UNIVERZA V LJUBLJANI | FGG Fakulteta za gradbeništvo in geodezijo

AFONSO PORTELA

HBIM FOR MONITORING AND PRESERVATION OF A CULTURAL HERITAGE STRUCTURE: CASE STUDY OF THE UNESCO-PROTECTED EMONA ROMAN WALL

HBIM ZA SPREMLJANJE IN OHRANJANJE KULTURNEGA DEDIŠČINSKEGA OBJEKTA: PRIMER UPORABE NA UNESCOVEM ZAŠČITENEM EMONSKEM RIMSKEM ZIDU

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Izvleček:

Možnosti upravljanja z informacijskim modeliranjem gradbenih objektov (ang. Building Information Modelling, BIM) se danes širijo tudi na ohranjanje dediščine preko zgodovinskega/dediščinskega BIM-a (ang. Historical/Heritage BIM, HBIM). To raziskovalno delo preučuje možnosti HBIM-a kot podpore pri diagnostiki in vzdrževanju zgodovinskih objektov v kontekstu različnih faz razvoja. Predlagamo metodologijo, ki združuje geometrijo z visoko ravnjo informacij (ang. high Level of Information, LoI) in jo uporabimo v študiji primera rimskega zidu v Ljubljani.

Študija se osredotoča na ustvarjanje modela HBIM z vključitvijo dejanske geometrije v standard IFC (ang. Industry Foundation Classes) preko delovnega toka Scan-to-Mesh HBIM. Mrežne (ang. mesh) objekte nato razčlenimo na manjše, semantično pomembne predmete (npr. ifcWall) in obogatimo s povezanimi tekstovnimi podatki (metapodatki, posredovani preko ontologij), kot so material, diagnoza in predhodni testi. Ta pristop lahko vidimo kot korak proti prihodnjemu standardu IFC5, ki bo omogočal pravilno upravljanje z mrežami in teksturami v okviru standarda IFC. Prav tako predlagamo metodologijo OpenBIM za interakcijo s temi informacijami, ki jih izvajamo v skupnem okolju: strežniku, ki poganja webIFC. Predpostavljamo, da je to prihodnost IFC sodelovanja: preko spleta, brez potrebnih avtorskih pravic za dostop in neodvisno od uporabljene programske opreme.

BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

Building Information Modelling (BIM) asset management´s capabilities are currently extending into heritage conservation through Historical/Heritage BIM (HBIM). This work explores HBIM's potential for supporting the diagnosis and maintenance phases of historical structures in heritage contexts. We propose a methodology which pairs mesh geometry with a high Level of Information (LoI) and apply them in Ljubljana's Roman Wall, as a case study.

It focuses on an HBIM model creation by bringing real world geometry into Industry Foundation Classes (IFC), via a Scan-to-MesHBIM workflow. These mesh entities are segmented into smaller IFC elements (i.e., IfcWall) and semantically enriched with linked data such as material, diagnosis, and previous tests, stored as *off-file* metadata and exposed via ontologies. This approach can thus be seen as *turning the page* towards the future IFC5 standard, which will allow mesh[1] and texture[2] to be properly handled by IFC. We also propose an openBIM methodology to interact with this information by deploying it on a common environment: a server running webIFC. We argue that this is the future of IFC collaboration: online, permissionless and software agnostic.

[1] David Delgado Vendrell, The Evolution of IFC: The path to IFC5, 2024 buildingSMART Spain
[2] Possibly, Dion Moult is working, since 2022, on bringing the X3D texture handling capabilities into IFC. This is a development unrelated to IFC5.

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LIST OF ACRONYMS USED

3D: Three-Dimensional

4D: Four-Dimensional

AI: Artificial Intelligence

API: Application Programming Interface

BIM: Building Information Modelling

CDE: Common Data Environment

CE: Common Era

CIDOC-CRM: Committee for Documentation, which is a committee under the International Council of Museums (ICOM) and CRM: Conceptual Reference Model, also known as the international standard ISO 21127:2023

CMD: Computerized Measuring Devices

DSM: Digital Surface Model

EW1, EW2, EW3, EW4, EW5, EWM: These are identifiers for specific sections of the Emona Wall remnants that were targets for the data acquisition. EWM refers to the Southern section of the wall, where the dataset of the inside of the Lapidarium belongs to (Mirje)

FPS: Frames Per Second

GCPs: Ground Control Points

GIS: Geographic Information Systems

GPR: Georadar Surveys

GUID: Globally Unique Identifier

HBIM: Historical/Heritage Building Information Modelling

HBIR: Heritage Building Information Repository

ICP: Iterative Closest Point

IFC: Industry Foundation Classes

JSON: JavaScript Object Notation

LAS: Laser And Scanner (file format)

LiDAR: Light Detection and Ranging

LOA: Level of Accuracy

LOD: Level of Detail

LOI: Level of Information

LOK: Level of Knowledge

MVC: Model-View-Controller

MVS: Multi-View Stereo

NIS: Nodes of Surface Information

NURBS: Non-Uniform Rational B-Splines

PDT: Product Data Template

PSR: Poisson Surface Reconstruction

QA/QC: Quality Assurance/Quality Control

RMS: Root Mean Square

SaaS: Software as a Service

SE: Semantic Enrichment

SfM: Structure from Motion algorithms

SQL: Structured Query Language

SSOT: Single Source of Truth

TLS: Terrestrial Laser Scanning

UI: User Interface

UNESCO: United Nations Educational, Scientific and Cultural Organization

ZVKDS: Institute for the Protection of Cultural Heritage of Slovenia

GLOSSARY

3D Model Web Viewer: Software or an online platform that allows users to interactively view and explore three-dimensional digital models, often with features for filtering, navigating, and linking documents.

Application Layer: Implements business logic and workflow. The Application Layer acts as the "brain" of the platform, coordinating interactions between the user interface, data processing modules, and storage layers.

Caching Strategies: Methods for storing recently used data for faster access.

Data Access Layer: Manages storage and retrieval of data.

Decimation: The process of reducing the number of polygons in a mesh to make files smaller and easier to manage, while maintaining an acceptable level of detail.

Documentary Resources: Documents linked to physical or semantic site entities.

IFC (Industry Foundation Classes): An open data format for sharing and exchanging building and infrastructure information models, central to BIM and HBIM.

Infrastructure Layer: Provides core services like authentication and logging.

Linked Data: Framework for publishing, interlinking, and accessing structured data on the web using standards such as RDF and URIs, enhancing data discoverability and interoperability.

Mesh: A collection of interconnected polygons (often triangles) that form a 3D digital surface, used to reconstruct geometry from point clouds.

Metadata: Descriptive or administrative data attached to digital entities (such as BIM objects), supporting classification, searchability, provenance tracking, and lifecycle management.

Microservices: Software architecture pattern where components are loosely coupled and communicate through defined interfaces.

Model Context Protocol (MCP) Server (in AI): A server that acts as a bridge between AI models (like large language models) and data sources. Enables real-time query and retrieval of data without the need for embedding or vector database storage. Provides fresh, precise, and secure access to multiple backend data systems to support AI workflows and reduce errors like hallucinations. Manages session context, security (e.g., role-based access control), and orchestrates backend data queries and responses

Ontology: A formal system for representing concepts and relationships within a specific domain (e.g., CIDOC-CRM for cultural heritage), facilitating standardized knowledge exchange, semantic linking, and automated analysis.

OpenBIM: Industry approach emphasizing platform-agnostic, standardized data formats (notably IFC), enabling transparent collaboration and long-term accessibility across diverse software ecosystems.

Open-Source Software: Software whose code is freely available for anyone to use, modify, and distribute, often employed in heritage documentation for flexibility and cost savings.

Point Cloud: A set of 3D data points collected by scanners (such as LiDAR and photogrammetry), used to digitally represent surfaces, structures, or objects for modelling and analysis.

Presentation Layer: Part of the software responsible for user interface and visualization.

Progressive Loading: Incremental data or asset loading enhancing responsiveness.

Property Set (PSet): A group of related attributes attached to objects in BIM/HBIM, used to store metadata (such as material, damage status, or historical context).

RESTful API: An application programming interface (API) that relies on HTTP protocol methods, like GET, POST, PUT, and DELETE, to access and manage resources defined by unique URLs.

Scan-to-MesHBIM: Workflow that converts real-world 3D survey data (point clouds, meshes) into HBIM models, including geometric, material, and semantic data for heritage documentation.

Search Modalities: Different methods for searching and retrieving information, e.g. full-text, structured, semantic, spatial.

Semantic enrichment: The process of adding structured metadata, linked ontological concepts, or machine-readable relationships to digital models, enabling advanced search, reasoning, and interoperability beyond graphical representation.

Semantic Queries: Search using relationships/meanings defined by ontologies like CIDOC-CRM.

Semantic Relationships: Connections between objects/data defined by meaning or context.

Semantic Tags: Labels describing the meaning/context of data.

SPARQL: A specialized query language for retrieving and manipulating data stored in databases that use the Resource Description Framework (RDF).

Spatial Queries: Search based on geometric location or model boundaries.

Stratigraphic unit: In archaeology and heritage BIM, a distinct layer or section of construction representing a chronological phase, material composition, or intervention, critical for historical analysis and model segmentation.

Temporal Modelling: Representation of data across multiple time dimensions (archaeological, excavation, documentation).

Versioning System: System for tracking changes, revisions, and history of files or models.

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1 INTRODUCTION

This dissertation presents an open-HBIM (Heritage Building Information Modelling) methodology for the monitoring and preservation of the UNESCO-protected Emona Roman wall in Ljubljana. Situated at the intersection of archaeological heritage, engineering, and digital documentation, the project addresses fragmented workflows and data interoperability challenges commonly encountered in heritage conservation. The work introduces a permissionless, open-access collaborative template for HBIM, based in Scan-to-MesHBIM techniques that balance geometric fidelity, high information richness, and semantic structuring. Through the integration of LiDAR, photogrammetry, CIDOC-CRM ontologies, and openBIM standards, the model centralizes historical, material, and diagnostic data within IFC files, making them accessible and updateable by stakeholders across disciplines. The key to merge all this is a web-based HBIM viewer, which allows access to robust metadata frameworks, and a scalable methodology extensible to other heritage assets. We want to demonstrate effective collaboration, transparent documentation, and a template for future research and digital conservation initiatives.

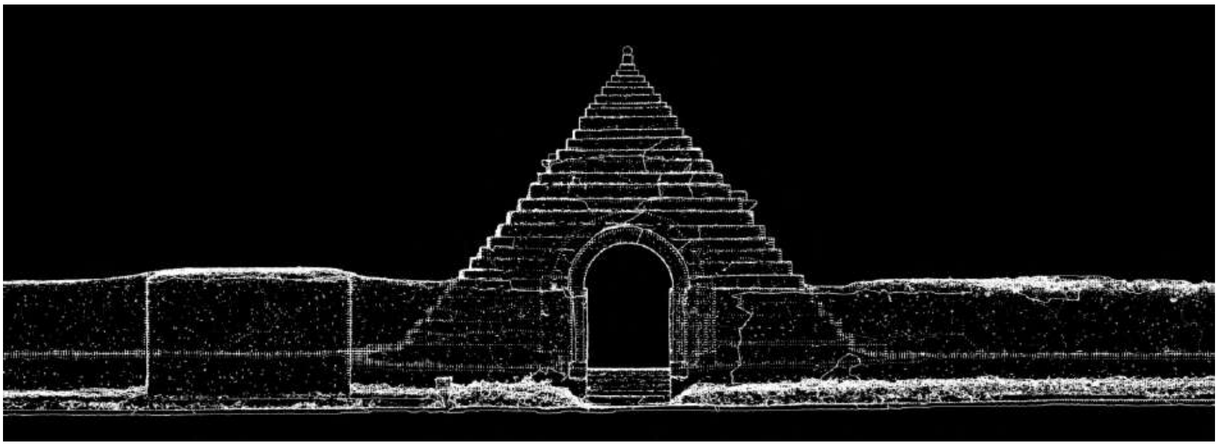

Figure 1. The Pyramid zone of the mesh object derived from the point cloud dataset visualized in technical view filter in Rhinoceros.

This image was used as the banner of the web application, as shown further, in Figure 67.

1.1 Background

This Roman wall is unique in the world since it contains two major developments, done with very different objectives in mind, as we will describe in the following sections.

1.1.1 Historical Significance of the Emona Wall and Vitruvian Principles

The Emona Wall, part of the Roman *Colonia Iulia Aemona* (est. 14–15 AD), represents one of Central Europe's most intact Late Roman fortifications. Constructed under Emperor Augustus and Tiberius, the wall formed a rectangular perimeter (540 m × 430 m) enclosing 23.2 hectares of urban space ("Emona," 2024). Its strategic role within the *Claustra Alpium Iuliarum* defensive system-a network of barriers protecting Italy's northeastern frontier-underscores its military importance [1]. The wall's technical specifications reveal advanced Roman engineering, on par with the typical structures described by Vitruvius, in the Ten Books of Architecture:

- **Dimensions**: 2.4 m width, which allowed armed defenders to manoeuvre atop, matching Vitruvius's recommendations [2], 6–8 m tall, with 29 trapezoidal towers (identified so far) and most probably a double moat on three sides, with up to 40m width [3]. The towers are positioned equidistant from each other, spaced *a bowshot apart* (approx. 30–50m) for overlapping defensive coverage [2,4], their placement was primarily at the side gates, corresponding to the town's side streets. Most discovered towers are rectangular, but two exceptions were the eastern tower at the northern main gate, which had an opening for access to the wall, and the southeastern corner tower was described as having rectangular foundations and a round superstructure, while the northeastern tower has round foundations [3].

- **Materials**: Local Lower Jurassic limestone from Podpeč (ca. 14km away) and Grajski grič (ca. 3km away) quarries, bound with hydraulic mortar containing volcanic pozzolana [3,5]. These materials are sourced near the Wall, adhering to the Vitruvian recommendation [2]. The interior texture of the wall was not uniform quarry stone but was instead built of a mixture. This mixture consisted of river cobbles, smaller stones, gravel, and partly of brick fragments and constitutes the inner filling of the emplekton construction technique. This internal structure is described as very hard and strong. Building the wall foundations for the Emona town wall, which spanned a total length of approximately 1950 m, required excavating probably more than 10,000 m³ of gravel and clay. Over 30,000 m³ of stone also had to be used and built into the walls.

- **City Layout**: Integrated *cloacae* (sewers) beneath cardo/decumanus streets channelled wastewater into the Ljubljanica River [3,6]. This rectangular grid with central forum and drainage (cloacae) mirrors Vitruvian ideals for orderly, hygienic cities [2]. However, Emona diverged from Vitruvius's preference for circular city layouts (to eliminate defensive blind spots), opting instead for a rectangular plan [2] (see Figure 2). This might be related to practical constraints of the site's terrain and pre-existing military camp layout.

