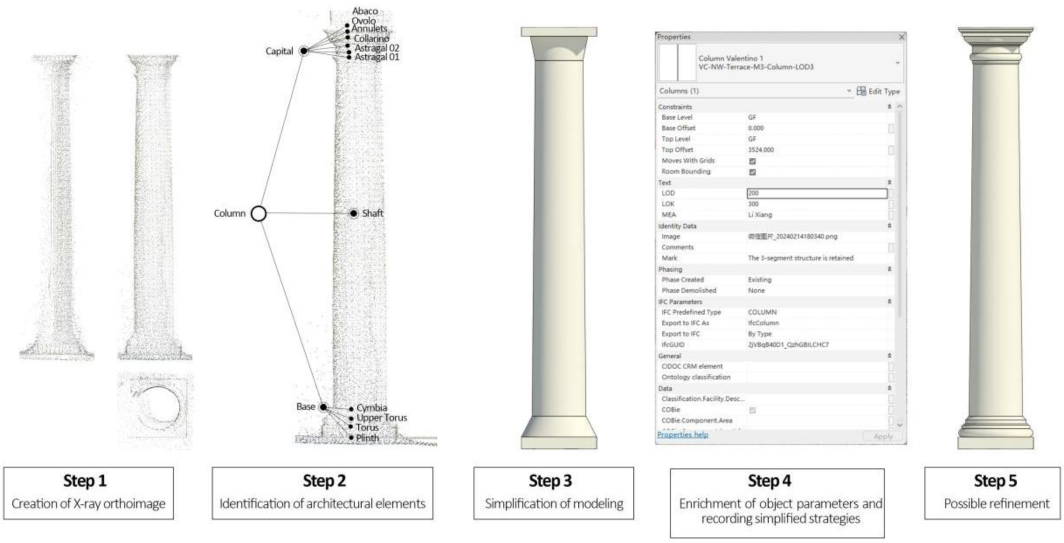


Figure 31 A simplified modelling approach for the column

Finally, in-place components are also used for most of the modeling of other architectural elements, and some subtle adjustments are made according to their different shapes to ensure that the basic shape is recognized. A smooth enveloping geometry is considered to be sufficient for purely decorative elements such as statuary, cornice decoration, etc.

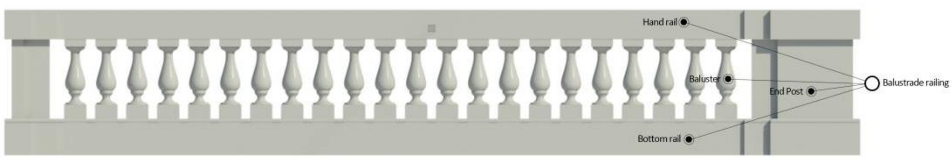


Figure 32 Balustrade modeling

5.2.3 Decay modeling

Regarding decay modeling, there are two main types of damage under consideration. The first type is local damage of specific components and elements (such as cracks, spalling, salt efflorescence, etc.). According to BS EN 17412-1:2020 and Barontini A, Alarcon C, Sousa H S, et al.[21], a pre-defined cuboid in -place component with a fixed thickness (0.01m) represents the damage to specific components in the project, that describes the position and scale. In the model, the size of the cuboid changes so that it completely covers the decay area according to the actual extent. At the same time, based on the specifications and literature of building damage types[70,71], a Catalog of Damage was established, and different colors were assigned in the cuboid to visualize different damage types. 1. Cracks and Deformation—red, 2. Detachments—blue, 3. Biological colonization—green, 4. Material losses—grey, 5. Discoloration / Deposit—orange, 6. Human intervention—purple, 7. Other—yellow. Each cuboid is set to a specific in-place component/Architecture/Signage category in the project to distinguish the decay models from architectural elements, and can be exported to IFC format to promote interoperability.

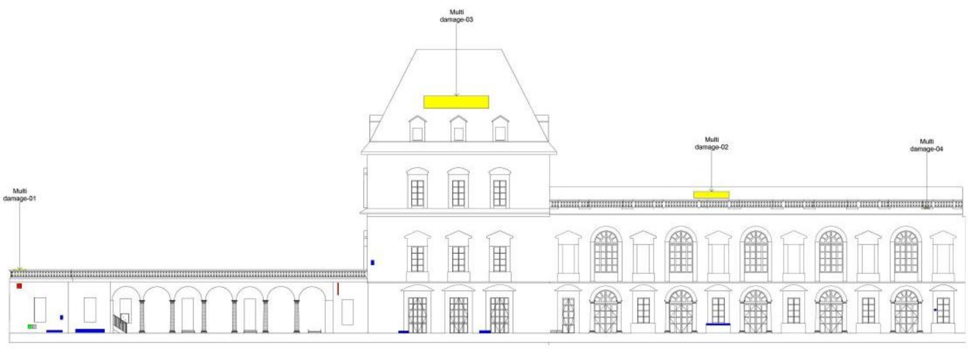


Figure 33 South facade decay representation

The second type is total or partial structural damage, such as wall tilt, roof truss system deformation, collapse, and so on. Modeling the overall structure with high LOG damage contradicts the strategy of simplification. Therefore, in the damage modeling of the north wing, a Multi-category tag with Other-Yellow patches marks the damage of the overall structure, to graphically represent the overall damage. These parameters, which describe and link to the main object, are automatically updated when the parameter value changes. This method only describes an overview of the overall damage and cannot be used for structural analysis.

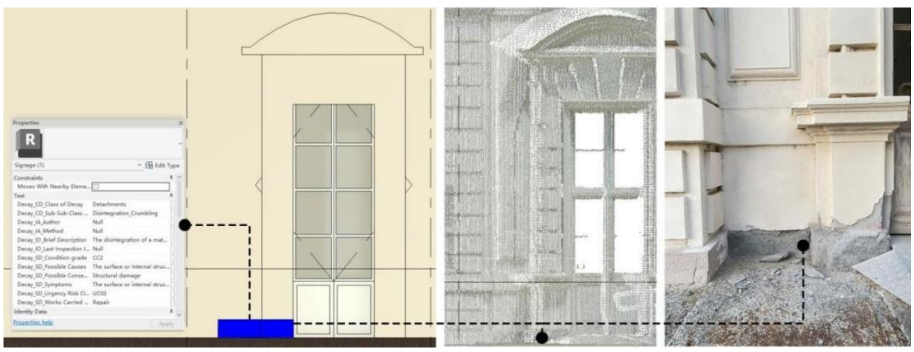


Figure 34 Patch-type object(in-place component/signage) to represent detachment(Blue)

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[70] Vergès-Belmin V. Illustrated glossary on stone deterioration patterns[M]. Icomos, 2008.

[71] Weyer A, Roig Picazo P, Pop D, et al. EwaGlos-European illustrated glossary of conservation terms for wall paintings and architectural surfaces[M]. Michael Imhof Verlag, 2015.

5.2.4 Settings of zones and rooms

In HBIMD, the definition of Level 2: Zones and Rooms is very important. On the one hand, the location and ownership of elements in the space can be identified, which is crucial for the asset management and facility management; on the other hand, Level 2: Zones and Rooms can establish the relationship between historical information and the current space. COBie zones can be defined by Revit rooms, Revit spaces, or a combination of both, depending on the classification of Revit elements. The Zone Manager enables creating COBie zones hierarchically. These areas can then be mapped to any existing Revit room or space in the current model. Areas are not modeled as independent objects, except at the building level. They are rather a set of building components, obtained through the "Create zones" function of Revit's interoperability tools.

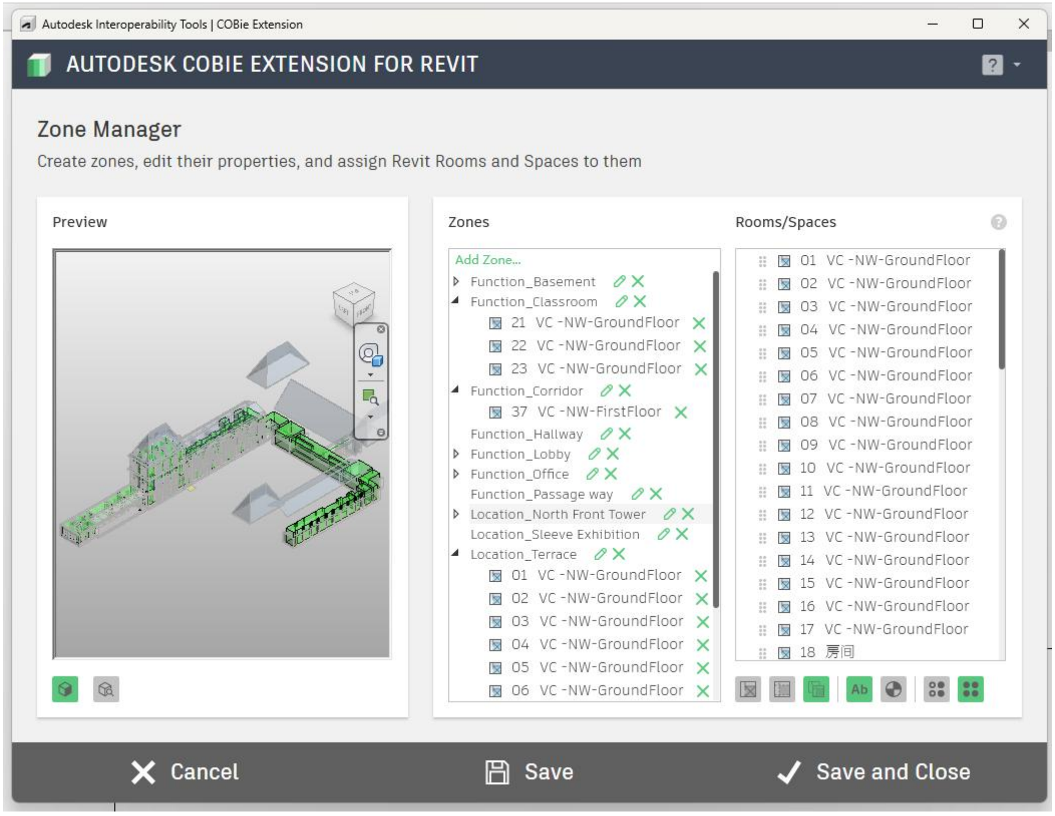


Figure 35 COBie Interoperability tool Zones Manager

Therefore, in this project, we defined the zones into two categories. The first category is the current functional zones: fire zone, circulation zone, office zone, classrooms, and so on. These zones are for asset management, facility management, and daily activities. The other category is the historical zoning. We divided the entire north wing into multiple zones such as the terrace, the north tower, the exhibition, and the church, to manage architectural elements under the semantics of historical buildings. Additionally, we modeled the center and south wing of the Valentino Castle as solid bodies, extruded from built-in volumes. The level of detail is very low and only suitable for establishing building locations and associated data.

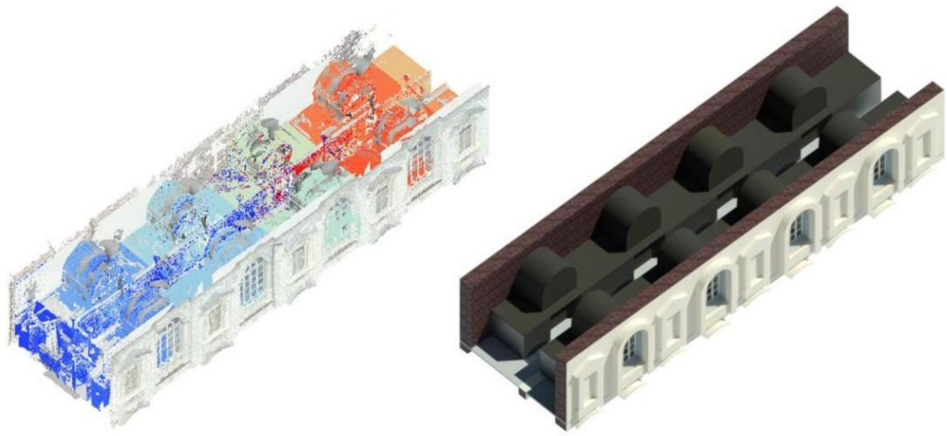


Figure 36 A modeling method for the mezzanine steel structure on the First Floor

One special zone that needs explanation is the office space on the first floor of the main north wing(**Figure 35**). The original walls in this space were removed and replaced with a mezzanine steel structure. To simplify its modeling, in-place components were used, and the basic volume was formed by extrusion and lofting. Its type was defined as a wall, so its form was correctly expressed in plan views.

5.3 Verification of model simplification

5.3.1 Verification of accuracy

After completing the model simplification work, a deviation analysis was performed to verify the accuracy of the model and avoid excessive errors and simplifications. In this project, the offset analysis in the AsBuild plug-in was used to quantify the deviation between the point cloud and the modeled object. Two surface analyses were conducted: a global offset analysis of the walls, floors and columns of the entire north wing, with a calculation range of up to 50mm; and an offset analysis of local key components and decorations, such as individual arches, doors, windows and surroundings, with a calculation range of 50mm-10mm. A false color scalar field layer was added to the model, with red indicating positive bias and blue indicating negative bias. The images show both the modeling tolerances and the deformations of the artefact itself.

