Politecnico di Torino
Department of Architecture and Design

Master of Sciences in Architecture for sustainability

2025

Enhancing HBIM Visualization and Multi-Scale Modeling for the Conservation of Palazzo Reale, Turin

Supervisor: Prof.ssa Nannina Spano (Politecnico di Torino)

Author: Hadi Babakhani (s313708)

Abstract

This thesis investigates the application of Historic Building Information Modeling (HBIM) for the conservation and management of the Palazzo Reale (Royal Palace) of Turin, a UNESCO World Heritage Site. The research aims to demonstrate how integrating digital technologies with heritage documentation can support effective preservation strategies.

The study develops a general HBIM workflow combining terrestrial laser scanning (TLS), close-range photogrammetry (CRP), and archival 2D drawings to create a multi-scale 3D representation of the palace. Recap used to register point clouds, Meta shape processed photogrammetric meshes, and Revit served as the core platform for parametric modeling. Cloud Compare has been used for validation through point cloud and mesh comparisons. Levels of Detail (LODs) ranging from 100 to 400 were applied according to data availability and conservation priorities. Higher levels of detail were used for areas such as the ceiling of the Salone degli Svizzeri and the Courtyard facades, while simpler volumetric modeling was adopted in parts with limited survey coverage.

The achievements highlight the benefits of using HBIM to document and analyze complex heritage architecture. The priority of focusing on precise geometric modeling rather than extensive semantic enrichment was by purpose, when having accurate space information is important for checking structural conditions, planning conservation to work with confidence, and making sure interventions rely on real measurements rather than assumptions. The study also faced challenges like areas hidden by vegetation, differences in data quality, and the complicated details of historic decorations. These issues were handled through flexible modeling methods and by carefully matching different types of data.

This research helps the field of heritage conservation by showing that HBIM tools can be easily adapted to support the recording, analysis, and management of historic sites. The progressed workflow offers a repeatable framework for similar heritage projects. Future work is recommended to enhance interoperability, standardization, and interdisciplinary collaboration to ensure wider adoption of HBIM Exercises. Overall, the project reflects the potential of digital

technologies to balance technical precision with cultural value in the preservation of historic buildings.

Acknowledgements

I would like to express my deep thank to my supervisor, Prof. Antonia Teresa Spano, which her expertise, patience, and continuous guide make this thesis helpful. Also, I want to thank to the Geomatics Laboratory at Politecnico di Torino for providing the photogrammetric datas and technical helpful Tipps. I am grateful to my family and my dear fiancé, Abigail Galartza for their support during this time for supporting and sacrificing the time and energy to help me finishing this process.

Table of Contents

INTRODUCTION

Section 1. Introduction

1.1 Importance of Digital Conservation

Today, preserving historic fabric is more than just protecting the physical structure itself. As UNESCO has noted, the rapid development of digital technologies is providing the cultural heritage field with unprecedented tools to safeguard, document, and share cultural resources. New tools such as 3D scanning, Building Information Modeling (BIM) have become inseparable parts of contemporary conservation practice. These technologies not only improve the accuracy and validity of documentation but also expand access to heritage materials for education, cultural tourism, and public engagement. Accepting new digital ways with traditional conservation methods provides an opportunity to strengthen urban resilience and reinforce the durability of historic places in designing community identity. Historic buildings like palaces and churches are not only Artistic works. Their deep connection with their cultural environment helps teach and inspire people during the time.

(UNESCO, 2023)

Among the many historic landmarks in mainland Italy, the Palazzo Reale in Turin is especially notable for its scale and significance. In this thesis, it will be used as a central example to illustrate the House of Savoy at the height of its power. The palace was first commissioned in the late sixteenth century, when Duke Emmanuel Philibert established Turin as the capital of his duchy. Over time, it expanded to meet changing political, civic, and artistic needs. Many architects helped for development of the Palazzo Reale, including Ascanio Vitozzi, Amedeo di Castellamonte, Filippo Juvarra, Benedetto Alfieri, Pelagio Palagi, and Emilio Stramucci. For the years, the building was expanded, It restored, and partially rebuilt after wartime damage. Combining Renaissance foundations, Baroque splendor, and nineteenth-century additions such as the Manica Nuova makes this building a masterpiece. Some parts were changed to be used as offices, but the ceremonial halls retained their original role as shape of dynastic prestige. This long history, including many restorations after World War II and again in recent decades, It shows the palace remained important for power and culture. Today, the Palazzo Reale is part of the Musei Reali di Torino and is recognized by UNESCO as one of the Residences of the Royal

House of Savoy, and it has been a UNESCO World Heritage Site since 1997. The highly decorated interior parts and highly detailed facades show the centuries of cultural and artistic heritage in Piedmont. This complexity makes the palace a great case study for exploring how digital technologies can help document, analyze, and preserve architectural heritage for future generations.

(Rovere, 1858; Musei Reali di Torino, 2021; MuseoTorino, n.d.)

Figure1.1. Palazzo Reale, Turin.

This thesis will examine HBIM as an approach for recording and managing historic buildings. While BIM is designed to support the development of new buildings based on rules set before, HBIM is for creating historical models that combine detailed geometric data with conservation and management data. This way also has great potential to improve how we understand and care for heritage sites, but it also brings challenges. Irregular geometries, fragmented archives, and the absence of shared data standards can complicate the modelling process. Also, the material decay in heritage buildings needs flexible methods that use historical knowledge along with today's conservation goals. However, HBIM is still valuable because it can bring together many data and help create preservation plans.

(Lovell et al., 2023)

In recent years, the Palazzo Reale has been used as a site for digital conservation experiments. Since 2021, it has served as a testing ground for the Take Care project, a multi-year initiative coordinated by the Musei Reali di Torino. The project combines laser scanning, HBIM modelling, and risk assessment to develop a comprehensive conservation and maintenance strategy. Areas including the southwest tower and the Salone degli Svizzeri have been digitally surveyed to analyse structural and environmental vulnerabilities. These efforts demonstrate that digital conservation is not only theoretically feasible but can be effectively applied to guide restoration and museum management practices. The Take Care project also focuses on integrating historical research, spatial analysis, and long-term maintenance planning, reflecting the need to safeguard cultural heritage sustainably.
(Feroggio et al., 2024)

1.2 Scope and Objectives

This research explores the suitability of Historic Building Information Modeling (HBIM) as a method for documenting historical structures. HBIM approaches historic building documentation through the creation of retrospective models that integrate accurate geometric measurements and conservation, related information for management purposes. The approach demonstrates significant potential to enhance heritage site understanding along with sustainable stewardship but also generates various operational difficulties. The modeling process becomes more difficult when working with irregular building shapes and incomplete archival records, and when there are no established data standards. The natural deterioration of cultural heritage, together with material uncertainties, demands flexible processes that can merge historical information with existing conservation demands. HBIM derives its worth from its capacity to unite scattered data while becoming an essential platform for creating informed preservation approaches.

(Lovell et al., 2023).

This research shows a motivation that comes from a growing understanding that HBIM works as an important tool for recording cultural heritage and doing conservation work. HBIM offers progressive tools by mixing exact forms with historical data in one unit platform. In this project, the main focus was on creating accurate shapes to help conservation decisions, not on adding a lot of extra information. Because of focusing on this target, the research shows how detailed spatial data can help to model complex building and make restoration plans that match with the real measurements.

The choice of Palazzo Reale in Turin as the main topic of this research was based on many important reasons. The palace is a mix of Renaissance, Baroque, and Neoclassical architecture, and it gives a good opportunity to test digital modeling methods. Its role as a pilot site in the Take Care project at the Musei Reali di Torino also allowed the team to bring together high-quality survey data by using laser scanning and photogrammetry for HBIM. The site offered an ideal case study to evaluate the strengths and limitations of HBIM approaches in real-world heritage conservation.

The main goal of this thesis is to develop and test an HBIM method that can create a multi-scale, detailed digital model of the Palazzo Reale. The research aims are:

1) Build a clear HBIM model by bringing together different spatial datasets.

2) Apply variable Levels of Detail (LOD) and Levels of Information (LOI) to reflect both data availability and conservation priorities

3) Evaluate the accuracy and consistency of the model using quantitative methods

4) Assess the model's potential as a tool for restoration planning, documentation, and public communication.

By meeting these goals, the project helps improve HBIM methods and shows how they can be used in real life to protect one of Italy's most important historic buildings.

HISTORICAL FRAMEWORK

Section 2. Historical Framework of Palazzo Reale

2.1 Chronological Development

The Palazzo Reale di Torino exists as a single continuous entity because of multiple historical periods that molded its construction to match the evolving needs of the House of Savoy and shifting architectural preferences and functional requirements. The palace evolved from its initial religious leadership function to become a royal residence where each development phase shaped its architectural structure and built heritage, which now forms a complex identity for the building.
(Rovere, 1858; MuseoTorino)

Figure 2.1. View of Piazza Castello designed by Ascanio Vitozzi in the general renewal program of Turin desired by Carlo Emanuele I, from Theatrum Sabaudiae, I, plate 11, (Historical Archive of the City of Turin)

Until the middle of the sixteenth century, the area that later became one of the city’s most important landmarks was not considered part of the court. Within the walls of the ancient Roman city, it housed the Cathedral priests' residences, the bishop's palace, cemeteries, and gardens. Following his return from war and the choice of Turin as his duchy's capital in 1562, Duke Emmanuel Philibert soon realized that if the seat of power was to represent his goals, the complex of Gothic and ecclesiastical structures had to give way to architecture that could openly declare his dominance. Instead of trying to restore what was left, he gave the order to have it

destroyed and to build a new palace that would better reflect the Glory of his court. The canons' residences were cleared during the initial building campaigns, and the original core of the palace was built. The space behind the second courtyard, which is where the modern northern wing of the Palazzo Vecchio is located, was part of this early stage. King Henry III of France had already been to this section of the house in 1574.In addition to establishing a policy of constant expansion that succeeding generations would carry on and expand, these early attempts clearly articulated the goal of building a palatial center that could compete with the courts of other European rulers.
(Rovere, 1858)

The scale and architectural program of the palace were most decisively defined during the seventeenth century. Although the Palazzo di San Giovanni also known as the Palazzo Vecchio predated Charles Emmanuel I’s reign, having originally served as the Bishop’s Palace and later incorporated into the complex by Emmanuel Philibert, it was during Charles Emmanuel I’s time that the residence underwent significant reorganization and enlargement. The palace expanded towards the cathedral, with new wings and connections linking the existing structures to the Castello. Architects such as Ascanio Vittozzi and Maurizio Valperga played critical roles in this transformation, designing grand galleries adorned with portraits of Savoy ancestors, scenes of conquest, and representations of saints invoked by the ruling family, thereby reinforcing the dynasty’s claim to legitimacy.

Figure 2.2. View of the Royal Palace of Turin from the Theatrum Sabaudiae, showing the Baroque façade and organized courtyards developed under Amedeo di Castellamonte after 1646, (Historical Archive of the City of Turin)

The siege of 1640 severely damaged much of the palace during the regency of Madama Reale Cristina di Francia. Recognizing both the symbolic value of the residence and the inadequacy of earlier structures, she commissioned a new construction campaign. In 1646, Amedeo di Castellamonte, son of Carlo di Castellamonte and Ascanio Vitozzi, who had contributed plans for the palace’s earlier development, was appointed to redesign what would become the Palazzo Grande. His project introduced a monumental Baroque façade facing Piazza Castello and an arrangement centered on ceremonial apartments, transforming the palace into a residence meant to convey dynastic prestige and modern functionality. Realizing this vision required the demolition of numerous older buildings and the use of materials such as bricks produced in Valdocco and marble extracted from Chianoc.

(Rovere, 1858)

A network of painters, sculptors, and craftspeople enhanced the interiors as the main structure developed. While Bartolommeo Caravoglia, Giovanni Andrea Casella, and others created intricate allegorical programs in the principal halls, Giovanni Miele, a former court employee, created ceiling paintings. Pietro Botto, Bartolommeo Botto, and Quirico Castelli all contributed

carved woodwork that brought the rooms together with a common decorative language. Carlo Morello created the terraces and porticoes that surrounded the main courtyard at the same time, giving the complex a sense of formal unity. The fundamental components of this change were mostly in place by the early 1660s, despite the fact that work was occasionally halted by local political events and financial difficulties.
(Rovere, 1858)

Figure 2.3. Anonymous engraving from the series produced for the 1737 wedding celebrations of Charles Emmanuel III, depicting the Royal Palace of Turin illuminated for the occasion, (Ministero della Cultura, Catalogo Generale).

After Charles Emmanuel II married Françoise of Orléans in 1663, important interiors were finished. To commemorate this union, the Duchess's Cabinet and the Alcove Room were embellished with symbols like the Savoy cross and the French fleur-de-lys. Through allusive narratives, the dynasty was even glorified in the iconography of places like the Gabinetto degli Enigmi. The Duke temporarily withdrew to the Castello in 1664 after the duchess' untimely death momentarily disrupted court life. The palace was once again the main seat of the Savoy court following his remarriage to Madama Reale Giovanna Battista di Savoia-Nemours. Bernardino Quadri created marble decorations during this time, while Bernardino Casella and Deodato Barnello created mosaics. Collectively, these pieces helped create interiors that reflected seventeenth-century court culture through their rich finishes, carved boiseries, and narrative ceilings.

(Rovere, 1858)

Figure 2.4. Filippo Juvarra (designer), A. Maisonneuve (engraver), *Illumination du Palais Royal*, ca. 1700–1725, Royal Palace of Turin, (Ministero della Cultura, Catalogo Generale).

Filippo Juvarra completed the most important Baroque renovation of the palace in the eighteenth century. The interior spaces gained a formal look, thanks to the architectural drawings and section plans made at that time. This information, kept in libraries and archives and reused in later books, shows how Juvarra's design combined ceremonial use with the experience of the space. His famous Scala delle Forbici was not only a way to move between floors but also showed architectural rank and status.
(Rovere, 1858; Biancolini, n.d.)

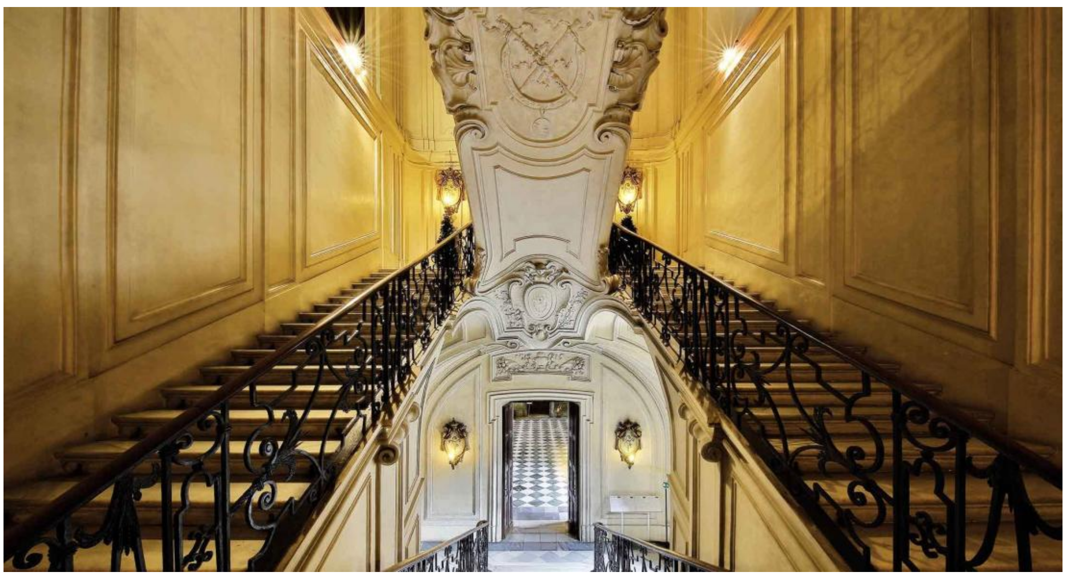


Figure 2.5. The Scala delle Forbici, designed by Filippo Juvarra, exemplifies the Baroque renovation of the Royal Palace interiors in the eighteenth century. The staircase integrates ceremonial function with spatial grandeur, serving both as a practical route and a statement of architectural hierarchy and status. (MuseoTorino digital archive).

The palace underwent a significant makeover in the late nineteenth century following a protracted eighteenth-century period of more gradual alterations. The Manica Nuova, a further north-west expansion that reshaped the palace's perimeter and produced new areas for representation and administration, was designed by architect Emilio Stramucci between 1899 and 1903. The last significant expansion before the twentieth century was this addition. (MuseoTorino, n.d.; Musei Reali di Torino, 2021).

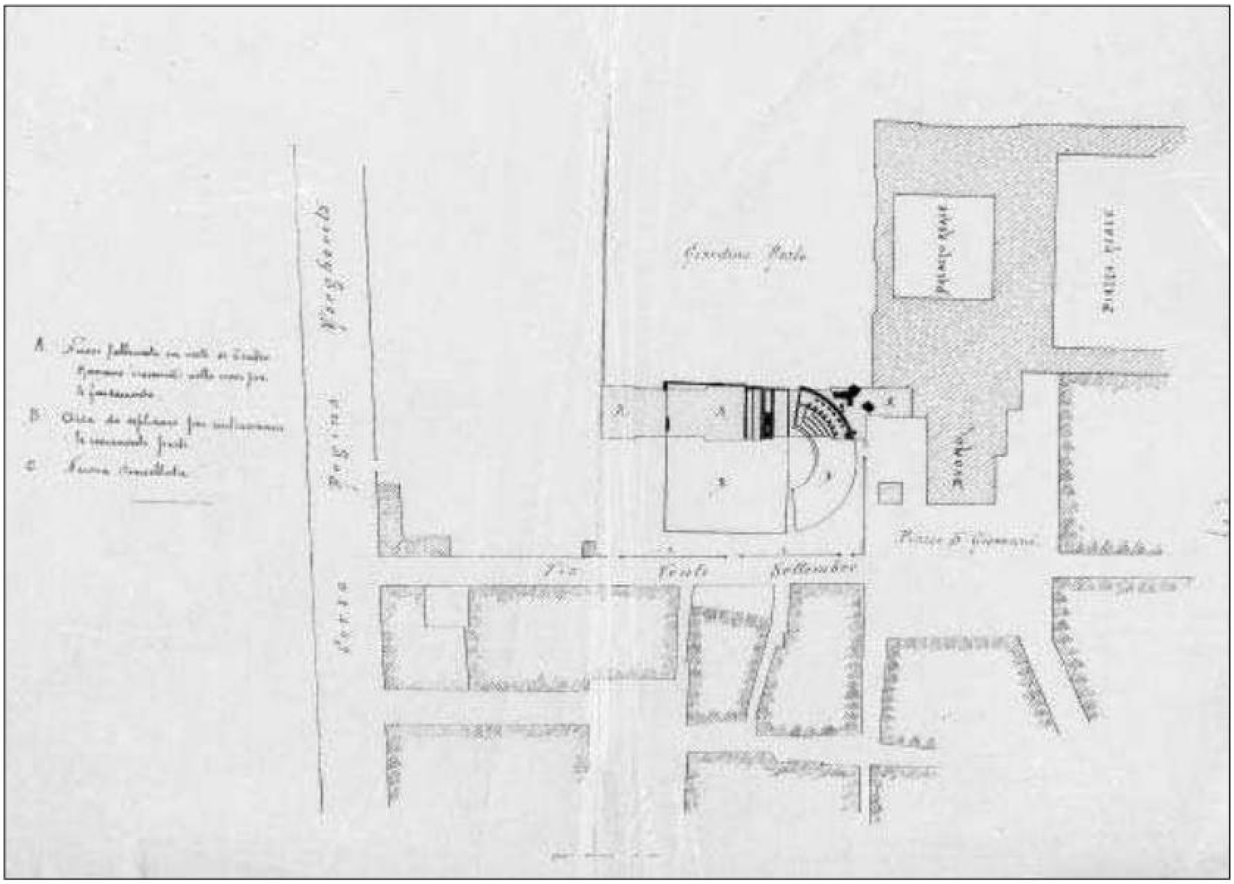


Figure 2.6. It shows the plan by the Technical Office of the Provincial Directorate of the Royal House in Turin, identifying the remains of the Roman theater incorporated into the construction of the Manica Nuova in autumn 1906.

2.2 Early Surveys and Architectural Documentation

This section explains the architectural history of Palazzo Reale and shows how it changed to fit new artistic styles, royal plans, and ways to protect it. The architectural drawing by the French court architect Robert de Cotte from 1690 is one of the oldest surveys we know. The Chapel of the Holy Shroud and the surrounding palace rooms are precisely laid out in this sheet. As showed by these architectural informations, the palace was already is included into a larger ceremonial and religious framework at this early stage, and de Cotte's visit shows that the Savoy court had international connections.

(Musei Reali di Torino, 2021; Biancolini, n.d.)

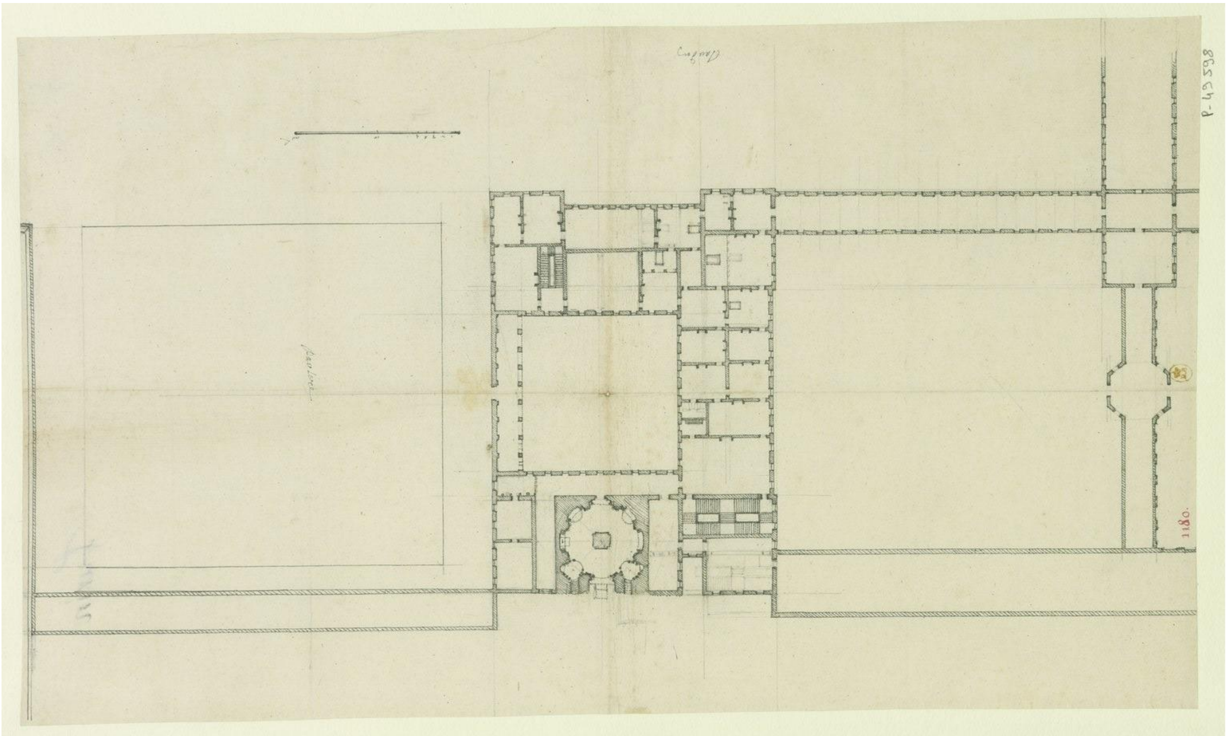


Figure 2.7. Robert de Cotte, Palazzo Reale, Turin, plan of piano nobile, pen and ink with traces of pencil, 1690

Source: Bibliothèque nationale de France

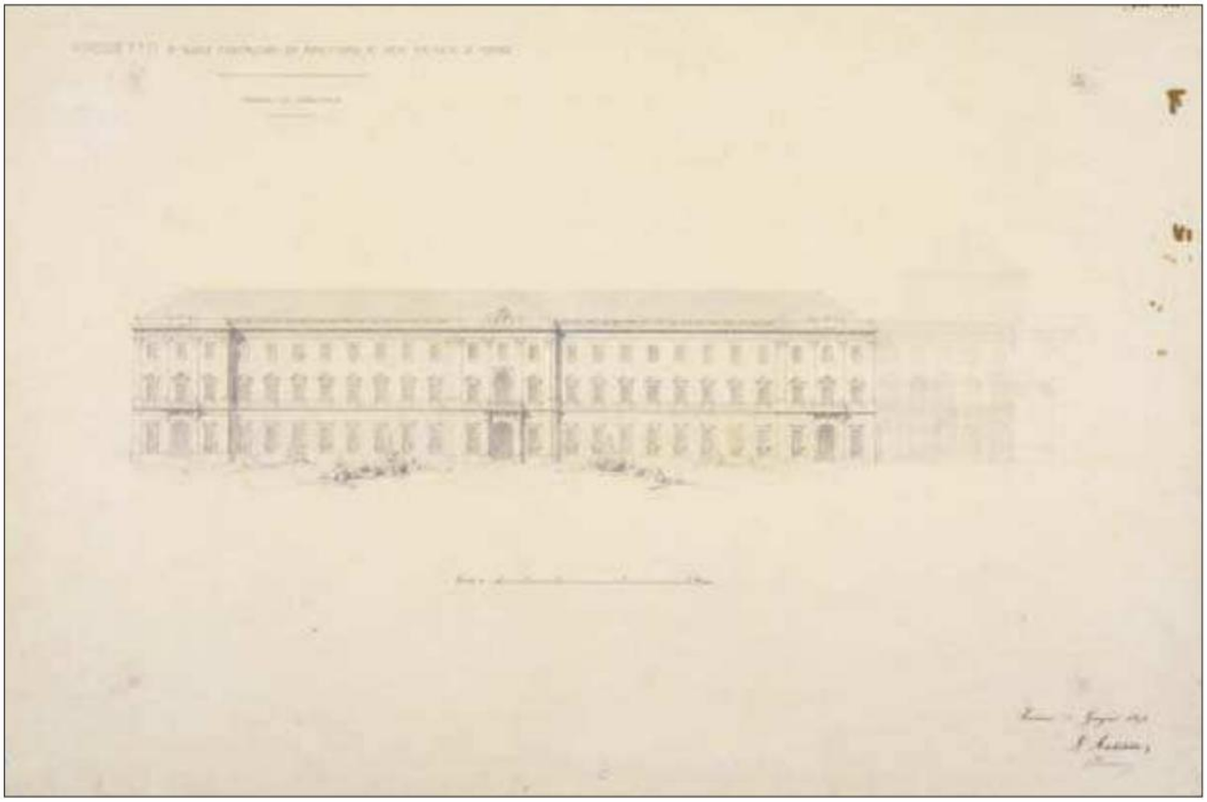


Figure 2.8. These show Stramucci's projects for the new constructions added to Palazzo Reale, dated around June 1894, highlighting his architectural interventions in the palace.