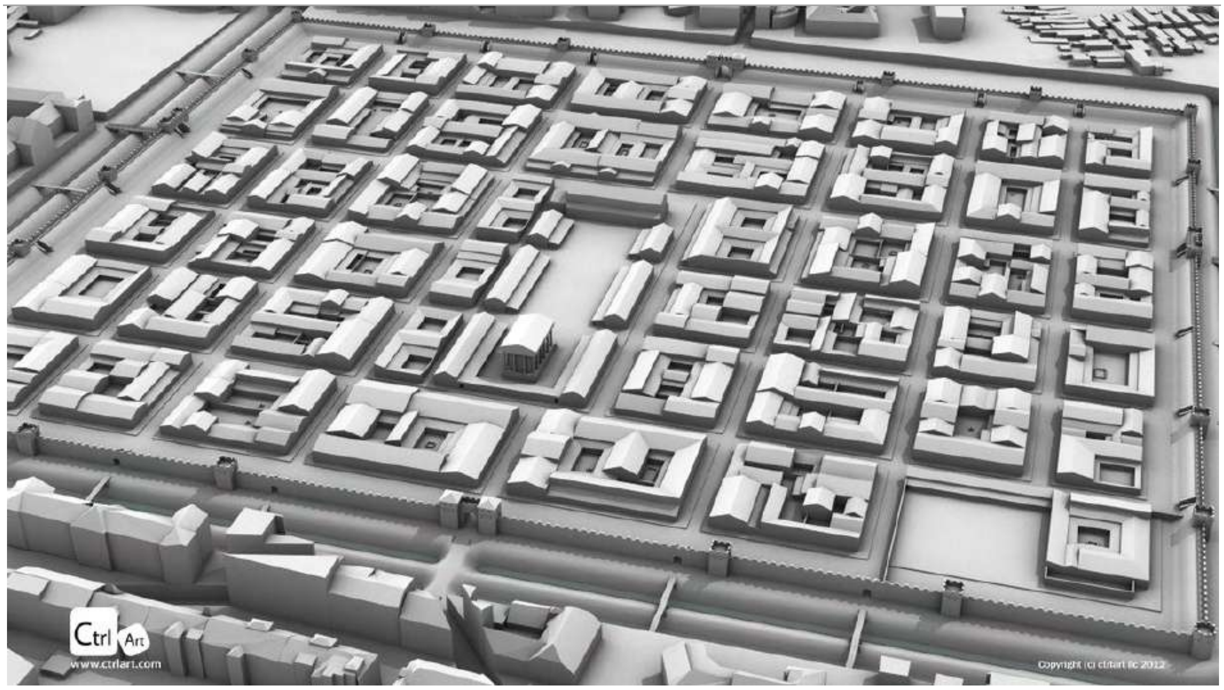

Figure 2. Digital model of the Roman city of Emona produced by CtrlArt for the iEmona digital exhibition as part of the 2000 years Emona (Ljubljana) anniversary.

1.1.2 Modern Reconstruction

Before the intervention of Plečnik it is worth mentioning that the Austrian geologist and mineralogist Walter Schmidt played a role in the early 20th-century rehabilitation and preservation of the Emona Roman wall. Following archaeological excavations, Schmidt undertook the reconstruction of the surviving sections of the wall, raising them to a uniform height and reinforcing them with an internal earth embankment. He carefully marked the boundary between the original and reconstructed parts using pebbles and protected the top of the wall with a layer of turf.[7]

Schmidt's vision extended beyond mere conservation: he aimed to safeguard the southern part of Emona with its preserved wall section and transform the area into a large open-air museum dedicated to Emona's Roman heritage. His successful archaeological work attracted significant attention, including a visit from Archduke Eugen of Austria, and inspired early postcard and photographic documentation of the site soon after the completion of his interventions [7].

Schmidt's interventions established key conservation practices for the site and set a precedent for later, more extensive renovations by Jože Plečnik, whom a lot of people mistakenly credit for Schmidt´s intervention. His work was foundational in raising public and professional awareness about the importance of preserving the Roman wall, and it contributed to the early development of monument protection services in Slovenia [7].

Between the 1920s and 1930s, and more intensely between 1934 and 1936[7], Plečnik undertook a series of interventions on the dilapidated Roman walls, particularly in the Mirje district and along the southern stretch (including sections near Zoisova cesta) [8]. His approach was not one of strict archaeological reconstruction or juxtaposition in sense of what is contemporarily considered *best practices*, which prioritize perception of original function and form. Instead, Plečnik engaged in a creative dialogue with the ancient remains, transforming them into a cultural monument imbued with layered historical meanings and aesthetic considerations that transcended their original defensive purpose. This monumentalization was driven by a strong desire from the city administration, conservator Dr. France Stele, who is crucial figure in modern Slovenian monument conservation: From 1919, he served as the provincial conservator at the Monument Office in Ljubljana, overseeing monument protection for the entire Slovene-speaking area in Yugoslavia. He was an advocate for the preservation of the Roman wall at Mirje, actively campaigning against its demolition and enlisting the support of other experts and the public. He had a strong professional and personal relationship with Plečnik, often defending his (sometimes controversial from a conservation perspective) interventions. He envisioned Ljubljana as a classical city and the spiritual capital of Slovenes and Plečnik plea to give Ljubljana a monument that would be "more ancient and more monumental than the 'real' Roman wall was, in his perspective, the approach needed to gain support from the people [7].

Plečnik understood and built on the idea of Schmidt, repurposing the ruins into a cultural monument [6], in a time when walling a city is no longer functionally needed, prioritized aesthetic values, demonstrating how ancient structures acquire layered historical meanings [8]. Most notably he introduced elements that were foreign to original Roman military architecture. These additions included:

- Ornamental Gates and Passages: He created new openings and monumental gateways through the ancient walls, such as the arched passage on Snežniška ulica (see Figure 3). These were not designed to replicate Roman gates but to provide access and create dramatic urban vistas.

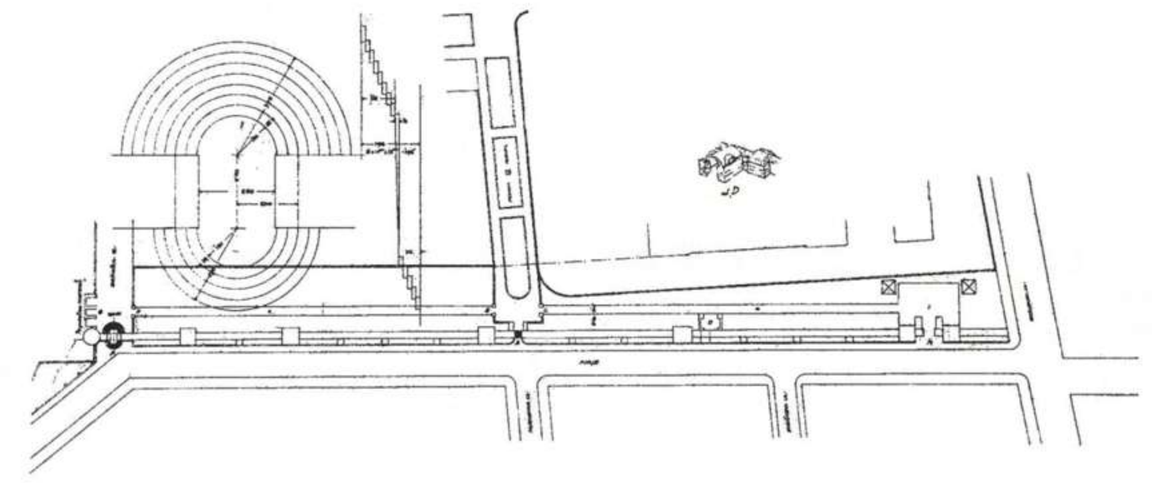

Figure 3. The original drawing produced by Plecnik, with a detail of the passage to Snežniška ulica [7].

- The Stepped Pyramid: Perhaps the most iconic of his additions at Mirje is a distinctive stepped stone pyramid. While drawing inspiration from ancient Egyptian and Roman funerary architecture (like the Pyramid of Cestius in Rome), it was an entirely new element superimposed onto the Roman wall, serving as a powerful visual marker and a space for contemplation. This pyramid was initially covered with grass turf, like the top of the wall (see Figure 5). While there was a plan in 1960 for its removal, the sources indicate that it was not completely dismantled; instead, after the Second World War, the grass turf was entirely removed to expose the stones beneath, aligning it with stricter criteria for monument authenticity, and allowing the visitors to see the repurposed stones. This pyramid has also undergone multiple repairs [7].

- Another early idea of Pletcnik was two extra pyramids, built of rubble and earth, on the inner side of the wall, near the former main Roman entrance to Emona (see Figure 4). These are also referred to as the "pyramids at the main southern entrance to the wall". Both pyramids were later removed because they began to decay due to rain soon after their construction [7]. This could have been a citation of the three pyramids of Giza.

Figure 4 Two extra pyramids, built of rubble and earth. In the database archived as EMONA-FGG-ZZ-PYR-PH-HI-007-19380000

Figure 5 Here it´s possible to see the stepped pyramid before the removal of the turf coverage. In the database archived as EMONA-FGG-G-PYR-PH-HI-004-19380501

- Lapidarium and Integration of Spolia: Plečnik incorporated a vaulted Lapidarium within his wall structures, a space designed to house and display Roman-era stone fragments, inscriptions, and architectural remnants discovered nearby. This act of curating and showcasing the past within his new design is a hallmark of his approach. He also creatively reused older architectural elements (spolia) in his constructions. The Lapidarium was also referred to in the document from 1960 advocating *radical changes* to the wall's appearance, which included the removal of the Lapidarium. These planned corrections, labelled as *protective works*, aimed to bring the wall closer to its original Roman form, but were never carried out in the end [7].

- Landscaped Parks and Promenades: Surrounding and integrating with the restored wall sections, Plečnik designed landscaped areas and promenades. He envisioned these spaces for public enjoyment and reflection, transforming the ruins from a mere archaeological site into a park-like cultural landscape (see Figure 6)

Figure 6. Promenade along the wall, with ramp. Archived as EMONA-FGG-G-PYR-PH-HI-006-19380000

- Colonnades and Symbolic Markers: The introduction of classical columns, often reinterpreted in his unique style, and other symbolic sculptural elements further emphasized the site's cultural significance over its lost military function. For instance, he placed eight massive columns made of conglomerate stone at the former main Roman entrance to Emona[7]. Now-a-days only 7 columns exist. (see Figure 7, from 1950)

Figure 7. Peristyle, in the westernmost section of the Wall on Mirje. Archived as EMONA-FGG-N-PER-PH-HI-001-19500000

In Summary, this approach is much more akin to a contemporary museum, with juxtaposition of several epochs and types of objects. His intention with these additions was to recreate the impression of antiquity and thereby enrich the archaeological monument, albeit in a deceiving way. He sought inspiration from Rome and neoclassical approaches, aiming for a *more elaborate, perhaps more timeless antiquity* rather than just the Emona remains themselves. This approach added *a new, emphatically ancient dimension with an eclectic collection of new and old elements* to the Emona wall [7]. While the result is a controversial architectural artifact, its significance lies in the exploration of the boundaries between conservation, restoration, and creative reinterpretation.

For a more detailed overview of the interventions see the appendix **Timeline of the Renovation and Monumentalization of the Roman Wall at Mirje** and for a detailed description of the people involved see the appendix **Principal persons involved in the modern transformation of the Wall**

1.2 Challenges in heritage restoration: fragmentation of disciplines, data interoperability, and documentation gaps.

Cultural heritage restoration is multi-disciplinary – requiring architects, archaeologists, engineers, conservation scientists and others to work together. However, these groups often and traditionally, operate in *silos* [9]. Scholars note a persistent gap between conservation science and practice: researchers publish materials analyses in journals that local practitioners rarely see, while field conservators seldom document their hands-on findings in a way that can inform scholars [10]. More broadly, surveys of heritage projects find that current documentation and workflows are *fragmented by a variety of work cycles and segmented by discipline* [11]. This independency working results in unproductive practices that cause distrust and uncertainties in costs and schedules for property developers. In practice this means that each professional team follows its own protocols and terminology, making joint decision-making difficult and a slow process. For example, one case study of a historic-site planning process found that weak coordination and departmental silos produced a fragmented approach where conservation efforts advanced according to each agency's own [12].

In short, misaligned goals and disconnected communication across architecture, archaeology, engineering and conservation undermine integrated project coordination and often lead to redundant or conflicting interventions. Digitization exposes similar fragmentation in data and documentation. Modern restoration relies on rich digital records (BIM models, GIS maps, 3D scans), but studies show these often cannot interoperate and are seldom used as aids throughout the heritage management process. Experts report that interoperability limits have long been *the main obstacle* in applying BIM and related tools to heritage [13]. In practice, different software vendors use proprietary data formats, so a model created by one discipline, e.g. an engineer's BIM may not "communicate" with a GIS or an archaeologist's point cloud without loss of information [13]. As a result, teams struggle to merge spatial, structural and survey data across platforms. These digital barriers are compounded by gaps in the historical record. UNESCO/ICOMOS reports warn that in many countries the true scope of cultural heritage is *partly recorded or not recorded at all* [14] – original drawings, archival plans or condition surveys may simply not exist. And when documentation does exist, it often follows inconsistent, non-standardized formats: one international task group notes that data from one heritage project can become *unusable by others* because of mismatched technical or thematic standards [11].

Existing HBIM approaches often do not fully incorporate the historical and cultural legacy of buildings and sites. Most HBIM publications focus on modelling rather than documenting. There is a need for managing an "extra layer of historic data" in heritage CDEs compared to general BIM. Previous HBIM models have mainly recorded maintenance information, not historic and archaeological documentation [10].

1.3 Research Objectives

Altogether, the lack of shared data standards, incompatible digital tools, and incomplete archives makes it very difficult for restoration teams to collaborate or to seamlessly preserve knowledge for the future.

This is why we want to develop a tool for use by all parties involved in the preservation of the Emona wall. We want it to be permissionless, meaning everyone can access the information autonomously, and we want to develop a template of a methodology to structure useful information and associate it with GUIDs from the IFC file, which will be the core of the work, it will be the central library, where all the information is referenced. Development of a full CDE framework, like the case study of BIMlegacy [9][3], was attempted. Some functionalities are still missing, but most of the structure is achieved.

In this sense, the work can go on being updated with new information and the data templates themselves can be updated, in a continuous search to encompass more data, more disciplines and remove friction between different parties involved in collaborative processes.

So, to guide us towards this goal, we set out three overarching objectives to test the initial hypothesis and define the scope of the study. These objectives aim to address key challenges in heritage recognition, architectural conservation, and information management and we propose that they are all answerable via a centralizing online platform.

Objective 1: Develop a semi-automatic methodology for IFC generation of complex geometries

The first objective focuses on designing a work system that ensures the visual and textual representation of heritage assets. This system must adhere to specific conditions, such as flexibility, allowing for interdisciplinarity, and reversibility, and should be applied before, during, and after architectural conservation processes, as a log of activities embedded or linked to the virtual heritage model. The outcome will be a simplified 3D survey of the building that captures its physical reality, which can be associated to its historical and cultural context, embedded in the IFC Mesh via Psets or linked databases via URIs or JSONs.

Objective 2: Generate Infographic Models for Knowledge and Management

The second objective involves creating one or more databases visualizable as infographic models, based on specific architectural examples. These models will serve as tools for intellectual analysis and reflection rather than merely producing visually appealing outputs. The focus will be on developing a practical tool for knowledge acquisition and management. These models will integrate spatial,

[3] It´s workflow design is explored in Figure 13.

morphological, material, structural, historical, and cultural data to facilitate visualization, updates, and management across various areas of intervention, research, or dissemination.

Specifically, we want to understand if a JSON-based catalogue system effectively replaces traditional relational databases for managing complex archaeological documentation while maintaining scalability and query performance, so we want to establish methods for linking graphic models with databases to enable seamless data entry and updates using user-friendly applications. A lightweight, portable database architecture using JSON catalogue structures that eliminates external database dependencies will be developed. An automated file scanning and metadata extraction algorithm that continuously synchronizes the catalogue with the file system.