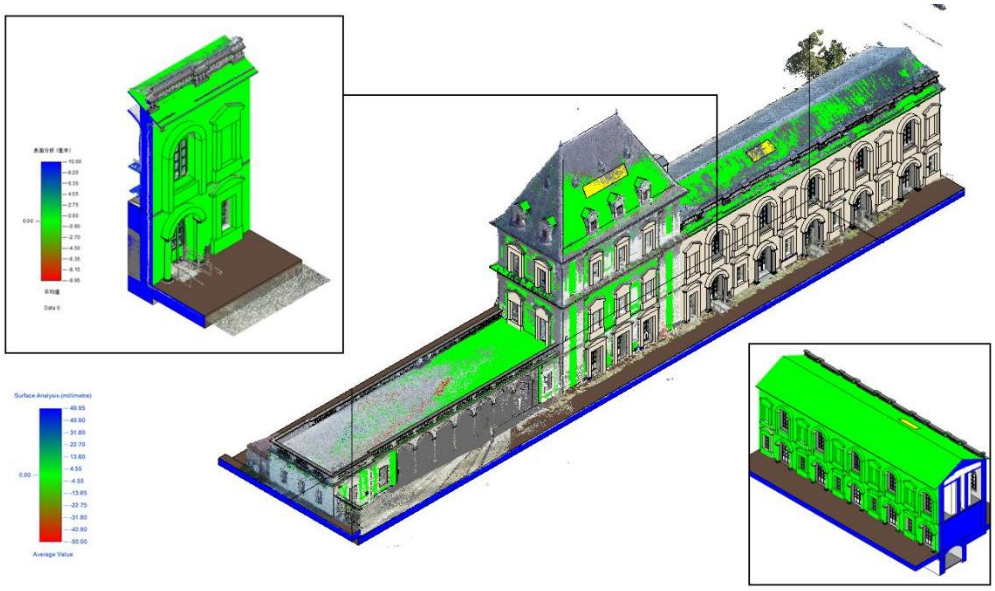


Figure 37 Deviation analysis (Distinguishing between errors and simplifications)

5.3.2 Refinability

To verify the feasibility and readability of the simplified schema, and whether it can be further modified, a unique verification method was applied in this project. The simplified model and rules were delivered to a project team member who had no prior knowledge of the simplification process. He then performed the deepening work on the model. After completing the model deepening, the deepened model was subjected to offset analysis and diachronic analysis separately, to simulate the actual project delivery. During this process, an external door and its decorative surroundings were chosen for modeling.

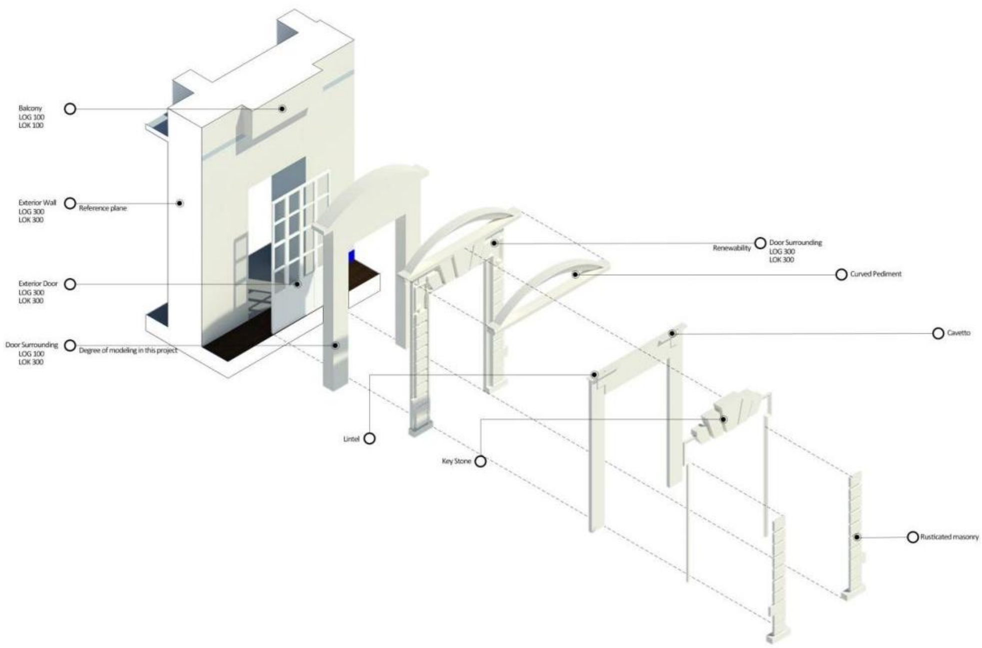


Figure 38 Exploded axonometry that shows the complex semantic decomposition of each single architectural subcomponent

Conclusion

This chapter introduces a standardized method for modeling simplification based on HBIMD, which aims to streamline the simplification steps while balancing semantic and geometric information. This approach is crucial for avoiding unnecessary in-depth modeling when high precision is not required, thereby maintaining the model's flexibility for future modifications and improvements.

During the simplified modeling process, this study identified that architectural components with a certain degree of reusability and shapes easily categorized as simple geometric forms, or custom damage modeling patches, are more suitable for the loadling families. This method facilitates subsequent model refinement and is more conducive to information management. For architectural elements that are difficult to define or have complex modeling logic (such as railings, truss systems, or stairs requiring numerous component definitions), using in-place families with simple volumes may be more efficient. However, this may render these elements' geometric forms unsuitable for structural analysis research.

Some structural architectural elements, particularly those defined as system families in BIM (such as walls, columns with simple shapes, floors, and simple-shaped doors and windows), can be automatically generated using the As-built plugin. However, the optimal method for modeling vaults remains under discussion. In-place families created through extrusion, sweep, and path generation offer simpler modeling operations, yet their accuracy and reusability present unresolved conflicts. While in-place components can meet the low requirements of geometric modeling, they may be unreliable for information management and transmission. Detailed vault modeling using Dynamo imposes high demands on the modeler's skills and proficiency, significantly increasing modeling time.

Another key aspect of this strategy is differentiating between simplification and errors. Simplified representations and metadata are stored in shared parameters and databases for reference. Concepts and relationships such as LOK, LOD, and LOG are proposed and integrated to ensure model accuracy and quantify simplification. Although this method is applicable under certain conditions, the simplified modeling process remains manual and relies heavily on the operator's knowledge of the object.

Chapter 6 Semantic data enrichment in HBIMD

After completing the simplified 3D model of the north wing of the Valentino Castle, the next step was semantic enrichment in the HBIM environment. This chapter describes how different types of information from various sources of information were stored at different levels in the HBIM model, and how they were managed using two methods. The first method was the parameter feature of Revit, especially shared parameters, which was very suitable for storing information on building elements in the Revit environment. The second method was controlling schedules/quantities through plug-ins, which was very suitable for storing global information and managing components and parameter information in Revit.

This chapter also introduces the data standards and management methods of interoperability during information transmission. Interoperability is the ability of different software applications to exchange and use data without losing information or quality. It is essential for the effective use of HBIM in the whole life cycle of heritage buildings.

6.1 Level 1. Building(Asset and program information)

This paragraph describes the information stored at Level 1: Building, which is the most extensive level in HBIMD. This level is responsible for storing information that is common to the whole building and information that is not specific to any building element. After sorting out all the information collected in the preliminary stage (see **4.2**), the information was mainly categorized as: 1. Global project information, OIR, AIR, PIR, and other information; 2. original files; 3. information that is not easily classified or structured (such as performance indicators, etc.)

6.1.1 Global project information

This paragraph describes the information requirements of the HBIM project that belong to level 1. These are pieces of information related to the whole project of the north wing of Valentino Castle and not to any specific building element. In order to make it easier to define and control various requirements and parameters at the initial stage of the project, these information documents are often shared among different parties and stakeholders in the form of spreadsheets. In order to better manage these files in Revit, external links are used:

1. Create an Excel spreadsheet of information requirements.

2. Import Excel into Revit's schedules/quantities through the Table Gen tool in the DirootsOne plug-in (**Figure 38**). By enabling the Auto Sync feature in the plug-in, the data from the external spreadsheet can be automatically updated to Revit's schedules/quantities every time the Revit project is opened.

This paragraph also describes how the essential information of the HBIM project is stored in the Revit file in the form of Revit project parameters. These parameter data are managed through the project information and global parameters in Revit Manage. Another source of parameters is the Revit project itself, which can be input through the Autodesk Interoperability Tools plug-in, such as specifying properties/attributes for the COBie spreadsheet, and the list of operators and information for the HBIM project.

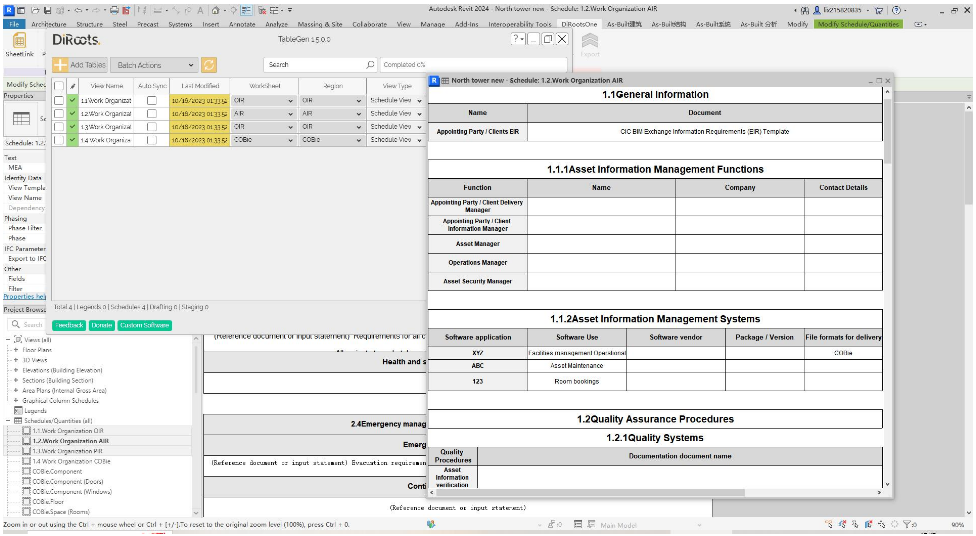


Figure 39 OIR, AIR, PIR management through TableGen in the DiRootsOne plug-in. (https://diroots.com/revit-plugins/dirootsone/)

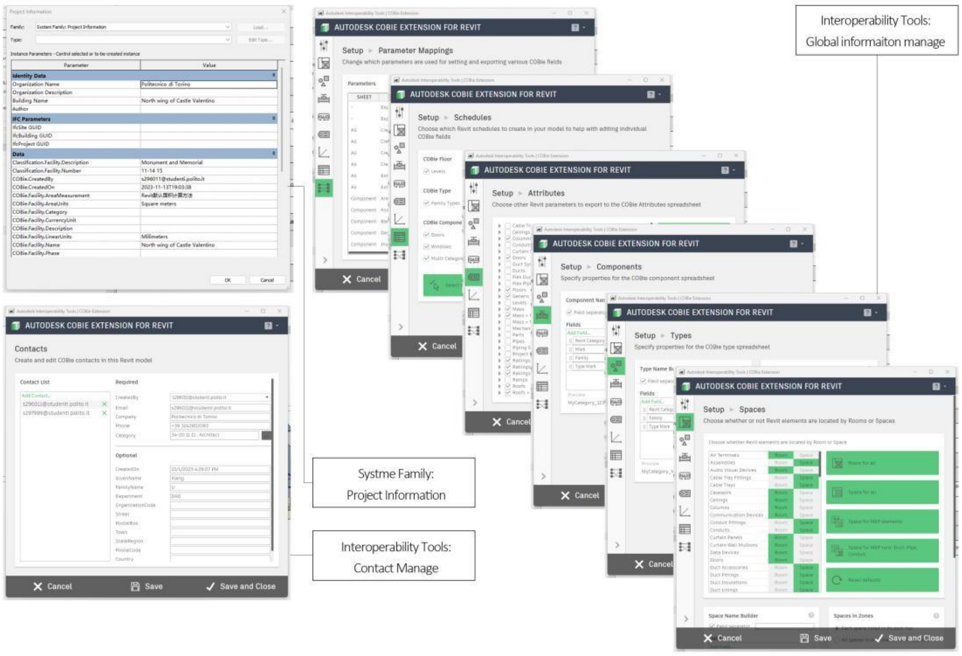


Figure 40 Storage of project information in project parameters and InteroperabilityTools plugins

6.1.2 Existing archives and documentation

Physical documents related to Valentino Castle will be converted into digital formats such as PDF, Image, video, etc., and stored in Level 1 of the data structure. The specific information in these documents can be further refined into new semantic or pictorial information and attached to the parameters of the component.