In the late nineteenth century, preservation as a separate goal started to gain traction. When Emilio Stramucci took over as the Royal Household's chief architect in 1888, he redecorated ceremonial rooms, rearranged portions of the interiors for administrative purposes, and made major structural reinforcements. His work represented a shift in perspective, viewing the palace as a national monument in need of constant maintenance and modification in addition to being a representation of monarchy.

(Feroggio et al., 2024; Musei Reali di Torino, 2021).

As photography got better, the visual view became more important. Around 1925, Mario Gabinio took a famous photo of the palace facade. After that, this picture has been used to track changes in the building's look over time. Its place in MuseoTorino's digital archive shows how early 20th-century surveys started mixing historical study with technical methods. (Biancolini, n.d)

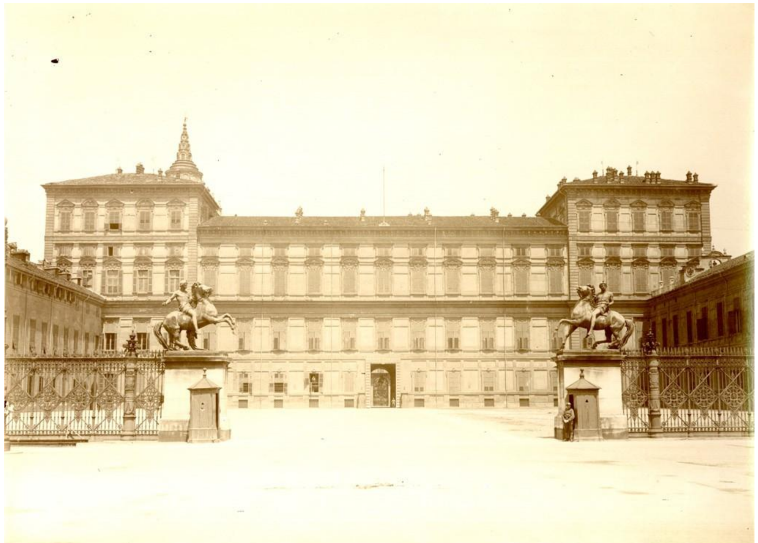


Figure 2.9. The Royal Palace Facade, circa 1925, Photo by Mario Gabinio.

(MuseoTorino digital archive).

2.3 Conservation History

The building was damaged during World War II. A portion of the roof collapsed during the bombing on July 13, 1943, and the Manica Nuova and its historic wings were destroyed. From the late 1940s to the 1980s, restoration work aimed to keep the remaining decorations while also making the structure stable. These efforts for repairing showed how it's hard to keep the building's original character while changing it for modern use.

(MuseoTorino, n.d.; Musei Reali di Torino, 2021).

After World War II damage, years of repairs and work to improve public access allowed to the reopening of the Palazzo Reale in 2007. Another major event affected the Chapel of the Holy Shroud, which was severely damaged by a fire in April 1997. Restoration of the chapel took more than twenty years, and it officially reopened on September 27, 2018. These efforts show how much it's hard to preserve historic monuments after major damage.

(MuseoTorino, n.d.; Musei Reali di Torino, 2021).

In the last decade, architectural documentation has moved to integrate and protective conservation. The Musei Reali di Torino has used HBIM-based digital tools and workflows in the Take Care project, working together with experts and developers. For experimental conservation, a vertical section of the palace comprising the eleven stories of the south-west tower was chosen. Using microclimatic data, laser scans, and semantic BIM components to coordinate conservation strategies, important spaces within this site, such as the Scalone d'Onore and the Salone degli Svizzeri, are now monitored, and targeted maintenance interventions are planned. This way of thinking reflects a larger movement away from extensive, reactive restorations and towards preventive measures backed by continuous real-time data monitoring and interdisciplinary cooperation.

(Feroggio et al., 2024; Musei Reali di Torino, 2024)

CASE STUDY OVERVIEW

Section 3. Case Study Overview and Digital Goals

3.1 General information about the building

This architectural complex, the Royal Palace of Turin (*Palazzo Reale*), preserves spaces, decorations, and artworks realized across several centuries.

Town: Torino, Italy

Designers and Architects:

Ascanio Vitozzi (initial late 16th-century design of the Ducal Palace)

Amedeo di Castellamonte (17th-century expansions and reconfiguration of the courtyard and main façades)

Filippo Juvarra (early 18th-century enlargements and decorative schemes)

Benedetto Alfieri (mid-18th-century works, interior refinements, and façade adjustments)

Pelagio Palagi (19th-century renovations)

Emilio Stramucci (Manica Nuova, 1899–1903)

Other artists involved:

Daniel Seiter, Claudio Francesco Beaumont, Jan Miel (painters)

Gabriele Capello (cabinetmaker)

Construction Period:

Original nucleus: late 16th century (Ducal Palace by Ascanio Vitozzi)

Major Baroque transformation: 17th century (Amedeo di Castellamonte)

Juvarra interventions: ca. 1713–1730

Alfieri interventions: mid-18th century

Palagi renovations: 1830s–1840s

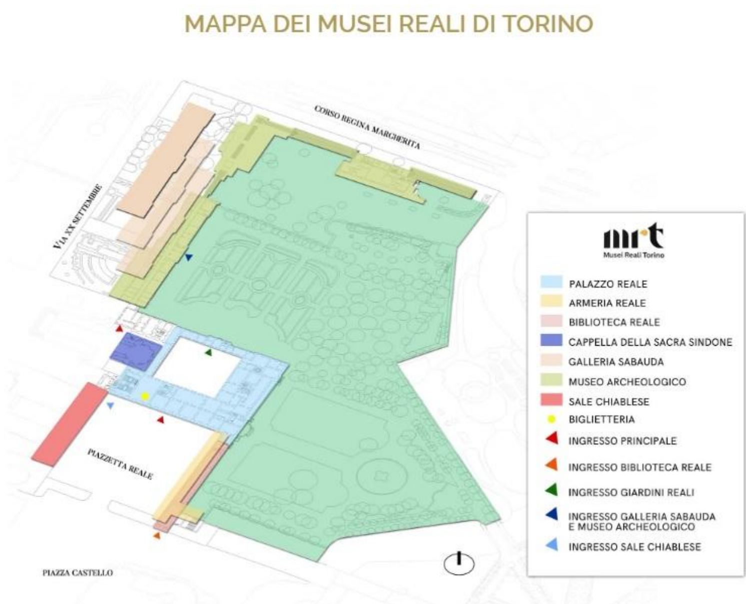


Figure 3.1. Map of the Royal Palace.

Ownership: State property (Musei Reali di Torino)

Current Use: Museum and cultural heritage site

Protection Status: Listed monument

Key Spaces and Features:

Sala del Trono (Throne Room): Reconfigured under Carlo Alberto; features the Trionfo della Pace ceiling by Jan Miel and 18th-century stucco decorations.

Figure 3.2. Sala del Trono (Throne Room) of Palazzo Reale, Turin. (Musei Reali Torino)

Sala da Ballo (Ballroom): Designed by Pelagio Palagi ca. 1840; neoclassical colonnade and coffered ceiling

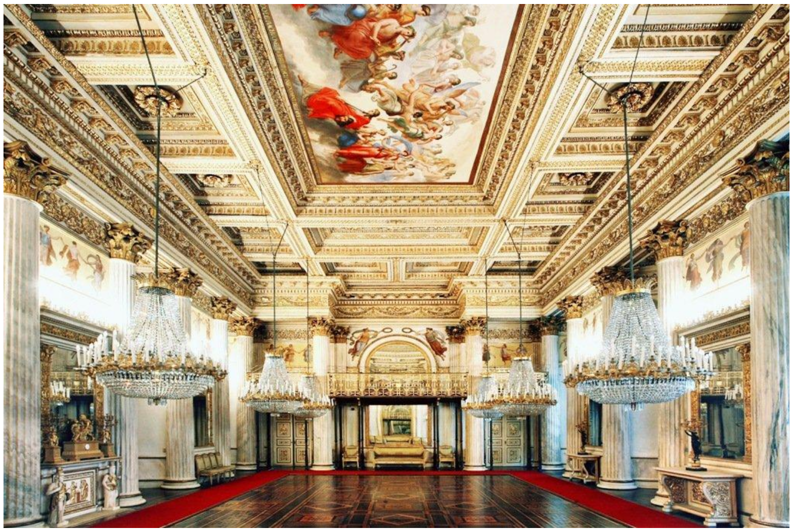


Figure 3.3. Sala da Ballo (Ballroom) of Palazzo Reale, Turin. (Musei Reali Torino)

Galleria del Daniel: Late 17th-century gallery decorated by Daniel Seiter

Figure 3.4. Ceiling of the Galleria del Daniel, Royal Palace . (Musei Reali Torino)

Armeria Reale: Opened to the public in 1832 by Carlo Alberto

Figure 3.5. Armeria Reale, Royal Palace of Turin. (Musei Reali Torino)

Cappella della Sindone: Baroque chapel by Guarino Guarini, completed 1694

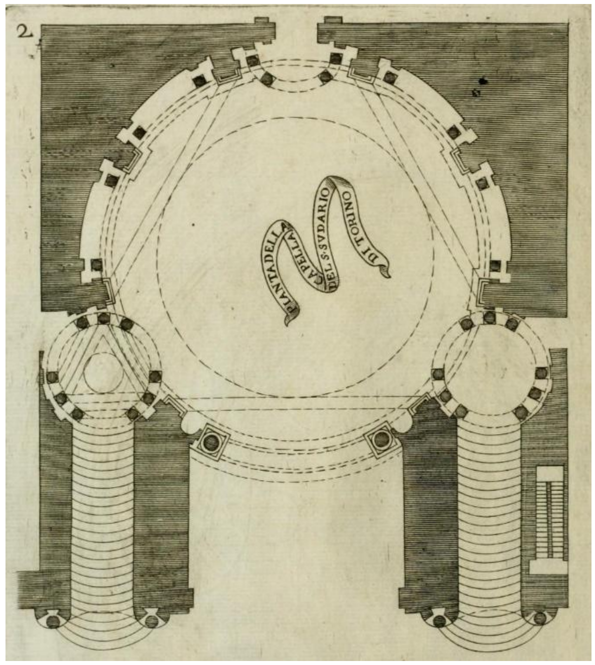


Figure 3.6. Drawing by Robert de Cotte, Baroque chapel, 1690 designed by Guarino Guarini

Source: Bibliothèque nationale de France

Figure 3.7. Cappella della Sacra Sindone, Royal Palace of Turin.
View of the Baroque chapel designed by Guarino Guarini (completed 1694), built to house the Holy Shroud. (Musei Reali Torino)

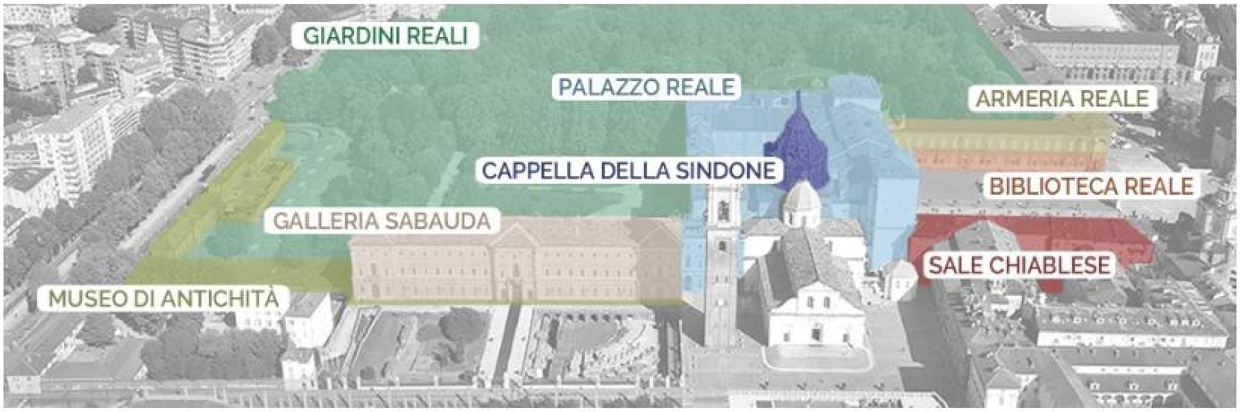


Figure 3.8. Master plan of the Musei Reali complex in Turin.
Source: Musei Reali di Torino (2021).

The project focuses on Turin's Palazzo Reale, a UNESCO heritage site and an important digital conservation test case. The building has many historical changes, different architectural areas. These features make it a unique place to bring various sources together in one HBIM project. The case study also shows the various research areas that Politecnico di Torino and Politecnico di Milano have developed as part of the Take Care methodologies. It raises the integration of digital tools, such as point cloud processing and photogrammetry, for protective conservation and data-based heritage management. The HBIM workflow in this study builds on earlier data collected through shared surveys.

(Feroggio et al. 2024, Spanò et al. 2024).

Figure 3.9. Historic photograph of the Royal Palace of Turin (Palazzo Reale), ca. late 19th century. The image shows the main façade, the equestrian statues at the gates, and people in period dress in the foreground.

3.2 Modeling Scope and Approach

The HBIM method of this thesis goes from the outer façades into the interior spaces to follow a clear layout. To balance scan detail, access, and architectural significance, the modeling used different Levels of Detail (LOD). The South and Courtyard façades, with high details and good scans, were made at higher LODs (LOD 300–400). For the East façade, photogrammetry and adaptive modeling filled gaps caused by plants blocking the view; as a result, we used LOD 100–200. Interior spaces, where scans were limited, were built with simpler LOD 100–200 shapes to match the outside walls and ceilings. This zone-based LOD approach keeps method keeps the data clear and consistent with saving time and effort.

Figure 3.10. Orthophotography of the East façade of Palazzo Reale showing partial occlusion due to vegetation (7mm resolution photogrammetry).

3.3 Data Sources and Tools

A combination of platforms and workflows were used to build the integrated HBIM model:

Autodesk Revit for parametric modeling and LOD management

Autodesk Recap and Faro Scene for LiDAR point cloud registration

Agisoft Metashape for mesh-based photogrammetry

CloudCompare for accuracy assessment and deviation analysis (C2C and C2M)

The model incorporates multiple evaluative and descriptive metrics:

LOD/LOG to distinguish levels of geometric and graphical complexity

LOI (Level of Information) for semantic enrichment

GOA and GOG to evaluate alignment with reality-based survey data and model generation quality

3.4 Digital Conservation Goals

The modeling process aims to demonstrate how HBIM can support:

Accurate geometric reconstruction for long-term documentation

Scenario planning for maintenance and preventive interventions

Educational visualization that connects historical narrative and contemporary preservation

The thesis adds to a scalable procedure for heritage HBIM development by utilising a systematic and repeatable workflow that combines strict data integration with flexibility to accommodate site-specific limitations.
In the end, this work emphasises how HBIM can actively bridge the gap between tradition and innovation, assisting in curatorial choices as well as public interaction with cultural heritage.
The modeling also considers contemporary activities in HBIM. In order to support the restoration process, it examines the data integration, conceptual increase, and scan-to-BIM methodologies. After that, we can produce reliable, fact-based documentation, which will raise educational standards.

Through the use of Palazzo Reale's flexible digital twin, this project attempted to enhance the function of HBIM. It fixes a variety of issues, including constraints, inconsistent data, and interior-exterior coherence. Using a workflow will solve all of these issues. This procedure is practical and scalable, making it helpful for subsequent attempts. In addition, the legacy visualization function for contexts has been observed. Technical, curatorial, and instructional applications are supported by the model. In terms of architectural preservation, it offers a link between innovation and tradition.

LITERATURE OVERVIEW

Section 4. Literature Review

4.1 Historical Building Information Modeling (HBIM)

The base for understanding HBIM as a method that contains parametric modelling, laser scanning, and photogrammetry to record and explain historic structures was claimed by Murphy, McGovern, and Pavia. Their research shows how HBIM is different from traditional BIM because it is made for heritage buildings, which often have complex histories, irregular shapes, and uncertain documentation. The authors explain how high-density point clouds produced by laser scanning, which form the base for building 3D models, are the initial step in the data collection process. These models include details about materials, construction methods, deterioration patterns, and historical context in addition to being geometric models.

The process of developing parametric models includes making reusable digital objects that represent architectural elements such as windows, arches, and vaults. To allow elements to be changed for different cases in the same building or other sites, this process often includes setting rules for shapes and allowing variations. Murphy and associates also emphasize the importance of checking the work by regularly comparing the point cloud with the parametric model to ensure accuracy. They also say that missing parts of a building can make the process take longer. But they believe creating reliable documents to support conservation needs this repeated improvement. The study emphasizes how HBIM helps the protectors view buildings as dynamic systems that change over time by organizing real data with historical and material information all in one place.

(Murphy, McGovern, and Pavia 2013)

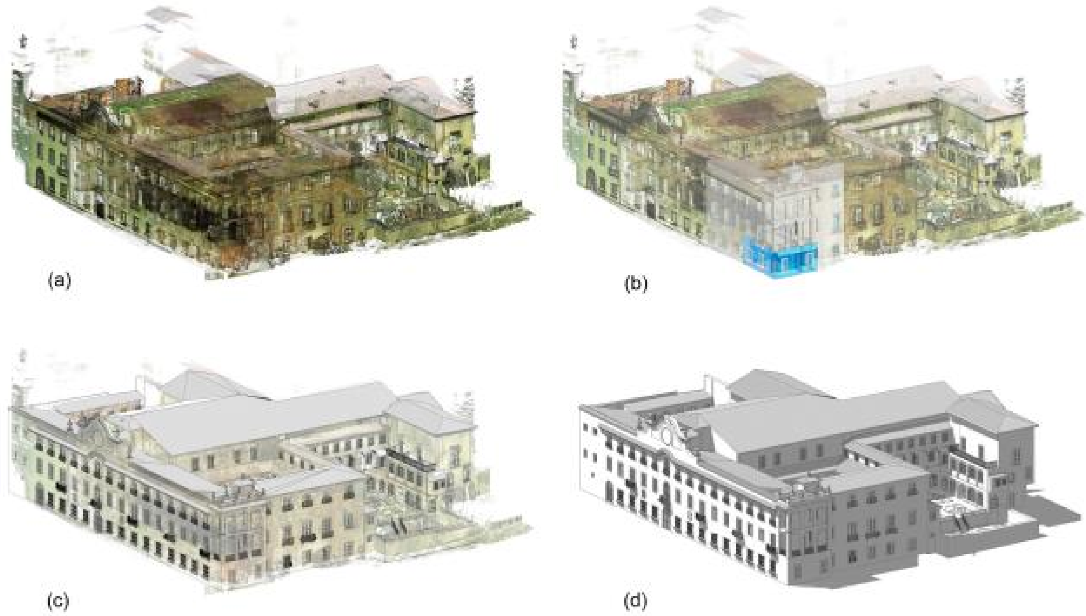


Figure 4.1. Workflow illustrating the main phases of HBIM modeling, from initial data acquisition to detailed 3D reconstruction. (a) Acquisition of point cloud data; (b) segmentation and processing of the scan; (c) overlay and validation of geometric model against the point cloud; (d) generation of the final parametric HBIM model. (Source: De Falco et al., 2024)

By using HBIM on the Basilica di Collemaggio following the L'Aquila earthquake, Brumana and associates extended these ideas and showed how this methodology can direct preservation in challenging real-world situations. Their case study demonstrates the use of laser scanning to find hidden damage and deformations that were missed by conventional surveys. To lower risks and improve the design of structural reinforcements, the HBIM model gave architects, engineers, and conservation experts a common platform to digitally test various restoration techniques prior to any physical intervention. Their method's use of software platform interoperability to manage metadata and geometric data was one of its unique features.

The authors explain how data processing in software that can handle complex shapes, then moves into BIM programs for more coordination and detail. They say that to prevent losing data, this process needs skilled experts and good communication between team members. Their study also highlights using HBIM to help with risk assessment and emergency plans, especially when heritage sites face natural hazards. They emphasized that the model needs regular updates as new information comes in to stay useful throughout the building’s life. The project also shows the need for Training cultural heritage experts so they can use digital tools, understand HBIM, and work well together.

(Brumana and others, 2017)

Megahed offered a theoretical framework that argues that HBIM is a move towards knowledge based and collaborative conservation practices, positioning it as more than just a technical tool. He says HBIM is a platform that brings experts from different fields together, letting them work on research, materials, engineering, and heritage management. In addition for improving technical documentation, this method helps to share knowledge about heritage. Megahed says HBIM can help heritage laws and policies by giving a clear and open base for making conservation decisions. Additionally, he highlights how HBIM can be used to integrate invisible heritage elements like social significance, cultural memory, and the stories that give places their meaning. He argues that to avoid heritage being seen just as measurable or pretty things, HBIM must be planned carefully. Also, being open and clear with data helps to build trust, but clear rules and guidelines are needed to ensure data is reliable and works well together. Megahed says that HBIM needs a lot of time, money, and skill. It is important for managing heritage sites today because it works as a digital archive and helps with engagement, education, and permanent preservation.

(Megahed, 2015)

4.2 Difference Between HBIM and BIM

Figure 4.2. Comparative Overview of BIM and HBIM Dimensions

(Adapted from Murphy & Dore, 2012; Volk et al., 2014; Jouan & Hallot, 2019)

According to Murphy and Dore (2012), HBIM evolved as a result of the inadequacy of standard BIM techniques and tools in handling the intricacy and unpredictability of historic buildings. Since precise design drawings, well-known material properties, and predictable workflows are standard in contemporary construction projects, BIM was initially created for these types of projects. From clash detection to facility management, this context enables the use of uniform parametric components, standard object libraries, and automated procedures. Murphy and Dore stress that there are numerous restrictions when using these same tools on heritage sites. For instance, traditional parametric families are unable to adequately capture the irregular shapes of walls, vaults, and other ornamental elements found in older structures. Furthermore, there is no one "correct" version of the building to model because the construction history of a heritage site may include unrecorded repairs or alterations. By combining laser scanning and photogrammetry to meticulously record as-built conditions and by producing unique parametric objects that are adapted to historical forms, HBIM fills these gaps. HBIM focuses on saving cultural value and helping with conservation, while BIM is more about improving performance and reducing costs.

Murphy and Dore also say that since HBIM data can be incorrect, more explanation and judgment are needed HBIM accepts uncertainty and focuses on carefully recording evidence instead of trying to make a perfect model. In this way, HBIM changes from just a technical process into a way to create an organized record of the building's identity that can be improved and updated over time.

(Murphy & Dore, 2012)

Volk, Stengel, and Schultmann (2014) offer a more comprehensive analysis of the practical distinctions between BIM and HBIM, particularly with regard to the data that underpins each system. Architects' and engineers' CAD drawings and design models, which clearly define the materials, dimensions, and performance characteristics, are usually the foundation of BIM. Schedule creation, cost estimation, and building performance simulation are just a few of the many tasks that BIM can automate thanks to this standardised and current data. On the other hand, HBIM must integrate a wide range of information sources, such as historical documents, old photos, previous restoration reports, and contemporary surveys. Managing this diversity is a significant challenge, as Volk and his co-authors emphasise. Data can be contradictory, incomplete, or deteriorated over time. Accordingly, HBIM necessitates meticulous source cross-checking and occasionally ambiguity acceptance. Additionally, they note that compared to traditional BIM, HBIM projects frequently involve a far greater number of stakeholders. HBIM comprises conservators, historians, heritage agencies, archaeologists, and occasionally local community representatives, whereas BIM is primarily utilised by designers, engineers, and contractors. Because every group has distinct priorities and values, this complicates decision-making. The distinction between legal and regulatory frameworks is another crucial aspect of their analysis. Modern building codes and standards that prioritise efficiency and safety serve as the foundation for BIM projects. In contrast, HBIM is required to adhere to international regulations such as those set forth by UNESCO, conservation charters, and heritage laws. Because of this, HBIM is more than just a technical method; it is also a cultural and moral practice that necessitates awareness of the site's significance and meaning.