Objective 3: Develop a Comprehensive Information Application

The final objective is to create a comprehensive application that centralizes both a 3D environment and a documents database, while leveraging the developed methodology as its conceptual foundation. This tool will enable the user to easily perceive relationships between captured data - spanning spatial, material, historical, cultural, and other dimensions - and support visualization, updating, and management processes. It must be accessible to all interested parties and transferable across different contexts.

In addition to these general objectives, several secondary goals are outlined:

- Develop a method for converting data from CMD (Computerized Measuring Devices, in our case Lidar scanners and Photographic cameras) into 3D entities that can form HBIM models at varying levels of refinement.
- Define segmentation processes to model objects at different scales for effective protection management.
- Test the feasibility of using HBIM models for rigorous representation of heritage architecture in conservation actions while ensuring adaptability for future updates.

2 LITERATURE REVIEW

2.1 Introduction and Scope

The digital transformation of architectural heritage documentation represents one of the most significant paradigm shifts in conservation practice of the 21st century. This chapter provides a critical synthesis of state-of-the-art techniques for capturing, transforming, and enriching real-world heritage data, examining 59 studies from 2013-2023 that highlight HBIM's capacity to document, analyse, and manage heritage structures Heritage building information modelling (HBIM) for heritage conservation: Framework of challenges, gaps, and existing limitations of HBIM [15]. The need for this methodological optimization cannot be overstated, as cultural heritage faces unprecedented threats from climate change, urbanization, armed conflicts, and natural disasters. Traditional documentation methods, while valuable for their historical continuity, prove increasingly inadequate for storing the complex relationships that historical assets have between geometries, material compositions, and temporal layers that characterize historic structures. We examine how HBIM fundamentally reconfigures the relationship between physical heritage and its digital representations, creating what might be termed *digital twins* that exist in parallel to their material counterparts. This duality raises profound questions about authenticity, interpretation, and the nature of heritage itself in the digital age. The review synthesizes findings from multiple disciplinary perspectives, including computer science, architecture, archaeology, conservation science, and heritage studies, reflecting the inherently interdisciplinary nature of contemporary heritage practice.

Furthermore, this chapter addresses the socio-technical dimensions of HBIM implementation, examining how these technologies reshape professional practices, institutional workflows, and stakeholder relationships. As systematic literature review from 2014-2024 demonstrates, digital technologies[4] have facilitated non-destructive evaluation of heritage sites while enhancing accessibility through virtual and augmented reality applications [16]. The open access of heritage documents through digital means presents both opportunities and challenges, requiring careful consideration of issues such as digital equity, cultural sensitivity, and intellectual property rights.

The temporal scope of this review is particularly significant, covering a period of rapid technological advancement coinciding with increasing global awareness of heritage vulnerability. The analysis traces the evolution from early experimental applications to mature implementations, identifying critical turning points, breakthrough innovations, and persistent challenges that have shaped the field's trajectory. By situating current developments within this historical context, we provide not only a

[4] As we can see in Figure 8, most of the developments are within Engineering and Computer Sciences, in line with this work´s subject scope.

snapshot of present capabilities but also a foundation for understanding future directions and potential paradigm shifts in heritage documentation.

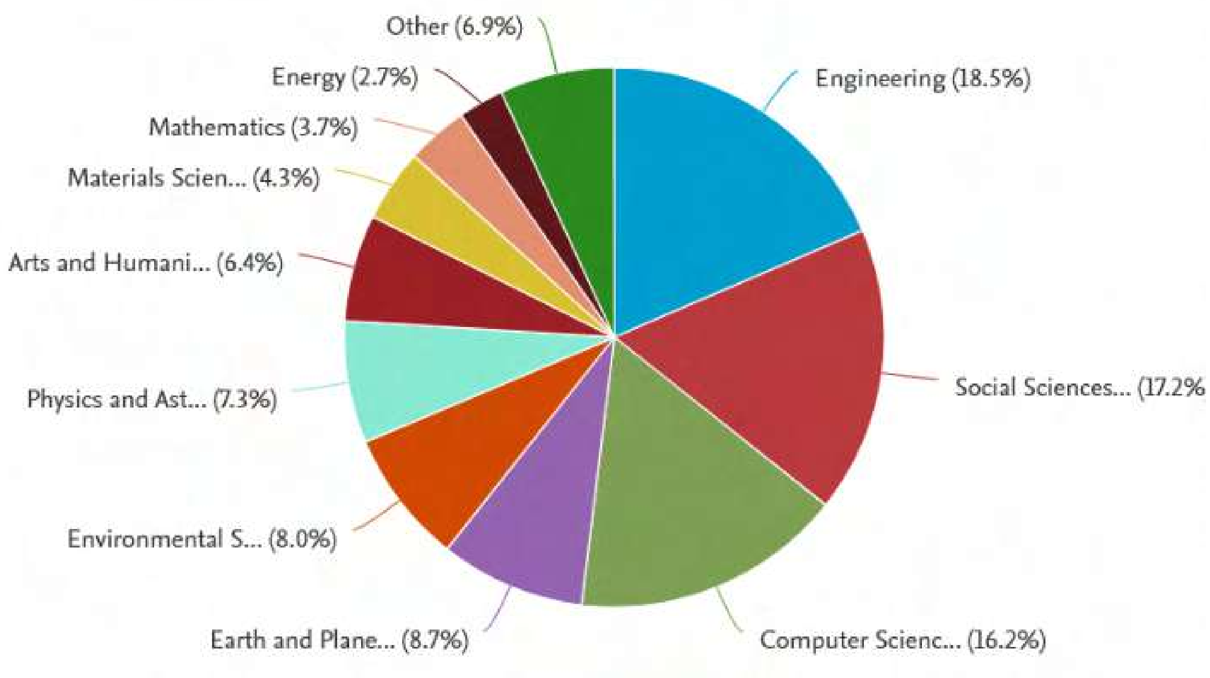

Figure 8. Distribution of HBIM articles according to subject area [17]

2.2 State of the Art Techniques for capturing, transforming and enriching real world data

The doctoral thesis of Roque Fornos [18], based at the University of Seville, explores how advanced technologies, particularly those evolving from CAD, can create graphic models capable of supporting dynamic processes of knowledge, intervention, management, and dissemination of architectural heritage.

The central hypothesis is that these models can serve as true information containers inherent to the building itself. Such a model can contain, manage, and visualise all information generated about a historical monument – whether prior, parallel, or after conservation and restoration efforts – thereby facilitating transversal relationships between different analyses related to its understanding. The model functions as a graphic database comprising parametric, tridimensional meshes, and spatial lines, surfaces, and volumes, capable of linking objects, measurements, and visible parts with various types of information (ideas, hypotheses, documents, records, decisions, operations).

To present this hypothesis Roque Fornos, used several specific case studies, chosen to illustrate the versatility of the methodological approach for various types of heritage objects and conditions. These include: the Renaissance doorway of the former Convent of San Agustín in Seville, which was digitally anastylosed (reconstructed from fragments) using advanced technological resources like digital photogrammetry, reverse engineering, HBIM, and visual programming, and the west façade of the Renaissance quadrant of Seville Cathedral (specifically the Atrio de San Cristóbal section), which was used for a pilot experience in creating an HBIM model for preventive conservation and to manage associated information.

The most important idea that will be borrowed for our workflow development was the semi-automatic modelling done in the elements of the azotea (rooftop) of La Capilla de la Antigua of Seville Cathedral, which is specifically illustrated through the example of one of its pinnacles. The workflow for this semi-automatic modelling method involves the following key steps:

1. Data Capture: The process begins with digital capture techniques, such as photogrammetry, to obtain a dense point cloud of the object. For the pinnacle, this would have been the initial raw data.
2. Point Cloud to Triangulated Mesh Conversion: The captured dense point cloud is then automatically converted into an optimised mesh of triangles.
3. Mesh Manipulation and CAD Entity Modelling: This triangulated mesh is then manipulated using appropriate software (such as Geomagic Design X as mentioned for similar processes in reverse engineering) to allow for the modelling of CAD entities. For the pinnacle, this included transforming the triangulated mesh into a quadrangular mesh and then a T-Spline surface.
4. Formalisation and Solid Generation: The generated surfaces are then refined, including the manual formalisation of intersections between surfaces and the definition of boundaries to control precision. These surfaces can then serve as a "mould" to create solid, massive 3D entities in conventional CAD software.
5. Export to BIM Environment: Finally, these CAD entities are exported to a BIM platform, where they can be further processed and managed as *smart* objects. In the pinnacle example, this resulted in a raw BIM object and subsequently a disassembled and categorised BIM object.

This semi-automatic approach is particularly valuable for modelling elements with complex geometries where traditional parametric modelling might be challenging or result in significant simplification. The intention is to create precise geometric models that can then be enriched with information within the HBIM framework. This is exactly what we tried to replicate in our case study.

Furthermore, Roque Angulo Fornos research group HUM-799-Estrategias de Conocimiento Patrimonial [18], enriched the BIM models by transforming raw geometric data into intelligent, information-rich entities suitable for HBIM usages. This enrichment process goes beyond mere visual representation to support comprehensive analysis and management of architectural heritage, as seen in Figure 9.

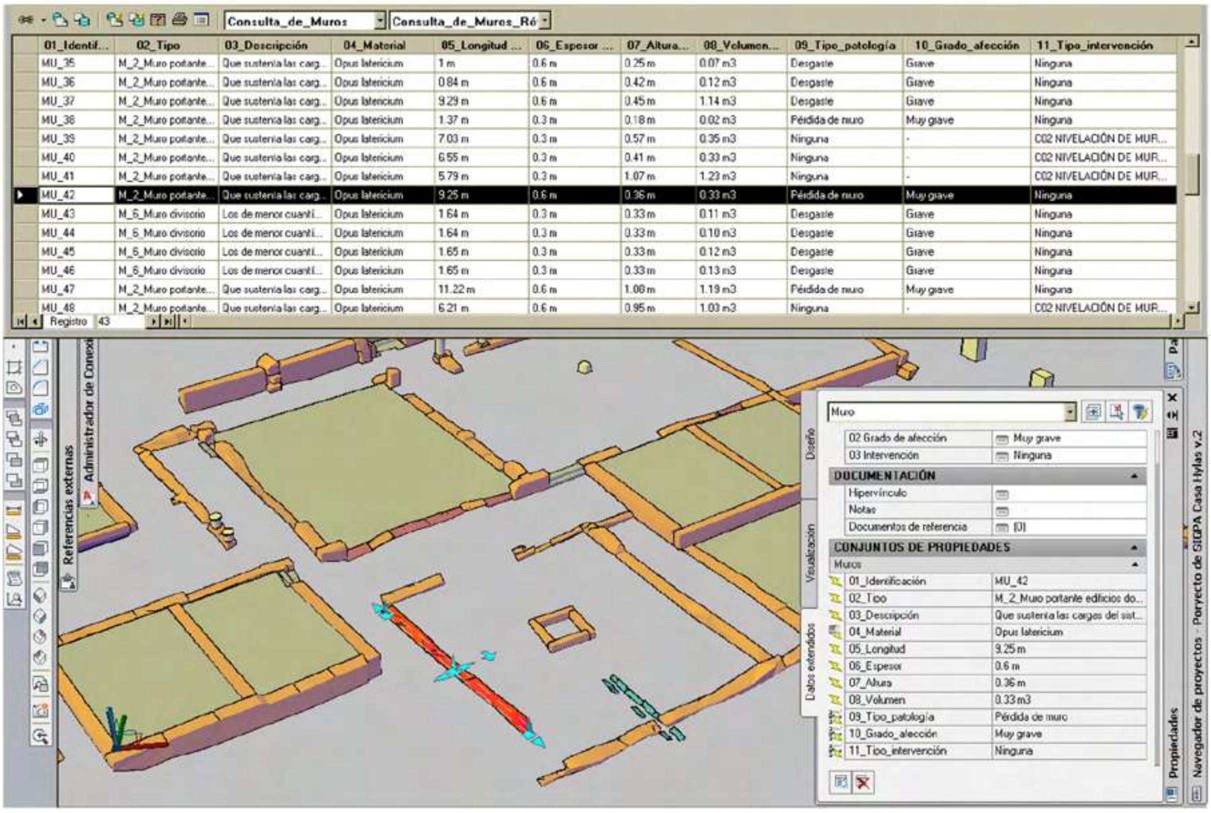

Figure 9. Example of connection between external database (OLE DB, ODBC9 and REVIT model [18].

The workflow for enriching the BIM models involved several key strategies and types of information:

After formalising intersections and defining boundaries, these solid CAD entities were then imported into BIM platforms, primarily Autodesk Revit, where they became *smart* or *intelligent geometric entities* capable of holding and generating information via the following workflow:

1. First, the model's structure was conceived as stratified by layers of different natures:
   1.1. Immaterial (Spatial) Layer: Contains information related to spatial aspects, functionality, environmental data, and geometric tracing. It can also act as a container for movable objects within the space.
   1.2. Massive (Material) Layer: Composed of constructive elements, storing data on their materiality and chronological information derived from historiographical and archaeological studies.
   1.3. Liminal Layer: A thin layer designed to hold surface-level information, whether measurable or not, such as pathological aspects or the nature of a surface's patina or finish.

1.4. Elements were then classified into these layers (e.g., by architectural object type) and assigned alphanumeric identifications for easier editing and management.

2. Types of Information Added for Enrichment:
   2.1. Physical and Material Properties: Such as the type of fabric, specific materials (e.g., different types of stone like calcarenite or porous stone, mortar types), and constructive characteristics.
   2.2. Pathological and Conservation Status: Details on the type of pathology, its severity, and proposed or executed interventions (e.g., re-setting fallen elements, replacing inappropriate mortar, cleaning surfaces, removing graffiti). This was a core focus for preventive conservation.
   2.3. Historical and Chronological Data: Incorporating information from historical documents, archaeological excavations, and prospections to reflect the building's diachronic transformations over time. The model allows for chronological phases to be visualised and filtered.
   2.4. Spatial and Functional Information: Including details on relationships between spaces, their functionality, and the placement of movable elements within them.
   2.5. Geometric and Morphological Detail: Capturing and representing precise deformations, irregularities, and defects, which is crucial for structural analysis and intervention planning.

3. Specific Methods and Tools for Adding Information:
   3.1. External Database Linkage: A key aspect of enrichment involved linking the HBIM model to external relational databases (it seems they used Microsoft Access). This allowed for the storage of extensive alphanumeric and iconographic data that could be queried and updated bidirectionally with the graphical model.
   3.2. Autodesk Dynamo, a graphical programming software, was extensively used to:
      3.2.1. Manage efficient and automatic flows of information between the BIM model and the external database, often using Excel files as intermediary *keys* maps.
      3.2.2. Automate the generation and assignment of unique identifiers to individual pieces.
      3.2.3. Control the insertion and distribution of Nodes of Surface Information (NIS).
      3.2.4. Nodes of Surface Information (NIS): This innovative concept was introduced for the Renaissance quadrant façade case study. NIS are simplified entities (modelled as three intersecting vectors) distributed as a grid (e.g., 5x5 cm) over the external surfaces of the model. These nodes can hold surface-level information such as biological colonisation, dirt, or specific pathologies.