However, we encountered an issue during the storage process. Although Revit's function list includes a link management feature, its management type is limited to Revit/DWG/Pointcloud/PDF/Image, etc. This method allows for straightforward import and export, but it does not support tagging comments on the files themselves. Currently, there are numerous intelligent data platforms available for managing CH archives, and personalized Revit plug-ins and ports can be customized through API interfaces. For instance, Mèmora is a new, free, public digital platform for describing CH in archives, cultural institutions, and museums. This project, a result of long-term collaboration with Compagnia di San Paolo and Polo del'900, consolidates thousands of digital objects, cards, and inventories from hundreds of institutions into a single application. This new digital tool, created by CSI Piemonte, is based on open technologies and is user-friendly; it manages different types of cultural assets through a web interface that integrates several recently used software. However, expecting BIM operators and archive managers to fully master a new platform is unrealistic, and customizing a personalized plug-in may also be time-consuming.

In this program, a compromise approach is adopted for managing external archives and the archive directory in Revit. The Mèmora platform provides the XLSM template (Template per importazione dati archivistici) and the museum data import template (Template per importazione dati museali) for importing archival data. These templates can be imported into the Mèmora platform where they are automatically recognized and managed. They can also be imported into Revit projects using the DirootsOne plug-in. The specific operation process aligns with section **6.1.1**.

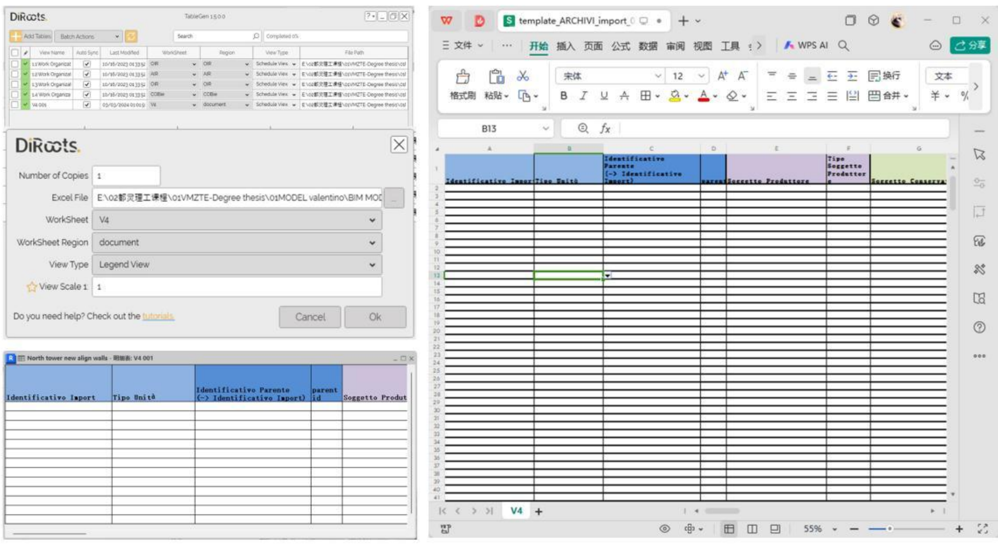


Figure 41 Mèmora documentation template(Web platform)- Excel- - Revit schedule(Diroots plug-in)

6.2 Level 2. Zones（Rooms and spaces）

The definition of Level 2 Zones is highly flexible and plays a crucial role in effective asset management. To define the relationship between facilities, components, and space more conveniently, and to manage the relevant information of a single room more efficiently, we establish an independent room information table for each room. This table includes basic spatial information, components belonging to the room, and other new information. The information in this table is input as shared parameters of the room and can also be linked to the schedule through plug-ins or Dynamo.

6.2.1 Room management

The current application of Level 2 in Valentino Castle is primarily reflected in two aspects: 1. Architectural elements are defined and assigned to different zones or rooms to facilitate information retrieval. For instance, elements such as walls, doors, and windows are allocated to their respective rooms. 2. Based on varying needs such as HVAC or ventilation systems, buildings can be segmented into specific zones and types to streamline the management of their facilities or systems. Currently, this section lacks content due to the absence of relevant data and requirements from professionals.

The parameters in the sheet are divided into four sections: 1) Basic information, which includes name, area, height, etc. , 2) Component information of the room, such as walls, doors, windows, etc., 3) Asset information, which encompasses various details such as facilities and furniture inside rooms. These details can be flexibly added or removed according to different usage needs. It's worth noting that a challenging issue arises when components like interior walls are recorded by multiple rooms, potentially leading to double counting of element information in the table. The solution adopted in this project is to have only one external room positioning parameter in the wall, but the description parameters in the room include all walls, thereby managing information on different faces of the same wall. 4) User-oriented information: This section is defined as the most flexible way to store operations, interventions, and any other information that takes place in the room alone.

Zones information Template						
1 Basic info						
Room Name	VC -NW-GroundFloor-06					
Level	Area		Height	IFCGUID		COBie
Mezzanine	13.426㎡		4.42m	04kd12Hnn5Vho3QiRZKk1e		SL_20_15_59
2 Components information						
Name	Location	Domain	Description	Information requirement	Format	Date
3 Asset information						
3.1 Facility management						
Name	Level	Description		Group/team		Date
4 User-oriented information						
4.1 (Eg.)						
Info name	Description	Work package/activity	Author	Information requirement	Format	Date

Table 5 Zones information Template(room)

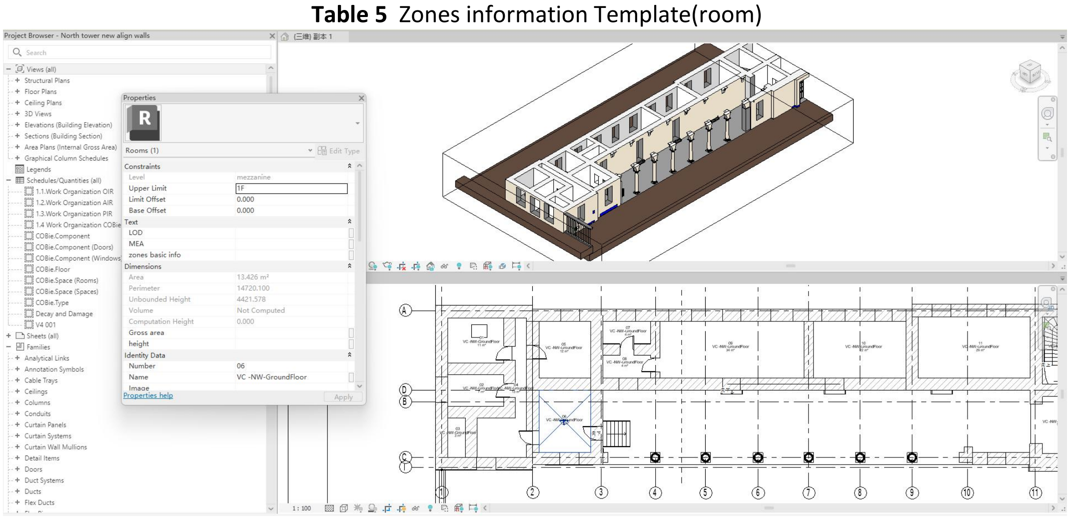


Figure 42 Shared parameters of the room are consistent with Zones information table

6.3 Level 3. Architectural Components A

Chapter 5.2 describes a simplified modeling of the geometry. To clearly distinguish between simplification and error, managing the semantic information of building components is crucial. The primary levels that manage this information are Level 3 Architectural Components A and Level 4 Architectural Components B.

6.3.1 Components management

In this project, Components A primarily define the basic information, simplified description, and description of the unmodeled parts of the north wing components to guide subsequent deepening. Simultaneously, the project's metadata accurately documents the different modeling strategies. This documentation ensures users are aware of the model's quality and reliability. Although the components are not modeled with high accuracy and precision, the metadata records the level of accuracy achieved, indirectly indicating the model's possible uses. As they belong to the respective building component entities, the information management at this level mainly manages component parameters through Revit's schedules/quantities.

The components' spreadsheets at this level are built based on COBie's defaults. The specific strategy is to automatically generate a form through the 'Create Spreadsheets' feature in the Interoperability Tools plugins. The advantage of this form is that its COBie parameters can ensure the components' interoperability. Other user-defined shared parameters such as LOK, LOG, etc., are added to this standard table.

6.3.2 Diachronic information

The diachronic analysis of the components of the Valentino Castle provides a detailed description of a special construction phase. It not only reflects the development process of the northern wing of the castle in terms of time, but also offers an information basis for its protection and repair. To further enrich the model, specific parameters were added that processed the results of the diachronic analysis of each architectural component so that filters could be used to distinguish different build phases. During this analysis phase, we tested two specific color displays. The first one is Revit's own phase function. This was used to display the time information of the component. The settings of Filters in this method were very detailed, but the process was very cumbersome.

We used the ColorSplasher by BIM One Inc, a plug-in in Revit that allows automatic execution of color schemes based on the values of elements. This way, we can add unique shared parameters to each element. For example, we defined an additional construction phase for each component in the shared parameter, and then used the BIM one plug-in to set the parameters of the components and filtering rules that need to be colored in, and customized the color matching. Currently, the plug-in has stopped updating in the Autodesk APP store, but is now available as open source on GitHub, so we downloaded and modified it ourselves to activate it in Revit 2024.

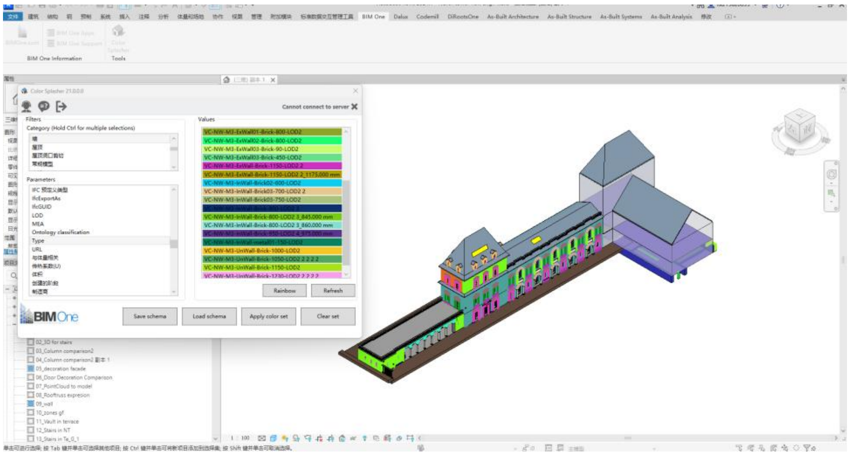


Figure 43 Diachronic analysis ColorSplasher by BIM One Inc(The parameter is set to the type of the component).

6.4 Level 4. Architectural Components B

At Level 4, Architectural Components B can either be used as a supplement to Components A or managed as a separate object, depending on what kind of component information needs to be represented. In this project, this level mainly stores decay information of building components. In Section 5.2.3, we propose a modeling strategy for building decay and damage. To summarize the previously collected damage information more accurately, we divide this section into three topics.

6.4.1 Decay and damage

The first step is the establishment of a damage catalog and term database. In this study, as described in **Section 5.2.3**, the modeling of building damage is simplified and the classification of building damage is distinguished by color. However, scientific and rigorous HBIMD should fully discuss the classification, phenomenon, and possible causes of damage. Therefore, this study mainly refers to the following books: ICOMOS illustrated glossary on stone deterioration patterns, Monuments and Sites XV, 2008, EwaGlos, European Illustrated Glossary of Conservation Terms for wall paintings and architectural surfaces and Classification scheme – Working group "Natural Stones and Weathering" , RWTH Aachen, and establishes a damage classification table, as shown in **Appendix D**.

Another step is to establish a grading system of impairment that can quantify the severity of impairment and the urgency of intervention, so that different experts and groups of people can intuitively understand the level of decay. Based on the European Norm for the Conservation of cultural property — Condition survey and report of built CH (EN 16096:2012)", the classification of damage is divided into Condition Class and Urgency Class. The former describes the degree of damage and decay, and the latter describes the urgency of intervention to deal with the decay.

Condition Class	**CC0**	**CC1**	**CC2**	**CC3**	**CC4**
Content	**No Symptoms**	**Minor Symptoms**	**Moderate Symptoms**	**Major Symptoms**	**Total Loss**
Description	Apparently without perceptible change in substance	Only superficially, without substantial changes (loss < 20%)	Locally limited damage / loss of surface (loss < 50%)	Serious damage, severe substantial loss / danger of collapse (loss > 50%)	Physically complete destruction of a building / component / element (loss > 90%)

Urgency Class	**UC0**	**UC1**	**UC2**	**UC3**	**UC4**
Content	**Without need for**	**Long term**	**Intermediate term**	**Short term**	**Urgent and**

	action				immediate
Description	Apparently without perceptible change in substance	from 3 years	1 – 3 years	within 1 year	within 3 month

Table 6 Class of Decay(Condition Class and Urgency Class)

The last step is to generate a spreadsheet of damage information for each damaged object. In this table, the damage information is divided into five sections.