(Volk, Stengel, & Schultmann, 2014)

By presenting HBIM as a model with a fundamentally different goal and viewpoint, Jouan and Hallot (2019) further clarify this distinction. They contend that the main goals of BIM are resource optimization, workflow simplification, and performance management throughout a building's life cycle. According to them, HBIM is about establishing a "temporal twin," or a record of a building's evolution over time. This implies that the HBIM model is a record of the building's evolution, including all the alterations, damages, and restorations it has experienced, rather than merely a snapshot of its current condition. They stress that the model must manage uncertainty, partial information, and several levels of detail in order to account for this temporal component. One aspect of a building, for instance, might have extensive survey and record documentation, while another might only be comprehended through archaeological interpretation. Jouan and Hallot also point out that conservation decisions that must strike a balance between technical specifications and cultural values are frequently informed by HBIM. They mention that HBIM depends on teamwork from many experts. Engineers, historians, conservators, and community members all need to work together to build and understand the model. The typical BIM workflows are more standard and step-by-step, which is very different from HBIM's teamwork approach. They also highlight how important HBIM is for public education and involvement. Because the model holds detailed information about the history of the building, it can be used to make virtual tours, exhibits, or learning materials that allow more people access to heritage. One big strength of HBIM is that it demonstrates both technical details and cultural stories.
(Jouan & Hallot, 2019)

4.3 Levels of Detail, Information & Geometry in HBIM

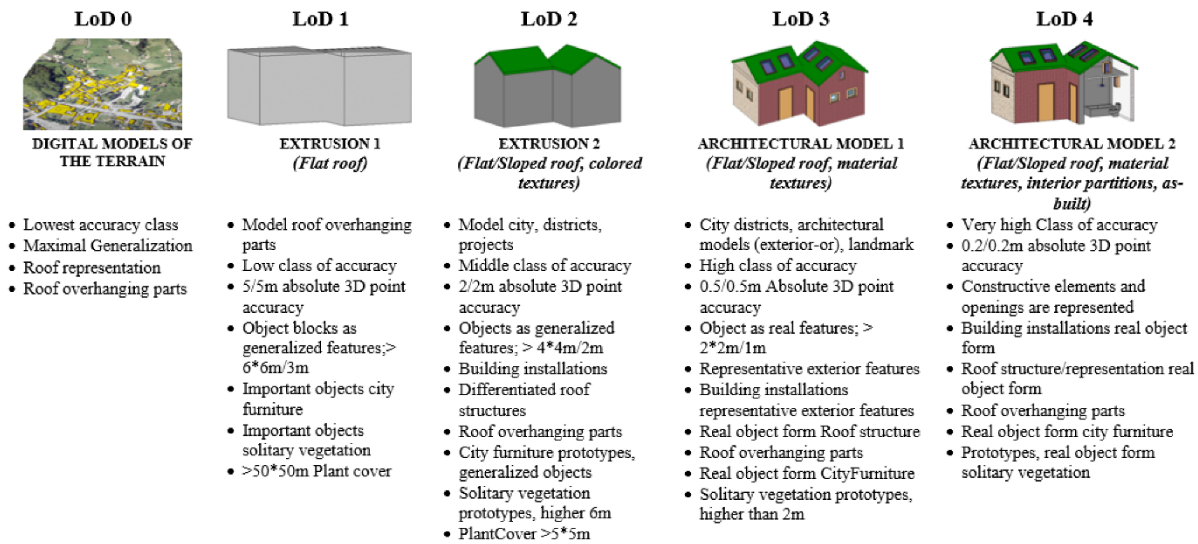


Figure 4.3. Example of progressive Levels of Detail (LOD) in Historic Building Information Modeling (HBIM), illustrating the transition from simplified volumetric representations to high-detail parametric components with enriched semantic information. (Source: Carrasco et al., 2022)

Levels of Detail (LOD) are a key concept in Historic Building Information Modelling (HBIM) that define how accurately a historic structure is depicted in a digital model. HBIM must take into consideration irregular geometries, incomplete records, and the need to respect cultural values, in contrast to standard BIM, where LOD primarily describes the progress of a design towards construction. This calls for a more adaptable, Classified strategy that blends various geometric and informational scales based on the project's goals and the building's actual state. (Murphy, 2013; Banfi, 2021)

LOD 100 offers a basic model of the massing and general shape of the building. This stage, which usually only displays approximate volumes without fine-grained textures or component distinctions, is helpful for early planning, visualization, or general feasibility studies. Primary structural components like walls, floors, and roofs are added more precisely as the model advances to LOD 200. Spatial zoning, conservation planning, and fundamental structural analysis are supported at this level. All of the major parts, such as windows, doors, and important decorative elements, are shown in detail in LOD 300. At this point, the model can be used to visualize the effects of interventions, create restoration plans, and coordinate efforts across disciplines.

(Murphy, 2013; Brumana et al., 2019)

Going a step further, LOD 400 includes construction-level information about the assemblies and materials, including how they fit together and details about their condition and prior repairs. For conservation projects that call for simulation, clash detection, or the integration of material science data, this level is especially crucial. Last but not least, LOD 500 shows the building's as-built or as-surveyed state, complete with verified geometry and metadata about materials, deterioration trends, and historical interventions. According to Banfi, this stage is getting close to the idea of a "digital twin," one that can facilitate ongoing upkeep, surveillance, and digital archiving.

(Banfi, 2021)

Banfi also presents the ideas of Levels of Geometry (LOG), Grades of Accuracy (GOA), and Grades of Generation (GOG) to elucidate the accuracy and dependability of a model. From coarse volumetric forms (LOG 100) to extremely accurate, richly textured models (LOG 500), LOG indicates the degree of geometric detail in a representation. While the Grade of Generation indicates whether elements were inferred from historical records or directly scanned, the Grade of Accuracy specifies the measurement tolerance (e.g., millimeter-level surveys for critical elements). Project teams and stakeholders can better understand how much trust to put in various HBIM model components and what degree of additional verification may be required by openly stating these levels.

(Banfi, 2021)

It is not necessary to model every surface in great detail, thanks to this classified approach. Brumana and colleagues say, Different parts of a heritage site are often modeled with different levels of detail based on their importance and use. For example, a service corridor might stay at

LOD 200, while a complex design staircase must be considered with decay mapping at LOD 400–500. Teams can put their effort where precision and data are needed by matching LOD, LOG, and LOI with their project goals.
(Brumana et al., 2019)

HBIM projects that document complex facades or vaulted systems are an example of this combined approach. In certain instances, less sensitive regions maintain more generic representations, while segments are meticulously modelled for structural monitoring and preventive conservation. In addition to lowering the possibility of over- or under-modeling, this combination of geometric accuracy and rich information allows for better informed decisions regarding maintenance and restoration. In this sense, HBIM generates a structured, multi-layered knowledge base that can develop over time and act as a basis for public engagement, education, and conservation rather than just producing a geometric replica of a building.

(Banfi, 2021; Brumana et al., 2019)

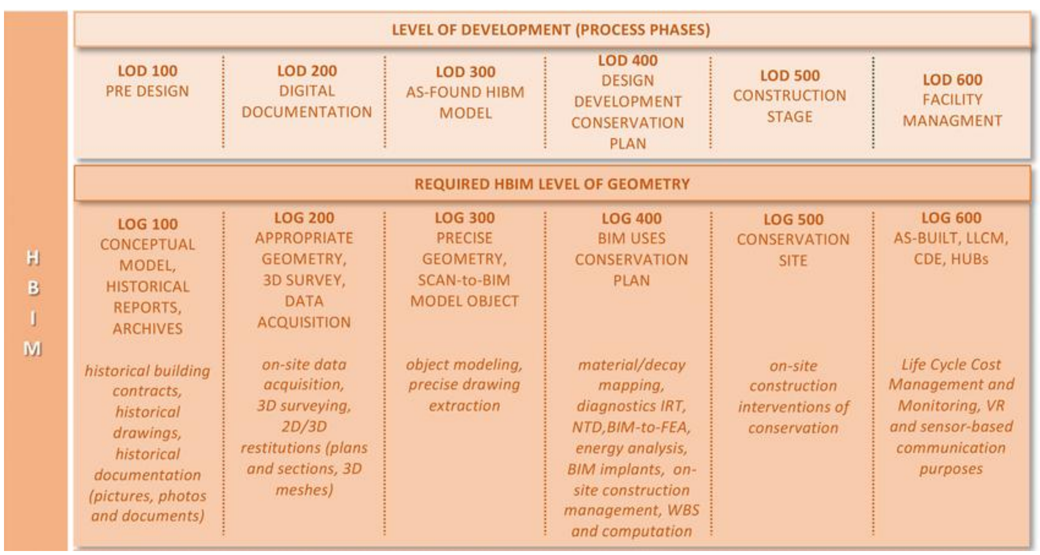


Figure 4.4. HBIM LOG and LOD Proposal for Built Heritage
Source: Brumana, R., Stanga, C., & Banfi, F. (2021).

4.4 Applications of HBIM and LOD in Heritage Conservation

When paired with clearly defined Levels of Detail (LOD), Historic Building Information Modelling (HBIM) has emerged as a game-changing method for managing, recording, and conserving architectural heritage. Professionals can create digital environments using HBIM that combine accurate geometry, historical records, and condition assessments into a single reference model, in contrast to traditional documentation methods. According to Banfi et al. (2019), HBIM's ability to centralise a variety of data is what makes it possible for it to support a range of goals, including public engagement and conservation planning. Teams can effectively allocate resources and priorities to crucial interventions while keeping a thorough, accurate record of a monument's changing state by modifying the model's level of detail to fit project objectives.

(Banfi et al., 2019)

Digital documentation and visualization are among the most common uses of HBIM. High-resolution models that capture the building's historical stratification as well as its current geometry can be created using laser scanning, photogrammetry, and archival drawings. These models, which are frequently built at LOD 300 or higher, offer sufficient detail for a detailed examination of the materials, structural components, and ornamental elements. Such documentation aids conservation architects in identifying decay and organizing restoration strategies, according to Brumana et al. (2019). Simultaneously, HBIM models can be made simpler for use with visualization tools, virtual tours, and augmented reality platforms that engage broader audiences without technical expertise and aid in communicating cultural value to the general public.

(Brumana et al., 2019)

Additionally, HBIM is frequently used in risk assessment and conservation planning. Heritage managers can identify structural deformation, moisture infiltration, and other issues that endanger long-term preservation with the use of models enhanced with semantic data and connected to environmental monitoring systems. Teams can test solutions virtually before putting them into practice by modelling the effects of various conservation scenarios. This predictive ability is particularly useful when budgets are tight and priorities need to be set impartially, according to Brumana & Banfi (2021). For instance, in order to save time and resources, less critical zones are modelled in simpler forms, while higher LOD representations can be applied selectively to areas of high significance or known vulnerability.

(Brumana & Banfi, 2021)

Regarding restoration and retrofitting, HBIM offers a methodical approach to coordinating interventions while honoring heritage restrictions. Conservation architects are able to design repairs or adaptations with the least amount of disturbance to authentic fabric because detailed models can accurately record the location of historical materials and structural systems. According to Banfi et al. (2019), the LOD 400 or LOD 500 models enable accurate planning for stabilizing damaged components or integrating new infrastructure, with all decisions being recorded and traceable within the digital environment. Additionally, this capability promotes adherence to conservation laws and increases transparency.

(Banfi et al., 2019)

Brumana & Banfi (2021) explain that HBIM is not used only for design and restoration but also to manage heritage buildings over their life. Detailed models become alive archives where maintenance records, inspections, and history are consistently updated. Facility managers can use the model to plan protective maintenance, check particular parts, and track changes over time. This helps to move from fixing problems after they happen to protecting them.

(Brumana & Banfi, 2021)

Finally, HBIM is critical to research collaboration, public engagement, and education. The models can be used as interactive teaching tools or platforms for scholarly research because they incorporate not only geometry but also historical narratives and semantic annotations. By allowing architects, archaeologists, and historians to examine construction sequences, test speculative reconstructions, and exchange findings in a common digital space, HBIM promotes interdisciplinary work, as noted by Brumana et al. (2019). Simplified visual outputs also assist heritage organizations and museums in engaging the public in appreciating and comprehending their built heritage.

(Brumana et al., 2019)

4.5 Interdisciplinary Methodologies in the Preservation of Historic Buildings

Since no single discipline can handle all the difficulties of documentation, conservation, and interpretation on its own, interdisciplinary cooperation is becoming more and more important in the preservation of historic structures. The skills of conservators, architectural historians, and digital experts are combined in Historic Building Information Modelling (HBIM), which provides a unifying framework. According to Lovell et al. (2023), this convergence enables the capture of a building's material history and cultural context in addition to precise geometric information. Their strategy views HBIM as a link between research, policy-making, and public involvement rather than as a purely technical tool. By taking an integrated approach, conservation strategies are guaranteed to be both culturally sensitive and scientifically sound.

(Lovell et al., 2023)

One important idea of this teamwork is preserving buildings. Conservators bring deep knowledge of how buildings made, how they decay, and understanding building materials. They use this knowledge to carefully label structural sections, save previous repairs, and clarify the true conservation actions within an HBIM system. Brumana et al. (2017) show this in their study of the Basilica di Collemaggio. Conservators worked nearly with survey teams to add restoration history and damage reports directly into the HBIM model. This complete documentation helps to create a better understanding and allows future experts to know why past repairs were done. (Brumana et al., 2017)

Architectural history is essential because it sheds light on a building's cultural and stylistic significance in addition to conservation. To reconstruct a site's evolution over centuries, historians look at written records, archival drawings, and comparative studies of similar structures. According to Lovell et al. (2023), these historical layers can be incorporated into HBIM as semantic information, which would enhance the model well beyond geometric accuracy. This background information is crucial for understanding the rationale behind specific architectural decisions and for directing restoration in a way that honors the original purpose of a building.
(Lovell et al., 2023)

Digital humanities, which provide strong instruments for organising and disseminating complicated heritage data, make up the third pillar. Experts in this area create interactive applications that increase accessibility to heritage and workflows for processing large datasets from photogrammetry and laser scans. Brumana et al. (2017) explain how digital humanities techniques, such as online repositories, GIS mapping, and 3D visualization, assist in converting technical models into interesting stories for academics and the general public. By allowing teams to exchange data and annotations across domains, these tools also support interdisciplinary research.
(Brumana et al., 2017)

When combined, these fields turn HBIM into a living, breathing document that documents historic buildings' changing meanings and social functions in addition to their shape and materials. According to Lovell et al. (2023), this strategy enables HBIM to serve as a storytelling tool in addition to a conservation tool. Professionals can develop models that encourage sustainable management, guide policy, and stimulate public appreciation for heritage by fusing conservation science, historical scholarship, and digital communication.
(Lovell et al., 2023)

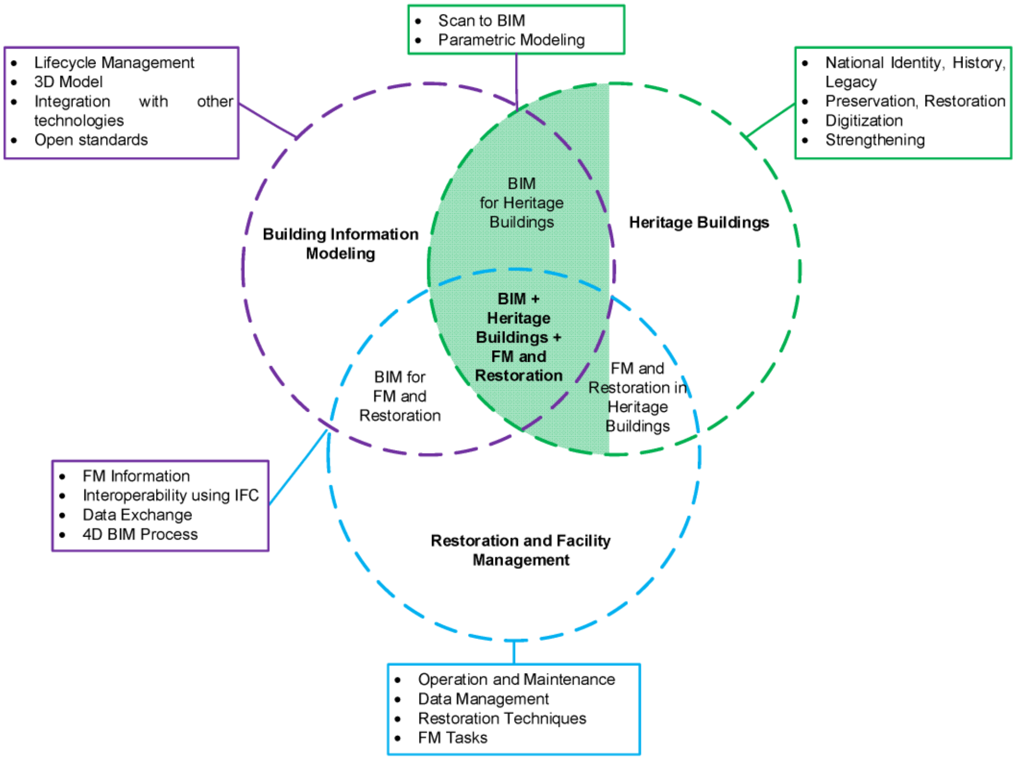


Figure 4.5. In the context of Historic Building Information Modelling (HBIM), this Venn diagram shows how Building Information Modelling (BIM), Heritage Buildings, Restoration and Facility Management, and Digital Humanities are integrated. It highlights how they work together to document, interpret, and plan for long-term conservation of cultural heritage. Source: Author's representation adapted from frameworks in Brumana et al. (2017) and Lovell et al. (2023).

4.6 HBIM Geometry Acquisition and Model Development

The accuracy of the building's geometry survey is the first step in any conservation or documentation project using Historic Building Information Modelling (HBIM). Because it produces high-density point clouds that can record minute surface deviations, deformation patterns, and irregularities typical of historic structures, Terrestrial Laser Scanning (TLS) has emerged as a key technique. According to Avena et al., TLS is particularly useful in places with intricate vaulting, cloisters, and cramped interiors where other techniques are ineffective. In order to achieve overlapping coverage and remove blind spots, TLS campaigns typically entail placing the scanner at several different viewpoints. Reference spheres or targets are then used to register these scans collectively. As a result, a continuous dataset with accuracy within a few

millimeters is produced. The high resolution is particularly important in heritage settings where even slight deformations or inclinations can indicate structural weaknesses or past interventions that must be preserved or reinforced.
(Avena et al,2021.)

By quickly scanning roofs, cornices, towers, and any other exterior areas that are inaccessible to terrestrial equipment, UAV photogrammetry enhances TLS. Chiabrando et al. (2016) explain how Structure from Motion algorithms are commonly used in drone-based imagery acquisition to reconstruct textured 3D surfaces using high-overlap photos and pre-planned flight paths. The point clouds produced from UAV data are extremely useful for recording the visual characteristics of materials, roof coverings, and building contexts, despite the fact that they are typically less accurate—often with errors ranging from 1 to 3 cm. According to Brumana et al. (2019), UAV photogrammetry is especially helpful for heritage sites where scaffolding would be inconvenient or invasive. Practitioners can create a hybrid dataset that combines the advantages of both approaches by combining TLS and UAV data: UAV for more comprehensive contextual capture, TLS for high-precision geometry.
(Chiabrando et al., 2016; Brumana et al., 2019)

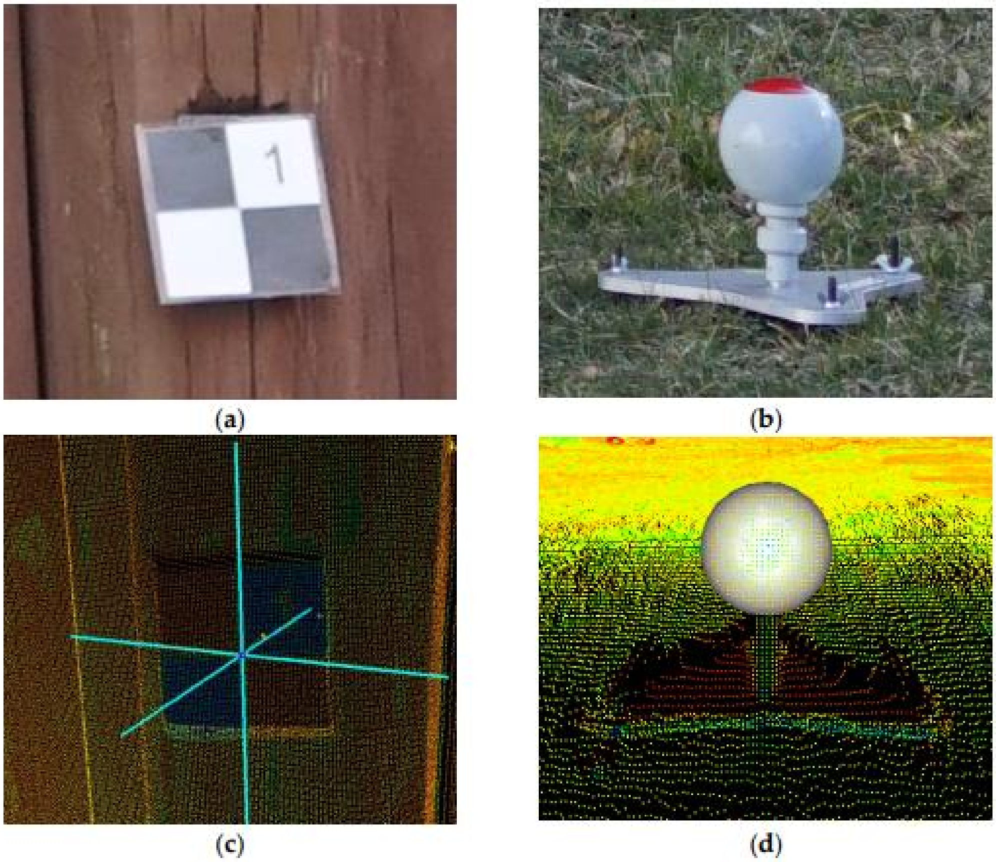


Figure 4.6. This figure shows typical georeferencing targets used to align UAV photogrammetry and terrestrial laser scanning (TLS) datasets. (a) Black and white coded target plate for photogrammetry control, (b) Reference sphere for TLS registration, (c) Target plate visible in the point cloud, (d) Reference sphere in the model space. This workflow supports accurate hybrid point cloud generation in heritage documentation projects. Source: Grilli, E., Menna, F., Remondino, F. (2019).

A well-defined georeferencing and alignment protocol is necessary for managing these hybrid datasets. Usually, the point clouds are registered into the same coordinate system using targets that are visible in both the TLS and UAV datasets. When combining datasets, this single reference guarantees uniformity and prevents distortions that can endanger the accuracy of the model. According to Banfi (2021), this stage is crucial since mistakes made here have the potential to spread throughout the entire workflow. Additional preprocessing is necessary after the point clouds are aligned. Stray points brought on by reflections or atmospheric interference

are removed by noise filtering. While segmentation divides the data into logical components, like facades, vaults, or decorative elements, Destruction is reduced. the point cloud density in large, featureless areas to make the files easier to handle. Brumana et al. (2019) explain that this Division helps assign appropriate Levels of Geometry and makes later modeling stages more efficient.
(Banfi, 2021; Brumana et al., 2019)

The modelling process starts after the point cloud has been cleaned and divided into segments. According to Banfi's (2021) progressive approach, as modelling progresses, the geometry progresses from coarse representations (LOG 100 and LOG 200) to higher precision Levels of Geometry (LOG 300–500). Usually, the process starts with meshing, which turns the point cloud into a polygonal surface model that depicts the structure's topology and shape. Modelers can then use Revit or ArchiCAD to extract parametric elements, tracing openings, vaults, and walls using the mesh as a guide. Many heritage elements need to be manually modelled in order to account for their deformations and asymmetries, even though standard features like planar walls and arches can be modelled using predefined libraries. For example, Chiabrando et al. (2016) describe modeling Grooved vaults by generating NURBS surfaces that conform precisely to the measured data rather than forcing a simplified template. This approach guarantees that the HBIM model accurately reflects the actual built conditions.
(Banfi, 2021; Chiabrando et al., 2016)

Grades of Generation (GOG), first proposed by Banfi (2021), is another crucial idea in this process. GOG makes a distinction between model elements that are reconstructed through interpretation and those that are directly derived from measured data. For example, a section of wall would be designated as a reconstructed grade if it were blocked and needed to be extrapolated from nearby geometry. Future researchers and conservators will be able to distinguish between the hypothetical and empirically validated components of the model thanks to this distinction, which is crucial for clarity and transparency. Avena et al. also stress that models can be used responsibly for restoration planning and compliance verification if the Grade of Generation and Level of Geometry are documented. (Banfi, 2021; Avena et al,2021)

Validation and accuracy evaluation are required at every stage of the modelling process. To verify deviations, Brumana et al. (2019) advise superimposing the parametric model on top of the original point cloud. Any deviations from the specified tolerance ranges, typically ranging from 5 to 15 mm, depending on the objectives of the project, are noted for correction. These checks are particularly crucial for heritage projects because even a minor mistake can skew how a historical element is interpreted. Validated models guarantee that structural analysis and conservation interventions are founded on trustworthy data in addition to adhering to best-practice documentation standards.
(Brumana et al., 2019)

Finally, Banfi (2021) and Avena et al. emphasize the need for interdisciplinary cooperation when integrating TLS, mesh processing, UAV photogrammetry, and parametric modelling. To set up procedures, verify results, and curate the finished model, surveyors, architects, BIM specialists, and conservation specialists must collaborate. The creation of HBIM datasets that combine geometric accuracy, reproducibility, and clarity, elements necessary for long-term preservation and reuse, is made possible by this integrated workflow.

(Banfi, 2021; Avena et al, 2021.)

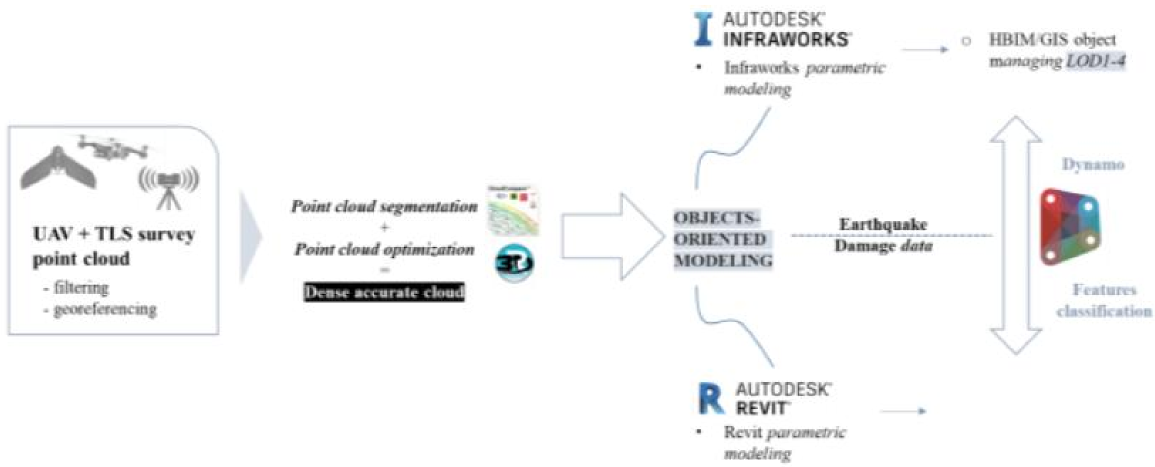


Figure 4.7. HBIM Workflow Integrating UAV Photogrammetry and TLS Point Clouds
The primary steps of the HBIM modelling process used in the Norcia case study are depicted in this diagram. It demonstrates how dense 3D data is produced by filtering, optimising, and segmenting TLS point clouds and UAV photogrammetry. After that, these data are imported into parametric modelling programs like Revit, where they are organized based on Levels of Detail (LOD). Tools such as Dynamo are then used to support further feature classification.

Source: Adapted from Avena, M., Colucci, E., Sammartano, G., & Spanò, A. (2021).

METHODOLOGY

Section 5. Methodology

Concentrating on accuracy and working well together, the method for digitally reconstructing Palazzo Reale uses a scan-to-HBIM approach made for historic buildings. It conitains different data sources, like photogrammetry, laser scans, and old 2D drawings, to create a parametric HBIM model from real-world data. This process supports long-term conservation planning and digital archiving while handling challenges like missing records, unusual shapes, and blocked views.