This allows for quantitative control and thematic visualisation of surface conditions, crucial for preventive conservation. They also introduced the concept of LOK (Level of Knowledge) to define the varying depths of information contained in different parts or versions of the model. For instance, a complete volumetric model might be assigned an LOK300, while individual, dissected pieces with detailed conservation information could be assigned an LOK500. This allows for multi-scale representation and information management based on the specific analytical needs.

In summary, the models become "active entities" that generate new knowledge through interactive visualisations and queries, supporting analytical processes that are difficult to achieve with traditional methods. The enriched models serve as an interactive drawing of the building, constantly updated and open to revisions and contributions, preventing information loss and duplication. The overall aim of this enrichment is to create a versatile and comprehensive HBIM tool that supports the entire lifecycle of heritage management, from initial knowledge acquisition and analysis to intervention planning, conservation, and public dissemination.

Another important development in this area is the work carried out by Barontini et al. [19] detailing the development of an HBIM framework specifically designed for the preventive conservation of cultural heritage. It addresses challenges in applying standard BIM to historical structures, focusing on standardisation, interoperability, and simplifying information management. The methodology proposes using PDTs and IFC for efficient data exchange and damage monitoring over time. The paper details this approach through the case study of the Ducal Palace in Guimarães, Portugal, illustrating how geometric modelling and non-geometric data integration can support ongoing inspections and structural assessments.

The PDTs are adapted from a concept typically used for new industrial products to serve the specific needs of HBIM and preventive conservation. The fundamental layout of the PDT, as exemplified by CIBSE for new manufacturer's products, is modified to suit the unique characteristics of historic construction elements and their intended uses within a BIM environment for heritage: Parameters that are not relevant to historical architectural elements, such as manufacturer data, application data, electrical data, or sustainability data, are excluded from the heritage-specific PDTs.

For historic elements like a stone masonry wall, the PDT is structured into specific categories to capture relevant heritage information. These categories include:

1. Construction Data: Information on construction dates, their accuracy, and records of previous interventions.
2. Inspection Data: Tracking of past surveys, including who performed them and where data is stored.

3. Dimensional Data: Basic measurements of the element.
4. Structural Data: For load-bearing elements, this includes mechanical properties, wall type (e.g., single or multi-leaf), joint characteristics, and Masonry Quality Index (MQI) metrics for qualitative evaluation of masonry behaviour.
5. Sub-elements Characterization: Details about individual components (e.g., stone blocks), including stone type, origin, hardness, density, porosity, and mechanical strengths, which are crucial for preservation and material compatibility during interventions.
6. Global Level Damage Information: Non-graphical linked features that describe decay affecting the entire element, such as various types of deformation (e.g., in-plane/out-of-plane deviation, buckling, leaning).

For localised damages, such as a structural deep crack, a dedicated PDT is defined to standardise the required information, drawing from the HeritageCare damage atlas. This PDT includes categories like:

1. Classification Data: Defines the class and sub-sub-class of damage based on the HeritageCare classification system.
2. Inspection Data: Records previous inspection dates and relevant linked databases and pictures.
3. Geometric Data: Quantifies the damage in terms of affected area, and for cracks, includes length, depth, pattern, and form.
4. Symptoms and Diagnosis: Provides space to describe possible causes and consequences of the damage, condition grade (severity), and urgency risk.
5. Evolution Control Data: Specific metrics to track the evolution of the damage over time, which are essential for diagnosis and prognosis.

The usage of PDTs aims to standardise the information content for both construction elements and damage, promoting consistency. The structure of the PDTs facilitates interoperability by allowing for the creation of inspection forms (spreadsheets) that can automatically transfer information to and from the BIM model. Parameter names are defined with specific naming conventions (e.g., PascalCase, prefixed with parent class names) and units (international system) to comply with international standards and ensure clarity in data exchange. Data mapping lists are used to translate PDT data into proprietary software and open-source formats. If some PDT features are not readily available in the standard IFC schema, custom property sets are defined to ensure comprehensive information transfer in an open BIM scheme.[19]

In summary, this establishment of good practices conveys that in the context of HBIM for preventive conservation, alphanumerical information is not supplementary but fundamental. It enables comprehensive data collection, classification, and long-term monitoring of complex heritage assets by prioritising rich, non-graphical data over overly detailed geometric representations. This strategic balance addresses key issues of cost, complexity, standardisation, and interoperability, making HBIM a more practical and accessible tool for diverse stakeholders involved in cultural heritage management.

Another recent paper examines the current state of research regarding the integration of cultural heritage ontologies, particularly CIDOC-CRM and its extensions[5], with the IFC schema in HBIM workflows [20]. The review synthesizes existing approaches, identifies methodological gaps, and contextualizes recent contributions to semantic enrichment of 3D heritage documentation.

The integration of semantic ontologies with building information modelling represents a critical challenge in digital heritage documentation. Since Murphy et al. [21] introduced the concept of HBIM, the field has been torn between the standardized, rule-based nature of IFC schema and the complex, historically-layered information requirements of cultural heritage documentation. This review examines how researchers have attempted to bridge this gap, with particular focus on the integration of CIDOC-CRM ontologies with IFC standards.

The Industry Foundation Classes schema, utilizing EXPRESS as its modelling language, provides a robust framework for AEC-FM sectors but lacks dedicated classes for cultural heritage needs. Domer and Bernardello (2023)[6] highlight that while IFC defines four conceptual layers (Resource, Core, Interoperability, and Domain), no specific cultural heritage domain exists, creating fundamental challenges for HBIM implementation. This absence has prompted various workarounds and extensions in the literature, like the CIDOC Conceptual Reference Model, as described by Doerr et al. [22] has emerged as the dominant ontology for cultural heritage documentation. Its extension, CIDOC-CRMba, developed by Ronzino et al. [23], specifically addresses archaeological buildings through functional and structural decomposition.

Early attempts at integration focused on format conversion. Beetz et al. [24] presented the ifcOWL ontology, addressing BIM project management in the Semantic Web through EXPRESS to OWL conversion. This approach, further refined by Pauwels and Terkaj [25], revealed both the potential and limitations of direct conversion strategies. The resulting ontologies often proved unwieldy, leading to simplified alternatives like the Building Topology Ontology (BOT), which offers reduced complexity at the cost of expressiveness [26].

Several researchers have developed platform-specific integrations. Acierno et al. [27] demonstrated ontology-based knowledge management within specific BIM platforms, while Yang et al. [28] connected BIM software with ontology-based knowledge models. However, these approaches often

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[5] This standard will be more thoroughly explored in Chapter 3.3.4 ISO 21127 - A reference ontology for the interchange of cultural heritage information
[6] Cross-reference, not available to me.

sacrifice interoperability for functionality, creating vendor lock-in situations that limit broader adoption, which we want to avoid.

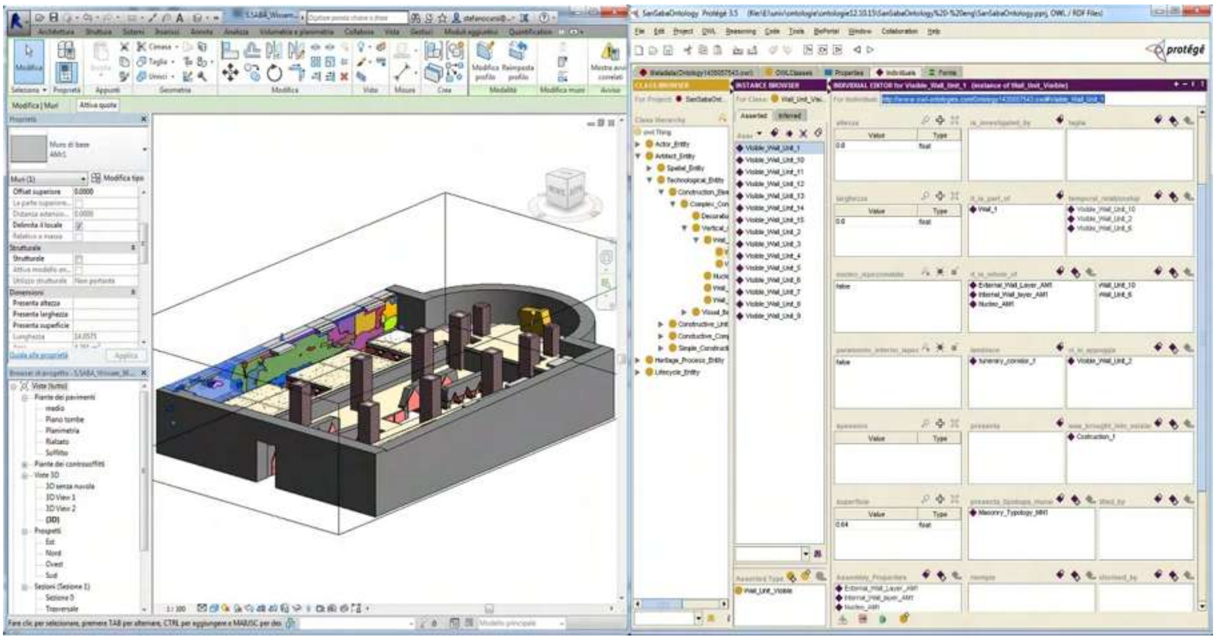

Figure 10. Example of a direct connection of ontology editor Protégé to Revit via a relational database [27]

Recent work has explored hybrid methodologies that maintain both IFC compliance and semantic richness. Quattrini et al. [29] enhanced interoperability through shared parameters, enabling Semantic Web queries while preserving IFC structure. Similarly, Cheng et al. [30] combined HBIM with ontology-based systems for conservation decision-making in VR environments, though still relying on customized object libraries.

Despite these efforts, the literature reveals a critical gap: the lack of direct integration methods that preserve IFC schema integrity while incorporating CIDOC-CRM semantics without format conversion. Most existing approaches either require conversion between formats, rely on proprietary platforms, or sacrifice semantic richness for technical compatibility.

Recognizing the limitations of standard LOD frameworks for heritage, Castellano-Román and Pinto-Puerto [31] proposed the Level of Knowledge (LOK) concept, specifically tailored to cultural heritage requirements. This adaptation acknowledges that heritage documentation requires different metrics than new construction, emphasizing historical and archaeological information alongside geometric precision.

Figure 11. Characterization scheme of the Levels of Knowledge LOK in HBIM [18,31]

The challenge of integrating geometric models with semantic data has been addressed through various approaches. Demetrescu et al. [32] introduced EMtools and EMviq for enhancing 3D archaeological models with semantic data, while Bruno and Roncella [33] developed methods linking 2D annotations with 3D models for conservation planning. These efforts highlight the ongoing struggle to balance geometric accuracy with semantic richness.

Muñoz-Cádiz et al. [20] present a significant advancement through their A²Heritage data library, which directly maps CIDOC-CRMba concepts into IFC schema without conversion. This approach addresses several persistent challenges:

The progression from conversion-based to direct integration methods represents significant advancement. However, several limitations persist. The time-intensive nature of information architecture construction within BIM environments, noted by multiple authors, remains unresolved. Additionally, the lack of automated reasoning capabilities in current implementations limits the potential for intelligent heritage management systems.

Recent developments in machine learning and automated reasoning present opportunities for advancement. The integration of Python-based reasoning with XML format data from ontologies, as suggested by Muñoz-Cádiz et al. [20], could enable more intelligent systems. Furthermore, the adoption of standards for heritage documentation provides a framework for standardization that has been lacking.

The literature reveals an evolving landscape of approaches to integrating semantic heritage ontologies with IFC schema. While early efforts focused on format conversion and platform-specific solutions, recent work demonstrates the viability of direct integration methods that preserve both semantic richness and technical interoperability. The A²Heritage framework represents a significant step toward standardized, open-source solutions for heritage documentation. However, challenges remain in automation, reasoning capabilities, and the time-intensive nature of implementation. Future research should focus on developing automated tools for semantic enrichment, expanding ontological coverage to include temporal and stratigraphic relationships, and creating standardized workflows that can be adopted across the heritage sector.

Having examined these three representative contributions in depth, a broader synthesis is needed to determine which findings are idiosyncratic and which reflect field-wide patterns. The following meta-analysis consolidates evidence across documented HBIM implementations to characterize prevailing toolchains, data-linking strategies, and collaboration models, and to situate the preceding case insights within a comparative landscape. Specifically, it maps methodological preferences (e.g., relational versus ontological enrichment), software/database couplings, and regional uptake, thereby revealing common constraints, recurring design choices, and transferable practices.

To that end, Martinelli et al. [34] and Penjor et al. [15] adopt a structure to classify studies and project reports against consistent descriptors (platform, linkage mechanism, data governance, and declared use-cases), complemented by qualitative coding of interoperability and lifecycle claims. We first summarize headline tendencies reported by Martinelli et al. [34], then deepen the analysis by aligning those trends with the technical and organizational themes surfaced in the three exemplar papers, clarifying convergences, tensions, and actionable gaps for heritage-grade HBIM.

The meta-analysis of Martinelli et al. [34] provides us with the general landscape of research in this area: 23 case studies are analysed, and it is found that most of them are anchored in the relational approach and use Autodesk Revit paired with a relational database, predominantly across Italian heritage projects, with additional examples in Portugal and Spain, indicating that southern Europe heritage assets dominate the reviewed implementations.

A smaller subset relies on Rhinoceros or unspecified BIM tools, and linkages range from Revit DBLink to custom plug-ins, web APIs, and Dynamo scripts to synchronize external knowledge with HBIM models:

Relational databases predominate: Microsoft SQL Server (e.g., Rodrigues [35]; Bruno & Roncella [33]; Palomar [9]) and PostgreSQL (e.g., Fassi [36]; Achille [37]) recur, alongside Microsoft Access (Apollonio [38]) and spreadsheets (Barontini et al. [19]), evidencing strong reliance on RDBMS backends for enrichment and FM data flows.

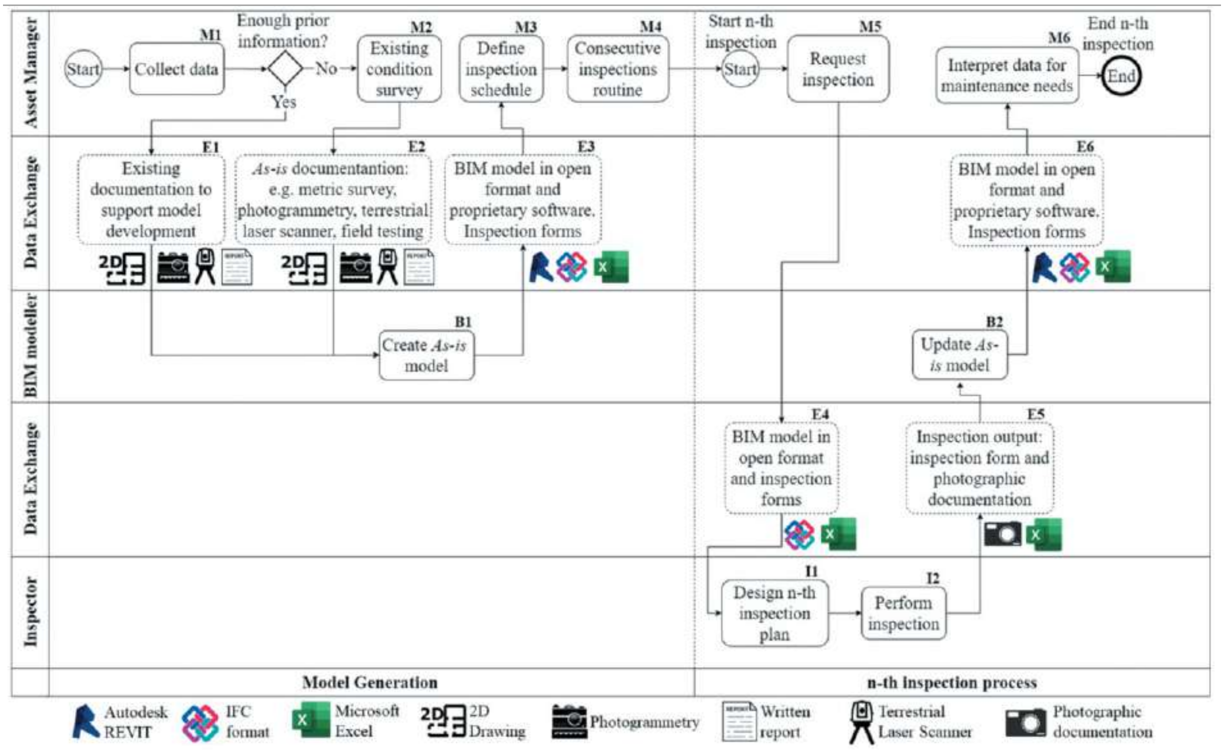

Figure 12. Process-map illustrating the workflow of the HBIM methodology developed by Barontini et al. [19]

Link mechanisms: Common linkage patterns include Revit DBLink for import/export, bespoke plug-ins, web APIs to synchronize model parameters and metadata, and Dynamo scripts to push/pull inspection or maintenance data, illustrating a spectrum from off-the-shelf connectors to custom middleware. GUIDs serve as stable keys between BIM objects and external tables, enabling object-level synchronization and version tracking across iterative conservation workflows.