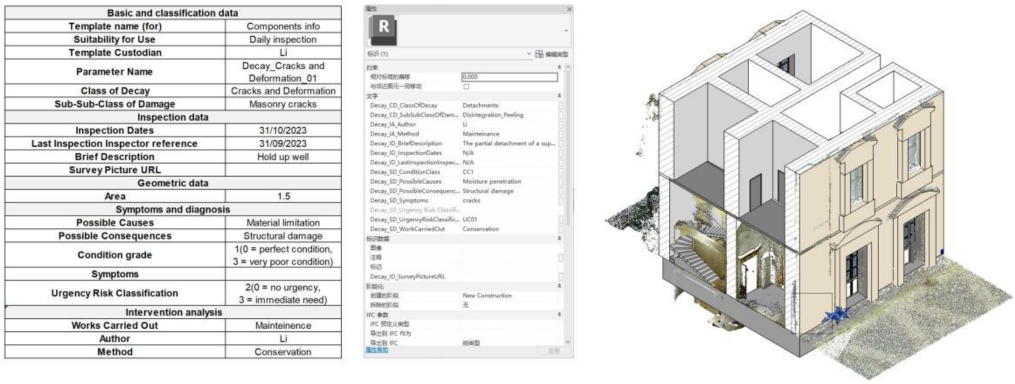
1) Basic and classification data: This part describes the basic information of the damaged object, the author of the information input and the name of the damage.

2) Inspection data: This part describes the change process of the damage over time.

3) Geometric data: This part records the geometric information of the damage, including the quantity, area and scope, etc.

4) Symptoms and diagnosis: This part describes the cause, symptoms, and related picture information of the damage, etc., in addition to the above-mentioned Condition Class and Urgency Class.

5) Intervention analysis: This part describes the overall recommendations for the impairment.



Basic and classification data	
Template name (for)	Components info
Suitability for Use	Daily inspection
Template Custodian	Li
Parameter Name	Decay_Cracks and Deformation_01
Class of Decay	Cracks and Deformation
Sub-Sub-Class of Damage	Masonry cracks
Inspection data	
Inspection Dates	31/10/2023
Last Inspection Inspector reference	31/09/2023
Brief Description	Hold up well
Survey Picture URL	
Geometric data	
Area	1.5
Symptoms and diagnosis	
Possible Causes	Material limitation
Possible Consequences	Structural damage
Condition grade	1(0 = perfect condition, 3 = very poor condition)
Symptoms	
Urgency Risk Classification	2(0 = no urgency, 3 = immediate need)
Intervention analysis	
Works Carried Out	Mainteinence
Author	Li
Method	Conservation

Figure 44 Spreadsheet of damage information and Revit Parameter management

6.5 Interoperability of information

Besides the semantic information of entity objects, interoperability-related information is also very important, which is the foundation for realizing the specification of HBIMD.

6.5.1 IFC, COBie and Uniclass

In the HBIMD of Valentino North Wing, three data exchange strategies are simultaneously used: IFC, Classification system (Uniclass/Omniclass) and COBie to meet the interoperability requirements of different stages and different information. IFC is used as an open data schema and format to support the exchange of graphical and non-graphical information, while Uniclass is used to classify both information containers and their contents. IFC is a standardized, digital description of the built asset industry. It is an open international standard (ISO 16739-1:2018) that facilitates vendor-neutral or agnostic functionality available across a variety of hardware devices, software platforms, and interfaces for many different use cases. In order to export from Revit, instances of the Revit family need to be associated with IFC classes. Category assignment in Revit is done through a dialog box, where each row represents a category or a subcategory of an element.

Classification of 'object' is an integral part in the successful delivery of interoperable data, allowing information to be organised and easily retrieved. To support the industry in assigning classification, many different organizations and governments have undertaken an alignment exercise between Uniclass and IFC, removing the need to work through a manual decision process and improving consistent selection within the industry. In addition, the Classification system is also used in the geometric model simplification strategy, as described in **Section 5.1.1**.

Construction Operations Building Information Exchange (COBie) is a specification originating from the United States that involves managing asset information (including space and equipment). It is closely related to the Building Information Modeling (BIM) approach to the design, construction and management of built assets. In June 2011, the UK Government published the Building Information Modeling (BIM) Working Group Strategy. The report announced that the government would require collaborative 3D BIM (all project and asset information, documentation and data electronically) for its projects by 2016. The software and data requirements detailed in the report were Construction Operations Building Information Exchange (COBie). In January 2019, the UK National Annex to BS EN ISO 19650-2 specified that the exchange of non-geometric information in open data formats should use the COBie format.

The requirements and specifications of the three interoperability-related formats and systems are stored in the PIR table during the project formulation phase and linked to the schedule/quantity of Revit.

	IFC (Industry Foundation Classes)	**COBie (Construction Operations Building Information Exchange)**	**Uniclass/Omniclass**
Purpose	IFC is an open and neutral file format standard for exchanging data in the building and construction industry. It is designed to facilitate interoperability between different software applications used in the AEC (Architecture, Engineering, and Construction) industry.	COBie is a standard for the exchange of facility information during the design and construction phases of a project. It focuses on delivering information that is needed for the operations and maintenance of the facility once construction is completed.	Uniclass is a classification system for organizing information in the construction industry. It provides a common language and framework for classifying and organizing information about the built environment.
Functionality	IFC provides a common data model that allows the exchange of information about a building or infrastructure project across various software platforms. It includes information about the geometry, spatial relationships, quantities, and properties of building elements.	COBie defines a set of data requirements and an exchange format that ensures the delivery of key information such as equipment lists, maintenance schedules, and warranty details in a structured and standardized way.	Uniclass categorizes information into tables, each addressing a specific aspect of the construction process, such as elements, spaces, systems, and products. It helps in standardizing the way information is organized and referenced in construction projects.
Role	IFC serves as a common language for BIM data exchange, enabling different software tools to work together seamlessly.	COBie helps in the transition from construction to facility management by providing a standardized format for the exchange of information about a facility's assets.	Uniclass supports the consistent classification of information, making it easier to manage and exchange data between different parties involved in a construction project.

Table 7 Comparison between applied standards (IFC, COBie, Uniclass/Omniclass)

IFC and COBie can be used together to exchange information throughout the building lifecycle. IFC facilitates the exchange of geometric and non-geometric data during design and construction, while COBie focuses on delivering specific information for facility management.Uniclass can be used alongside IFC and COBie to provide a standardized way of classifying information. Uniclass helps ensure that information is consistently organized and referenced throughout the project, contributing to overall data consistency and interoperability.

In summary, IFC, COBie, and Uniclass play complementary roles in the BIM process, supporting the exchange, organization, and classification of information throughout the life cycle of a construction project.

6.5.2 Manage of the standards

The project uses the AUTODESK INTEROPERABILITY TOOLS package to manage IFC, Uniclass/Omniclass and COBie. The plug-ins import the IFC format and Classification system into shared parameters. The Parameters mapping function in the AUTODESK INTEROPERABILITY TOOLS package completes the COBie parameter setting. After mapping the COBie parameters to Revit's shared parameters, the spreadsheet can be exported. Stakeholders such as different experts and managers can enter parameters in the spreadsheet. They can then return to the shared parameters through the import function.

Conclusion

The semantic information management of HBIMD depends on the standardization of information management. The framework and ontology of semantic information are an open topic. At the same time, the multi-disciplinary characteristics of semantic information also increase the difficulty of standardization. Based on the basic framework of four levels of building, area, component A and B proposed by Nazarena Bruno et al., this chapter proposes an overall management idea of semantic information in the north wing of Valentino Castle. This idea allows information management methods and strategies to be distributed on this basic framework. In addition, the project proposes the content and specifications for the input of component information and damage information. Another important part is the delivery and interoperability of semantic information, because the input and output of semantic information depend on different groups of people and experts. The formulation of interoperability specifications and system selection provide the solid foundation for achieving archive interoperability.

Chapter 7 External documentation management

In Chapter 6, we proposed a basic table template for various information that is combined with Revit parameters to manage different information. This method is highly adaptable and does not rely on additional software and skill requirements. Therefore, it can meet most of the requirements for documentation. However, documentation-oriented projects may place higher demands on data interoperability.

The project tested three different strategies for managing information. The first is the management of external spreadsheets. This strategy is regarded as a supplement to the method described in Chapter 6, with the purpose of enhancing the interoperability of table management to adapt to more filing needs. This project tested several table management methods. The first method is to connect the values of the shared parameters with an external spreadsheet using a generator. Secondly, a management method for tables generated and exported by multiple plug-ins such as Interoperability Tools and DiRootsOne is proposed, and the links between different tables are implemented through excel's own formulas.

The second strategy is external database. Since there are relationships between data in CH, Relational database management system is considered to be a suitable management system. This project uses SQL's Database manager to create and manage external database. At the same time, the data in Revit is also connected to external databases through DB LINK and CodeMill Manager.

The last strategy is documentation management on the web platform. Recently, the discussion of web- and cloud-based HBIM development has become more heated. Compared with data management or database management within the BIM platform, Web-HBIM is more interoperable: it can simplify data exchange and verification between collaborators and stakeholders, and establish a multidisciplinary approach. Currently, the vast majority of online BIM platforms are established for AEC projects, but there are fewer web platforms for heritage, and even fewer free and open-source web platforms. Hence, the last strategy will discuss the performance of the web platform application of the HBIMD project in the north wing of Valentino Castle. On the one hand, through the transfer of information on the web platform, the effectiveness of the interoperability of the documentation system will be verified. On the other hand, through implementation on different network platforms, the storage of heritage information on the web platform under the existing conditions will be explored. In addition, the issues and deficiencies of the existing web platforms will be summarized to provide a foundation and reference for promotion and renovation.

7.1 Spreadsheets management

Linkage between schedule/quantity and external tables can be achieved through Revit plug-ins such as DiRootsOne. But linking specific parameters requires more methods and management methods. At the same time, links between different tables also require some methods outside of Revit to achieve.

The first way is to use the VPL generated by the Dynamo plug-in to manage the input and output of the Excel. Taking the connection between the Revit parameters of the damaged in-place components (see **4.2.3**) and the external spreadsheet as an example, the main ideas are: 1. Filter out the damaged components that need to be assigned values in the Revit project and obtain their "ifcGUID" parameters . 2. Filter out the ifcGUID of Decay patches in the Excel table. 3. Match the ifcGUID of the damaged patches in Revit with the ifcGUID in the Excel table. 4. Assign values according to the damaged parameter names, and the order is the order of ifcGUID matching. 5. Link tables and Revit data at the same time.

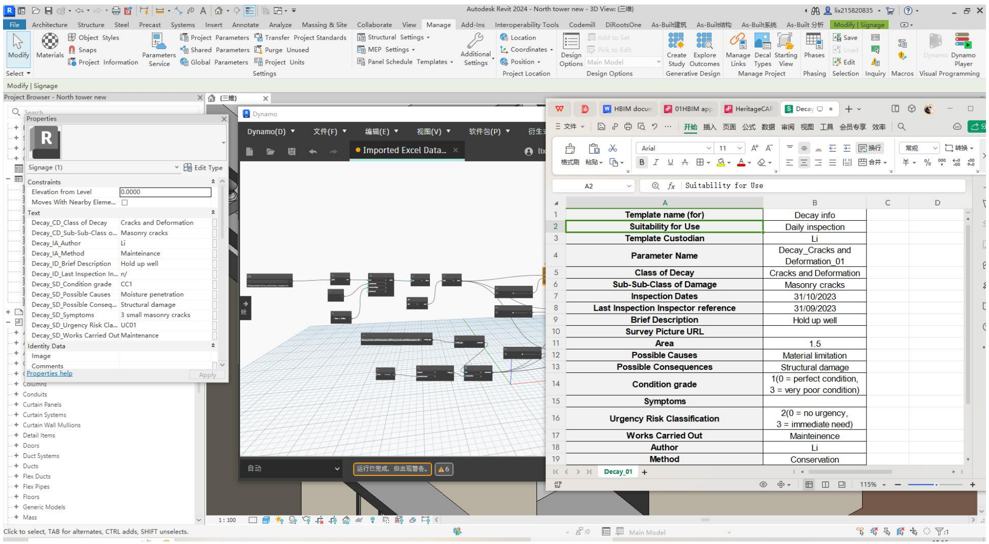


Figure 45 Parameters of Decay on the left, Dynamo script from Excel to Parameter in the middle, and Linked Spreadsheet on the right.