The method has five main steps:

1. Planning phase, Software Environment and Platform Roles: deciding which software tools do what for modeling, registration, and checking.
2. Data Acquisition and Source Evaluation: finding and combining different data types like laser scans, photos, and drawings.
3. Multi-Source Registration and Fusion: aligning all data into one model and optimizing point clouds.
4. HBIM Workflow Execution: following steps from breaking down point clouds to creating parametric models and assigning detail levels.
5. Limitations and Workarounds: explaining technical issues found and how they were fixed to keep the model accurate.

This method is inspired by earlier HBIM studies by Banfi et al. (2019) and Brumana et al. (2017), which focus on working well with different data, managing levels of details, and using digital tools in heritage projects.

5.1 Data Acquisition and Sources

The method created for digitally reconstructing Palazzo Reale uses a scan-to-HBIM approach made for documenting historic buildings. It focuses on accurate shapes, working well with different data, and long-term conservation value. The process builds a parametric HBIM model from several types of real-world data, including photogrammetry, Terrestrial Laser Scanning (TLS), and old 2D drawings. A system for combining these data sources makes sure each one adds useful information, improving the accuracy of the model and detail. This method deals with common errors in documenting heritage, like missing archives, irregular shapes, and blocked views, while designing a strong digital tool to help conservation planning and future achievements.

Terrestrial Laser Scanning (TLS):

Terrestrial Laser Scanners: These scanners are used to collect data from a fixed point on the ground. They are tripod-mounted. In addition to providing extremely accurate point cloud data from less than a millimeter for short range (less than 1 meter) to 2 centimeters for long range (some hundreds of meters), they usually have a range of several hundred meters. Mobile Laser Scanners: To collect data while moving, these scanners are installed on automobiles, drones, or boats. They work well for gathering data on a large scale, like in aerial surveys or urban mapping. Handheld Laser Scanners: These scanners are manually operated and portable. They are helpful for gathering comprehensive data in confined spaces or difficult-to-reach locations.

Figure 5.1. Different Types of laser scanners

Architecture and Construction: Renovation and retrofit projects can benefit from the precise as-built measurements that laser scanning can provide of existing structures. Additionally, it is employed for quality assurance, conflict identification, and construction progress tracking. Cultural Heritage Documentation: Sites, monuments, and artefacts can be digitally preserved thanks to laser scanning. It makes it possible to take exact measurements, record minute details, and create 3D virtual models for public use, research, and conservation. Surveying and Mapping: For land surveying, terrain modelling, and cartography, laser scanning offers quick and precise topographic data. It is useful for environmental monitoring, infrastructure development, and urban planning.

(Spanò, 2024)

Architecture and Construction: The accurate as-built measurements of existing structures that laser scanning can provide are useful for renovation and retrofit projects. It is also used for tracking construction progress, identifying conflicts, and ensuring quality. Cultural Heritage Documentation: Laser scanning helps digitally save monuments, sites, and objects. It gives accurate measurements, correct details, and 3D models that can be used for the public, research, and conservation. Surveying and Mapping: Laser scanning rapidly provides exact land data for surveys, making maps, and modeling. It supports urban planning, building projects, and protecting the environment.

Photogrammetry:

Photogrammetry is the process of using photos to make exact measurements and 3D models of things or places. It looks at shapes in many photos taken from different angles to get accurate sizes and recreate how the object is shaped. Photogrammetry is used in many fields like surveying, engineering, architecture, archaeology, and forestry. It allows us to create accurate 3D models, maps, and measurements without touching the objects or disturbing the area.

(Avena, 2021)

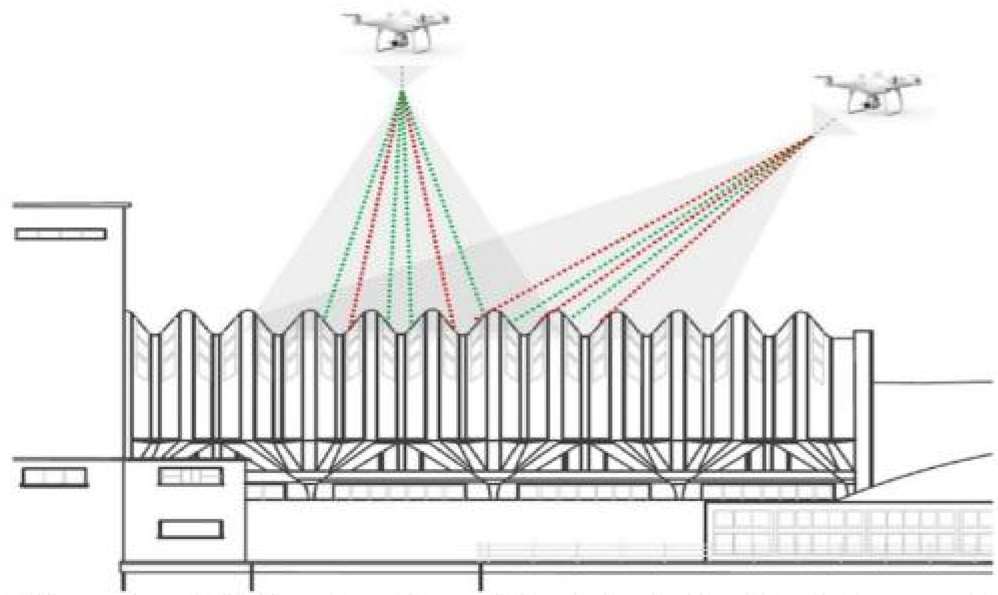


Figure 5.2. Image is illustrating standard photogrammetric image acquisition with drones. The figure shows the principle of achieving optimal image overlap for accurate 3D reconstruction: 75% front overlap and 75% side overlap between photographs. This configuration helps ensure comprehensive coverage and minimizes gaps or distortions in the resulting photogrammetric model. (Spano, A., 2023)

With the introduction of digital photography, computer vision algorithms, and powerful computing resources, photogrammetry techniques have made significant strides. This has improved the process's accuracy, efficiency, and accessibility, enabling realistic and intricate 3D reconstructions from ordinary photos. The subject is captured in several high-resolution photos from various perspectives. Digital cameras, drones, or even smartphones can be used to take these pictures. Photogrammetry has many different uses. For instance, photogrammetry can be used to produce precise digital elevation models, orthophotos, and topographic maps in surveying and mapping. It can help with the creation of 3D models of structures and locations for planning and design purposes in the fields of architecture and construction. Photogrammetry can be used in archaeology to record and recreate historic buildings and artefacts.

Figure 5.3. Manual photogrammetry data acquisition using a digital camera and coded targets for ground control referencing and scaling. This procedure ensures accurate alignment and metric reliability of the 3D reconstruction. (Spanò et al., 2024)

The photogrammetry process uses image matching algorithms to find matching points in overlapping photos. Bundle adjustment calculates the exact positions of each camera when the photos were taken. Then, the Structure from Motion method intersects millions of these points to create a 3D point cloud.

Image Processing: Specialized photogrammetry software is used to process the obtained images. Feature Matching: The program finds points or details that appear in a lot of photos, like textures, edges, or landmarks. By spotting these, it can locate the same spots in different images. Camera Calibration: The software adjusts for the settings of cameras like lens size, focus, and distortions. Accurate camera settings are required for correct measurements and 3D models 3D Reconstruction: Using the aligned points and camera informations, the software calculates where points are in 3D space andmake a point cloud, then a group of 3D points showing the object's surface.

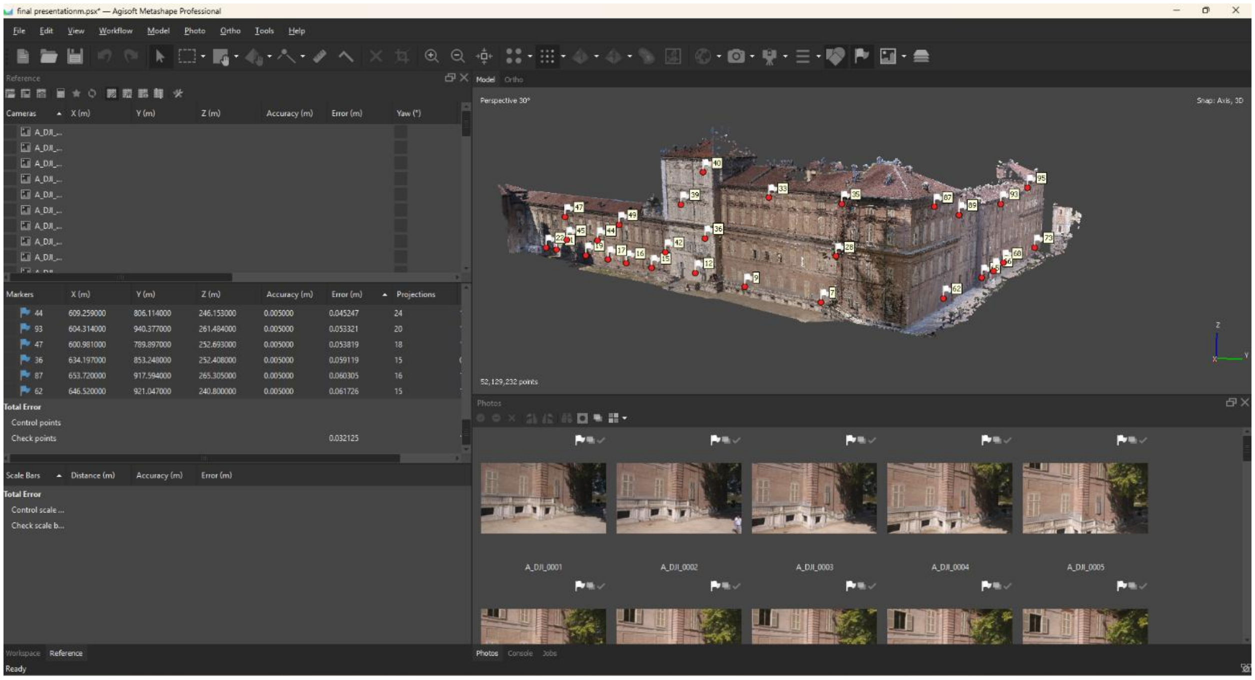


Figure 5.4. Photogrammetric Processing Workflow in Agisoft Metashape
The picture illustrates the photogrammetric 3D model of the Palazzo Reale façades designed with Agisoft Metashape Professional. A dense point cloud made by aligning many calibrated photos (bottom panel) and put accurately using ground control points (numbered markers) seen on the 3D model. Every marker is a surveyed point that improves location accuracy. This process made a accurate 3D dataset with shapes and textures for HBIM modeling and analysis.

Surface Reconstruction: The point cloud is processed more to make a overall surface, usually by connecting triangles into a mesh. Texture Mapping: The main photos add colors and textures to the surface, making the 3D model look as built. Model Refinement: The model is improved by removing errors, filling in missing sections, or adding more informations. Visualization and Analysis**:** Special software allows you to see and study the 3D model. It can be used for measuring, adding notes, virtual tours, and other studies. Photogrammetry is used in many fields like architecture, archaeology, virtual reality, gaming, design, and heritage preservation. It provides a cheap and non-harmful way to make accurate and precise 3D models.

(Remondino & Rizzi, 2010)

Photogrammetric methods were used to supplement the TLS data, with an emphasis on the East façade's central zone. High-resolution photos were processed to create intricate 3D meshes using Agisoft Metashape. Fine surface textures and complex details that may be difficult for TLS alone to capture are particularly well-captured by photogrammetry. A richer and more complex digital model was made possible by this integration, improving the HBIM's overall quality.

Archival 2D Drawings:

In order to provide alignment references for the modelling process, archival-2D DWG drawings were located and georeferenced. These archival-records, performed by the geomatic team of Politecnico more than 20 years ago, offered important new information about Palazzo Reale's original structural arrangements and design goals. By including these drawings, the HBIM model was able to bridge the gap between historical and contemporary representations while maintaining geometric accuracy.

A strong basis for the HBIM process was created by the convergence of these data sources: archival drawings for historical context, photogrammetry for surface detail, and TLS for structural accuracy. In order to produce thorough and trustworthy digital reconstructions, multi-source data fusion is recommended in heritage documentation best practices, which this integrative approach supports.

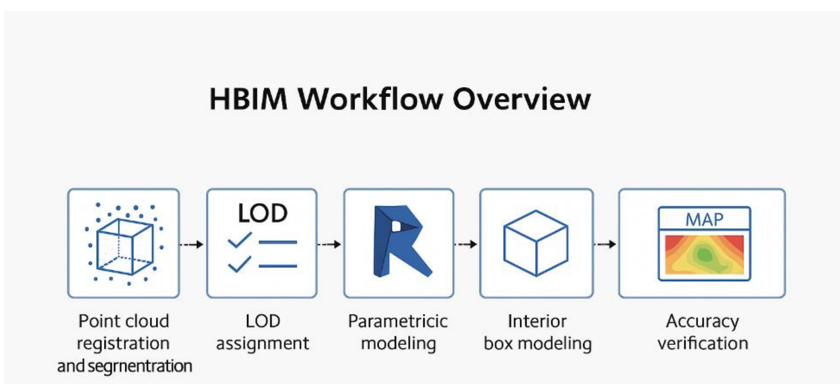


Figure 5.5. Author-generated HBIM workflow diagram summarizing this project's scan-to-HBIM process (inspired by Rocha et al., 2020)

5.2 Software Tools Used

The HBIM process for Palazzo Reale required a number of specialized software tools, each selected for its ability to improve the accuracy, integrity, and geometric precision of the model. These platforms were used in a collaborative and interoperable environment rather than separately to enable cross-platform data exchange and refinement at various modelling stages. This section outlines the purpose of each program and justifies its inclusion in the heritage modelling line.

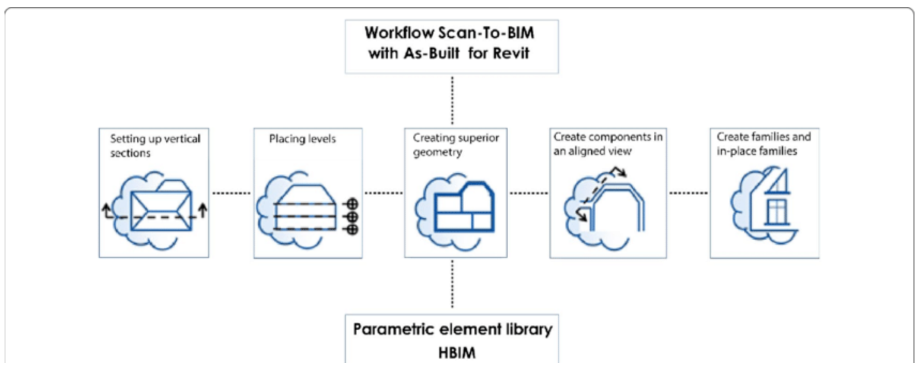


Figure 5.6. Scan-to-BIM Software Workflow in Revit for HBIM
This diagram shows how to create geometry, assign levels, and develop parametric families using laser scan data in the HBIM environment. It also shows a step-by-step scan-to-BIM workflow. Source: Adapted from Graitec Ltd. (n.d.). Scan-to-BIM Workflow with As-Built for Revit.

Autodesk ReCap was the main tool used to provide data and align point clouds. ReCap helped to mix scans, align different views, and clean the basic point clouds from laser scanning and photogrammetry. The files it made (RCP/RCS) allowed dense real-world data to be brought into Revit without creating problems. This section of the process was important to make sure all modeling used the correct coordinate system.

(Chiabrando et al., 2016).

Agisoft Metashape was used to create dense photogrammetric meshes from DSLR image datasets, especially for occluded or inaccessible regions like the center of the East façade. The programm was a supplement to TLS because it could create textured 3D models with sub-centimeter resolution. CloudCompare was used to import Metashape meshes for additional alignment and GOA (Grade of Accuracy) verification.

(Agisoft LLC, 2023; CloudCompare, 2022).

Autodesk Revit used as the core software to create the HBIM model. It was trying to manage Levels of Detail (LOD), make parametric models, and build editable adaptive parts. Historic building parts are designed for using Revit's Family Editor and linked to non-shape data (LOI) to add more importance to the HBIM model. The connection of Revit with point clouds and orthophotos allowed accurate measuring, which is crucial for 3D modeling.

(Autodesk Revit, 2023).

CloudCompare was important for checking the accuracy of the model. It helped compare the HBIM elements to the main scan data using Cloud-to-Cloud (C2C) and Cloud-to-Mesh (C2M) methods and reporting the results. It was also used for grouping the data, cleaning meshes, and matching photogrammetry with laser scans. The software helped analyze model accuracy in various detail zones by using heatmaps for GOA classification.

(CloudCompare, 2022).

AutoCAD used to work with 2D DWG files. Old architectural drawings were used and positioned exactly in AutoCAD before being imported into Revit as guides. This process helped check and rebuild by exactly matching old data with 3D models.

Microsoft PowerPoint was employed for HBIM metrics like LOD, GOA, and LOG classifications, as well as internal reporting. Although it wasn't directly related to modelling, it made it easier to visualize and share methodology results for scholarly and cooperative purposes.

Using these tools together gave a workflow that mixes a variety of data sources and checks them with each other for high accuracy and unit geometry. This teamwork helped build a reliable HBIM model that supports long-term conservation planning and detailed documentation.

5.3 Workflow Overview

Data collection was the first step in the structured, scan-to-BIM methodology used in the HBIM workflow for Palazzo Reale, which ended with a multi-LOD, semantically rich digital model. This workflow integrated laser scans, photogrammetry, archival DWG drawings, and parametric modelling into a single process. Every stage of the project is built on the one before it to ensure spatial logic and geometric fidelity.

The all-modeling process is planned in five steps consistently:

1. Point Cloud Registration and Segmentation by Area
   The initial movement was to register the point cloud from laser scanning and photogrammetry. By using Autodesk ReCap, scans from different stations were aligned and combined into one system. This made a single RCP file, split by façade to manage the data better.

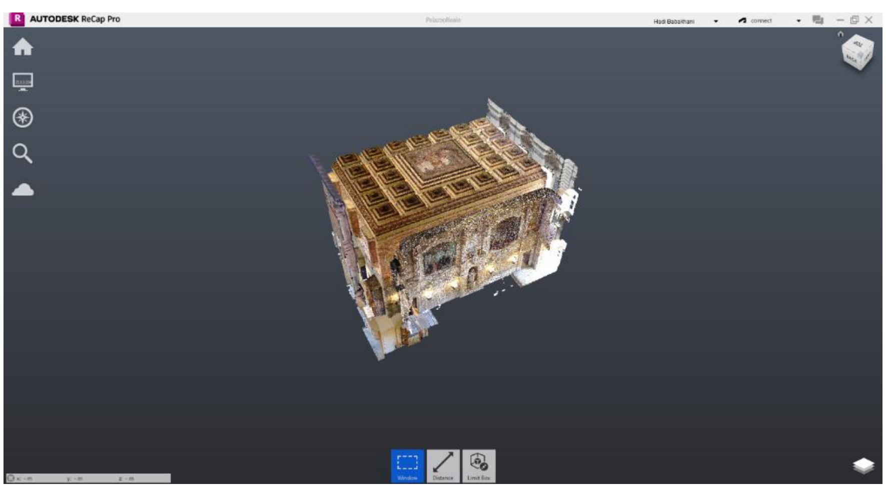


Figure 5.7. Point cloud registration and ceiling extraction in Autodesk Recap, Svizzeri Room

2. LOD Assignment Based on Data Quality and Architectural Significance
   Each façade and architectural zone was assigned an appropriate Level of Detail (LOD), ranging from 100 to 400. The South and Courtyard façades were modeled at higher

LODs (300–400) due to scan richness and ornamentation, while the East façade was handled with a hybrid method due to partial occlusion.

3. Modeling in Revit Using Parametric and Adaptive Tools
   After importing the registered point clouds and photogrammetry data into Revit, HBIM elements were built using adaptive families, extrusion forms, and sweep profiles. Every section was designed with respect to Adjust for that Level of Detail (LOD) to keep accuracy and consistency.

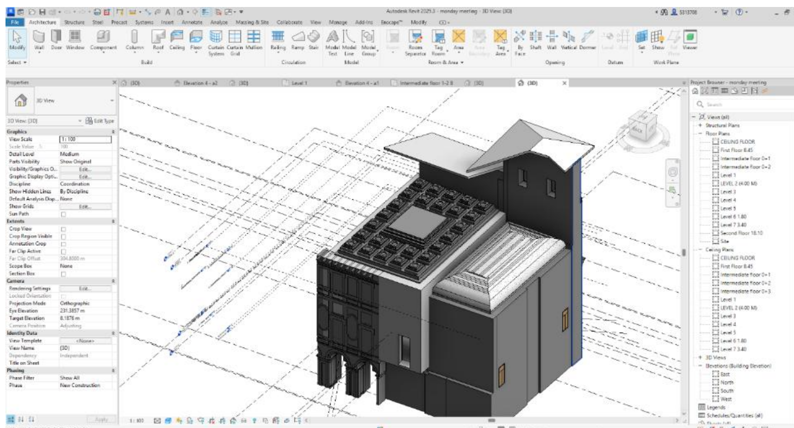


Figure 5.8. Detailed ceiling of the Svizzeri Room modeled separately for higher LOD integration.

4. Accuracy Verification with Cloud Compare
   The final results are checked for geometric accuracy by using CloudCompare. Comparisons between point clouds and meshes (C2M) and between point clouds (C2C) are used to make heatmaps illustrating differences and calculate accuracy scores (GOA).

Each Level of Detail (LOD) supported by geometric data, so every modeling part can be aligned to the original source. This step-by-step process made a strong HBIM model that supports conservation and future digital archiving. Using different platforms (ReCap, Revit, CloudCompare, Metashape, AutoCAD) working together ensured consistency in the workflow and made data reliable.

5.4 Co-Registration and Multi-Source Fusion

A important part of the HBIM process for Palazzo Reale was mixing different spatial data sources. Creating a detailed 3D model needed accurate alignment of photogrammetry, laser scans (TLS), and 2D DWG drawings. To make sure the geometry was correct and make a connection between data with various detail levels, both automatic and manual methods were used.

Alignment of Photogrammetric and TLS Data

Three different data sources were used to model the East façade, which showed partial occlusion from vegetation:

High-resolution TLS data was used to model the southern part, photogrammetric meshes made with Agisoft Metashape were used for the central area, and TLS data from the north façade helped build the northern part. CloudCompare was used to align the photogrammetry and TLS point clouds with a repeated (ICP) method. This holds a high level of accuracy while creating a shared coordinate system.

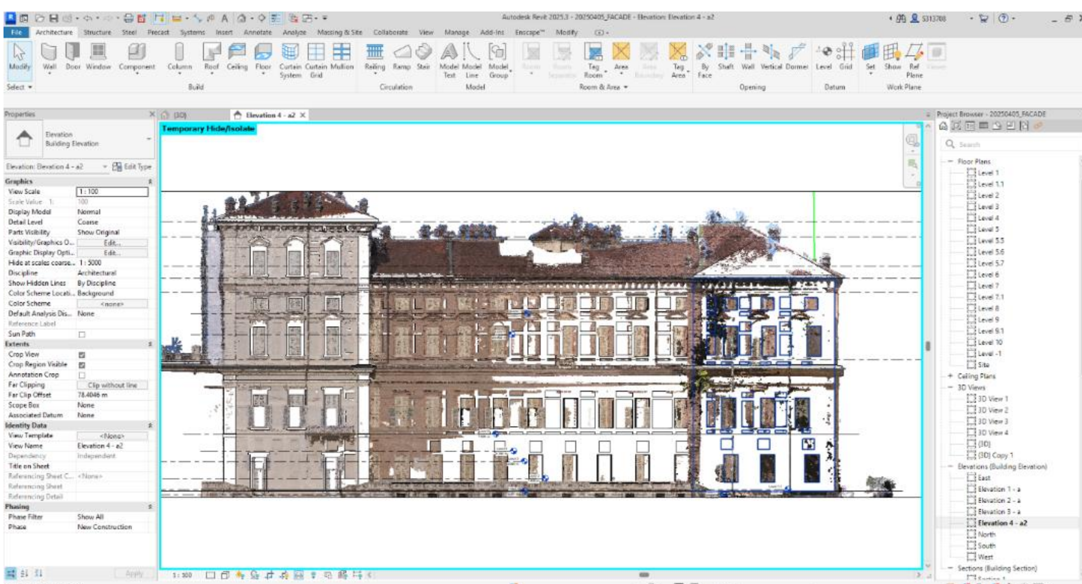


Figure 5.9. East façade point cloud file of the north façade

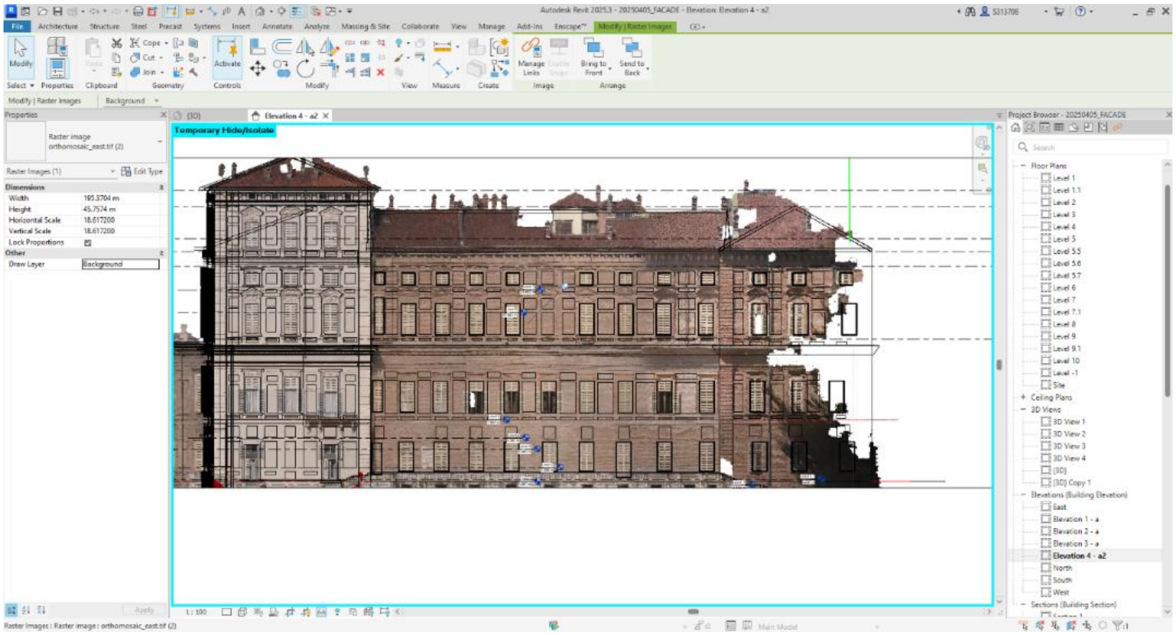


Figure 5.10. East façade metashape file for the middle and East part

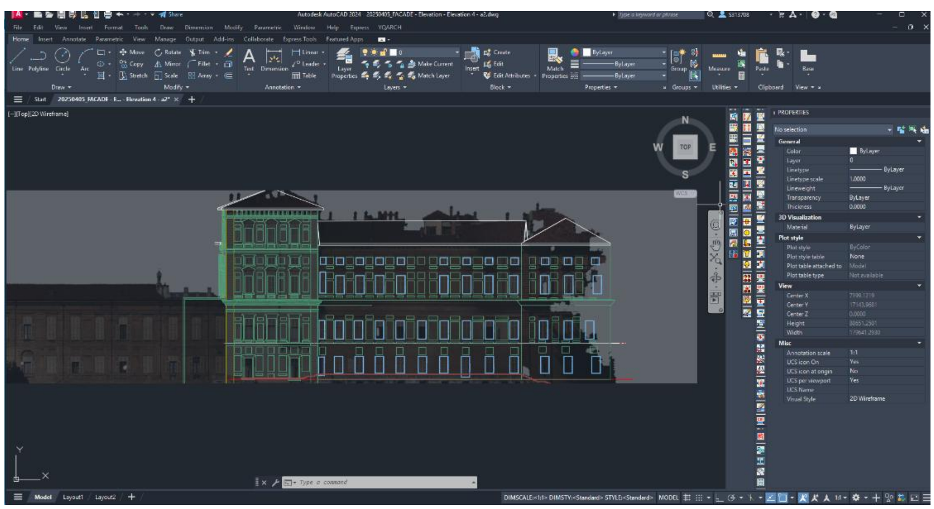


Figure 5.11. Overlay of georeferenced DWG drawings onto the 3D model, illustrating alignment and integration. The screenshot shows alignment between the 2D vector drawing and the captured scan/photogrammetric data, facilitating accurate modeling within the HBIM environment.