Use-case focus: The dominant themes are maintenance and conservation management (e.g., Milan Cathedral [36]; HeritageCare [19] projects), documentation and monitoring (e.g., Sacri Monti [37]; Basilica di Collemaggio [39]), and post-disaster reconstruction or information recovery (e.g., San Salvatore in Norcia), showing HBIM's emphasis on lifecycle stewardship over new-build design. Several systems add web interfaces to broaden access for non-BIM specialists (e.g., BIMlegacy [9], see interaction map on Figure 13), emphasizing collaborative data entry, curation, and query across stakeholders like conservators, managers, and historians.

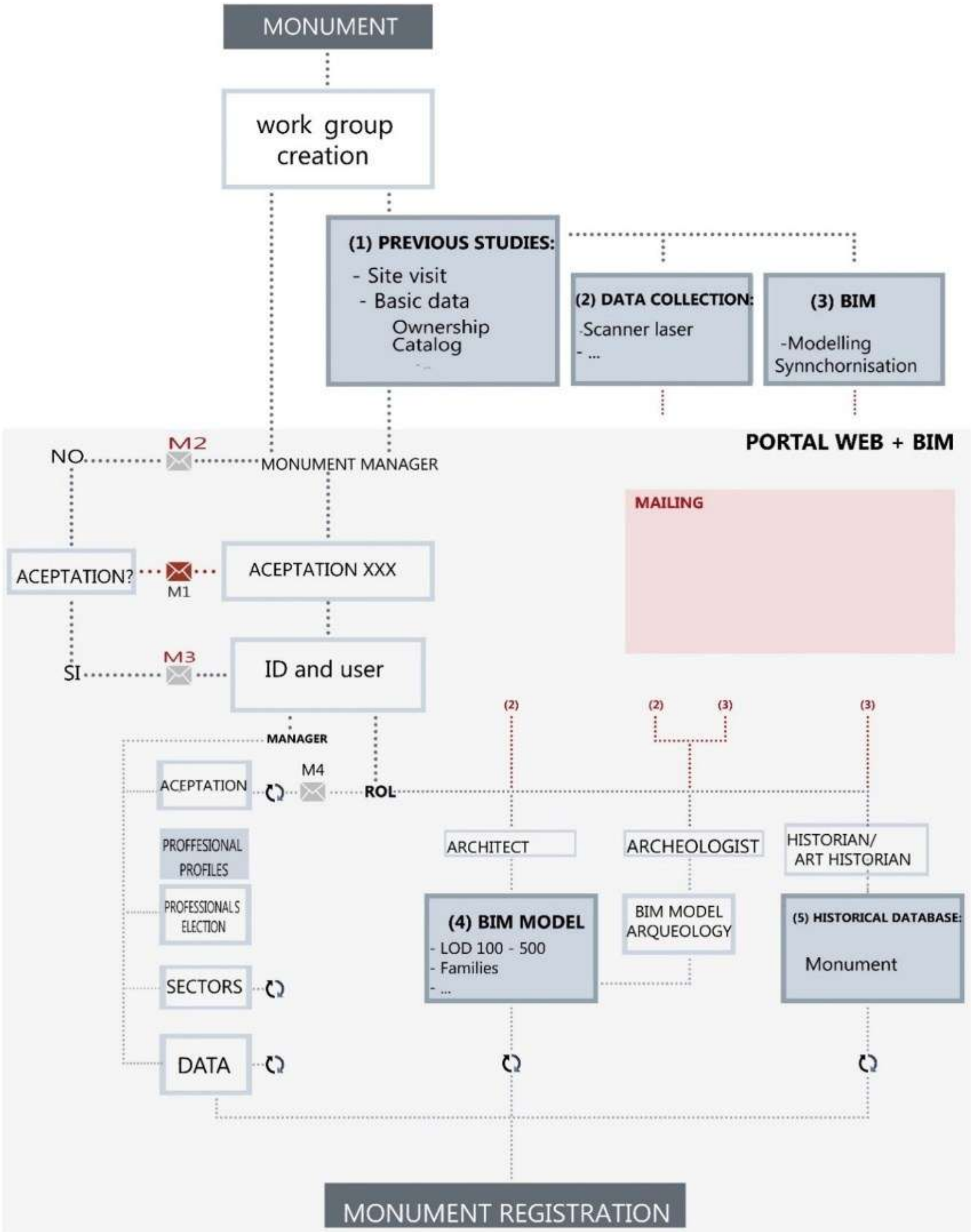

Figure 13. Workflow in BIMlegacy [9]

Quantitative takeaways (from entries explicitly described):

- At least 8 case studies explicitly use Revit, confirming a clear tool majority among the listed implementations.

- At least 7 case studies explicitly use relational DBs (MSSQL, PostgreSQL, Access, or spreadsheets), underscoring the prevalence of RDBMS integration for semantic enrichment and FM.
- Italy accounts for the largest share of named sites, with further cases in Portugal and Spain, indicating a regional concentration in Southern Europe within the reviewed set.

So, most case studies presented align with the relational approach, i.e., bottom-up enrichment through external databases tied to BIM object classes and instances. This relational approach, representing enrichment through external databases linked to BIM objects, predominates in 8 of 23 analysed case studies, and aligns with traditional database theory, where normalization principles ensure data integrity and minimize redundancy.

The ontological approach, by contrast, represents a top-down semantic integration using standardized vocabularies. This paradigm draws from semantic web technologies and knowledge engineering, emphasizing the formal representation of concepts and relationships. The adoption of ontologies like CIDOC-CRM [22] provides a shared conceptual framework that transcends individual projects or institutions, enabling semantic interoperability across diverse heritage datasets. The integration of CIDOC-CRM concepts into HBIM represents a significant advancement, as demonstrated in recent projects where decay phenomena were ontologically classified and spatially linked to models.

The schism between these paradigms reflects deeper epistemological differences about the nature of heritage knowledge. The relational approach, with its emphasis on structured data and predefined schemas, aligns with positivist traditions that seek objective, quantifiable information. The ontological approach, with its focus on meaning and relationships, reflects more interpretive traditions that acknowledge the constructed nature of heritage knowledge. In practice, many contemporary HBIM implementations adopt hybrid approaches that combine elements of both paradigms, recognizing that different types of information require different representational strategies.

As such, we believe that the research in HBIM must address both immediate technical challenges and longer-term theoretical questions. Priority areas for technical research include the automation of feature extraction and classification from point clouds, with particular emphasis on handling the irregular geometries and weathered surfaces characteristic of heritage structures. For instance, the development of AI models specifically trained on heritage data, rather than adapted from modern architecture datasets, could significantly improve automation capabilities.

The integration of multi-modal and multi-temporal data presents rich opportunities for research. Combining visible light imagery with infrared, ultraviolet, and other spectral bands can reveal hidden features and material conditions. The fusion of contemporary documentation with historical photographs, drawings, and descriptions enables the reconstruction of lost or altered elements. Research into data fusion algorithms, uncertainty quantification, and visualization techniques for multi-dimensional heritage data requires interdisciplinary collaboration.

The development of heritage-specific standards and ontologies remains a critical research priority. While CIDOC-CRM [22] provides a solid foundation, extensions for specific heritage types, conservation processes, and regional practices require development. Research into automated mapping between different standards and ontologies could facilitate data integration across heterogeneous sources. The creation of validation tools and compliance checking systems would support standard adoption and ensure data quality.

This literature review has traced the evolution of HBIM from an experimental concept to operational reality, revealing a field in its infancy. The synthesis of evidence from hundreds of implementations worldwide demonstrates that HBIM has transcended its origins as a documentation tool to become a comprehensive framework for heritage knowledge management. The convergence of reality capture technologies, artificial intelligence, and semantic web technologies is creating unprecedented capabilities for documenting, analysing, and preserving cultural heritage.

Yet significant challenges remain that prevent HBIM from reaching its full potential. Technical limitations in automating complex modelling tasks, methodological gaps in quality assurance and validation, and institutional barriers to adoption all require sustained attention. The absence of comprehensive standards, the shortage of skilled professionals, and the economic challenges of sustainable implementation threaten to limit HBIM to well-resourced institutions in developed countries. The implications of HBIM extend beyond technical and practical considerations to fundamental questions about the nature of heritage in the digital age. The creation of perfect digital twins, the democratization of heritage access, and the potential for virtual reconstruction of lost heritage are exciting developments available to us with our current technologies.

Looking forward, the future of HBIM will be probably continuing to be shaped by these four converging trends:

- The integration of AI and machine learning will continue to automate routine tasks while enabling new forms of analysis and interpretation.
- The adoption of Digital Twin approaches will transform static documentation into dynamic monitoring and management systems.
- The development of immersive technologies will create new forms of heritage experience and engagement.
- The evolution of standards and ontologies will improve interoperability and data exchange.

However, technology alone will not determine the future of heritage documentation. The successful implementation of HBIM requires institutional change, professional development, and sustained investment. It requires collaboration across disciplines, institutions, and nations. Most importantly, it requires a commitment to preserving not just the physical fabric of heritage but also its cultural significance and social meaning. The ultimate success of HBIM will be measured not by technical sophistication but by its contribution to heritage conservation and public benefit.

2.3 Gaps in Research

While the workflows developed by Roques Forno and the HUM-799-ECP group [18] and Barontini et al. [19] demonstrates a sophisticated pipeline from digital capture to HBIM enrichment, two research gaps are evident:

1. Using external databases and custom scripts for data enrichment. The lack of standardized protocols for linking HBIM models with external data sources may hinder interoperability, especially in multi-stakeholder or cross-platform environments. In this sense developing an Automated Information Flow between HBIM, HBIR (Heritage Building Information Repository), and external databases is an ongoing research area. This consolidation is considered key to materialising a true Heritage Information System. Furthermore, integrating HBIM models with Geographic Information Systems (GIS) technology is a significant line of advance, aiming to project the benefits of HBIM across all scales for comprehensive heritage knowledge and management.
2. The case studies focus on specific elements or portions of buildings. There is only speculation about if the workflow performs well when applied to entire, highly complex monuments or sites with a wide variety of materials and conditions. Despite our site not being highly complex in the sense that it doesn't contain a big variety of building typologies, it is still complex in the procedures and time-layers that can be identified.
3. Standardisation and Ontological Codification: establishing necessary protocols for adopting or assimilating normalised coding systems. This includes ontological frameworks for architectural elements and taxonomies (like CIDOC-CRMba), as well as glossaries related to conservation aspects like pathologies and treatments, particularly given the lack of standardised terminology in the field.
4. Long-Term Interoperability IFC Custom Property Sets: While custom property sets extend IFC for heritage needs, there is a risk of fragmentation if these are not widely adopted or standardized across the sector, potentially limiting long-term interoperability and data exchange.
5. Developing other techniques for embedding damage representational objects in the models, for instance, sub-sub-classes of damage may be further distinguished through the use of hatch patterns living inside the same object, which would be an enhancement to the visual representation of localised damages, beyond the simple colour-coding for main classes: The current methodology

uses a simple patch-type object with a fixed thickness and a colour representing the damage class, this future development would add another layer of graphical detail to convey more specific information about the anomaly's sub-sub-class.

6. Using systems which can superimpose, in the same geographical position as the HBIM model, other kinds of assets, like point-clouds, super-high-density texturized meshes or even gaussian splats, which would really enable the assets to be suitable for a VR experience or at least deliver an experience as near as possible to visiting the work in situ, on a particular point in time, or even in several points in time.

The identified gaps highlight very specific areas for improvement, which the subsequent case study will seek to address. Hopefully it will read like a manual, so that the proposed methodology can be further enhanced and applied.

3 FIELD WORK AND METHODOLOGY

One of the main challenges to be solved in the 3D modelling, especially for historical structures, is the representation of elements with highly irregular sections that vary both horizontally and vertically, like the Emona wall. These irregularities may be due to the extraction and production processes, thus existing since the initial construction, or due to biotic or abiotic degradation or damage [40]. In this sense, we want to test if a higher geometrical fidelity is possible to achieve, without performance setbacks. This would increase the ease of identification of features for someone that consults the model but has not visited the structure in situ.

The study is structured in a phased workflow, moving systematically from acquisition to alignment, from modelling to semantic structuring, and finally to web delivery for cross-disciplinary use:

- **Phase 1**: Capturing missing data.
- **Phase 2**: Point cloud alignment and geometric modelling.
- **Phase 3**: Semantic enrichment (materials, pathologies, conservation history).
- **Phase 4**: Integration/creation of online platform for assessing all the information

3.1 Data Acquisition for the missing parts of the Wall

This part of the work was conducted with the supervision of dr. Tilen Urbančič, who provided the equipment and shared the know-how. Due to lack of time some fragments of the wall were not captured, but nonetheless the aim of this work is to explain the workflow and not to have the most complete data of the wall possible. In fact, it will be interesting to add other parts to the model in the future, enlarging the HBIM model to an ever nearer state of completeness.

Capturing the data for missing sections of the wall focused on the following remnants:

1. the one near the Presidential Palace, EW1
2. a small remnant in the back of the Uršulinski samostan monastery, EW2 (still missing)
3. the Praetorian City Gate, EW3
4. a small remnant near the houses in the southern part of the wall, EW4 (only photogrammetric dataset)
5. the southwestern corner, EW5
6. the inside of the Lapidarium in the Southern section of the Wall, which was not captured in the previous dataset, merged with the previously created point cloud, EWM

This endeavour consisted of a blend of LiDAR scanning and photogrammetry to overcome the inherent limitations of each technology. For instance, texture and damage types are only perceptible in the photogrammetric dataset, while overall shapes and sizes of the features are better encoded in the LiDAR capture. Below is the detailed workflow used and a small explanation of each technology.