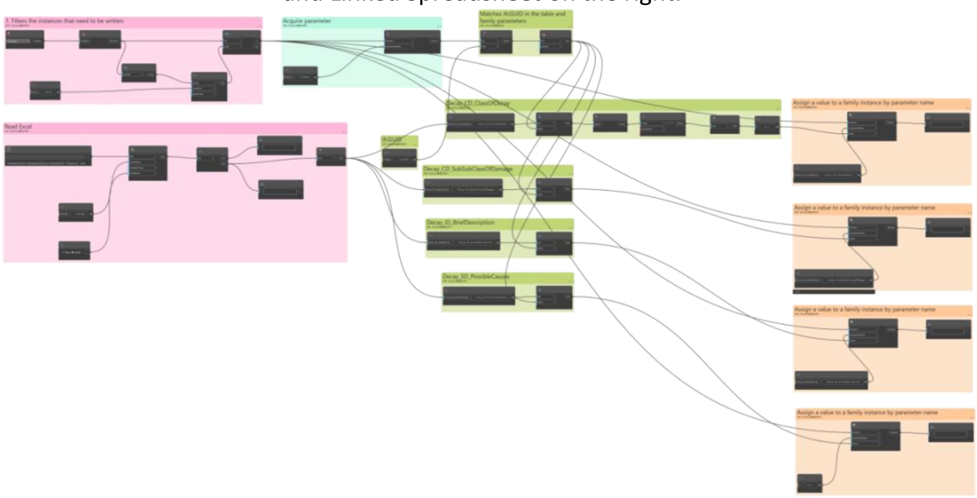


Figure 46 Dynamo script for link between Excel and Parameter

The second method is to manage the external Excel table and then import the updated parameters, which uses a widespread office software rather than external databases or Revit's Dynamo plug-in, thereby reducing the software gap in information transfer. There are two main software tested: one is Microsoft Excel and the other is WPS Office (Writer, Presentation and Spreadsheets). The first step is to export the schedules/quantities, called the main table, of a certain type or component through the SheetLink function in the DiRootsOne package. In the second step, a query table corresponding to a single component is generated based on the parameter name of the main table, and then the input of new information for any component can be completed in the respective component table. In the third step, the table information of the individual components is connected to the corresponding position of the main table through the VLOOKUP formula.

However, this method has two issues. First, the formula input part needs to be completed manually, so this method is suitable for a small number of tables. Second, the formula values in the main table are not recognized by Revit. Hence, the summarized main table needs to format all formulas to specific values before it can be correctly imported into Revit.

Another method of data transfer between tables can be completed through the data/get data/cross-sheet connection/function in Excel or WPS Office. The advantage of this method is that the data transfer is real-time and does not require repeated input and output information. First, save all the XLS files that need to be merged in one folder. Create a new summary table file, open it and click [Data Connection], click [Add] in the open worksheet connection, and import the workbook files that need to be merged into the connection one by one. Locate cell A1, click [Data Existing Connection], click on the connection file added above, then select [Table] as the display mode in the window that opens, enter [=SA1] for the existing worksheet, and click [OK]. The data can be imported for work. In addition, if there are many tables that need to be imported, it can be quickly achieved with the help of VBA (Visual Basic for Application) scripts. The script code is preset, so there is no need to learn additional code or script. Enter the code you received when prompted and save it. Return to the summary table window and click [Development Tools/Macros/Merge Worksheets/Execute]. After executing this macro, select all the workbook files that need to be imported in the opened browser window to complete the summary.

Another approach that has great potential is implemented in WPS Office. WPS Office has a large number of preset convenient formulas. One of them is the function [data/search and entry function] that can quickly update and summarize the table information of individual components in the main table. This function can automatically match information based on the header. When the information is read incorrectly, the matching parameters can be modified manually to achieve accurate connections. The advantage of this method is that it does not rely on database knowledge or programming knowledge.

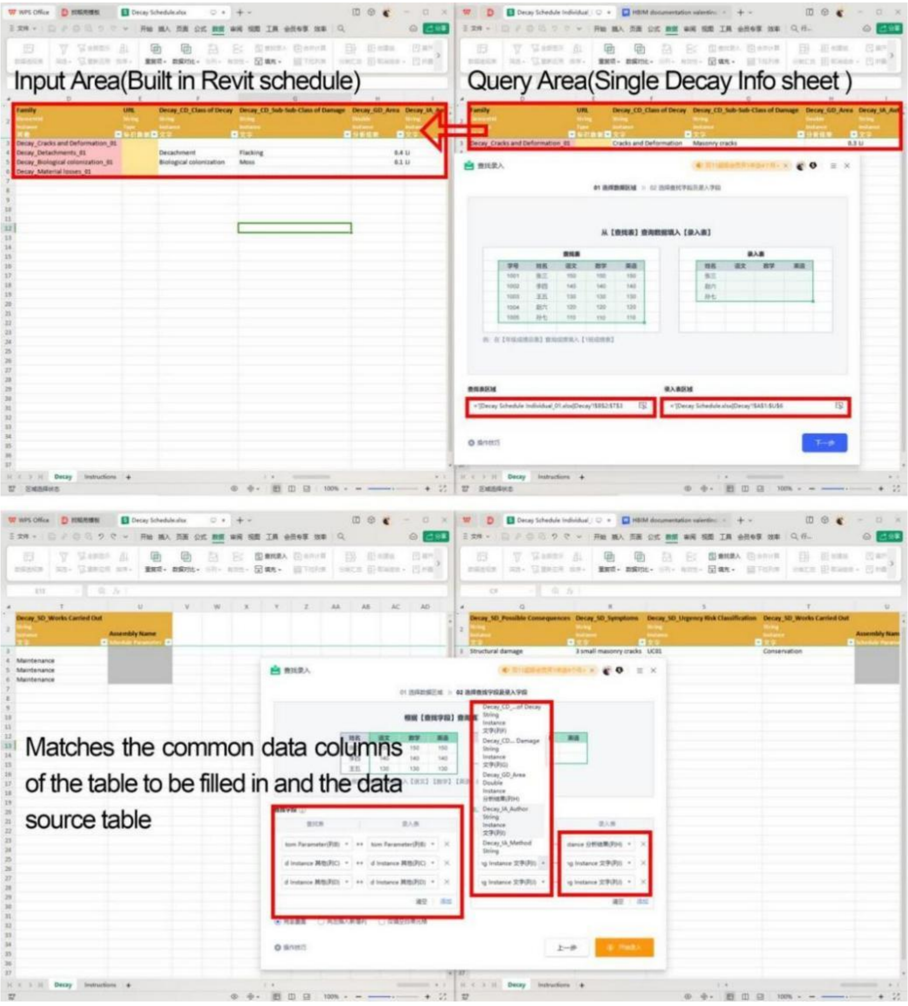


Figure 47 Predefined formula-Searching and input.

7.2 External Database

Besides the management of Spreadsheets, this project also tested External Database. In this project, all data for the north wing of the Valentino Castle was stored in a relational database and linked to objects at all levels of the 3D model. Relational databases organize data into rows and columns, which together form a table. Data is often structured across multiple tables, which can be joined together by primary key or foreign key. These unique identifiers illustrate the different relationships that exist between tables, and these relationships are often described through different types of data models. Therefore, the table information generated in **5.3** can be naturally transformed into database information. Compared with Excel's spreadsheet management, which is essentially a database format, external databases are more convenient.

7.2.1 Database system

In this project, all data for the north wing of the Valentino Castle was stored in a relational database and linked to objects at all levels of the 3D model. Relational databases organize data into rows and columns, which together form a table. Data is often structured across multiple tables, which can be joined together by primary key or foreign key. These unique identifiers illustrate the different relationships that exist between tables, and these relationships are often described through different types of data models. Analysts use SQL queries to combine disparate data points and summarize the data, enabling organizations to gain insights, optimize workflows, and uncover new opportunities.

The database and the model objects are linked by four central main entities, which provide flexibility to the database and the overall system. The link to the 3D model is based on the object ID, which makes it independent of any specific software solution. The system can interface with other RDBMS and various commercial and open source BIM software, regardless of the software used in these applications. This enables flexible data access and authoring. The system connects a conventional 3D model of the asset (created by a commercial BIM software) with a well-structured external relational database to process multidisciplinary data. The link between the 3D model and the database is ensured by a unique identification code (ID) that distinguishes each object in each BIM model. Every element of the model has a unique counterpart in the database, and any information in the relational model is associated with it (see **Figure 47**). From a methodological perspective, the choice of a specific BIM software, an RDBMS (relational database management system), or even the data structure within the database, is completely irrelevant, because the ID is the sole key to the connection.

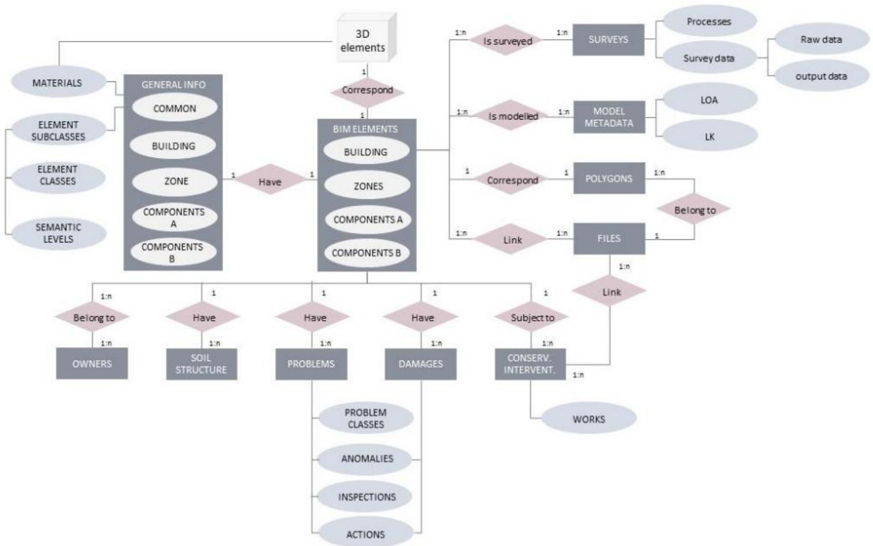


Figure 48 Entity—relationships database schema.
Source: HBIM for Conservation: A New Proposal for Information Modeling

7.2.2 Database manage tool

In this study, the database management tool used was Codemill DataManager, an Autodesk® Revit® plug-in for design and construction project lifecycle management, asset management, and facilities management. It can also be integrated with other desktop management tools. Its specific management strategy can be described by the following steps:

1. Database establishment. The database is created by Microsoft SQL server, and the link between Revit and the database is established by Codemill DataManager, or by Revit's own DB LINK module, whose architecture is shown in **Figure 48**.

2. Data management. Specifications are set up, and the management of various semantic information is standardized into table templates.

3. Revit project parameters and shared parameters. They correspond to the table template and are identified by a unique identification code (ID).

4. Codemill and Dynamo plug-ins. They jointly enable the link between the parameters in the project and the database table. Therefore, the database and the subordinate tables in the database can be used independently without depending on specific software and tools to achieve information interoperability.

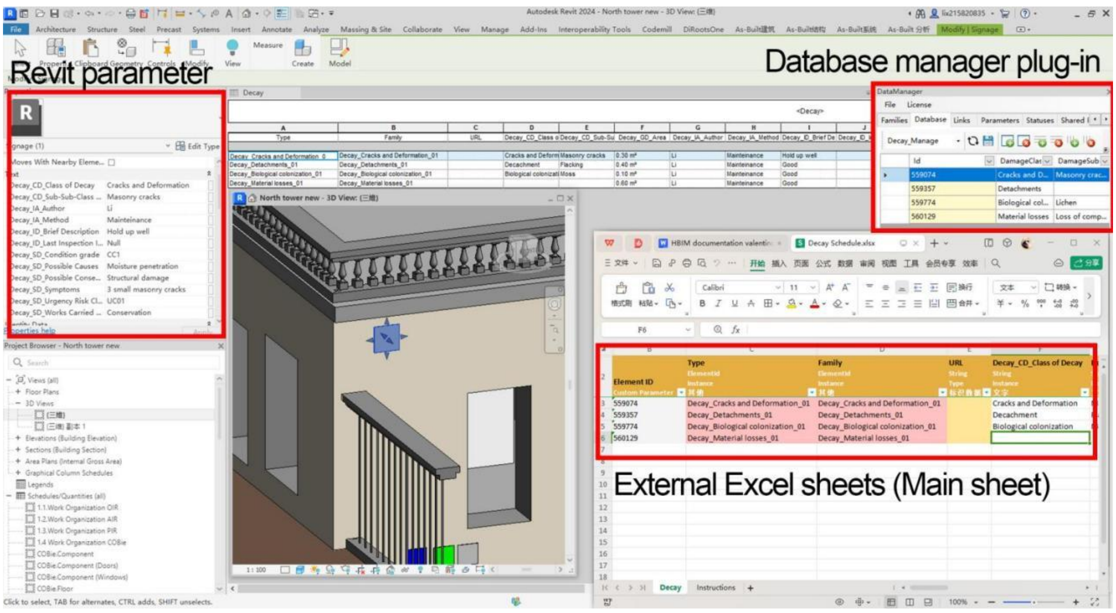


Figure 49 Codemill DataManager Plug-in to link Revit parameters, External database and External Excel

After completing the database construction and linking, a performance comparison was placed between the external database and the spreadsheet to show the pros and cons between different strategies.