Overlay of Orthophotos and DWG Plans

For extra validation and reference, historical 2D DWG drawings were brought into Revit and georeferenced so they matched up with the full 3D model. Orthophotos were also added as raster images to help check texture accuracy and profile alignment, especially in areas that were hidden or had less detail.

This strategy of combining different data sources allowed the team to assign the right level of detail to each façade segment and to accurately merge old documentation with new survey data. By breaking the model into sections, realigning elements, and visually checking everything, they were able to solve inconsistencies and reach a level of precision suitable for both academic study and conservation planning.

5.5 Limitations and Workarounds

The HBIM reconstruction of Palazzo Reale ran into a number of practical and technical issues in spite of the meticulous methodology and the thoughtful application of multi-source data. These limitations resulted from data inconsistencies, restrictions on on-site access, and difficulties modelling historic architecture. Based on the most recent research and heritage BIM best practices, a number of workarounds were implemented to preserve modelling accuracy.

1. Occlusion from Vegetation and Physical Barriers

Dense vegetation, especially on the East and North façades, was one of the main obstacles since it blocked the laser scanner's view of a significant portion of the building. Because of the incomplete point clouds caused by this occlusion, there was less geometric data available for precise modelling.

Workaround:

As supplemental datasets, high-resolution photogrammetric meshes were added, particularly in occluded regions. ICP (Iterative Closest Point) alignment in CloudCompare was used to align these with pre-existing TLS point clouds. When required, low LOD (LOD 200) modelling was carried out using streamlined parametric assumptions that were informed by historical drawings.

Figure 5.12. Orthophotography of the east façade Occlusion

Caption: Vegetation coverage on the East façade limited TLS visibility. The occluded areas were supplemented using photogrammetric meshes from Agisoft Metashape.

Source: Author, 7mm resolution photogrammetry dataset.

2. Dataset Inconsistencies and Multi-source Misalignment

Small misalignments and data discontinuities were found as a result of the combination of two distinct reality capture techniques (TLS and photogrammetry), especially at the intersections of façade segments.

Workaround:

The modelling workflow used segmented façade logic to address these discrepancies. Each segment (such as the South, Central, and North of East façades) was processed separately before being manually co-registered. Transitions were iteratively adjusted using the visual controls in Revit and the deviation analysis in Cloud Compare.

3. Complex Ornamental Geometry (e.g., Ceilings, Cornices)

Interior ceiling elements with intricate details, like the Svizzeri Room and First Floor ceilings, had elaborate geometries that were beyond the scope of Revit's standard parametric modelling tools.

Workaround:

Custom adaptive families and sweep-based detailing were used to model these components as isolated high LOD elements. Results were labelled with GOA scores in PowerPoint-based internal reporting, and accuracy was confirmed using C2M analysis in Cloud Compare.

4. Discontinuous LOD Between Connected Zones

Because of differences in scan quality or architectural significance, adjacent façades or rooms in some parts of the model required notably different LODs. For instance, there were geometric and visual discontinuities when the high LOD Courtyard façades gave way to the box-modeled interiors with less detail.

Workaround:

Blended massing and profile sweeps were used to introduce intermediate geometry at LOD 200–300 in order to smooth out LOD transitions. This maintained visual and spatial coherence without sacrificing accuracy or inflating the volume of data.

DEVELOPMENT

Section 6. Development of the HBIM Model

Using a zone-based approach, the HBIM (Historic Building Information Modelling) model for Palazzo Reale was developed, giving the site's architectural and spatial diversity top priority. The palace proposed particular difficulties about historical accuracy, architectural complexity, and data completeness. As a result, the modelling workflow was created using a progression from general massing to fine detail and from exterior to interior, guided by the quality of the data that was available and the LOD (Level of Detail) requirements.

This section shows how various aspects of the building, like outside walls, inside spaces, and ceilings, are designed. By using data from old DWG drawings, photogrammetry (Agisoft Metashape), and laser scanning (TLS), every section was created in Autodesk Revit. To make sure the models aligned with the source data and had accuracy standards (GOA), they analyzed by using CloudCompare and ReCap.

By giving the correct Levels of Detail (LOD) to every space, the modeling also handled architectural differences and data quality. Simple forms (LOD 100–200) has been designed inside, where scans were limited, while higher LODs (300–400) are used for important, well-scanned areas like the South and Courtyard façades. This progressive process workflow, step-by-step, created an effective HBIM model that supports conservation, visualization, and archiving.

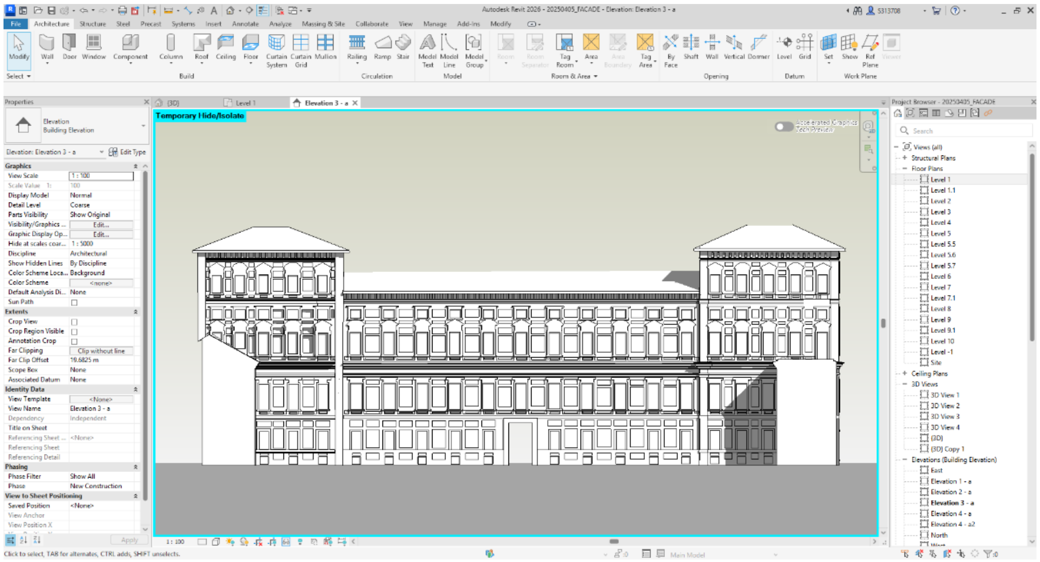


Figure 6.1. HBIM Modeling Zones, The South façade Palazzo Reale

6.1 North Façade (LOD 200)

Using data from terrestrial laser scans that were entered into Autodesk Recap, the North Façade was modelled at LOD 200. Owing to partial data dispersion and vegetation occlusion, a volumetric approach was used, simplifying small decorative details while maintaining window and door alignments. In the HBIM model, this section mainly maintains external massing and spatial coherence, guaranteeing alignment with nearby wings.

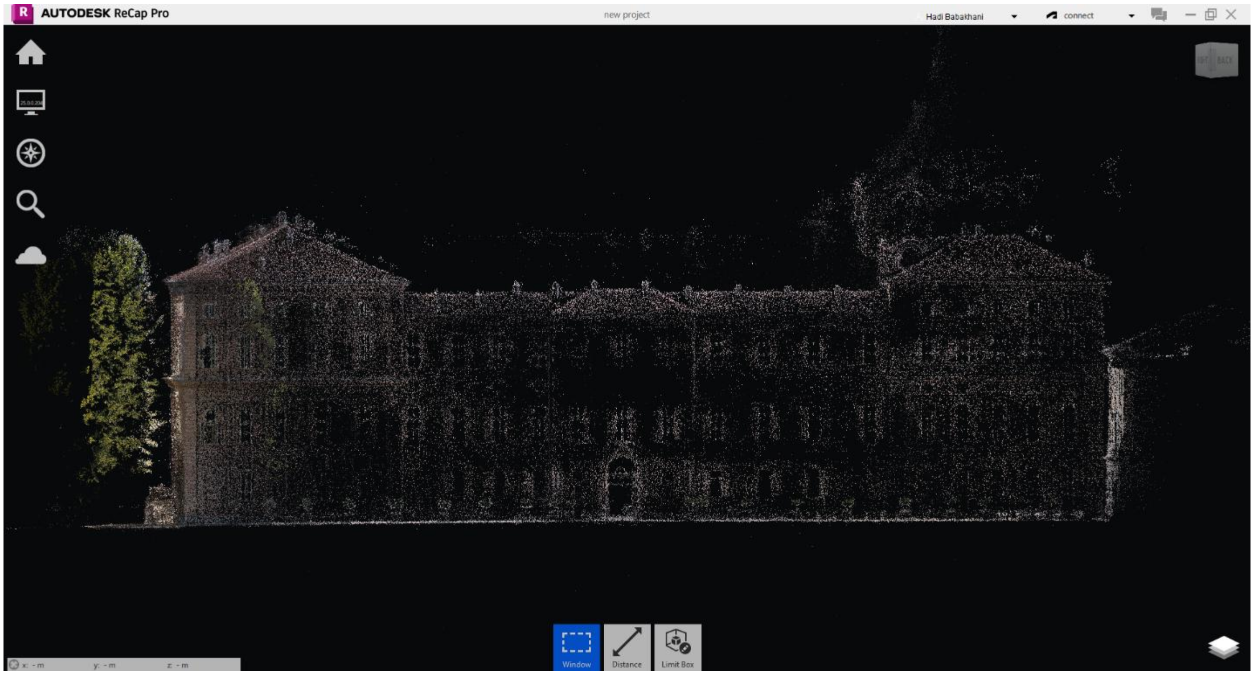


Figure 6.2. Point cloud alignment and coverage of the north façade in Autodesk Recap

Registered scan data of the North Façade shown in Autodesk Recap, illustrating scan station distribution, data density, and alignment prior to HBIM modeling.

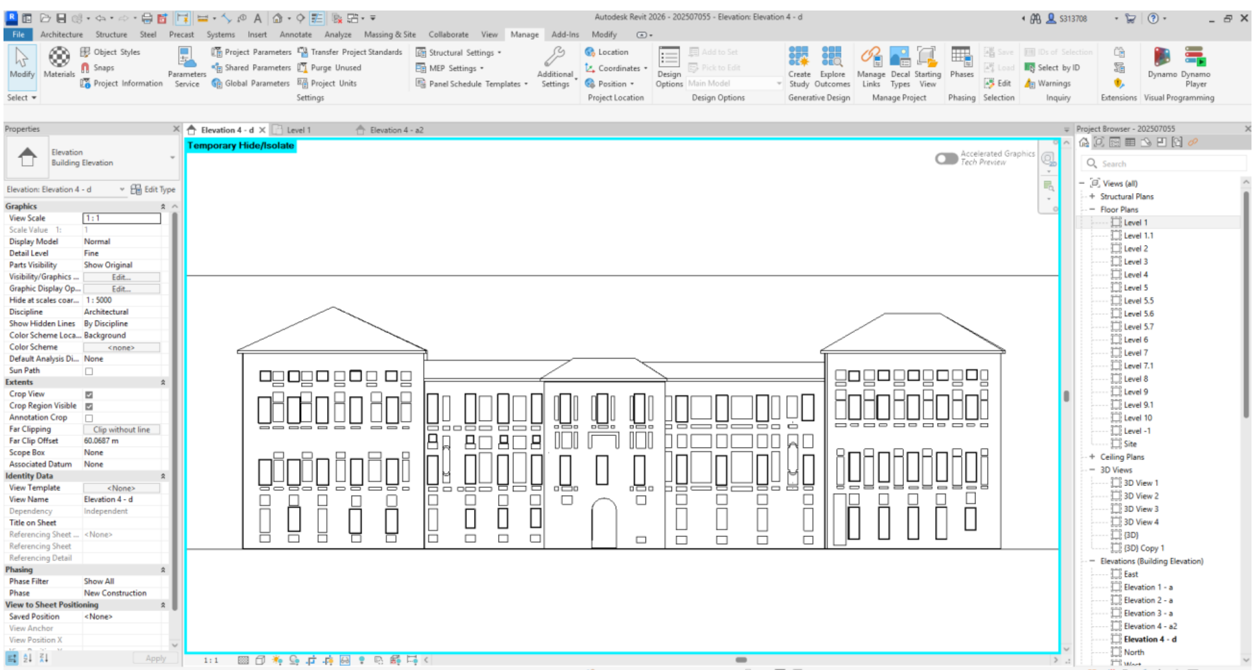


Figure 6.3. HBIM Revit model of the North Façade at LOD 200, showing accurate massing and window positions.

The methods used in other complicated heritage studies are consistent with this multi-scale LOD approach. In the Basilica di Collemaggio, for instance, Brumana et al. (2017) used a similar hybrid HBIM workflow, allocating variable LODs across various zones according to material heterogeneity and accessibility.

6.2 East Façade (LOD 200–350)

A mixed method was used for designing the East Façade, aligning laser scans (TLS), photogrammetry for the center, and aligning with DWG drawings. Because plants blocked some scans, we used partial 3D modeling at Levels of Detail between 200 and 300, based on how much data was available. On the sides, we focused on keeping the total form correct, while photogrammetry from Metashape gave more detail in the middle and some parts near to the north.

Due to the vegetation occlusion, this façade was especially challenging to capture accurately. The model was divided into three parts: the south section, which connected to the South Façade at LOD 300–350; the middle section, based on Metashape data with an LOD around 250; and the north section, which was aligned with the North Façade and kept at LOD 200.

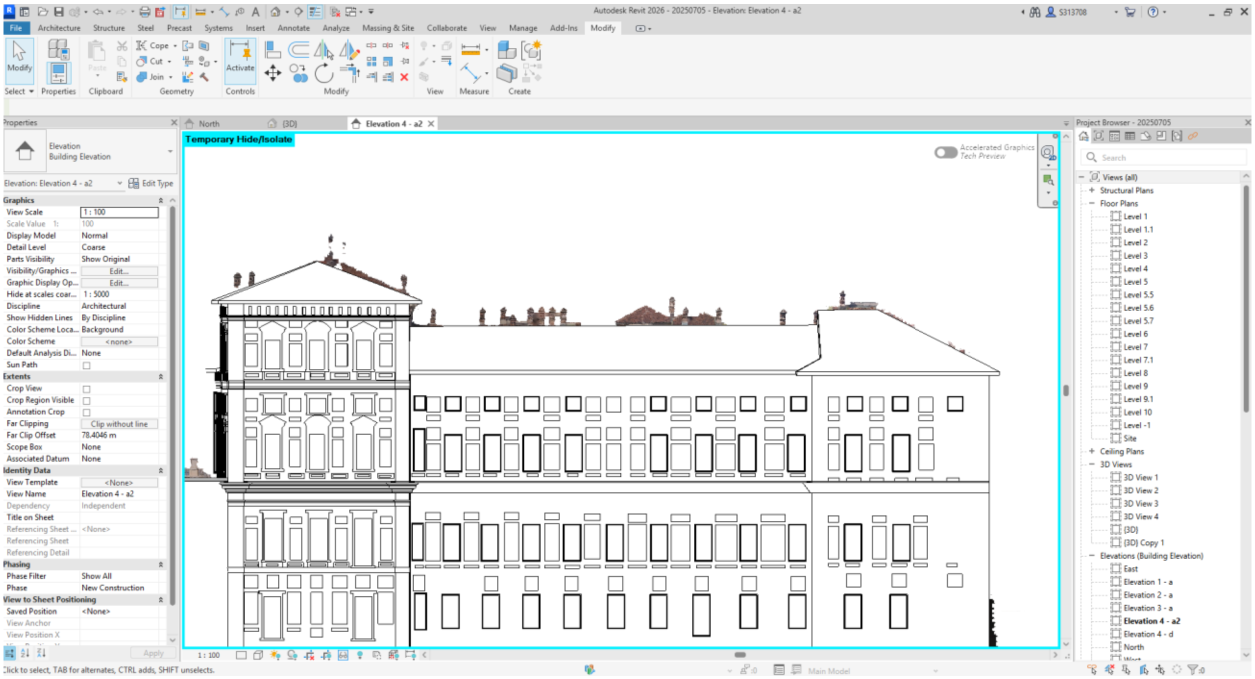


Figure 6.4. Main HBIM file of east façade

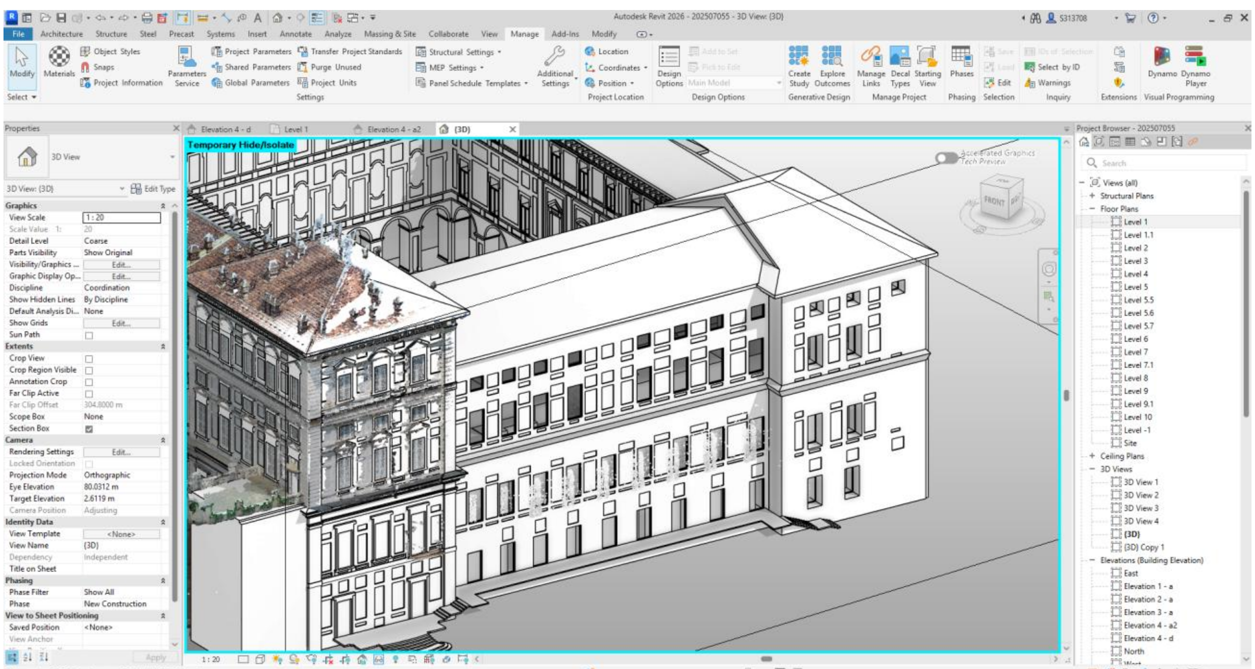


Figure 6.5. Perspective view of Main HBIM file of east façade. East façade with blended LODs; southern elements derived from detailed point clouds, northern from volumetric modeling.

6.3 South Façade (LOD 300–400)

High-resolution TLS data used to redesign the South Façade at a higher Level of Detail (LOD 300–400). Window types, balconies, and façade details are designed by using parametric Revit families. Because the South Façade is more important and has better data, the model focused on accuracy to help with future condition checks and restoration plans.

Figure 6.6. HBIM view of south façade, LOD 300–400

6.4 Courtyard Façades (LOD 400)

Using DWG plan references and laser scanning, the Courtyard façades were created at LOD 300–400. A lot of care was taken to accurately model arcades, column arrangements, and upper window modules because of the symmetrical layout and elaborate decorative profiles. The courtyard modelling approach made it possible for internal spatial layouts and external façades to connect seamlessly.

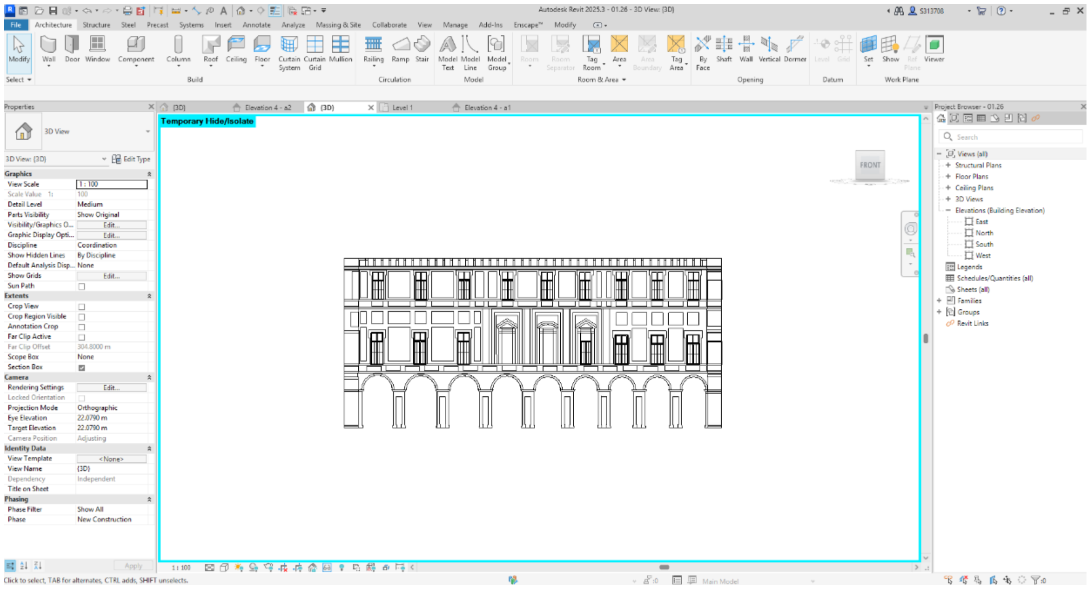


Figure 6.7. Courtyard north façade

Figure 6.8. Courtyard LOG modeling. Detailed HBIM representation of the Courtyard façade at LOG 400, showing accurate modeling of arches, cornices, and column bases derived from point cloud data. The geometric fully reflects advanced parametric design practices in Revit for heritage modeling.

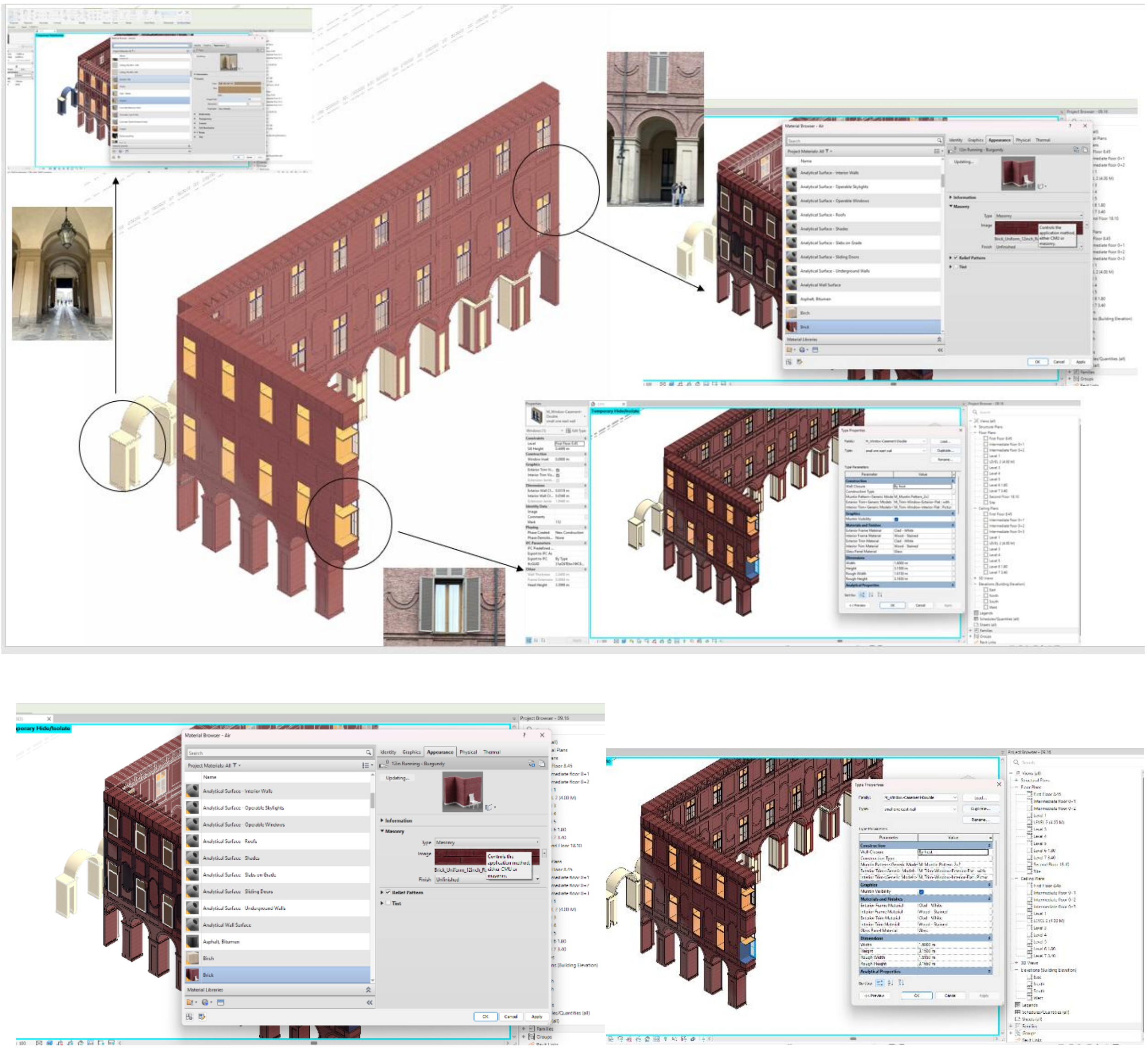


Figure 6.9. Courtyard LOI. A detailed HBIM model of the Courtyard façade at Level of Geometry (LOG) 400 shows accurate arches, cornices, and column bases. These made by using point clouds and photogrammetry. The accuracy of the model shows high parametric design in Revit for heritage buildings.