3.1.1 LiDAR Scanning

Laser scanning has been utilized as a surveying technique since the 1960s, enabling the collection of precise spatial data from a wide range of surfaces, including buildings, landscapes, and various objects. This method, known as LiDAR (Light Detection and Ranging), generates point clouds composed of millions of X, Y, and Z coordinate measurements[7], offering a highly detailed three-dimensional representation of the scanned environment.[41]

Modern laser scanners are equipped with photodetectors, sensors, receivers, laser emitters, and GNSS (Global Navigation Satellite System) modules. GNSS technology leverages multiple satellite systems[8] to provide accurate positioning in globally recognized coordinate systems like WGS84, ITRF, and ETRF. Depending on their design, these devices can emit millions of laser pulses per second. Each pulse travels to a surface, reflects to the scanner, and the time taken is used to calculate the distance, resulting in a single measured point. Collectively, these points form a comprehensive 3D point cloud that closely mirrors real-world conditions.

There are several types of LiDARs, but we will focus only on Terrestrial Laser Scanners (TLS), which is the technology we have used. This method involves stationary, ground-based scanners typically mounted on tripods. These devices rapidly emit laser beams to capture dense point clouds. TLS systems measure points using spherical coordinates - range, horizontal angle, and vertical angle - which are then converted into Cartesian coordinates (x, y, z).

In our case, we used a Time of Flight (ToF) Scanner[9], the Leica ScanStation P40, which has the capability of processing the connection of multiple scan points, if the positions are cross-referenceable, this means that each scan position should, at least, be able to see another scan position.

The actual capturing takes ca. 3min per position and typically achieves a density ≈0.5 mm at 10 meters from the scanner, meaning clouds of between 50 million and 100 million points per position.

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[7] And now-a-days it’s common that RGB values are projected from the embedded 360 Camera onto these points.
[8] Including the American GPS, Europe’s Galileo, Russia’s GLONASS, and China’s BeiDou.
[9] Time of Flight scanners measure the time taken for a laser pulse to travel to the object and back. There are also Phase shift (PS) scanners, which determine distances by analysing the phase difference between emitted and received signals. Recent ToF scanners incorporate waveform digitization, which maintains high point density, accuracy, and resolution across extensive measurement ranges. This technology is especially valuable in heritage conservation and documentation. Other alternatives, like Simultaneous Localization and Mapping (SLAM) technology to create a map of an environment while simultaneously determining its own position within that environment. SLAM algorithms process data from various sensors - such as LiDAR, cameras, and inertial measurement units (IMUs) - to continuously update both the map and the device’s location as it moves. This technology is widely used in robotics, autonomous vehicles, and mobile mapping devices, enabling real-time 3D mapping and navigation in environments where GPS may not be available or reliable.

We have translated all our scan captures to the Slovenian WGS84 / D96 format for consistency. Some programs don´t have an auxiliary coordinate system, like Revit does, so this x,y,z position must be retained in the main coordinate system, which causes problems when too far away from the origin point, like in our case. To solve this, we create a translation vector that we apply on import and reverse on export, after each program specific steps are completed.[10]

In the appendix Capturing of the LiDAR point clouds are some pictures (Figure 71,Figure 73Figure 75Figure 77Figure 78Figure 79) of the fieldwork and obtained point clouds from these scan positions (Figure 71Figure 72Figure 74, Figure 76Figure 80). For the remnant in the back of the Uršulinski samostan monastery, EW2 we could not gain access, so it will be added to the database in the future.

3.1.2 Photogrammetry

Photogrammetry is the science and technology of obtaining reliable measurements and information about physical objects and environments by combining similar photographs. The core idea is to extract accurate spatial data from images taken from different viewpoints, via a Structure from Motion (SfM)[42] algorithm, which estimates both the 3D geometry of the scene, and the positions (x, y, z, vector) of the cameras used to capture the images, even if the camera positions are initially not geotagged. By identifying common points in two or more images, photogrammetry uses the principle of triangulation to calculate the 3D coordinates of those points. Essentially, if you know where the cameras were positioned and can match the same feature in multiple photos, you can mathematically determine its location in three-dimensional space (see Figure 14). So, it's possible to manually match points in several pictures to aid the software, or to let it run all the process automatically, depending on the quality of the overlapping features. With enough matched points, software's can reconstruct a detailed 3D model or map of the object or environment. For this we have used Reality Capture software, which has a feature-rich free version.

We have used a Canon EOS R5 with 100-250 ISO[11] and 1/125 seconds of exposure, aperture (f/8 to f/11), to ensure consistent exposure and sharp images across shots, because of the cloud cover.[12]

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[10] Creating a script to perform this automatically, like for instance CloudCompare does, would be a useful future development.

[11] Using low ISOs minimizes noise and artifacts that worsen feature detection.

[12] Cloud cover provides diffuse and uniform lighting conditions. This prevents harsh shadows and glare, enhancing the visibility of surface details and resulting in more consistent images. Soft lighting improves the accuracy of feature detection and matching by the SfM algorithm, leading to higher quality 3D reconstructions.

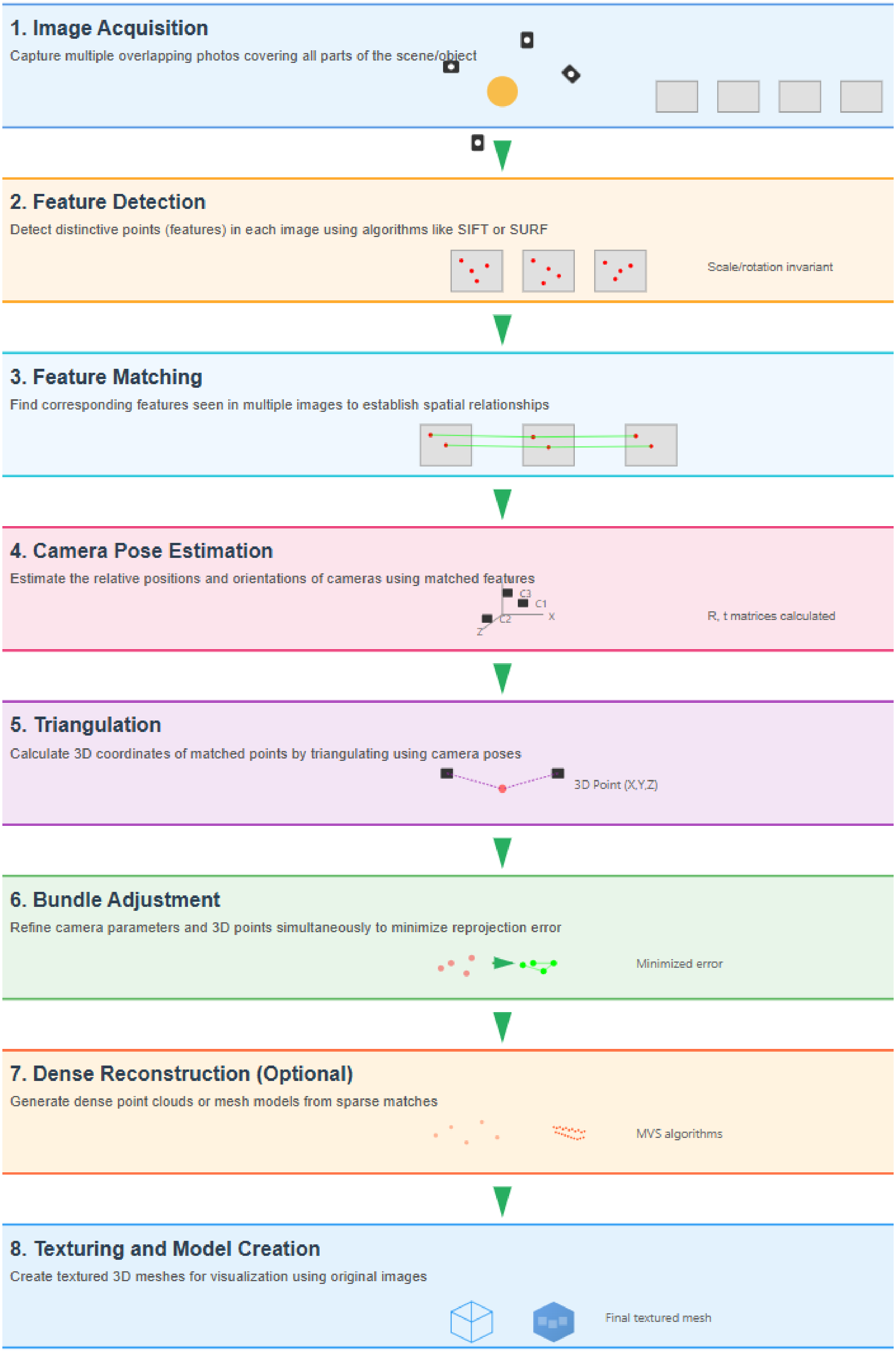

Figure 14. The multi-step process known as Structure from Motion (obtained from Claude).

See Appendix Capturing of the photogrammetric dataset for pictures (Figure 81Figure 82Figure 84) of the fieldwork and obtained mesh models from these scan positions (Figure 83Figure 85Figure 86Figure 87Figure 88). For the remnant in the back of the Uršulinski samostan monastery, EW2 we could not gain access, so it will be added to the database in the future.

Due to technical difficulties[13] in creating a closed working mesh for the interior and exterior of the Lapidarium it was decided that this part of the new dataset would be modelled via classical tools, in this case ArchiCAD was used. This is because even advanced mesh-processing tools (e.g. CloudCompare, Instant Meshes, Geomagic[14]) can fail to resolve complex surface overlaps or internal cavities, especially when automatically merging scans. Manual editing is often needed but it would be so time consuming that the idea was abandoned.

Given these constraints, the Lapidarium interior–exterior portion was modelled with classical BIM tools to preserve geometric coherence and interpretability, while the remaining areas continue to rely on algorithmic reconstruction wherever the survey supports robust meshing workflows. This pragmatic bifurcation ensures continuity of the HBIM dataset without overcommitting to mesh healing where data sparsity, occlusion, or interior–exterior discontinuities would compromise reliability or demand prohibitive manual editing. In the sections that follow, the analysis therefore focuses on the algorithmically derived meshes, explicitly documenting the implications of remeshing, decimation, and segmentation for downstream enrichment and exchange.

To properly access *fitness for purpose*, the next subsection adopts established accuracy frameworks to quantify how close the represented geometry is to the underlying measurements and to make those tolerances explicit at component level. In particular, the 'USIBD Level of Accuracy' [43] convention and DIN 18710 are used to distinguish Measured Accuracy from Represented Accuracy, relate both to practical decimation and file-size budgets, and define the thresholds within which the ensuing mesh comparisons are evaluated. This provides a transparent basis for selecting acceptable error bands and for recording them as properties in the HBIM model, aligning accuracy verification with the intended analytical and conservation uses.

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[13] Accurate alignment of interior and exterior scan datasets is challenging. Scans taken from different sides of thick walls or structures may not have enough overlapping features for software to register them precisely, especially if access is limited or geometry is complex. In our case the interior point cloud had too much dark zones (where no points or very sparse points were created, and Meshing software must interpolate between dense and sparse data, often producing artifacts or unreliable surfaces at these transitions. Even merging with photogrammetry dataset gave us bad results. The geometry is too complex to accurately represent with these methods, and the resulting meshes were too noisy (enough points but wrong geometry) or too sparse (less errors but too few points), after postprocessing.

[14] A trial was obtained to perform mesh cleanups and post-processing for this work.

3.1.3 LOA - The DIN 18710 Standard and mesh accuracy

The 'USIBD Level of Accuracy (LOA) Specification Guide' (U.S. Institute of Building Documentation, 2025, [44] establishes five distinct levels of accuracy for building documentation, ranging from LOA10 (lowest accuracy) to LOA50 (highest accuracy). Each level is defined by a specific range of standard deviation, with these ranges set at a 95% confidence interval (2σ), ensuring that most measurements fall within the specified tolerance band.

It is important to note the distinction between two types of accuracy: Measured Accuracy and Represented Accuracy. Measured Accuracy refers to the precision of the final measurements obtained, regardless of the equipment or method used. Represented Accuracy, on the other hand, addresses the deviation introduced when this measured data is transformed into another format, such as a 2D drawing or a 3D model. This distinction acknowledges that some error is inevitably introduced during data processing, so the accuracy of the representation may differ from that of the original measurements.

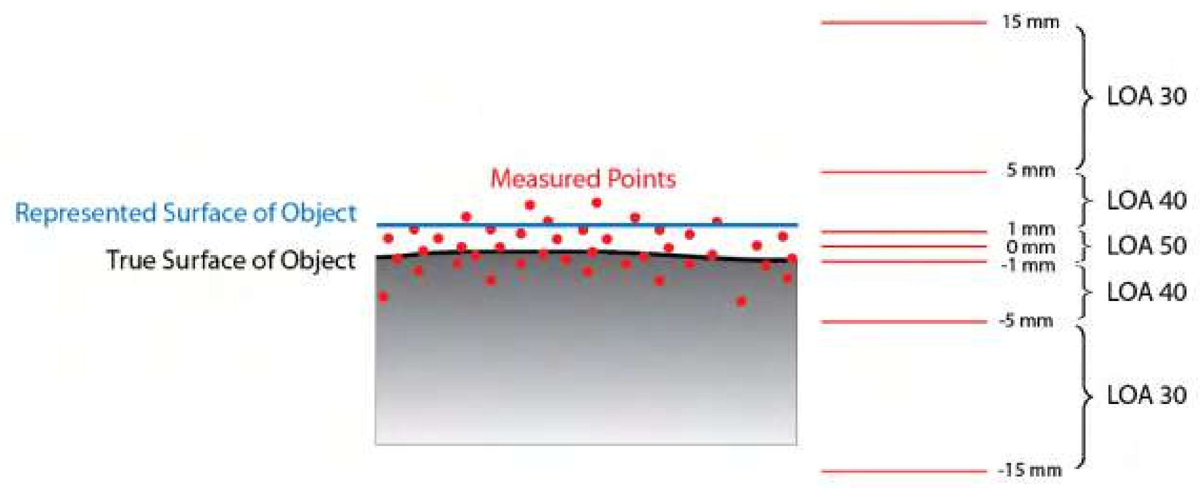


Figure 15. comparison between the true object's surface, the measured points and the traditionally modelled representation, [43].

When it comes to assessing the LOA of a model or its components, several analytical approaches exist. The most straightforward method involves calculating the distance from each point (potentially after subsampling) to the nearest point on the model, which was performed using the mesh to cloud component of CloudCompare.

$	Measured Accuracy	$$$$$				
X	Absolute	If Absolute - describe reference frame here				
	Relative	If Relative - describe measure of relativity here				
Level of Accuracy (2 σ std dev)						
-	5cm	15mm	5mm	1mm	Upper Range (Metric)	
5cm	15mm	5mm	1mm	0	Lower Range(Metric)	
LOA10	LOA20	LOA30	LOA40	LOA50	(A, B, or C) Validation	Note

$	Represented Accuracy	$$$$$				
X	Absolute	If Absolute - describe reference frame here				
	Relative	If Relative - describe measure of relativity here				
Level of Accuracy (2 σ std dev)						
-	5cm	15mm	5mm	1mm	Upper Range (Metric)	
5cm	15mm	5mm	1mm	0	Lower Range(Metric)	
LOA10	LOA20	LOA30	LOA40	LOA50	(A, B, or C) Validation	Note

Figure 16. Specification of the accuracy of each LOA bracket, [43].