Method	Dynamo	Microsoft Excel/WPS Office		WPS Office	Microsoft Excel/WPS Office	Database	
Content	Excel data to Revit Family Parameters script	VLOOKUP/XLOOKUP Formula	VBA	Predefined formula 'Query and input'	Database Link / Link to other sheets	Revit DB Link	External Database
Commercial/ Free	Free	Free	Free	Free	Free	Free	Commercial/ Free
Main Features	1. Direct link between tables and Revit, data updated in real time. 2. Flexible and customizable	1. Main Table to Single Component table connection 2. Main table to revit by DiRootsOne	Good at handling large numbers of spreadsheets	Automatically complete the input of single spreadsheet information into the main spreadsheet	1. xport model data to a database, edit and import it back. 2. Data updated in real time.	Export model data to a database, edit and import it back	Physically complete destruction of a building / component / element (loss > 90%)
Issues	1. The need for VPL knowledge. 2. Cumbersome	1. Updated information needs to be refreshed manually. 2. The main sheet needs to be saved as a copy and all formulas formatted, in order to import to revit correctly		1. Updated information needs to be refreshed manually.	Requires knowledge of database language	Requires knowledge of database language	1. Requires knowledge of database language

Table 8 Main features of the mentioned methods/tools for data management in HBIMD.

7.3 Web platform

Currently, there are many mature and comprehensive BIM network platforms. Autodesk BIM 360 is a complete and stable cloud-based online platform that is perfectly compatible with Autodesk Revit for data sharing and exchange. However, the lack of a free version and the high price are a real drawback. In addition, some other online platforms that offer free basic versions, such as Dalux and Plannerly, also have great potential and have their own unique advantages. For instance, Dalux can be considered as an alternative to Autodesk BIM 360. It includes most of the functions of BIM 360. One of the most valuable features is that Dalux provides a Revit plug-in, which can directly upload Revit files to the cloud and annotate and modify them without losing any information.

Web platforms for CH also show great potential. SICaRweb is an online information system for the documentation, planning and management of heritage sites, which integrates the geometric representation of the heritage required for restoration and the corresponding thematic maps and manages the heterogeneous information organized in a database, which has a dedicated tab for each site. The online information system is more like a public database where information can be edited and accessed online, rather than a BIM platform. However, its website structure that closely matches the CH is still a valuable example to learn from and refer to.

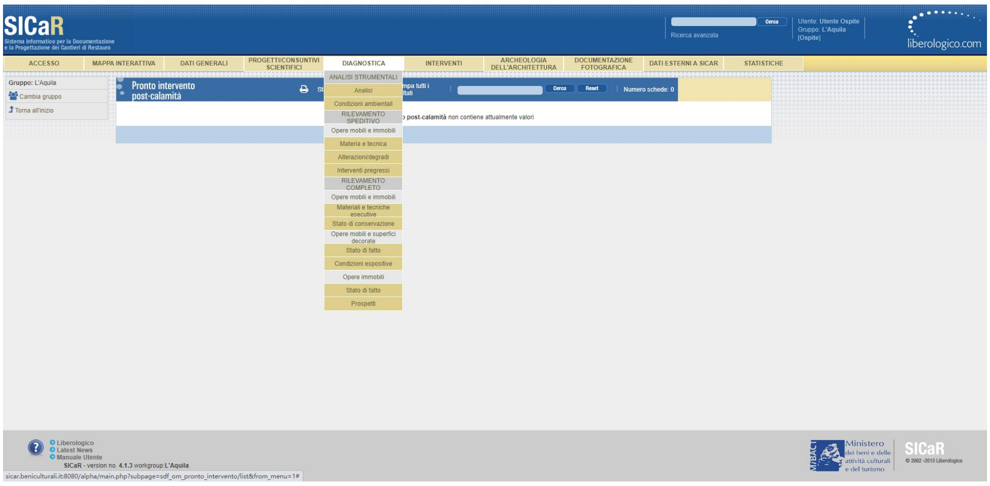


Figure 50 SICaR network platform interface

AÏOLI is a collaborative platform for sharing and enhancing knowledge on heritage objects of different sizes and types. Unlike other web platforms that use Mesh or NURBS models, it starts from the photogrammetric point cloud, and allows users to annotate the object directly, add semantic information, link to external resources, and perform multi-temporal analysis. However, since the platform relies on geometric models generated from point clouds of photogrammetry, it was not suitable for the project on the northern wing of the Valentino Castle.

With the development of web API (Application Programming Interface), many web-BIM platforms provide related interfaces, which enable the customization of CH-related functions and modules. For instance, BIMData is a very powerful FOSS system that represents a perfect match between functionality, design stability, user-friendly interface and source code accessibility. One of the most important features of BIMData is the BIM Collaboration Format (BCF) option, which allows reporting of issues and reviewing of data and documentation for consistency. BIMData is mainly based on VueJS (design system), JavaScript and XEOKIT, an open source programming 3D toolkit (WebGL SDK) developed by XEOLABS and designed for BIM and AEC. BIMData's development team is committed to sharing the source code, giving users full access to the main viewer, interface and plug-in design. In fact, the official website includes an important section covering source code documentation and tutorials; through the tutorials, all developers can access and modify/adjust the BIMData code and structure according to their specific needs. Diara F and Rinaudo F customized ARK-BIM, an online BIM platform for CH, based on the BIMData viewer and plug-in system. Currently, the website provides and opens multiple plug-in source codes for CH, such as References plug-in, Isolate Elements, Pick Stratigraphic Units, Measurements center, Edit properties, Hotspot models, etc. They can be applied in BIMData to create a customized network platform. Therefore, this project adopted BIMData as the main testing network platform.

7.3.1 Test method

The purpose of this research is to propose an overall strategy of HBIM with documentation as the core goal. The documentation work of the north wing of Valentino Castle is divided into six steps according to the documentation framework (see **3.3**). Therefore, the test will mainly focus on the performance of information storage, retrieval and management on the network platform. The specific strategies are as follows:

1. Export Rvt model to IFC format, etc. Export related external tables, documents, point clouds, and more.

2. Import into the WEB platform and set up multiple groups of comparison network platforms.

3. Verify the performance of information management methods and strategies according to the complete documentation workflow (see **3.2.1**).

4. Check the way information is transmitted (different roles in the same platform, modifications and annotations between the network platform and the Revit platform).

5. Record the missing functions and shortcomings of the network platform based on the complete workflow of HBIMD.

6. Develop an overall strategy for HBIM network platform documentation under existing conditions.

In the documentation project of the north wing of the Valentino Castle, two different types of web-BIM platforms, namely Dalux and BIMData, were mainly tested and compared as control groups. The aim of this documentation work was to lower the threshold and difficulty for HBIMD. Therefore, the documentation work on the Dalux platform aimed to explore the effectiveness and limitations of the most advanced AEC project BIM platform in HBIM project documentation, and then find a method and strategy that could efficiently create documentation on the network platform. The documentation work on BIMData focused on the potential of customized APIs in specific heritage conservation documentation topics. In addition, some other popular online platforms were also briefly tested and compared.

7.3.2 DALUX and BIMData

Unlike many BIM platforms that rely on the translation of open formats such as IFC, DALUX provides a plug-in that works with Revit, Dalux_Revit Plugin (https://dalux.zendesk.com/hc/en-us/articles/360003051773-Revit-Plugin). This plug-in allows models in Rvt. format to be directly uploaded to the cloud. The advantage of this is that all information such as views, parameters, sheets, level mapping, room properties and document properties in the Revit project can be imported into the Dalux platform without any loss, thus freeing the project from the limitations of the software.

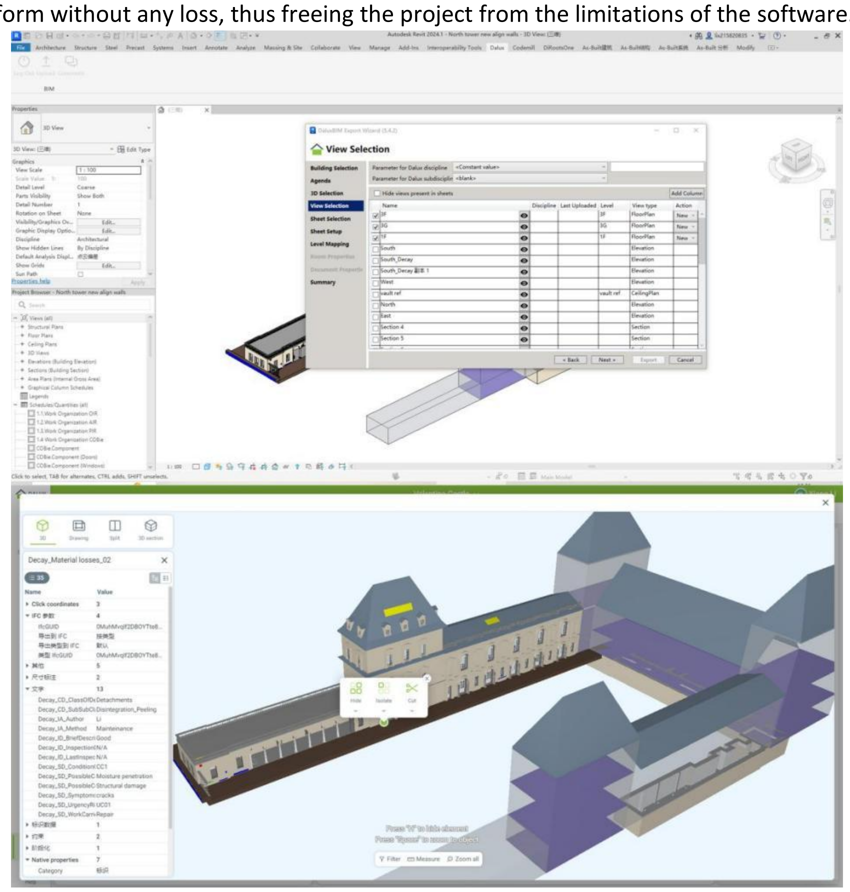


Figure 51 Dalux plug-in in the Revit interface that can upload local RVT models to the web platform

Another important function is the Comment link to Revit. This plug-in allows comments and information added by professionals on the web platform to be directly transferred to the local files of Revit, thus enabling interoperability among different professionals, managers and BIM operators. Document management can be achieved through file management, and the OCR function is embedded in the platform, so the content in the document can be directly retrieved and converted into different formats.

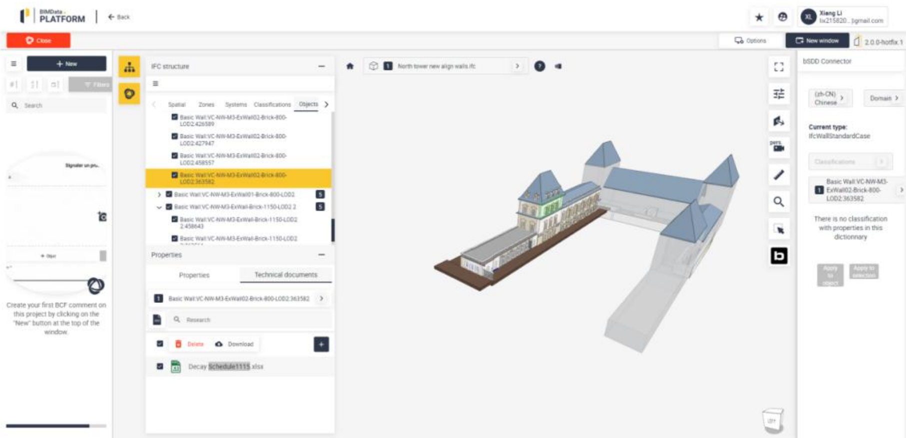


Figure 52 Interface of the Valentino Castle project on the BIMData platform

Another remarkable web-BIM platform is FOSS's BIMData. The functions of BIMData itself are enough to meet the needs of basic AEC projects, as well as the basic needs of HBIMD: BIM Model Viewer, IFC, PDF, Point Cloud, etc. Similar to DALUX, one of the most important features of BIMData is the BIM Collaboration Format (BCF) option, which can run independently of the 3D model. IFC contains data (GUID) linked to building objects and is therefore not suitable for documenting issues or workflows. BCF (BIM Collaboration Format) is an open file format that allows text annotations, screenshots, etc. to be added on top of the IFC model layer for better communication among coordinating parties. BCF was developed to simplify collaboration among parties involved in model research, allowing them to ask questions, provide answers and comment in an open file format that does not contain any model elements. The most appealing feature of BIMData is that it provides development tools that can create customized plug-ins: SDK, system design and API. Therefore, in theory, any function required by CH can be customized and developed.