Figure 6.10. courtyard south façade

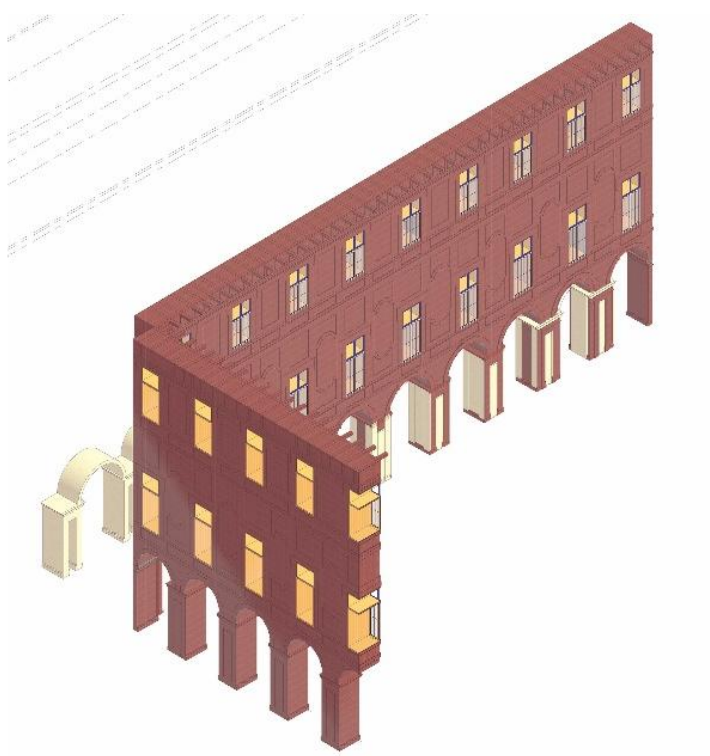


Figure 6.11. courtyard east façade

Figure 6.12. Courtyard west façade. Full set of courtyard façades modeled in high detail (LOD 400) showing symmetry and structural articulation.

6.5 Interior Boxes (LOD 100–200)

A simplified volumetric modeling approach was used to recreate the interior rooms of Palazzo Reale because many of the spaces did not have full laser scan coverage. This method helped keep the palace’s spatial structure consistent by making sure the ceilings, internal walls, and exterior façades all stayed properly aligned.

The volumetric models were built at Levels of Detail between 100 and 200, focusing on showing room boundaries with mass elements, keeping vertical and horizontal continuity across different floors, and creating a geometric base to connect the façades with the more detailed ceiling models. Room volumes were reconstructed by combining 2D DWG floor plans, registered laser scan point clouds where they existed, and photogrammetric mesh data in some areas like the rooms along the East façade. This strategy made it possible to extend the model evenly across the palace, even in places where scan data was missing or hard to collect.

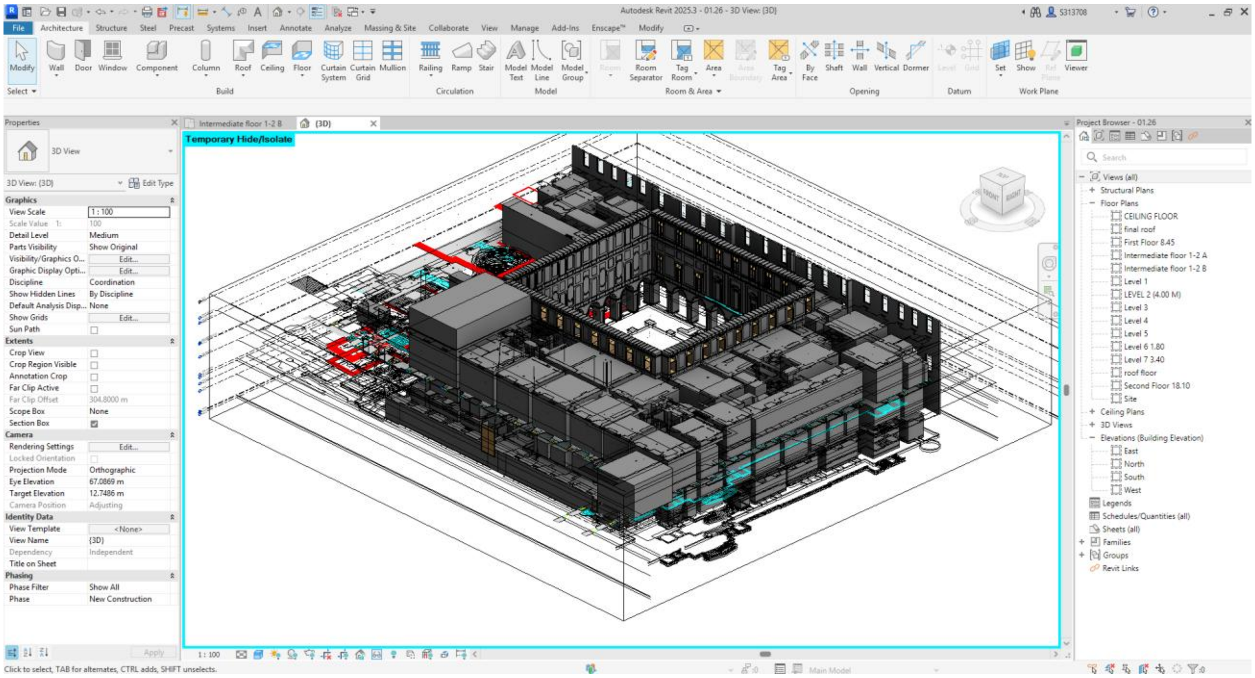


Figure 6.13. Interior volumetric modeling based on DWG and point cloud references

Using 2D survey drawings and laser scan data as references, simplified volumetric representations of Palazzo Reale's interior spaces were produced in Revit.

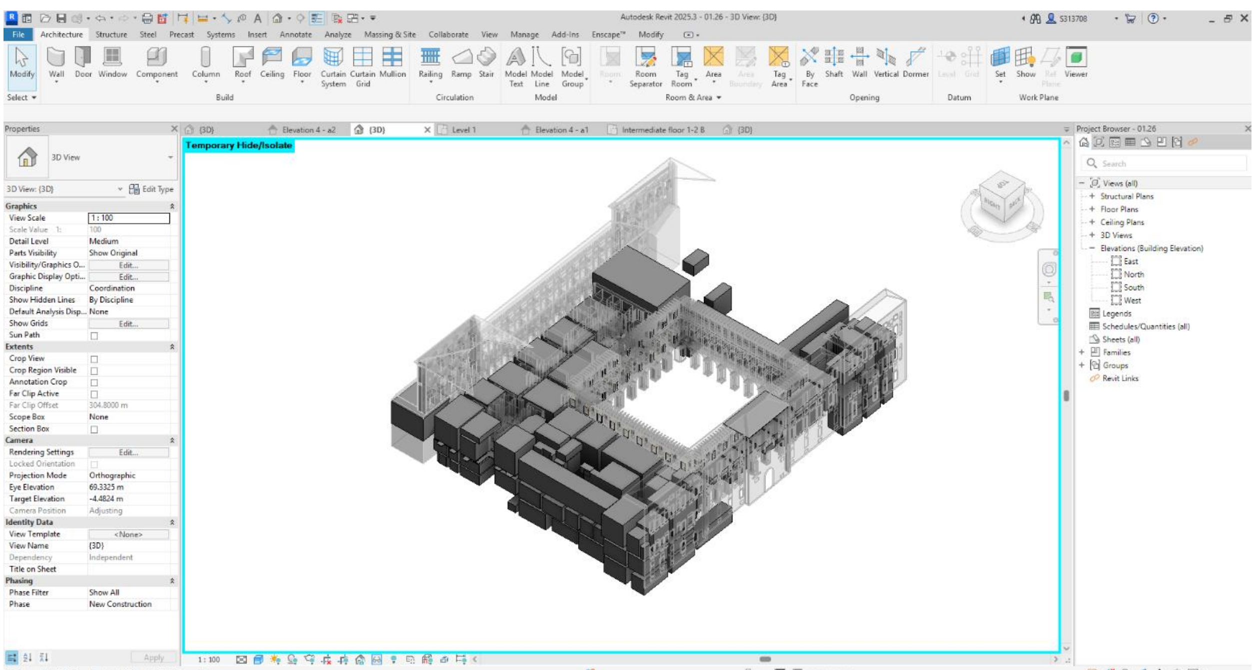


Figure 6.14. Interior box models serve as low-LOD placeholders to support spatial integration.

6.6 First Floor Room Ceilings (South Façade Zone)

Using point cloud segmentation, DWG plans, and manual tracing in Revit, a selection of the first floor's ceilings were modelled at LOD 300–350. For ceiling coffers and ornamental elements with partial scan coverage, simplified parametric extrusion techniques were used. A logical connection between volumetric room spaces and higher-fidelity ceiling geometries was made possible by this tactic. decorated ceiling forms were modelled and compared to point clouds in six rooms along the south façade.

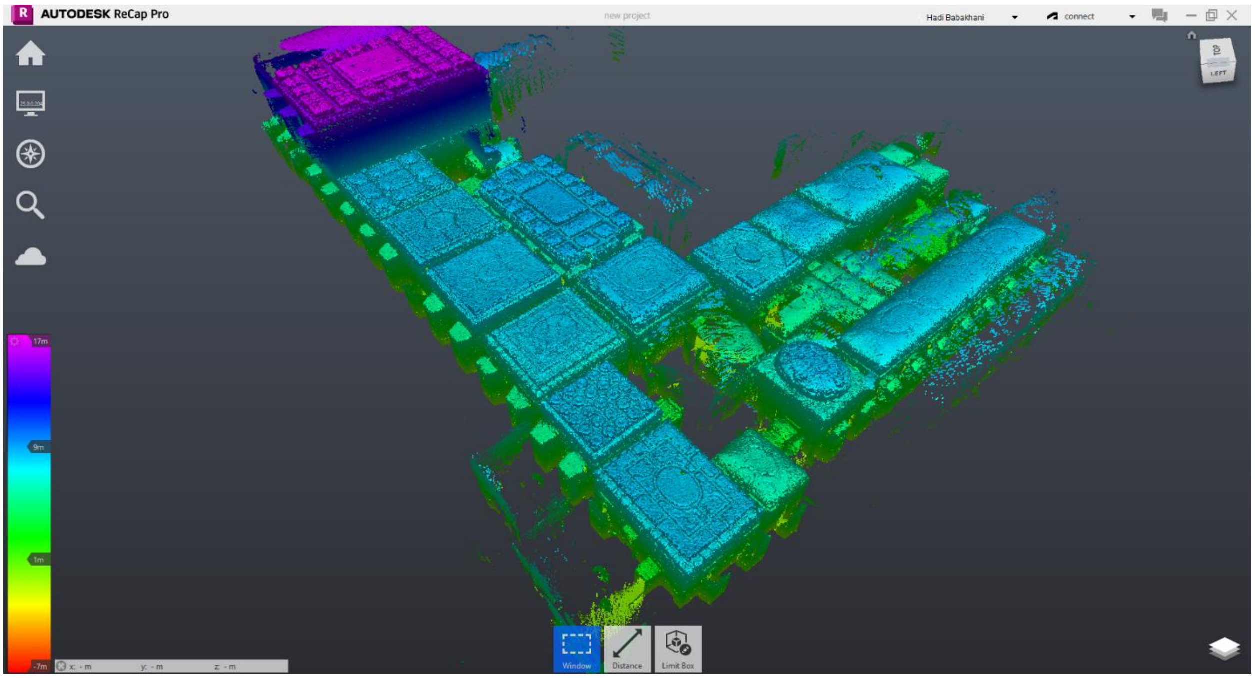


Figure 6.15. Recap registration of ceiling scans. First Floor South Rooms

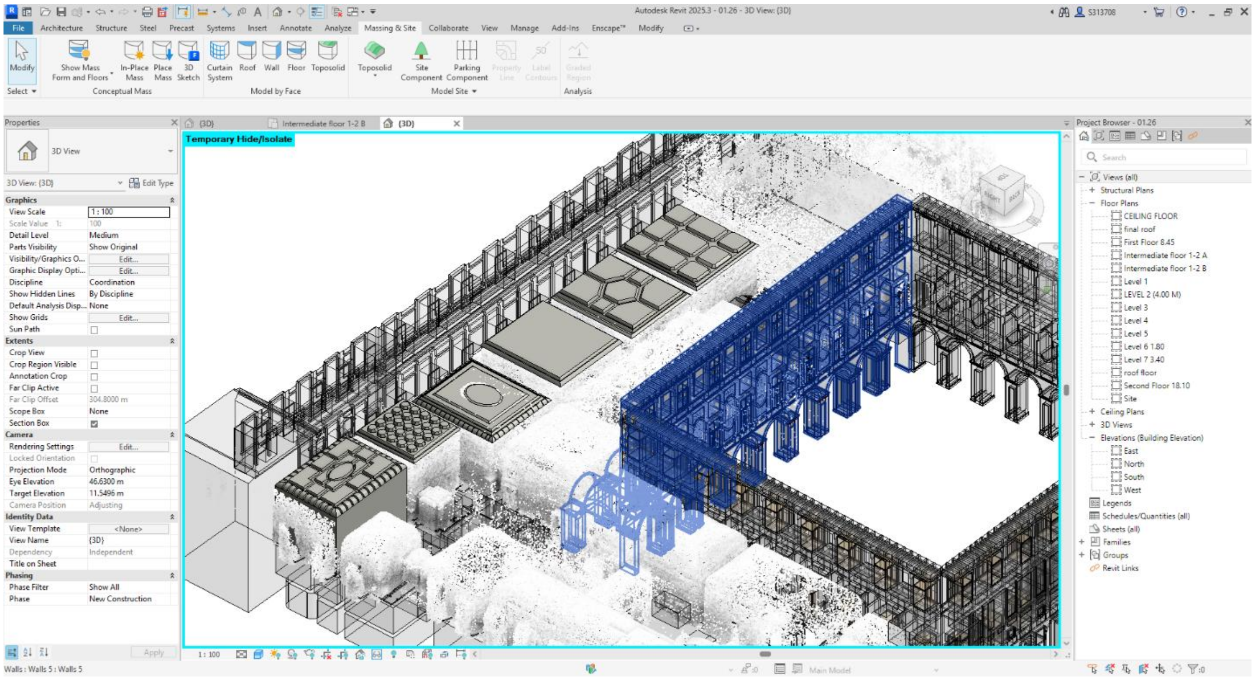


Figure 6.16. Six first-floor rooms ceiling to the south façade.

6.7 Svizzeri Room Ceiling (LOD 400)

The highest degree of geometric and visual fidelity in the project was achieved when the ceiling of the Svizzeri Room was rebuilt at LOD 400. Beams, coffers, and decorative motifs could be precisely modelled thanks to dense TLS data and manual mesh cleaning. Additionally, C2C and C2M accuracy assessments in CloudCompare were conducted on this zone, confirming the spatial alignment of scan data and HBIM elements.CloudCompare was used to validate the high-level detail modelling of this ceiling.

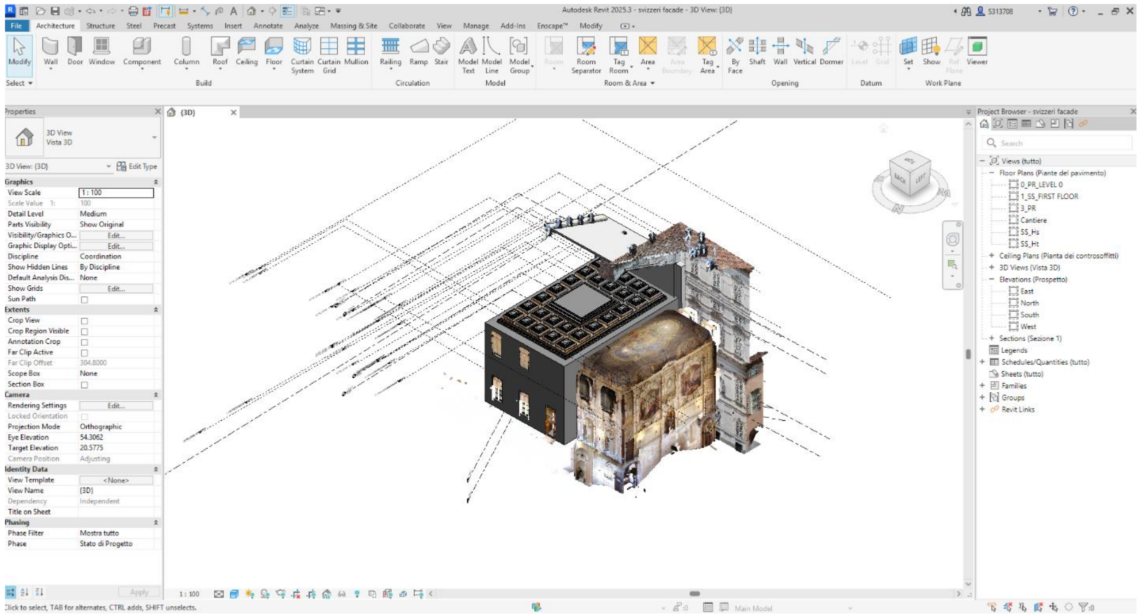


Figure 6.17. Svizzeri's room ceiling. The figure demonstrate the alignment of the point cloud and HBIM model of the Svizzeri Room ceiling,

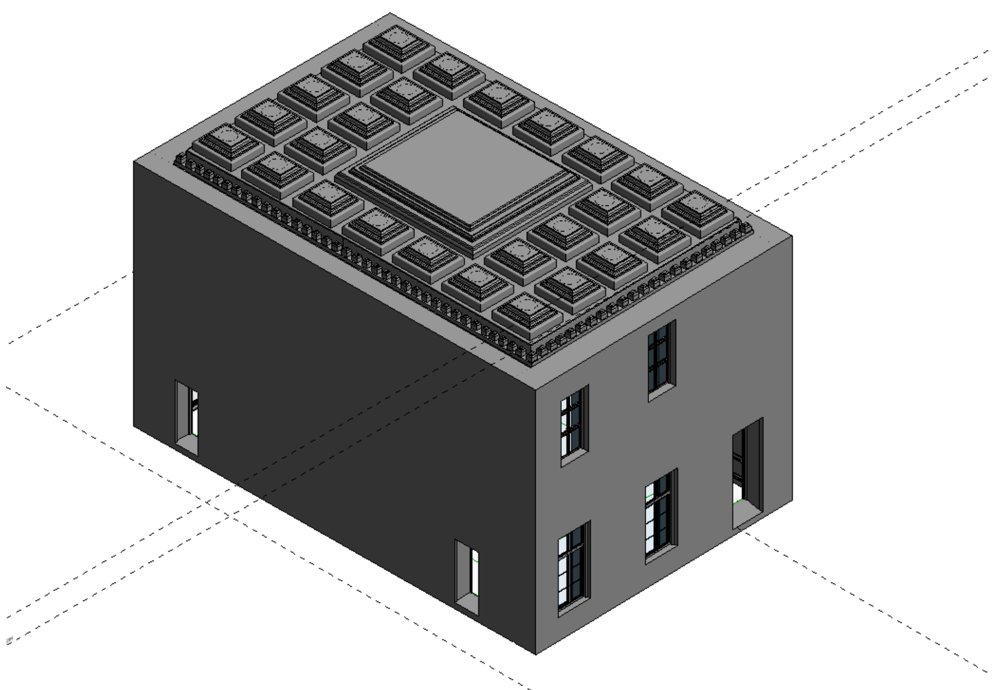


Figure 6.18. Svizzeri's room ceiling. HBIM model of the Svizzeri Room ceiling using Revit adaptive masses.

EVALUATIONS

Section 7. Analysis and Evaluation

This section provides a critical evaluation of the HBIM models developed for Palazzo Reale, focusing on geometric accuracy, multi-LOD integration. Tools like CloudCompare and Revit were used to assess how well the model geometry and the source data aligned, and qualitative analysis was used to highlight the challenges and solutions faced during the modelling process. The goal was to weigh the benefits and drawbacks of the selected methodology in addition to verifying fidelity.

7.1 Grade of Accuracy (GOA)

Accuracy was assessed using both Cloud-to-Cloud (C2C) and Cloud-to-Mesh (C2M) comparisons, which quantified the differences between the HBIM model and the original laser scan or photogrammetry datasets. For high-detail areas such as the Svizzeri Room ceiling and the windows on the South Façade, the C2M analysis demonstrated sub-centimeter accuracy, with a few centimeters of deviation. This result highlights the effectiveness of Revit's adaptive modelling techniques in capturing intricate ornamental features. In contrast, regions modelled with photogrammetry under occluded conditions, like the middle section of the East Façade, exhibited localized differences above a few centimeters, revealing the limitations of mesh-based reconstructions without clear line-of-sight or sufficient point density. Additional analysis of the Courtyard Façade confirmed an overall dimensional alignment of approximately 80% between the HBIM model and the laser scanning point cloud, with only minimal discrepancies observed in arch curvature and window placement, underscoring the high geometric fidelity achieved in this area.

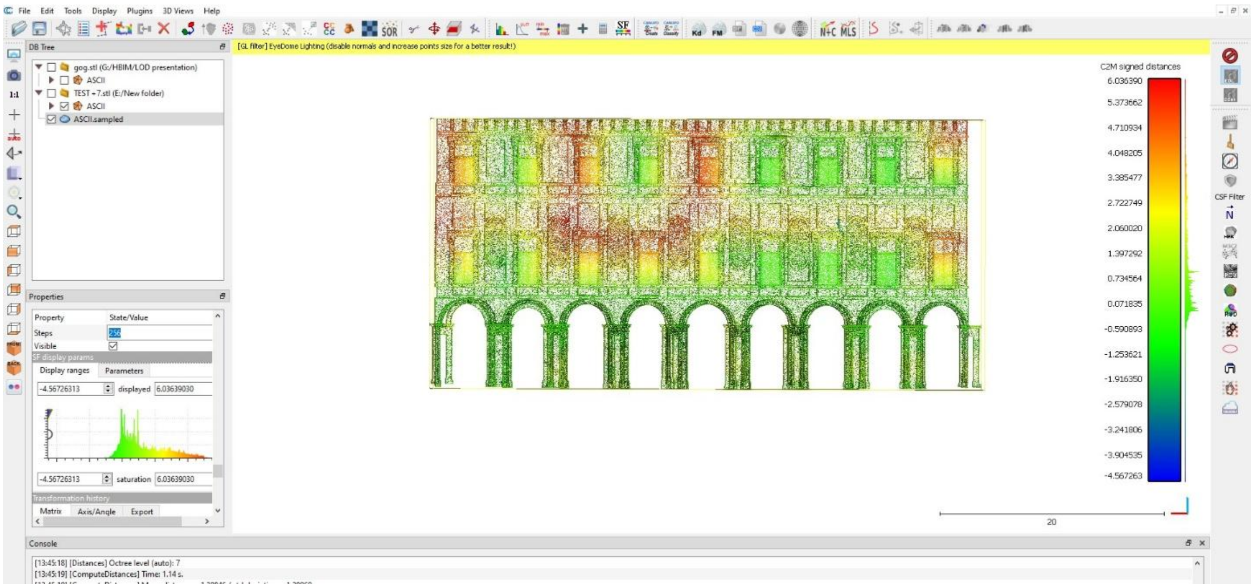


Figure 7.1. C2M analysis showed that over 80% of the surface differences stayed within an acceptable range, confirming the model's high geometric accuracy.

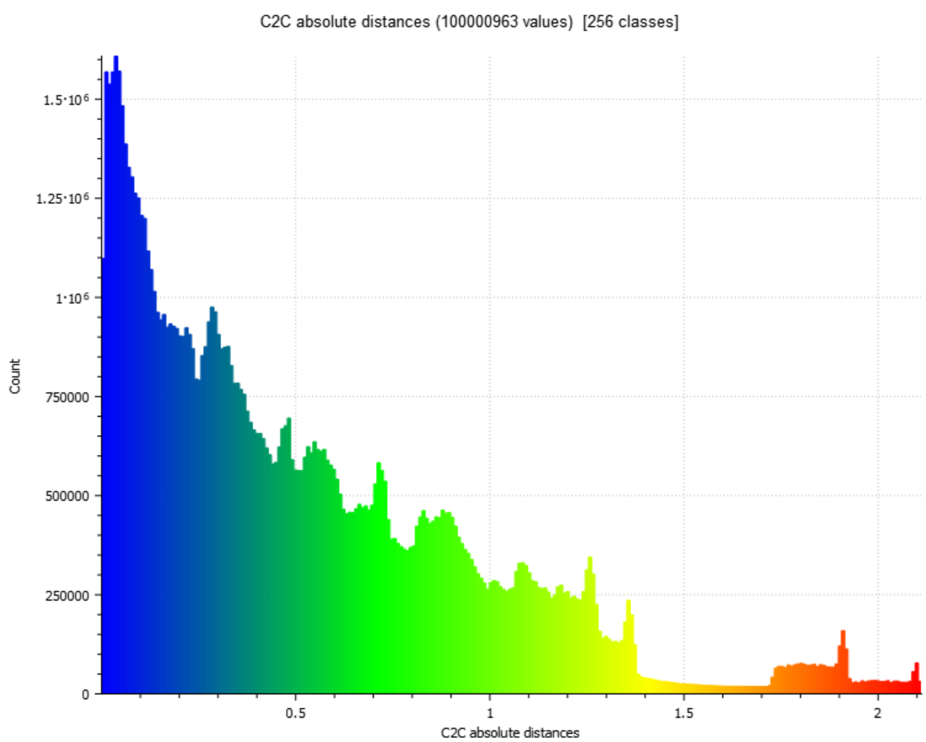


Figure 7.2. Histogram C2C.csv, This svizzeri room ceiling histogram shows the distances between two point clouds in meters. Most points have small differences (blue-green), showing good alignment. Larger differences (yellow to red) are less common. This measures how closely the two datasets match.