Due to all the required geometrical simplifications, we can safely assume that a LOA10 has been achieved, (see Figure 18, Figure 19, Figure 20, Figure 21) with an upper threshold of 10cm and a downer threshold of 1cm. The majority of the calculated meshes are within the LOA20 ($2\sigma < 50$ mm), ca. 95% of the faces, but we must use the worst-case performance for our overall benchmark and since some areas of the meshes are deviated more than 2.5cm from the point clouds, we assume LOA10. However, the raw data produced is enough to achieve LOA20 and, indeed, some of the datasets allow achieving this accuracy interval.

Documenting these differences in accuracy remains a challenge, as there are currently no established standards for linking such metadata to BIM models; existing BIM standards are primarily tailored to new constructions. One practical solution is to insert a property set (PSet) in the modelled components to communicate the achieved accuracy.

This approach is consistent with the DIN 18710 standard, which, as previously described, defines five LOA brackets [45]. For standard heritage documentation, LOA20 (15 mm–5 cm) is typically sufficient, while LOA30 (5 mm–15 mm) is preferred for projects requiring higher geometric fidelity [45]. However, as experienced in recent HBIM case studies, the raw survey data often exceeds these requirements, supporting even higher LOA levels. In practice, the selection of LOA is dictated not only by technical capability but by project intent and practical constraints: higher accuracy exponentially increases file sizes and processing demands, which can hinder model usability within BIM environments [27]. For heritage modelling assets like the Emona Roman walls, the ontological significance - how the model is segmented, classified, and relates its components - often outweighs the benefits of maximal geometric precision [4], [5], [30].

As such, the focus of the work shifts to achieving a level of accuracy that supports meaningful semantic segmentation and properties annotation, enabling the model to serve as a rich, accessible repository of historical, material, and diagnostic information [28], [30], [31]. This approach aligns with the guiding principle that 'intent defines process,' ensuring that both geometric and ontological aspects are balanced to best meet the project's conservation and research goals.[26]

Some studies between the best ratios of triangle density and IFC file size were performed (see Figure 17), showing that, roughly, every 1 million mesh faces add approximately 160 MB to the IFC file size and confirms a linear relationship.[15]

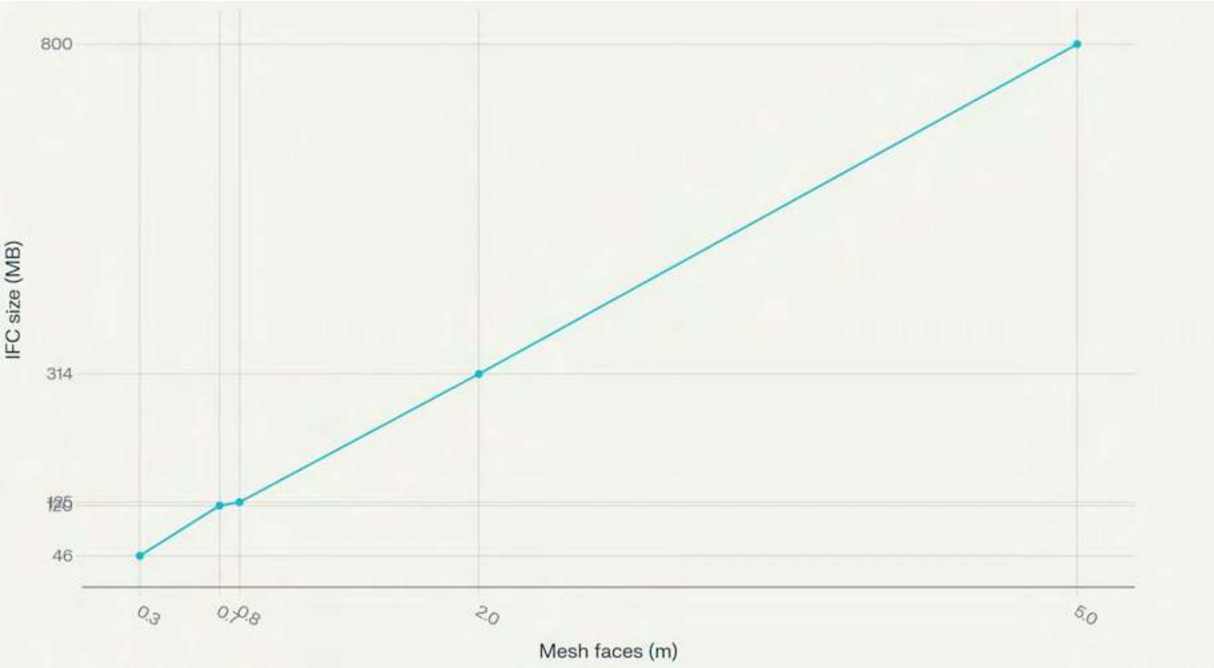


Figure 17. The relationship of several decimations performed on the photogrammetry mesh and their corresponding filesizes in IFC.

To try to achieve a balance between accuracy and file size we have progressively decimated the mesh:

1. In Figure 18 we can see that most of the faces are within ±2.5cm deviation from the point cloud (the hidden colour coding on the faces is inside the mesh but within the same limit values. However, this mesh produces a 0.8GB IFC file size, which is not practical for our use case.
2. In Figure 19 we can see that also most of the faces continue to be containerized within ±2.5cm deviation from the point cloud. This mesh produces a 120MB IFC file size, which is ok for our use case but if we infer this mesh density for all the wall fragments, the master file will be around 2GB, which is still impractical.
3. Finally, in Figure 20, we can see that most of the faces are within ±2.5cm deviation from the point cloud but already some parts fall outside of this threshold, so we must assume a ±5cm accuracy. This mesh produces a 46MB IFC file size, which is practical to our use case.

[15] In this case the mesh of the fragment near the Presidential Palace, EW1 and EW3 fragments were used to study the amount of decimation as a benchmark, but the results are generalizable to all files, if exporting to IFC 2.3, and representing the entities via IfcCartesianPoint and IfcPolyLoop. In IFC4, the use of IfcTessellatedFaceSet is more efficient.

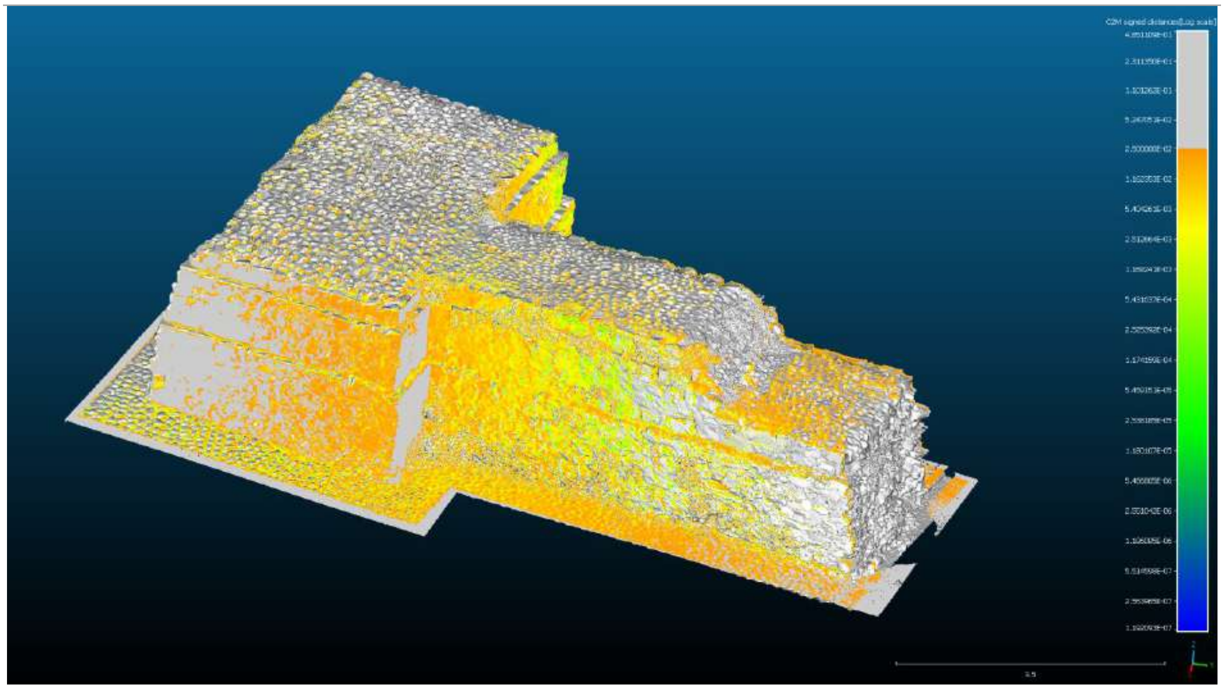


Figure 18. Comparison of the pointcloud data of the fragment near the Presidential Palace, EW1, with the photogrammetric data decimated to 5M faces.

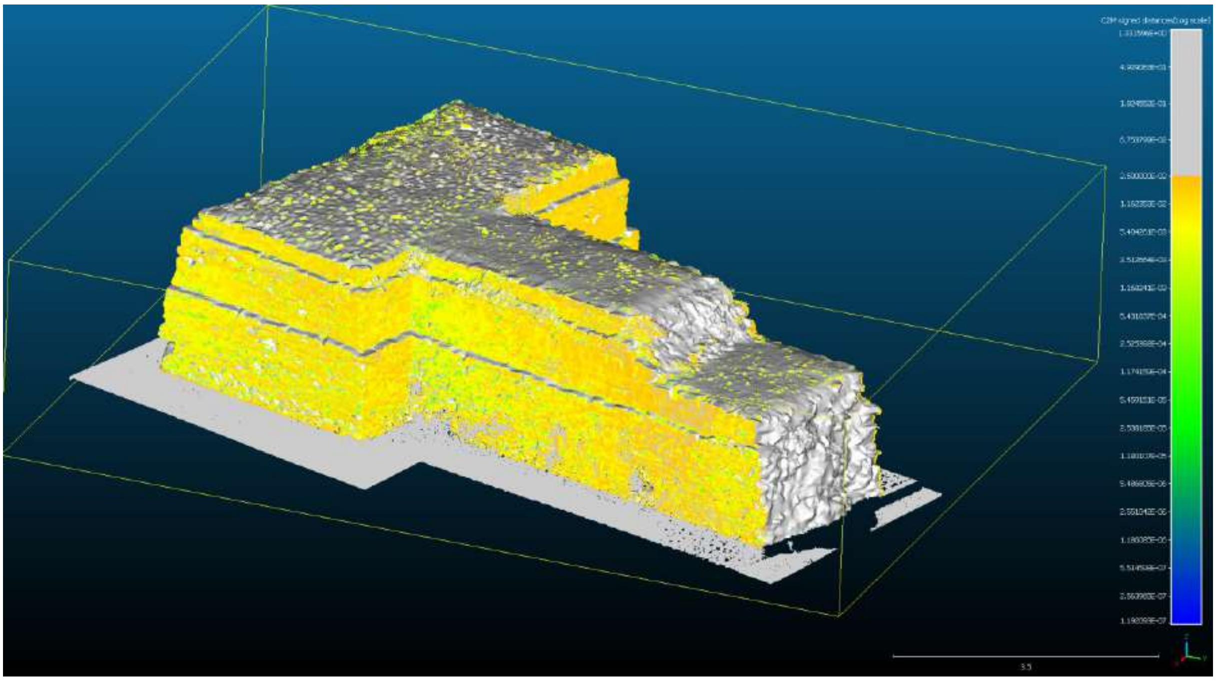


Figure 19. Comparison of the point cloud data of the fragment near the Presidential Palace, EW1, with the photogrammetric data decimated to ca. 0.7M faces.

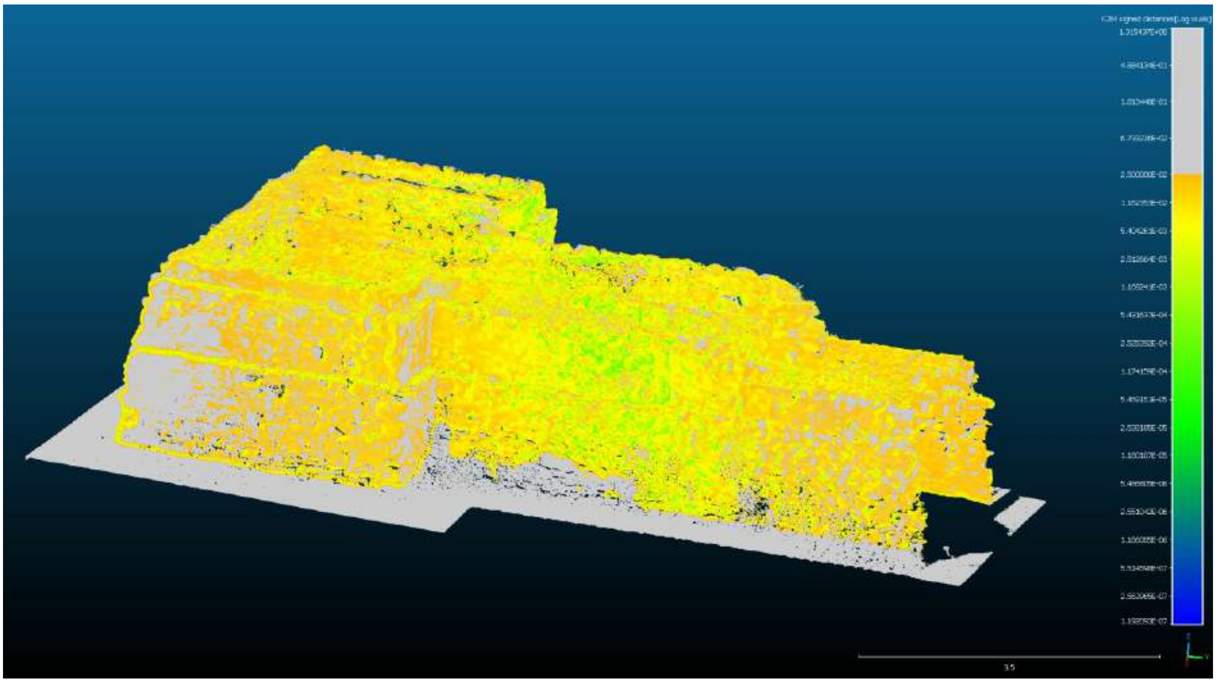


Figure 20. Comparison of the point cloud data of the fragment near the Presidential Palace, EW1, with the photogrammetric data decimated to ca. 0.3M faces.

This amount of decimation was then applied to the other fragments, see Figure 21 for the case of EW2: all the faces are within ±2.5cm deviation from the point cloud. The grey areas are filtered out, not because the accuracy is outside of bounds, but because these parts were not modelled.