7.3.3 Comparison between different web-HBIM platform

Besides the BIMData and Dalux platforms mentioned above, some other platforms were also used in the documentation work of the north wing of Valentino Castle. Tests were conducted based on the steps and key functions of the documentation project to determine how well each platform matched the complete documentation work.

Stages	Recommended Functions	Software and applications			
		BIMData	BIM360	Plannerly	Dalux
1.1.Work Organization	1. Predefined OIR/AIR/PIR/OIM/AIM/PIM	×	×	√	×
	2. Inquiry of laws and regulations	√	√	√	√
	3. Execution Plan	√	√	√	√
2.Preliminary Information	1. Management of Geometric survey	√	√	×	√

Collection	2. Semantic information collection and management	√	√	√	√
	3. OCR search in documentation	×	×	×	√
3.Point Cloud acquisition	1. Point cloud reading and support	√	√	×	×
	2. Notes and links to point clouds	√	√	×	×
4.Geometric modeling	1. Model view	√	√	√	√
	2.Filters/parameters management	√	√	√	√
5.Performance Assessment	1. Structural reinforcement(FEA)	×	×	×	×
	2.Asset mainteinance Log	×	×	×	√
	3.Inspection management	×	√	√	√
	4. Facility management	√	√	√	√
	5. Zones and rooms	√	√	×	√
6.Refurbishment Project	1. Issue management	√	√	×	√
	2. Quality control	√	√	×	√
	3. Comments 2D/3D	√	√	×	√
7.Deliverable	1.IFC transfer	√	√	×	√
	2.Database Link	√	√	×	√

Table 9 Information storage performance of several major network platforms at different documentation stages

Conclusion

As an information management platform for CH, HBIM has excellent advantages in data management. However, when dealing with interdisciplinary staff and different needs, interoperability is still an open and ongoing issue. This chapter tries three different strategies to meet the documentation needs of different people. Each of them has its pros and cons. In summary, using a spreadsheet to achieve data linkage and connection with Revit is the method that requires the least software skills. It does not require the operator to know any computer language or advanced VPL skills. However, its operation is also the most tedious, and input depends on the operator's manual input, which may introduce many errors and mistakes.

An external database is the best way to deal with massive files. Its stable data structure and database link to Revit make data management very efficient. However, the creation of external databases requires certain skills in computer languages such as SQL (Structured Query Language). Moreover, the design of database structures also needs more research to ensure the validity and durability of information storage.

Web-HBIM has become increasingly popular recently. Web applications eliminate the need for software environments, creating a more inclusive CDE that also supports multi-person management and interdisciplinary research. However, there are currently few dedicated websites for heritage, and their functions cannot fulfill all file management needs. Commercial software significantly raises the cost of project management. Currently, some open source FOSS platforms offer customizable functions, which may provide a very good basis for future archive management, but they also require programming skills for researchers.

Discussion and future work

This study aims to conduct HBIMD work on the north wing of Valentino Castle, which involves reviewing and summarizing previous data, as well as digitally translating and preserving heterogeneous data. This provides a solid foundation for future cultural heritage preservation and documentation. Despite the widespread application of HBIM technology in cultural heritage preservation projects, the inherent complexity of cultural heritage still leads to a lack of standardization and clarity in document management.

In light of this, and incorporating the latest research findings and strategies, this project proposes a document-oriented HBIM system method based on the widely used scan-to-BIM workflow. The goal is to structurally manage existing archives and semantic information from an architectural perspective, following the logical sequence of project execution stages.

Firstly, the study established a standardized research framework and workflow paradigm to provide reference and comparison for specific project workflows, quantifying the completeness of the project framework and its omissions. Secondly, for the geometric modeling of architectural elements, a detailed method for geometric simplification modeling was formulated, combining the content of building construction science with HBIM technology. Thirdly, for the semantic and heterogeneous information of the north wing of the Valentino Castle, the study introduced a four-level information framework (Level 1 Building, Level 2 Zone, Level 3 Components A, Level 4 Components B) to manage the information of different types and objects in the project. Based on this framework, external database and table management methods were established. Lastly, the study tested the implementation efficiency of the HBIM archive on the FOSS platform to enhance information interoperability, thereby achieving a more extensive multi-disciplinary research environment.

By adopting the proposed HBIM method, the preliminary documentation work of the north wing of Valentino Castle has been realized. According to the logical sequence of project execution stages, the study highlights the following findings, emphasizing the added value and advantages of this new method:

· Simplified Documentation Project Framework and Detailed Workflow: Compared to the scan-to-BIM workflow, HBIM projects aimed at documentation are not driven by preservation and restoration but by the architectural logic management of all past archives. Therefore, this workflow can be more flexibly adjusted according to the specific conditions of the architectural heritage. By setting a "complete" scan-to-BIM framework as a reference group in advance, it is clear to know the steps actually implemented and "omitted" in the documentation-oriented HBIM workflow, thereby making the documentation work clearer.

·Four-Level Information Framework and Ontology: The four-level information framework introduced by this study provides a standardized storage structure for various heterogeneous information in Valentino Castle, facilitating query and management. Meanwhile, this four-level information framework is also matched with a customized Foundation Ontology, which provides important guarantees for potential semantic web or other research in future HBIM projects. This method initially realizes information management in the HBIM environment and proves its potential in subsequent external database and ontology management.

·Detailed Geometric Model Simplification Method: To actively reduce the accuracy of geometric modeling in HBIMD to improve modeling efficiency, it is necessary to address the issue of distinguishing between intentional simplification and modeling errors. Therefore, this study designs a method for identifying architectural elements, aligned with the four-level information framework. At the same time, the study designs targeted simplification modeling methods for various types of architectural components. Among these modeling methods, the study tests various manual and semi-automatic modeling methods, aiming to lower the threshold for HBIM geometric modeling as much as possible.

·Open HBIM Plugins and Web BIM Platforms: On the official platform of Autodesk Revit and many free platforms, numerous free or commercial BIM plugins are provided. Some plugins are highly efficient in HBIM documentation management, such as Interoperability Tools, which are very powerful in component parameter management and room management. The Codemill plugin, combined with BIM's own DBLink tool, can also well realize database construction in the Revit environment while minimizing the need for mastery of database tools. DirootsOne performs exceptionally well in spreadsheets, enabling efficient and simple data transfer between semantic information in the Revit environment and office software by combining with external common office software.

Among open web BIM platforms, DALUX and BIMData stand out. BIMData, with its powerful API and open-source programs, allows any researcher proficient in software development to quickly customize functions that meet HBIM Documentation requirements. Platforms like Dalux not only support the transmission of information in general IFC formats but also enable rapid linkage between local BIM and models on the web platform through their self-developed BIM plugins, greatly enhancing interoperability.

·Application and Potential of AI Tools: Throughout the documentation work of the north wing of Valentino Castle, many tools, plugins, and platforms used have shown extraordinary advantages and potential. On the one hand, the proliferation of AI tools has greatly expanded the efficiency and methods of many tasks. In the information acquisition stage, besides the widely known tools like ChatGPT for retrieval and semantic knowledge answering, various text extraction functions in text office software and web platforms, as well as other text and image recognition technologies, can also be well utilized in the reading of cultural heritage archives. This greatly increases the semantic reading and transfer of physical archives. Additionally, AI tools are also embedded in office software like WPS Excel, where AI scripts provide data transfer functions between different spreadsheets, offering a very good approach for HBIM project management, significantly reducing the skill requirements for participants in database languages.

In summary, this method promotes the systematic, digital, and sustainable management of various heterogeneous information in the north wing, effectively reducing redundancy and ambiguity in the information transmission process. Furthermore, by associating and matching semantic information with geometric information, the readability of the information is improved. This not only lays the foundation for future standardized digital information research of Valentino Castle but also provides valuable references for other cultural heritage documentation projects.

However, the study currently faces some limitations. Firstly, geometric information modeling and the decomposition and recording of semantic information rely on manual operations, requiring a high level of proficiency in the proposed workflow, which may lead to unexpected errors and deviations. Secondly, although LOD and LOI model levels are introduced to provide reference value for model users, precise quantification methods are lacking. Thirdly, geometric modeling still faces issues of low reuse rate and low modeling efficiency. Additionally, there is a lack of geographic information management.

To address these issues, future work will consider the following four improvement directions: Firstly, establishing automated processes through visual programming and artificial intelligence technologies to advance the automation of geometric simplification modeling, thereby reducing the time cost of modeling. Secondly, introducing more scientific ontologies, using more precise structured language patterns to encode and translate various heterogeneous semantic information. Thirdly, integrating external database or spreadsheet information models into the cloud using the latest web technologies to manage and record heritage information in more widely accepted internet formats, achieving more efficient and convenient interoperability. Finally, introducing GIS information platforms to manage geographic information from a more macro perspective, thereby achieving more comprehensive management of cultural heritage information. In conclusion, this study not only advances the field of cultural heritage preservation but also sets a precedent for future HBIM documentation and management research.

Conclusion

In summary, this study proposes a document-oriented HBIM system method, providing an innovative solution for the digital preservation and management of the north wing of Valentino Castle. To some extent, this method can be seen as preparatory work for protective interventions and precise field research, aiming to create a public digital environment from an architectural perspective for subsequent research and preservation efforts. Therefore, it is necessary to standardize and simplify complex workflows, whether in geometric modeling or semantic enrichment, to enable researchers to use the model more efficiently and conveniently. In the subsequent implementation process, by actively reducing the difficulty of geometric modeling and utilizing various plugins and tools, this method also demonstrates its potential for application in different cultural heritage contexts. This offers an opportunity for recording and digitizing numerous architectural heritages that have not yet received protective interventions in increasingly adverse environments. In the future, this research will continue to optimize and expand existing methods, providing new perspectives and approaches for the digitization of architectural cultural heritage, thereby further advancing the field of cultural heritage preservation.

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During this research journey, I often felt that my research experience was like building my own house. However, a towering building is never the result of one person's efforts alone; it is the culmination of countless people's hard work. Reflecting on this challenging research path, I am deeply grateful to the many individuals who have helped me along the way.

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Appendix A

OIR Template

Organisation Information Requirements	
1.1General Information	
Organisation Name	(Add Organisation Name)
Organisation Address	(Add Organisation Address)
Organisation Section / Team	(Add Organisation section or team information if applicable)
Main Contact	(Add Contact Name)
Contact phone	(Add Contact phone number)
Contact email	(Add Contact email address)

1.1.1Organisation Management Functions (Roles and responsibilities)			
Function (Role / Responsibility)	Name	Company	Contact Details

1.1.2Organisation Management Systems				
Software application	Software vendor	Package	Version	File formats for any delivery

1.2Quality assurance procedures（1.2.1Quality Systems）	
Quality Procedures	Documentation document name
(ISO 9001 Processes)	(Identified Quality processes and quality systems should be included within any project information standards or project information production methods and procedures as relevant).

2 Organisation Policies
2.1Capital investment and life cycle costing policy
Capital investment policy
(Reference document or input statement) Strategic Asset Management Portfolio requirements including financial actuals, full year, and project forecasts to be delivered monthly.
Capital Investment requirements
Lifecycle costing policy
(Reference document or input statement) Lifecycles costing information requirements settings out asset lifecycle, capital costs, maintenance costs, resource requirements, and replacement to establish best value.)
Lifecycle costing requirements

2.2Health and safety compliance and management policy
Health and safety policy
(Reference document or input statement) Good Practice on preventative measure against COVID 19 for all students and staffs
Health and safety compliance
Health and safety management policy
(Reference document or input statement) Lifting Safety requirements.
Health and safety management
2.3Security management policy
Security management policy
(Reference document or input statement) Requirements for all cloud-based solutions to be in accordance with ISO 27000 and stored on a EU based server. All projects to undertake a security triage process prior to commencement.)
Health and safety compliance/management
2.4Emergency management and contingency planning policy
Emergency management policy
(Reference document or input statement) Evacuation requirements; Response to Medical incident; Response to Fire; andResponse to a terrorist event.
Contingency planning policy
(Reference document or input statement)
2.5Environmental management policy
Environmental management policy
(Reference document or input statement) Monitor legal duties and statutory obligations, Minimise waste generated from construction and operations;Minimise energy consumption generated from construction and operations; Identified measurable target for improving environmental performance; and Use of reduction in energy use.
2.6Sustainability policy
Sustainability policy
Monitor legal duties and statutory obligations,Use of materials from sustainable sources,Prioritise sustainability initiatives; and, Participate in circular economy approach.
2.7Supply chain management policy
Supply chain management policy
Compliance with legal duties and statutory obligations; Modern Slavery policy; Ethical working policy; Demand Management; Acquisition Management; Logistics Management; Disposal management; and Risk management.
2.8Space utilisation policy
Capital Investment requirements
Principles of Space Allocation; and Space definitions and uses.(Tour / Teaching/ Office.)
Lifecycle costing requirements
(Reference document or input statement)
2.9Risk assessment and management policy
Risk assessment requirements
Risk from fire, Security risks and management, Personal risks and management, Financial risks and management; and Risk and management associated with loss.
Risk management requirements
(Reference document or input statement)
2.10Maintenance and repairs policy
Maintenance requirements

(Reference document or input statement)
Repair's requirements
(Reference document or input statement)
2.11Asset modifications policy
Asset modification requirements
Information needs for replacement items: Information needs for minor works; and Information needs for major works.
2.12Asset operations policy
Asset Operations Policy
Information required for insurance purposes; Cleaning in accordance with manufacturer's requirements; Compliance with warranty requirements; and Compliance with maintenance regime requirements.
2.13Human resources, skills development, training, and competencies policy
Human Resources Policy
(Reference document or input statement)
Skills Development Policy
(Reference document or input statement)
Training Policy
(Reference document or input statement)
Competency Policy
(Reference document or input statement)
2.14Technologies adoption policy; and
Technology adoption policy
Adoption of proven technologies; Investment criteria for new technologies; Adoption of OPEN data standards and schemas; and Compliance with legal duties and statutory obligations.)
2.15Value management policy
Value management policy
Initial or capital expenditure requirements; Procurement, Maintenance resource and replacement costs; Environmental cost and impacts; and Social costs.