7.2 Grade of Generation (GOG)

The Grade of Generation (GOG) was assessed using the Level of Geometry (LOG) and Level of Information (LOI) metrics. High LOG scores were achieved in the Courtyard and South Façade zones, where scan data was closely followed by intricate modelling of decorative frames, arches, and cornices. These zones also contained semantic metadata (LOI 300–400), which mentioned architect credit, building stages, and material types.

The Level of Geometry (LOG) and Level of Information (LOI) were used to measure the Grade of Generation (GOG). In the Courtyard and South Façade areas, detailed modeling of decorative frames, arches, and cornices closely matched the scan data, earning high LOG scores. These zones also included rich information (LOI 300–400) about materials, building phases, and architects. The Courtyard Façade got a GOG grade of 400, showing the HBIM model matches the real building very well. The detailed windows, arches, and columns prove the model's high quality.

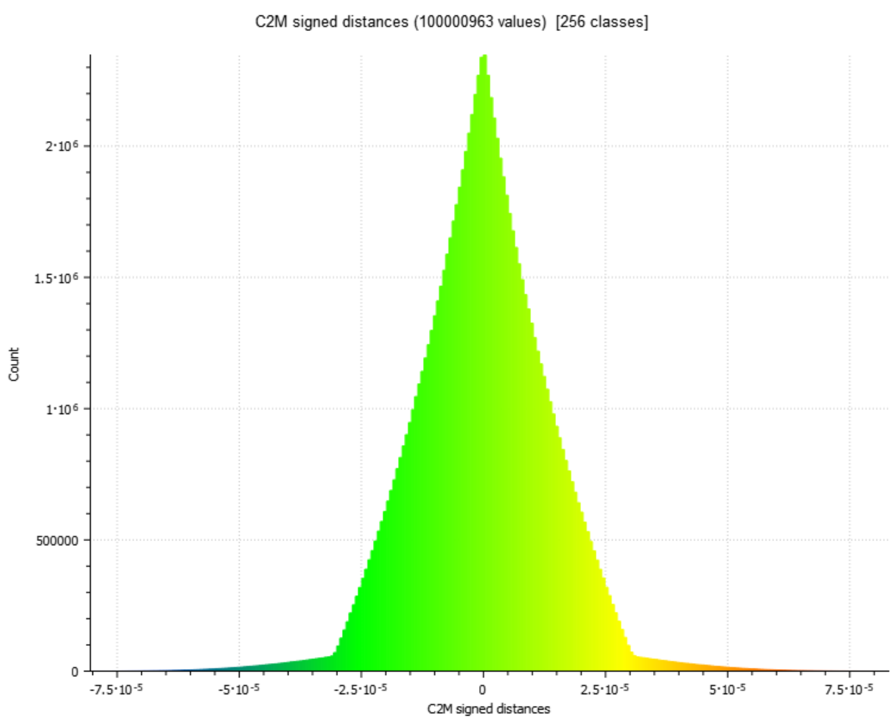


Figure 7.3. Histogram C2M.csv. This svizzeri room ceiling histogram shows distances between a point cloud and a mesh (C2M). The balanced form means points closely match the mesh, showing high geometric accuracy.

7.3 LOG and LOI Evaluation

In addition to GOA and GOG, the Courtyard and South façades were evaluated using the LOG (Level of Geometry) and LOI (Level of Information) standards:
LOG 400 was attained by the courtyard façades, which featured geometrically complex elements such as arches, cornices, and projections that were closely aligned with geometric references and point cloud curvature. The Courtyard Façade's LOG was rated at 400, based on precise modelling of complex geometries. LOI 400 was partly reached by adding metadata in Revit. The model included details like the windows and balconies on the south façade had LOI tags noting possible restoration needs and symmetry checks between the two sides.

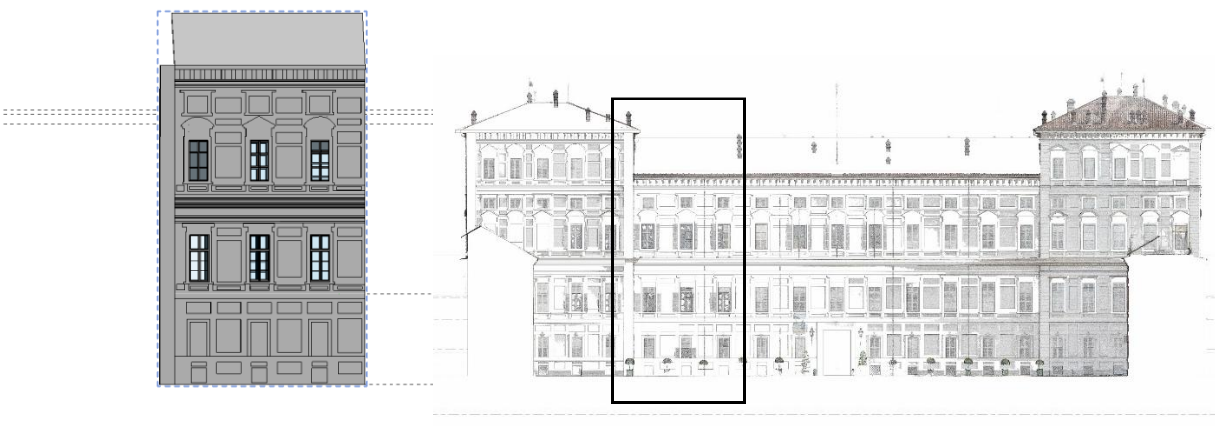
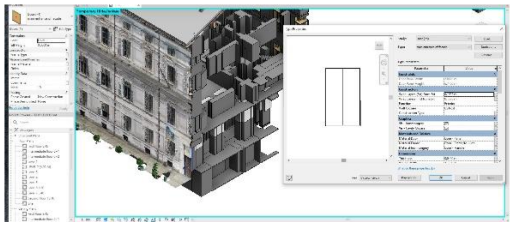
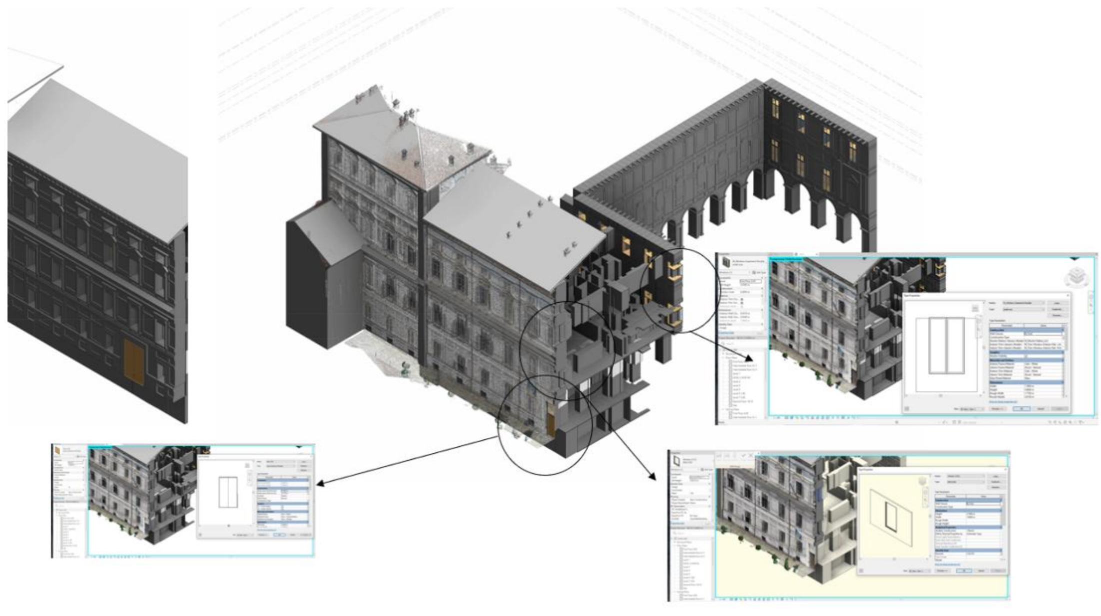


Figure 7.4. South Façade LOG**.** The South Façade's high-precision HBIM geometry, which was modelled at LOG 300-400.





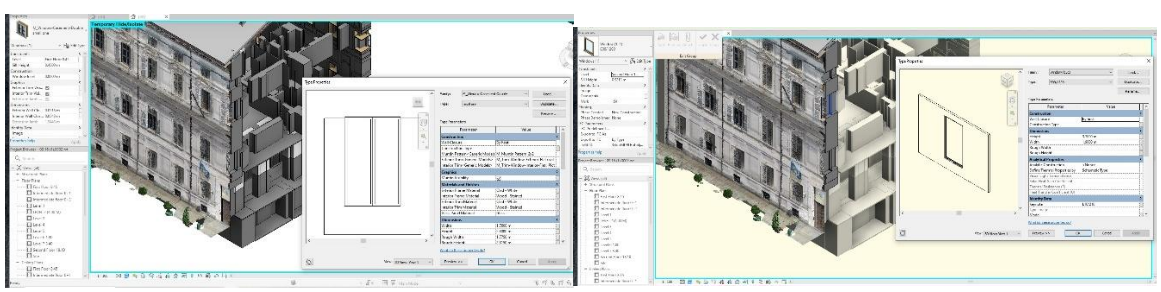


Figure 7.5. South Façade LOI. Revit metadata panel illustrating LOI integration for the South Façade.

The model shows different detail levels depending on the area. The North Façade focuses mostly on shape and geometry, with little extra information, and has a Level of Geometry around 200. The interior box models are simple, mainly showing general space without details. In contrast, the Svizzeri Room ceiling was designed with much higher accuracy using adaptive tools in Revit. This part matched the point cloud data very well.

The east façade was divided into three parts: the southern side was modeled using the point cloud data and showed very good alignment at a higher level of detail (LOD 300). The middle section was modeled using orthomosaic images, which caused some minor alignment issues. The northern part was modeled using the point cloud from that area and was simpler (LOD 200), showing some generalization. Heatmaps helped highlight areas of varying accuracy, with blue and green colors indicating tight alignment, and isolated yellow to red zones corresponding to areas with more complexity, occlusion, or scan noise.

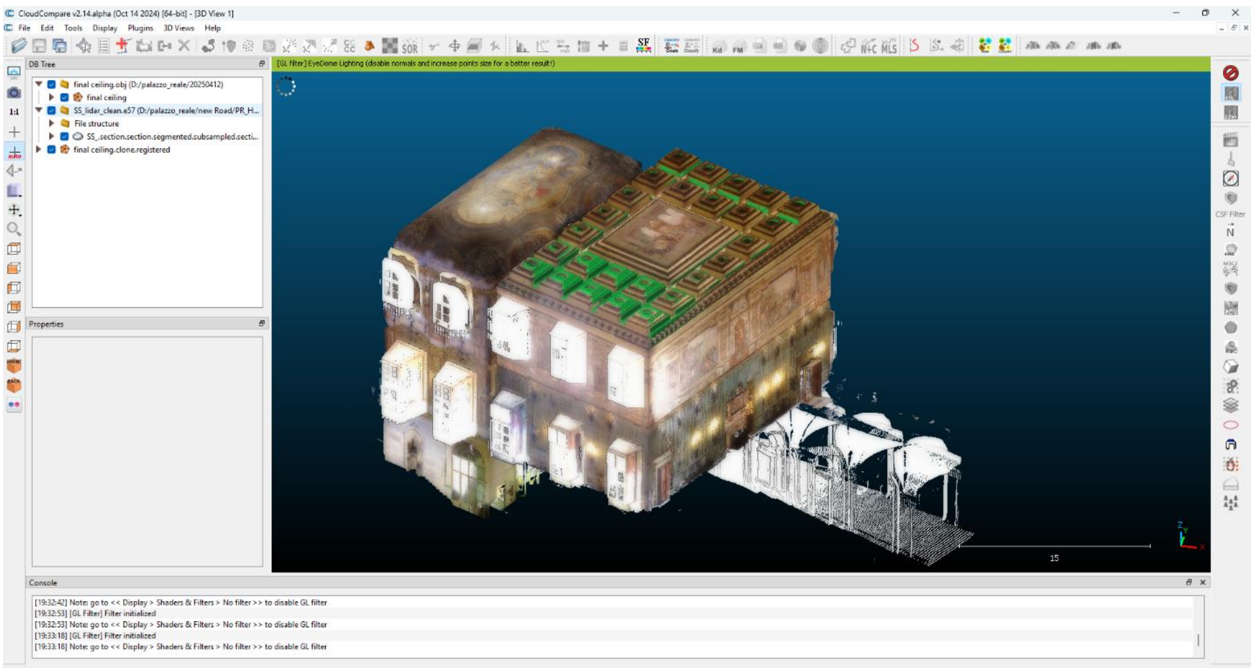


Figure 7.6. Svizzeri room ceiling comparision Cloud Compare with HBIM

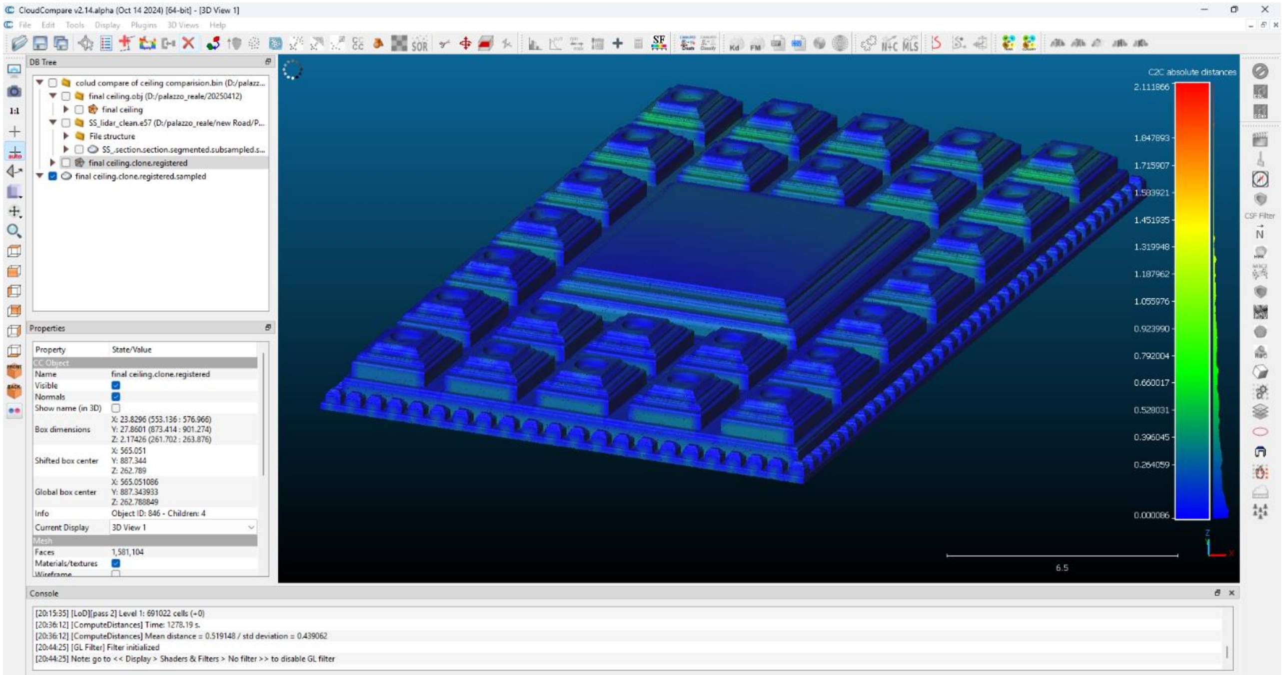


Figure 7.7. Svizzeri room ceilingC2C. Heatmap overlays comparing Revit model of Svizzeri Room ceiling to the original point cloud. Most areas have a few centimeters deviation (blue-green, indicating overall good alignment.

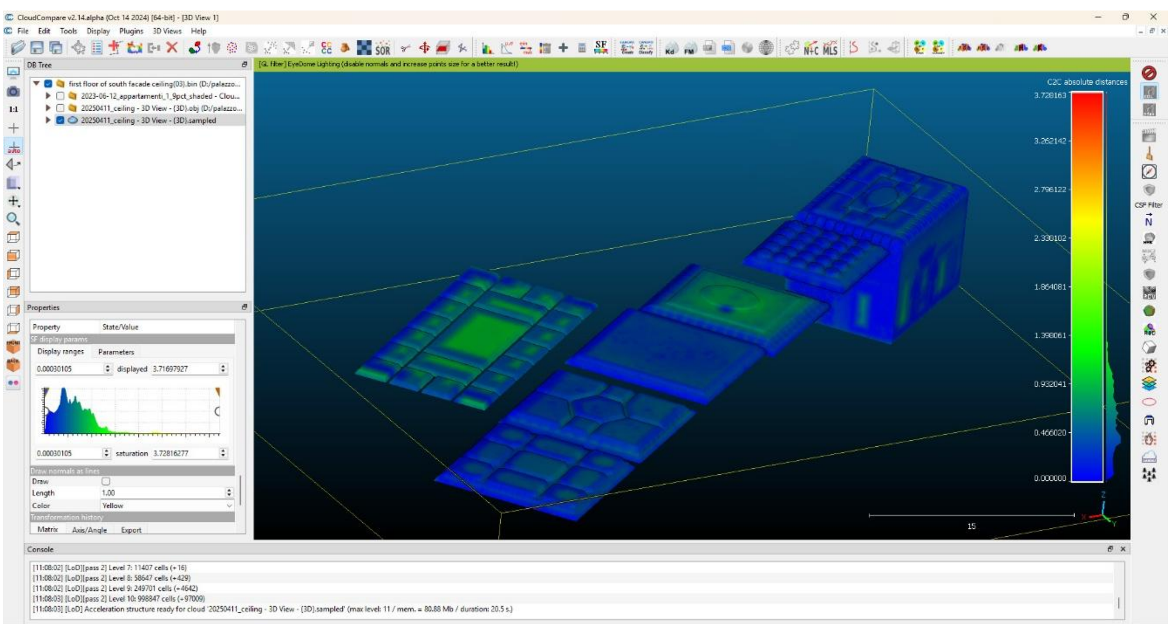


Figure 7.8. Six-room ceilings (South) C2C. The analysis shows overall good alignment between the model and the scan with minimal deviations.

7.4 Multi-LOD Integration and Transitions

The HBIM model of Palazzo Reale was built using a multi-scale approach that moves gradually from simple overall shapes to very detailed parametric features. This strategy was necessary because different parts of the building had different levels of architectural complexity, priorities, and available data.

To deal with gaps in laser scanning (TLS) and photogrammetry coverage, and to follow good practices for documenting cultural heritage, the team organized the model from the outside in, and from low to high levels of detail. The simplest block-like geometries were used for general volumes and hidden façades, while areas that were more complex or culturally important, like the Courtyard façades and the Svizzeri Room ceiling, were recreated with high-accuracy geometry and detailed components. Transitions between these levels were carefully managed so everything stayed properly aligned, for example, keeping façades and ceilings connected correctly. Where data was missing, orthographic DWG plans were used to fill the gaps. When possible, the team also suggested likely architectural types, such as vault styles or frame patterns, using semantic logic, while making sure everything stayed lined up with reliable reference planes and confirmed scan data. This mix of different detail levels made the model useful both as an analytical tool and as a resource for conservation work.

Summary Table – LOD / LOI / LOG / GOA by Area

Area/Element	LOD	LOI	LOG	GOA Method	Notes
East Façade	200–300	Low-Mid	Medium	Visual + C2C	Occluded zones; photogrammetry used for reconstruction
North Façade	200	Low	Medium	Visual + C2C	TLS-based, moderate complexity
South Façade	350–400	Medium	High	C2C + Visual	High scan quality; richly detailed; window frames & ornaments
:ourtyard Façades	300–400	Medium	High	C2C	Accessible and symmetrical; parametric logic applied
Interior Boxes	200	None	Low	Visual	Volumetric placeholders
First Floor Ceilings	200	Low-Mid	Medium	C2C	simplified geometry
Svizzeri Room Ceiling	400	Medium-High	High	C2C	full accuracy assessment numeric data

Table 7.9. summary of the evaluated areas.

7.5 Modeling Challenges and Responses

Several challenges affected the quality of the HBIM model. On the East façade, vegetation blocked some laser scans, and we used less accurate data in the north part. This highlights the importance of careful scan planning and removing obstacles, especially for heritage projects.

In addition, some of the datasets did not line up perfectly and needed manual adjustments in Revit, which caused small inconsistencies and made the modeling process more tiring. A stronger automatic registration system or a pre-calibration step could help combine the data more accurately in the future. The high level of detail in ornamental areas, especially vaulted ceilings, also pushed the limits of parametric modeling tools. Adaptive components were helpful, but manual tracing still took a lot of time and effort. New AI-assisted modeling tools could eventually make this work faster and easier. Even with these challenges, the HBIM model proved to be flexible, scalable, and accurate enough to support conservation and visualization tasks. The project also showed the Ongoing choices between precision, speed, and detailed information, choices that always have to be balanced based on resources and project goals.

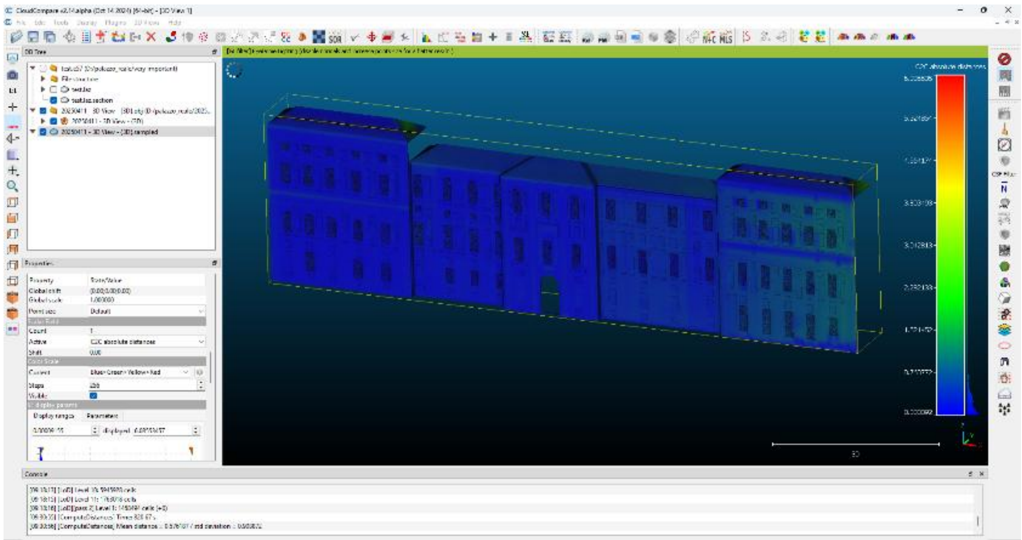


Figure 7.10. C2C Heatmap, comparing the Revit model of the north facade with the original point cloud. Most areas show small deviations (blue), typically within a few centimeters, reflecting good overall alignment.

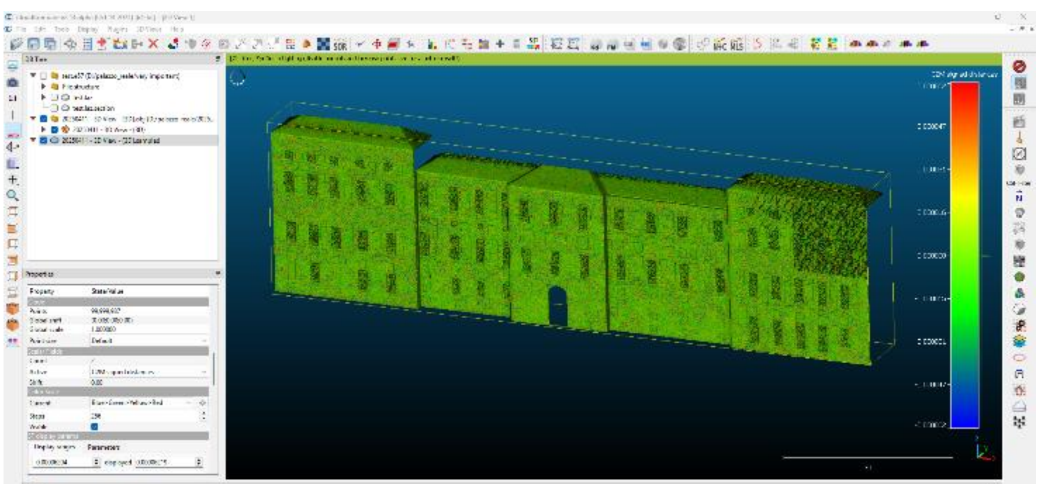


Figure 7.11. C2M Heatmap overlay comparing the Revit model with the original point cloud using Cloud-to-Mesh (C2M) distances. The average shows a very small standard deviation, indicating excellent alignment between the model and the mesh.

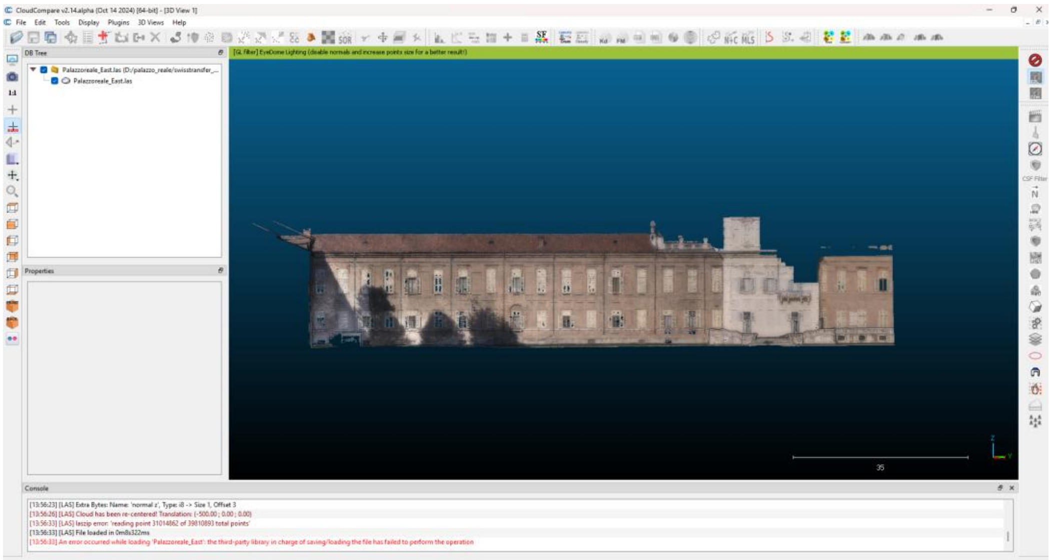


Figure 7.12. East façade of Palazzo Reale, LAS point cloud visualization.