Appendix B

AIR Template

1.1General Information	
Name	**Document**
Appointing Party / Clients EIR	CIC BIM Exchange Information Requirements (EIR) Template

1.1.1Asset Information Management Functions			
Function	**Name**	**Company**	**Contact Details**
Appointing Party / Client Delivery Manager			
Appointing Party / Client Information Manager			
Asset Manager			
Operations Manager			
Asset Security Manager			

1.1.2Asset Information Management Systems				
Software application	**Software Use**	**Software vendor**	**Package / Version**	**File formats for delivery**
XYZ	Facilities management Operational			COBie
ABC	Asset Maintenance			
123	Room bookings			

1.2Quality Assurance Procedures

1.2.1Quality Systems

Quality Procedures	Documentation document name
Asset Information verification process	
COBie validation procedure	
Handover Procedure	
Asset Coding and numbering	

1.2.2Responsibility					
Identified responsibilities (using RACI) R = Responsible A = Accountable C = Consulted I = Informed	**Lead Designer**	**Designer**	**Main Contractor**	**Sub-Contractor / Installer**	**Manufacturer**

Design and performance criteria for each work package	R					
Coordinated design model			R			
Coordinated construction model				R		
As Built model delivery				R		
Provide digital O&M				R		
Provide product data						R
Provide warranty information, maintenance and operational requirements and spares					R	
COBie data						

Asset Information Requirements		
2.1AIR delivery formats		
Information Type	**Format**	**Version / build**
Models	.rvt	R2024
Drawings	.dwg / .pdf	R2024, PDF
Schedule	.xlsx	Excel 2019/ WPS
Product Data	.json	JavaScript

2.2Model breakdown structure for Asset Management			
Req.	**Element**	**Model(s)**	**Discipline(s)**
☒	Structure, Shell, and Core	Substructure, structure, façade	Structure / Architecture
☐	Fixture and fittings		
☐	Loose fittings		
☐	Drainage		
☐	HVAC		
☐			

2.3Systems breakdown Information				
Req.	**System name**	**System ID**	**Circuit IDs**	**Nomenclature**

☐	HVAC Supply			
☐	HVAC Return			
☐	HVAC Intake			
☐	Drainage Soil, below ground			
☐	Drainage Surface Water, below ground			

2.4Nomenclature

Item	Nomenclature	Example
File Unique ID		
BIM object naming		
Asset Unique ID		
Systems		
Facility		
Levels		
Zones		
Spaces		
Rooms		
Windows		
Doors		

2.5BIM Object

Requirements	Reference
BIM Object Standard	CIC Production of BIM Object Guide - General Requirements (August 2019) or later version

2.5.1Library requirements

Requirements	Reference
BIM Object Source	*(BIM Objects | Resources |*
BIM Object Library	

2.5.2Object Library Types

Object Library Types	

	BS 8541-2:2011

2.5.3Symbology requirements	
Object	**Reference**
Architectural Symbols	*BS 8541-2:2011*
Electrical Symbols	
Mechanical Symbols	

2.6Classification		
Objects	**Table**	**Description**
Entities	Table 11	Construction Entities by Function
Spaces	Table 14	Space by Form
Works Results	Table 22	Results
Products	Table 23	Products

2.7Schedule of Asset		
Asset	**Classification**	**Product Data Template** ***(Asset Template with list of properties or attributes)***
Actuator	23-27 33 00	BIM-AM MEP Asset Template
Air Blower	23-33 31 13 11	BIM-AM MEP Asset Template
Air Compressor	23-27 21 00	BIM-AM MEP Asset Template

2.8Accuracy of Information	
Item	**Tolerance**
Building structure	+/- 5mm in 1000mm
External items	+/- 10mm in 1000mm

2.9Schedule of Information Requirements	
Headings	Aspect
Legal	Details of ownership, guardianship/stewardship, leases
	Asset-related contractual information
	Maintenance responsibilities and extents
	Legal obligations/statutory and regulatory information, such as health and safety, environmental, scheduling

	Works instructions, orders, contracts
Commercial information	Asset description, which in a heritage context might include asset type or monument category, such as roofed, unroofed, ruins, etc
	Asset function
	Statements of significance, such as historical significance, commercial significance
	Asset condition and intensity of use, such as monument condition indicators
	Condition standards, minimum standards of repair
	Key performance indicators
Financial information	Cost of planned and preventative maintenance tasks
	Downtime impact/loss of revenue if monuments are closed for conservation works
	Value of defect liabilities
Technical information	structural survey records
	material specifications
	stone analysis and sourcing reports
	mortar specification and mortar analysis records
	environmental monitoring data and limits
	existing technical and geospatial survey drawings
Managerial information	Unique asset identification numbers
	Asset locations, possibly using spatial data or geographic information systems (GIS)
	Spatial data, such as space type, use, size, accessibility, availability, presentation standards
	Conservation management plans, such as risks and opportunities, conservation repair philosophy
	Cyclical/maintenance schedules and records
	Survey records, including condition, ecology, structural, high level, asbestos
	Asbestos register and management plan
	Specialist inspections
	Health and safety inspections and records, including inspection certificates, due dates
	Consent details, such as standing consent, historic consent applications
	Curatorial and interpretation details
	Collections details, records, catalogues
	Archaeological records
	Emergency plans

Appendix C

PIR Template

<table>
<tr><th colspan="7">Project Information Requirements (PIR)</th></tr>
<tr><th colspan="7">1Project scope</th></tr>
<tr><td>1.1 Project purpose</td><td colspan="6"></td></tr>
<tr><td>1.2 Project objectives</td><td colspan="6"></td></tr>
<tr><td>1.3 Project details</td><td colspan="6"></td></tr>
<tr><th colspan="7">1.4 Legacy information</th></tr>
<tr><th>Reference</th><th>Revision</th><th>Date</th><th>Information container name/ description</th><th>Format</th><th>Team originator</th><th>Location /URL</th></tr>
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<tr><th colspan="7">2 Plan of works</th></tr>
<tr><th colspan="7">2.1 Information delivery milestones</th></tr>
<tr><th>Work stage</th><th>Milestone</th><th colspan="2">Work package/activity</th><th colspan="2">Group/team</th><th>Date</th></tr>
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<tr><th colspan="7">3 Information requirements</th></tr>
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<tr><th>Work stage</th><th>Milestone</th><th>Work package/activity</th><th>Policy or external influencer</th><th>Information requirement</th><th>Information container</th><th>Acceptance criteria</th></tr>
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Appendix D

Catalogue of Damage

Theme	Deterioration Category	Deterioration Type	Deterioration Phenomenal
Structural damages / Phenomena	Total loss and collapse		
	(Partial) collapse		
	(Multiple) mechanical damage		
surface and material	Cracks and Deformation	Cracks	Structural crack / Settling crack
			Masonry cracks
			Design and construction cracks
			Incompatibility cracks
		Cracks of construction	Fracture
			Star crack
			Shrinkage / hairline crack
			Craquelee
		Deformation	Wall bulging
			Wall swelling
	Detachments	Blistering	
		Bursting	
		Delamination	Exfoliation
		Disintegration	Crumbling
			Sanding
		Fragmentation	
		Peeling	
		Scaling	Flacking
			Spalling/ Contour scaling
	Biological colonization	Alga	
		Lichen	
		Moss	
		Mould	
		Plants	Roots
		Insects	Microbes
	Material losses	Alveolization	
		Erosion phenomena	Differential erosion (back weathering)
			Loss of components, matrix
			Rounding
			Roughening
		Mechanical damages	Impacts (hole-shaped)
			Bullet holes
			Impacts (surficial)
			Cuts
			Scratches
			Abrasion – Keying
		Dissolution	
		Microkarst	
		Missing part, element	Gaps (lacuna)
			Perforation
	Discoloration / Deposit	Crust	
		Deposit	
		Discoloration	Coloration
			Bleaching / Yellowing
			Darkening / Moist area
		Efflorescence	
		Encrustation	
		Film	
		Glossy aspect	
		Graffiti / color	
		Patina / Traces of usage	
		Pollution / Soiling	
		Subflorescence	
	Human intervention	Missing fixtures (looting)	
		Relocation of fixtures and fittings	
		Improper modification/ dismantling/ finishing	
		Unsuitable change of use	
		Loss of architectural character	

		Loss of heritage values
		Improvement / rehabilitation
		Restoration / Recovery
		Replacement of loss
		Traces of use

Appendix E

Historic masonry wall

Suitability for use	Asset management		
Template custodian	HeritageCare		
Parameter name	Value	Units	Notes
Masonry wall construction data			
Construction date		Years	Example: 1500
Construction date degree of accuracy		0 to 5	0 = rough estimation without support, 5 = totally sure — Example: 2
Previous intervention dates		Years	Example: 1590, 1650, 1900, 2015
Intervention dates degree of accuracy		0 to 5	0 = rough estimation without support, 5 = totally sure- Example: 0, 5, 4, 5
Inspection data			
Inspection dates		Date	Example: 1985/07, 1994/05, 2010/05
Last inspection reference			Name, address or any other reference to track the source
Brief description			General description of last inspection
Survey picture URL			
Dimensional data			
Thickness		m	Example: 1.25
Height		m	Example: 2.55
Length		m	Example: 15.23
Wall structural data			
Load Bearing			Yes, No
Compressive Strength		MPa	
Elastic Modulus		MPa	
Type of Wall			Single leaf, Multiple leaves.
Morphology			Bond Type
Joint Type			“Dry Joint”, “Mortared Joint” or “Other”
MQI_SS (Stone Shape)			NF, PF, F
MQI_WC (Wall Leaf Connection)			NF, PF, F
MQI_HJ (Horizontality Bed of Joints)			NF, PF, F
MQI_MM (Mortar Properties)			NF, PF, F
MQI_VJ (Vertical Joints)			NF, PF, F
MQI_SM (Stone/Brick Mechanical Properties)			NF, PF, F
MQI_SD (Stone/Brick Dimensions)			NF, PF, F
Stone characterization			
Stone Type			Example: Granite, Basalt, Limestone
Stone Origin			Fill this if you can track the origin of the stone
Stone Hardness			Mohs scale.
Stone Density		kg/m3	
Stone Porosity			
Stone Compressive Strength		MPa	
Stone Tensile Strength		MPa	
Stone Elastic Module		MPa	
Deformation			
In Plane Deviation		m	From Damage Atlas HC

Out of Plane Deviation		m	From Damage Atlas HC
Buckling		m	From Damage Atlas HC
Leaning		m	From Damage Atlas HC
Bending/Bulging		m	From Damage Atlas HC
Excessive Deflection	Template name (for)	m	From Damage Atlas HC
Lateral Buckling		m	From Damage Atlas HC
Asset management (maintenance)			
Operation and Maintenance Manual			Hyperlink to Manufacturer O&M Data
Daily			Maintenance tasks or SFG20 codes
Weekly			Maintenance tasks or SFG20 codes
Monthly			Maintenance tasks or SFG20 codes
Quarterly			Maintenance tasks or SFG20 codes
6 Monthly			Maintenance tasks or SFG20 codes
Annually			Maintenance tasks or SFG20 codes
Bespoke Timeframe			Maintenance tasks or SFG20 codes

Appendix F

Metric survey method

	Cultural Heritage objects						
		Buildings			Movable assets		
			Indoor				
Method	Large heritage areas	Outdoor	Spacious areas	Narrow areas	Large-medium scale assets	Small-scale assets	Underwater heritage
Close-range terrestrial photogrammetry	••	•••	•••	•	•••	•••	•••
Close-range aerial photogrammetry	•••	•••	••	‡	‡	‡	‡
Static laser scanner	••	•••	•••	•	••	•	••*
Back-pack mapping	•••	•	••	•••	•	•	‡