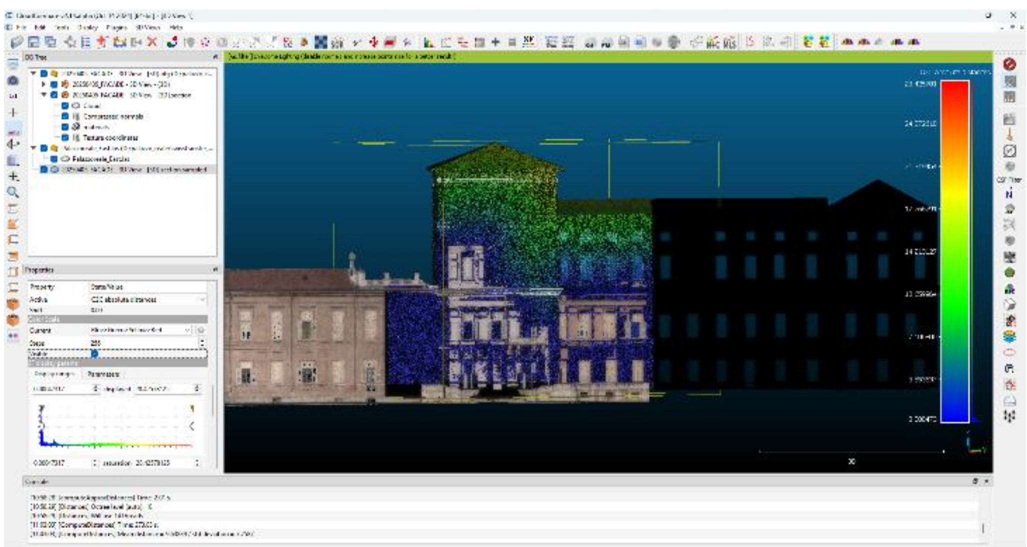


Figure 7.13. C2C Heatmap overlay comparing the Revit model of the East façade shows that most of the surfaces captured by laser scanning deviated within 2–3 centimeters. However, areas reconstructed from orthophotos and interpolated geometry exhibited higher discrepancies, in some cases exceeding 1 meter, due to incomplete scan coverage and occlusions.

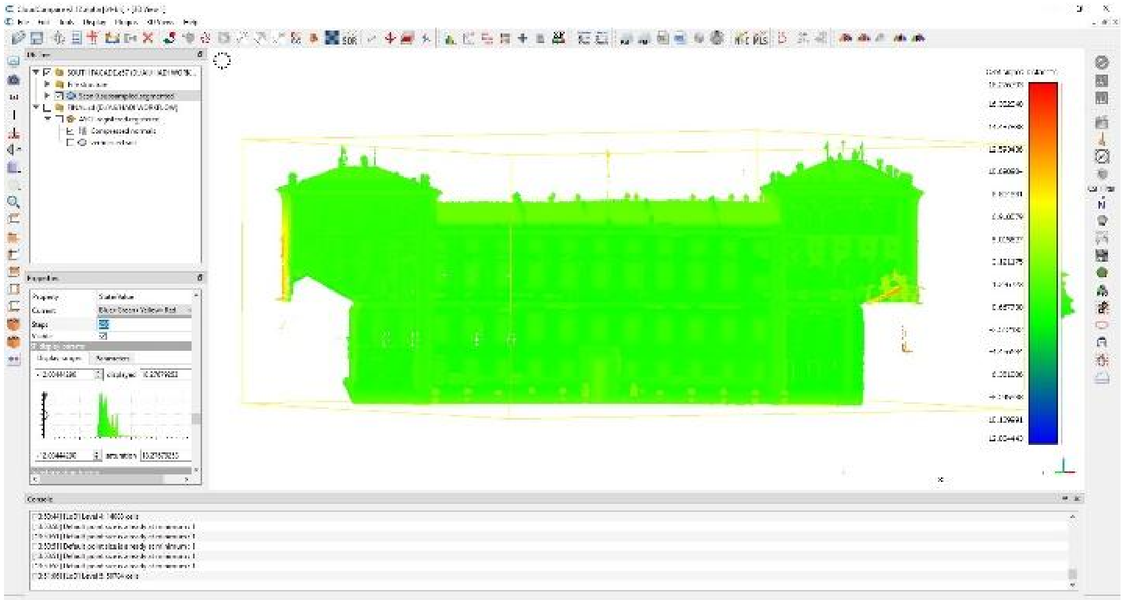


Figure 7.14. C2M Heatmap illustrates that most of the façade shows few centimeters differences, indicated by the green color.

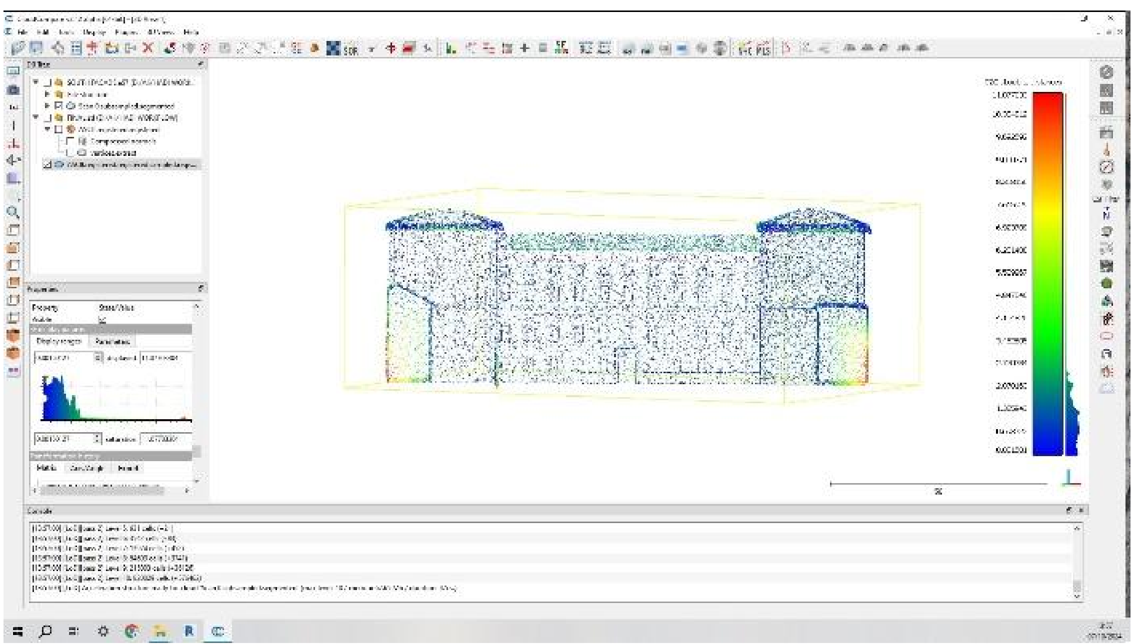


Figure 7.15. C2C Heatmap overlay comparison shows that the average deviation is remaining consistently within low centimeter tolerances (blue-green areas).

7.6 Conclusion of Grade of Accuracy Evaluation:

The Grade of Accuracy (GOA) assessment for the Palazzo Reale's architectural elements shows good overall alignment between the HBIM models and the original laser scan data. Both Cloud-to-Cloud (C2C) and Cloud-to-Mesh (C2M) analyses show that Most differences are small, typically within a few centimeters, reflecting the precision of the scan-to-BIM workflow. Larger deviations were limited to localized areas with incomplete point cloud data. Some higher differences occur in areas with partial point cloud coverage or where supplementary data like orthophotos were used, which may result in small differences. Overall, the results validate the modeling workflow applied and confirm that the digital models are suitable for detailed architectural documentation and analysis. This comprehensive evaluation highlights the importance of integrating multiple data sources carefully while critically assessing their alignment to produce robust and accurate HBIM outputs.

CONSERVATION APPLICATIONS

Section 8. Conservation Applications and Discussion

The HBIM model developed for Palazzo Reale illustrates its practical applications in conservation planning, facilitating integrated teamwork, and enabling sustainable digital heritage management. This part highlights how the model addresses the different needs of conservation professionals by facilitating restoration planning, integrating documentation, and providing tools for both visual assessment and precise measurement.

8.1 Visual and Metric Evaluation

The HBIM environment gave both qualitative and quantitative insights into the current geometry of the building. By integrating point clouds, photogrammetric textures, and CAD drawings, the model precisely showed façade, ceiling geometries, and room layouts. These visualizations not only helped restoration teams identify critical areas but also provided accurate metric references for survey planning. Dividing the model into parts based on their Level of Detail (LOD) made it possible to evaluate each section according to its significance and accuracy.

8.2 Multi-Source Documentation and Traceability

The model's layered structure was one of its key advantages since it allowed for the full traceability of various data sources, including laser scans, photogrammetry, and old DWG plans. Transparency in the creation and validation of the geometry is ensured by each modelled element referencing the source of its data. In heritage projects, where the quality of the documentation is just as important as the finished product, this trackability is crucial. Every object's source, creation date, and method are recorded thanks to the usage of metadata.

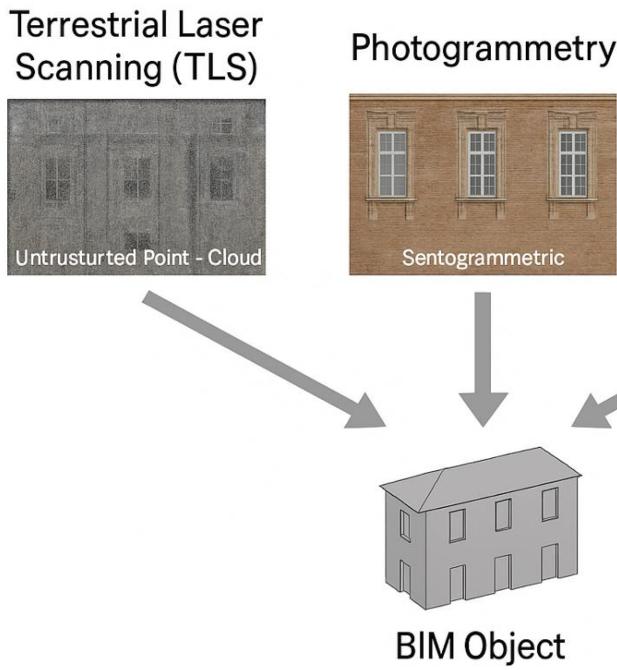


Figure 8.1. Multi-source data integration for BIM object generation.
This figure illustrates how historical DWG plans, photogrammetry, and Terrestrial Laser Scanning (TLS) are combined into a single HBIM object. It was made up of several layers. The geometry is reliable because of this traceable, Classified workflow. As a result, the origin of every reference used in heritage modelling is mentioned. Source: Author-generated diagram based on workflow developed in this thesis.

8.3 Long-Term Conservation Planning

The HBIM model functions as a living document for the building by using a digital twin approach. As new surveys or restoration phases take place, the model can be updated and audited over time thanks to the addition of LOG (Level of Geometry), LOI (Level of Information), and GOA (Grade of Accuracy) metrics. The model can be used as a Reliable foundation for tracking material decline or structural movement, thanks to the use of Cloud Compare for deviation analysis. Future interventions can be directly documented within the HBIM environment thanks to its phase-based modelling and structured hierarchy.

CONCLUSION

Section 9. Conclusion and Reflections

9.1 Summary of Key Findings

This thesis has demonstrated the potential of Historic Building Information Modelling (HBIM) as a potent tool for digitally documenting and conserving intricate heritage sites. I created a multi-source, multi-scale HBIM model that accurately Described the geometry and historical character of the Palazzo Reale in Turin using it as a case study.

In order to create detailed spatial data, the project used a scan-to-HBIM workflow that integrated photogrammetry, archival drawings, and terrestrial laser scanning (TLS). Based on the quality of the data and conservation priorities, different Levels of Detail (LOD) were used. For areas like the courtyard facades and the ceiling of the Salone degli Svizzeri, high-fidelity representations (LOD 400) were used, while for less accessible spaces, simpler volumetric models (LOD 100–200) were used.

Cloud-to-Cloud and Cloud-to-Mesh deviation analyses in CloudCompare used to analysis accuracy. The most detailed areas showed accuracy within a small fraction of a meter, proving the reliability of this adaptive modeling. However, areas mainly built with photogrammetry had larger deviations, reflecting challenges in capturing blocked geometry.

This zone-based LOD way made it possible to balance the need for consistent, obvious models with the right use of resources. Also, the semantic information was kept minimal, by focusing on key details and geometric accuracy, the mixed model was still very useful for analysis, visualization, and conservation planning.

The project also found usual problems like using guessed geometry in some interior areas, dealing with missing records, and aligning different types of data. These problems show the need for better tools to organize information and improved methods for data alignment.

All things considered, the thesis shows that multi-sensor HBIM workflows can generate reliable, scalable documentation for remarkable heritage sites, while also highlighting areas in which the techniques can still advance.

9.2 Contributions to the Field

This work presents a Carefully verified reconstruction of a historically significant European monument, contributing to the expanding field of Historic Building Information Modelling. It offers some unique contributions while building upon previous works, such as Banfi's micro-scale detailing of the Sforza Castle and Murphy et al.'s parametric modelling of Clonmacnoise Monastery.

First, the thesis illustrates that it's possible to combine multiple high-density point clouds and photogrammetry meshes inside one HBIM model, especially when focus is more on shape than detailed information. This project used a flexible way based on conservation needs and real-world limits.

Second, geomatic validation is emphasized heavily in the study. Using Cloud Compare's analysis tools methodically allowed it to create a transparent record of accuracy and dependability for every component of the model, which is crucial when HBIM outputs are used to guide conservation planning.

Third, the workflow established the foundation for future integration of attribute data, even though the semantic enrichment was purposefully kept to a minimum. Adding consistent labelling and structured metadata, even in a geometry, focused HBIM, helps to put the groundwork for future models that are more interoperable.

Finally, the project showed how important teamwork between different experts is. Besides technical skills, designing a good HBIM required knowledge of architectural history, conservation plans, and what heritage groups expect. Giving obvious version to control and linking accurate survey data with historical records helped make the workflow accurate and reliable.

All things considered, this study provides a useful and critically evaluated model that can guide future initiatives involving layered historic sites and rough documentation records. It should encourage heritage professionals to keep examining how to strike a balance between accuracy, usefulness, and interpretive nuance.

9.3 Reflections and Personal Learning Outcomes

One of the most influential aspects of my academic career has been creating this thesis. From creating an accurate 3D reconstruction to overcoming the moral and practical difficulties of working on a site of cultural significance, it required me to completely engage with both the theoretical and practical aspects of heritage conservation.

One of the biggest lessons I learned was the need to be flexible. Managing the variety of the point densities, solving data gaps, and deciding when to simplify challenges while modeling Palazzo Reale. I learned how to balance time, technology, and available data with my goal for accuracy.

The significance of interdisciplinary thinking was another insight. Even geomatics was my primary area of interest, it soon became evident that knowing each space's historical background was equally important. Considering the potential applications of the model by educators and conservation teams expanded my understanding of what HBIM can offer.

My technical abilities were also enhanced by this project. Working closely with Revit, Recap, Meta shape, and Cloud Compare increased my confidence and made me realize how crucial transparent, repeatable workflows are, particularly when other people will be building on your work.

Above all, this work deepened my respect for the responsibility that comes with modeling heritage architecture. Digital documentation is not just about creating accurate Copies; it’s about preserving cultural memory in a way that will remain meaningful for the future.

9.4 Suggestions for Future Research

While this project demonstrates the benefits of HBIM for heritage conservation, it also makes clear that there is still much to explore:

Semantic Integration: Future studies should work on embedding richer, standardized vocabularies and linking models to external ontologies such as CIDOC-CRM. This would allow HBIM to better support interpretation and long-term data stewardship.

Automated Data Registration: Manual alignment is slow and can have errors obviously. By Using AI such as edgewise to help with data registration and segmentation could make HBIM workflows faster and more reliable.

Dynamic Temporal Modeling: Historic sites change over time. Creating HBIM models that find and show these changes over years would be very useful.

Standardized Accuracy Metrics: Although this thesis applied Grades of Accuracy and Generation, the field still lacks universally accepted protocols for reporting and comparing HBIM precision. Establishing these standards would improve transparency and reliability across projects.

Interactive Visualization: Finally, combining HBIM with immersive experiences, like VR and AR, could help make heritage more accessible and engaging for the public and create new opportunities for education.

Final Reflection

This thesis concludes by emphasizing how HBIM can revolutionize historic architecture conservation and comprehension. The project adds to a body of practice that connects heritage stewardship's past and future by melting accurate geometric data, flexible modelling techniques, and open workflows. This work has taught me that rigors and careful approaches can help ensure cultural heritage remains alive and accessible for future generations, even though there is still more to learn and improve.

REFRENCES

Section 10. References

1. Abbate, E., Invernizzi, S. & Spanò, A. (2022). HBIM parametric modelling from clouds to perform structural analyses based on finite elements: a case study on a parabolic concrete vault. *Applied Geomatics*, 14 (Suppl 1), 79–96. https://doi.org/10.1007/s12518-020-00341-4
2. Agisoft LLC. Metashape Professional Edition User Manual (Version 1.8.5) [Software documentation]. (2023). https://www.agisoft.com/pdf/metashape-pro_1_8_en.pdf
3. Avena, M., Colucci, E., Sammartano, G., & Spanò, A. (2021). HBIM Modelling for an Historical Urban Centre. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B2-2021, 831–838. https://doi.org/10.5194/isprs-archives-XLIII-B2-2021-831-2021
4. Autodesk. Revit User Manual [Software documentation]. Autodesk Inc. https://help.autodesk.com/view/RVT/2023/ENU/
5. Autodesk. Recap Pro Documentation [Software documentation]. Autodesk Inc. https://help.autodesk.com/view/RECAP/ENU/
6. Banfi, F., Brumana, R., & Stanga, C. (2019). 3D modeling for HBIM applications. *Journal of Cultural Heritage*, 38, 176–185. https://doi.org/10.4995/var.2020.12416
7. Banfi, F., Brumana, R., & Stanga, C. (2019). Extended reality and informative models for the architectural heritage: From scan-to-BIM process to virtual and augmented reality. *Virtual Archaeology Review*, 10(21), 14–30. https://doi.org/10.4995/var.2019.11923
8. Barazzetti, L., Banfi, F., Brumana, R., Oreni, D., Previtali, M., and Roncoroni, F. (2015). HBIM and augmented information: towards a wider user community of image and range-based reconstructions, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XL-5/W7, 35–42, https://doi.org/10.5194/isprsarchives-XL-5-W7-35-2015
9. Biancolini, D. (n.d.). Il Palazzo Reale. MuseoTorino. Retrieved June 25, 2025, from https://www.museotorino.it/view/s/1895d34a70e84c2987752fb80bf54300

10. Brumana, R., Condoleo, P., Grimoldi, A., & Previtali, M. (2019). Towards a semantic-based hub platform of vaulted systems: HBIM meets a GeoDB. *ISPRS Archives*, Volume XLII 2/W11, 301–308. https://doi.org/10.5194/isprs-archives-XLII-2-W11-301-2019
11. Brumana, R., Della Torre, S., Oreni, D., Previtali, M., Cantini, L., Barazzetti, L., Franchi, A., & Banfi, F. (2017). HBIM challenge: The Basilica di Collemaggio. *ISPRS Archives*, XLII-2/W5, 97–104. https://doi.org/10.5194/isprs-archives-XLII-2-W5-97-2017
12. Brumana, R., Della Torre, S., Oreni, D., Banfi, F. (2017). Survey, HBIM and conservation plan of a monumental building damaged by earthquake. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-5/W1, 337–344. https://doi.org/10.5194/isprs-archives-XLII-5-W1-337-2017
13. Brumana, R., Oreni, D., Barazzetti, L., Cuca, B., Previtali , M., Banfi , F. (2019). Survey and Scan to BIM Model for the Knowledge of Built Heritage and the Management of Conservation Activities. *ISPRS Annals*, XLII-2/W11, 857–864. https://link.springer.com/chapter/10.1007/978-3-030-33570-0_35
14. Brumana, R., Stanga, C., & Banfi, F. (2021). Models and scales for quality control. *Journal of Cultural Heritage*, 50, 197–210. https://doi.org/10.1007/s12518-020-00351-2
15. Carrasco, C. A., Lombillo, I., Sánchez-Espeso, J. M., & Balbás, F. J. (2022). Quantitative and qualitative analysis on the integration of geographic information systems and building information modeling for the generation and management of 3D models. *Buildings*, 12(10), 1672. https://doi.org/10.3390/buildings12101672
16. Chiabrando, F., Sammartano, G., and Spanò, A. (2016). Historical Buildings Models and Their Handling via 3D Survey: From Points Clouds to User-Oriented HBIM, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B5, 633–640. https://doi.org/10.5194/isprs-archives-XLI-B5-633-2016

17. CloudCompare (Version 2.11). 3D point cloud and mesh processing software [GPL software]. (2022) https://www.danielgm.net/cc/
18. De Falco, A., Gaglio, F., Giuliani, F., Martino, M., & Messina, V. (2024). An HBIM approach for structural diagnosis and intervention design in heritage constructions: The case of the Certosa di Pisa. *Heritage*, 7(1), 1850–1869. https://doi.org/10.3390/heritage7040088
19. Dore, C., & Murphy, M. (2012). Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites https://ieeexplore.ieee.org/abstract/document/6365947 DOI: 10.1109/VSMM.2012.6365947
20. Feroggio, M., Moioli, R., Spanò, A., & Della Torre, S. (2024). "Take Care": I Musei Reali di Torino. In *La Conservazione preventiva e programmata*, 463–474. https://re.public.polimi.it/bitstream/11311/1269139/1/37%20Feroggio%20et%20al.pdf
21. Gabinio, P. (1924). Torino, Piazza Castello, view looking north from above with the Piazzetta and the Royal Palace in the background [Photograph]. http://93.62.170.226/foto/gabinio/012P16.jpg
22. Graitec Ltd. (n.d.). Scan-to-BIM workflow with As-Built for Revit. Retrieved June 26, 2025, from https://www.graitec.com
23. Grilli, E., Menna, F., & Remondino, F. (2017). A review of point clouds segmentation and classification algorithms. *ISPRS Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W3, 339–344. https://doi.org/10.5194/isprs-archives-XLII-2-W3-339-2017
24. Jouan, P., & Hallot, P. (2019). Digital twin: An HBIM-based methodology to support preventive conservation of historic assets through heritage significance awareness. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W15, 609–615. https://doi.org/10.5194/isprs-archives-XLII-2-W15-609-2019
25. Juvarra, F. (ca. 1715–1730). Design for a large hall with architectural ornament [Drawing]. The Morgan Library & Museum, New York. https://www.themorgan.org

26. Lovell, L. J., Davies, R. J., & Hunt, D. V. L. (2023). HBIM and Cultural Heritage. *Heritage*, 6(10), 6691–6717. https://www.mdpi.com/2571-9408/6/10/350
27. Megahed, N. A. (2015). Towards a theoretical framework for HBIM approach in historic preservation and management. *Archnet IJAR: International Journal of Architectural Research*, 9(3), 130–147. https://doi.org/10.26687/archnet-ijar.v9i3.737
28. MuseoTorino Archive. Palazzo Reale di Torino – Scheda e immagini storiche. https://www.museotorino.it
29. Musei Reali di Torino. Palazzo Reale – Documents and Digital Archive. https://museireali.beniculturali.it
30. Murphy, M., McGovern, E., & Pavia, S. (2013). HBIM – Adding intelligence to image-based surveys. *ISPRS Journal of Photogrammetry and Remote Sensing*, 76, 89–102. https://doi.org/10.1016/j.isprsjprs.2012.11.006
31. Remondino, F., & Rizzi, A. (2010). Reality-based 3D documentation of natural and cultural heritage sites—techniques, problems, and examples. *Applied Geomatics*, 2(3), 85–100. https://doi.org/10.1007/s12518-010-0025-x
32. Rocha, G., Mateus, L. M. C., Fernandez, J. G., & Ferreira, V. M. (2020). A scan-to-BIM methodology applied to heritage buildings. *Heritage*. https://doi.org/10.3390/heritage3010004
33. Rovere, C. Descrizione del Reale Palazzo di Torino. Eredi Botta. (1858). https://www.museotorino.it/view/s/25af4949bdc74937811c3e2a5b5de475
34. Spanò, A.; Patrucco, G.; Sammartano, G.; Perri, S.; Avena, M.; Fillia, E.; Milan, S. (2023). Digital Twinning for 20th Century Concrete Heritage: HBIM Cognitive Model for Torino Esposizioni Halls. *Sensors*, 23, 4791. https://doi.org/10.3390/s23104791
35. Spanò, A., Della Torre, S., Moioli, R., Patrucco, G., & Sammartano, G. (December 2024). Progetto di ricerca applicata “Digitalizzazione del processo di conservazione.” Report delle attività dei gruppi di Geomatica del Politecnico di Torino e di Restauro del Politecnico di Milano.

https://www.academia.edu/121963127/_TAKE_CARE_I_MUSEI_REALI_DI_TORINO_E_LA_CONSERVAZIONE_DI_UN_SISTEMA_COMPLESSO_DI_BENI

36. Tommasi, C., Achille, C., & Fassi, F. (2016). From point cloud to BIM. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B5, 429–436. https://isprs-archives.copernicus.org/articles/XLI-B5/429/2016/
37. UNESCO. Cultural and Digital Technologies. (2023). https://www.unesco.org/en/culture-and-digital-technologies
38. Volk, R., Stengel, J., & Schultmann, F. (2014). BIM for existing buildings: A review. *Automation in Construction*, 38, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023