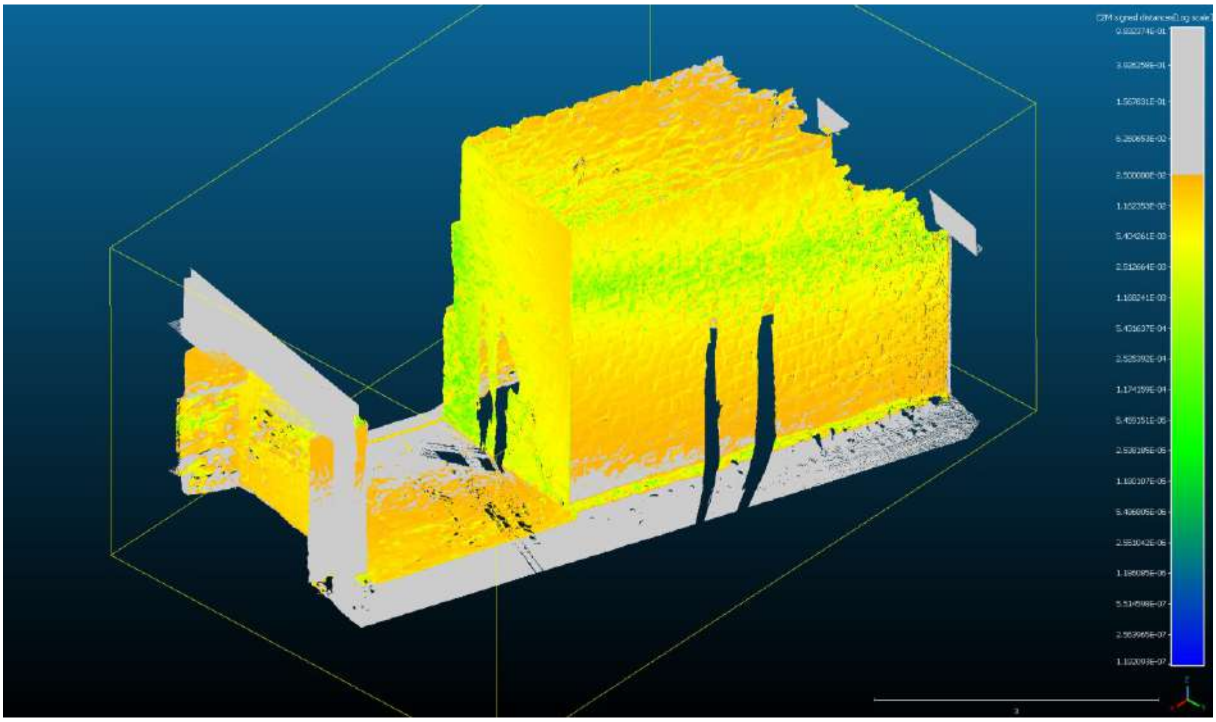


Figure 21. Comparison of the pointcloud data of the fragment of the Praetorian City gate, EW2, with the photogrammetric data decimated to ca. 0.25M faces.

In the case of the southwestern corner, EW5 (see Figure 22) the Poisson surface reconstruction has a bigger error, so we must classify this fragment as LOA10 (low accuracy). This is because the point cloud was used separately, and only the photogrammetric data was used to reconstruct the wall. In the future both data sets can be merged into one hybrid data set, to increase the accuracy of the mesh.

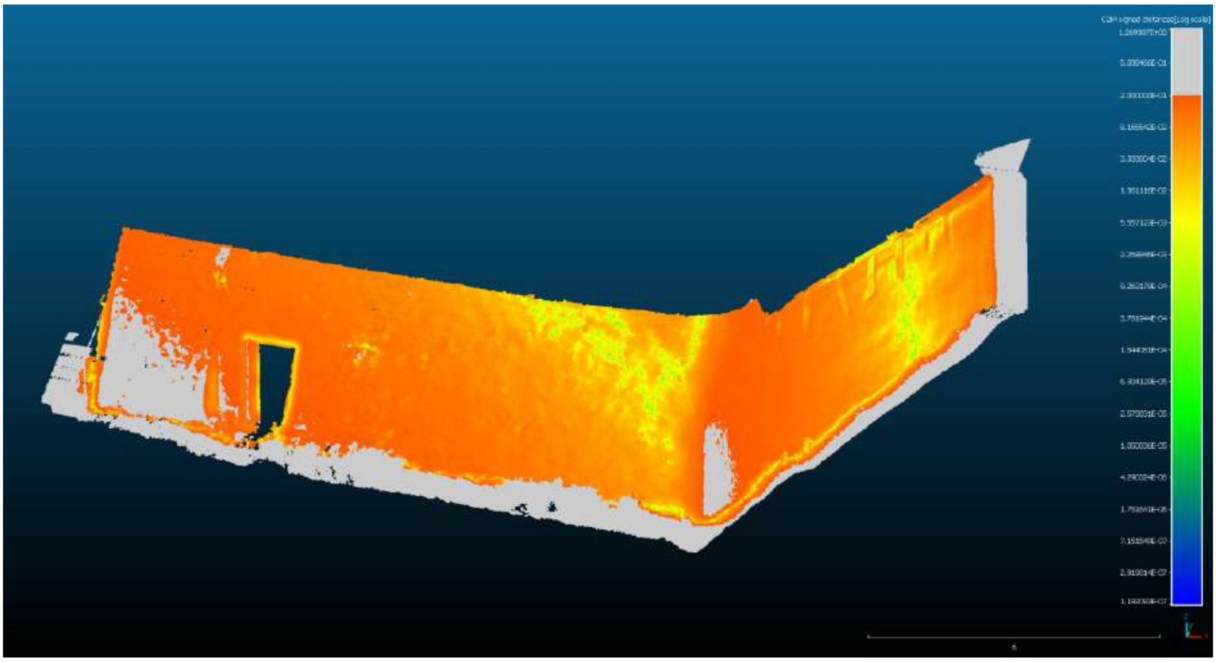


Figure 22. Comparison of the point cloud data of southwestern corner, EW5, with the photogrammetric data decimated to ca. 0.15M faces.

For the other fragments a decimation with the same settings, in the software InstantMeshes, by Wenzel Jakob, was performed. Quad-remeshing was also performed (see Figure 23), despite it not being supported by IFC, because it was also found that the computation inside VisualARQ from quadmeshes to trimeshes decreases the outputted IFC file size. In the Figure 24 we can see that the difference in mesh resolution between 20K and 55K quad faces is imperceptible.

VisualARQ exports geometry to IFC by converting all mesh faces to triangles, as required by the standard. We infer that if the original mesh is already well-structured (as with the quad-remeshing result of InstantMeshes), the resulting triangulated mesh may be more efficient, reducing file size, so the improvement in file size is a reasonable outcome of better mesh regularity and more optimal triangulation during export.

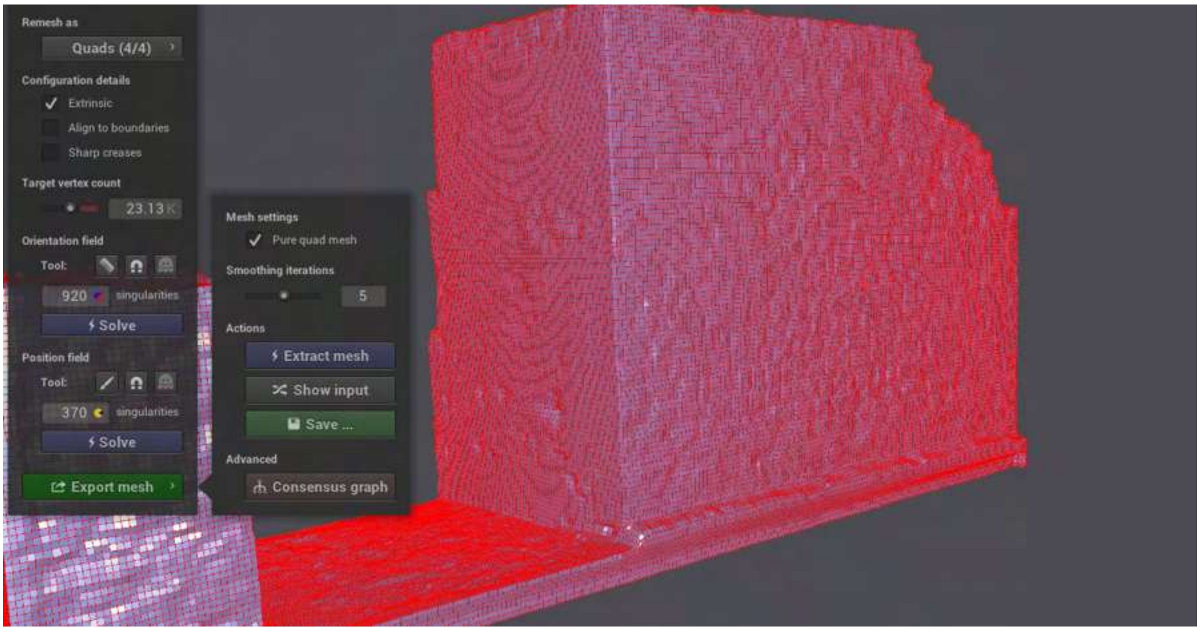


Figure 23. Example of the settings in InstantMeshes to achieve the quadmesh density allowing a LOA20 (2σ < 50 mm) and an acceptable converted file size.

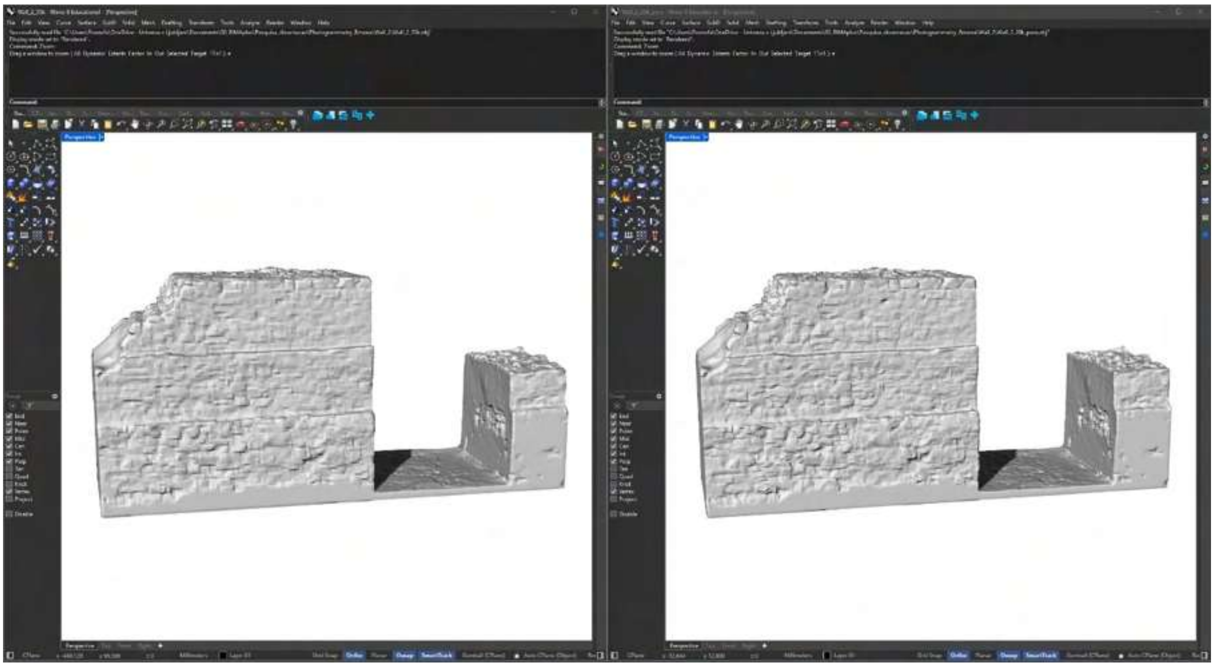


Figure 24. Visual comparison of the same model remeshed with 20K quad faces and 55K quad faces.

In summary, the integration of the USIBD and DIN 18710 Level of Accuracy frameworks provides a robust foundation for specifying, evaluating, and documenting mesh accuracy within heritage BIM workflows. This chapter has demonstrated that while high geometric fidelity is technically achievable - often surpassing standard documentation thresholds - the practical realities of file size, processing constraints, and BIM interoperability demand a balanced approach. By systematically analysing the relationship between mesh density, file size, and representational accuracy, it is possible to identify optimal decimation strategies that maintain necessary accuracy levels (such as LOA20) while ensuring model usability in real-world applications.

Moreover, the process has underscored the importance of transparent accuracy documentation, particularly given the absence of established standards for linking such metadata to BIM models. The proposed use of property sets (PSets) to record achieved accuracy within the modelled components offers a practical interim solution, supporting both technical validation and future data management.

Ultimately, the selection of LOA must be guided not only by technical capability but also by project intent and the ontological requirements of heritage assets. As we will see in chapter 3.3 Linked Data, meaningful semantic segmentation and property annotation take precedence over maximal geometric precision. This approach ensures that the resulting models are as geometrically reliable as possible within file size constrains, but also serve as rich, accessible repositories of historical and diagnostic information, aligning with the core principle that the intended use of the model should define the process.

3.1.4 Merging the old dataset with the new ones

Aligning point clouds to geographical positions in software such as CloudCompare is important because it allows the scanned data to be correctly located and integrated within a real-world coordinate system. For instance, aligning to geographical coordinates (such as WGS84 / D96 format) ensures that the data accurately represents its physical location on Earth. This spatial consistency allows for precise measurements, comparison with other geospatial data, and integration with GIS (Geographic Information Systems) software, and in this case, align to the previous dataset. It can also be used to compare progressions of damages, if several point clouds are produced of the same asset along several years, making it easy to do temporal analyses.

Georeferenced point clouds can also be imported into various CAD, GIS, BIM, and visualization platforms without losing positional meaning. This interoperability supports workflows across disciplines such as, in our use-case surveying and heritage conservation, but also urban planning, engineering and construction monitoring.

Overall, georeferencing transforms raw point clouds from relative or arbitrary coordinate frames (internal reference plane) into meaningful spatial assets that can be used confidently in real-world projects, analysis, and collaboration [46].

The process of aligning point clouds in CloudCompare typically involves two main phases: a rough manual alignment followed by a fine automatic registration.

Manual Rough Alignment Using Picked Point Pairs sequence of interaction:

1. Load both point clouds into CloudCompare.
2. Select the two clouds to be aligned.
3. Use the Align tool (available under Tools > Registration > Align or via the toolbar icon).
4. Manually pick at least three pairs of corresponding points between the two clouds. These should be easily identifiable, distinctive features present in both datasets.
5. Preview the result and the RMS error before applying the transformation.

CloudCompare uses these pairs to compute an initial transformation (translation, rotation, scale if allowed) to roughly align the "to be aligned" cloud to the reference cloud. We can add more point pairs for better accuracy or remove poor matches using the align tool interface. This rough alignment is crucial when the two clouds have large differences in position or orientation, where automatic-only methods struggle.

After rough alignment, ICP registration was performed to refine the match and deeply minimize the distance between point clouds. ICP iteratively finds closest point pairs between the clouds and computes the optimal transformation to reduce alignment errors. Choose appropriate parameters such as maximum distance for point pairing and number of iterations. Once ICP converges, the wanted result is a highly accurate alignment. This can be verified using tools like Cloud/Cloud Distance to verify registration quality. Afterwords we can confidently export our clouds in the geographical position.

In this case our reference cloud (apart from the EWM, which is very dense) is very sparce, produced by a LiDAR mounted on a flying instrument. The produced dataset is open-source accessible via the CCLSS viewer (a web tool for viewing 2D and Airborne Laser Scanning (ALS) data from across Slovenia [47], see Figure 25) and the resulting alignment might not be very accurate.

Figure 25. Downloading the .laz files for better visual confirmation inside CloudCompare.

Section near the Presidential Palace, EW1

In this case, near the Presidential Palace, we don´t have a cross-reference to the old dataset, of the already geo-referenced Wall on Mirje. So we must extract easily recognizable coordinates (normally the four corners of the wall are the easiest) in the WGS84 / D96 format and use this point list as reference inside CloudCompare (see Figure 26Figure 27)

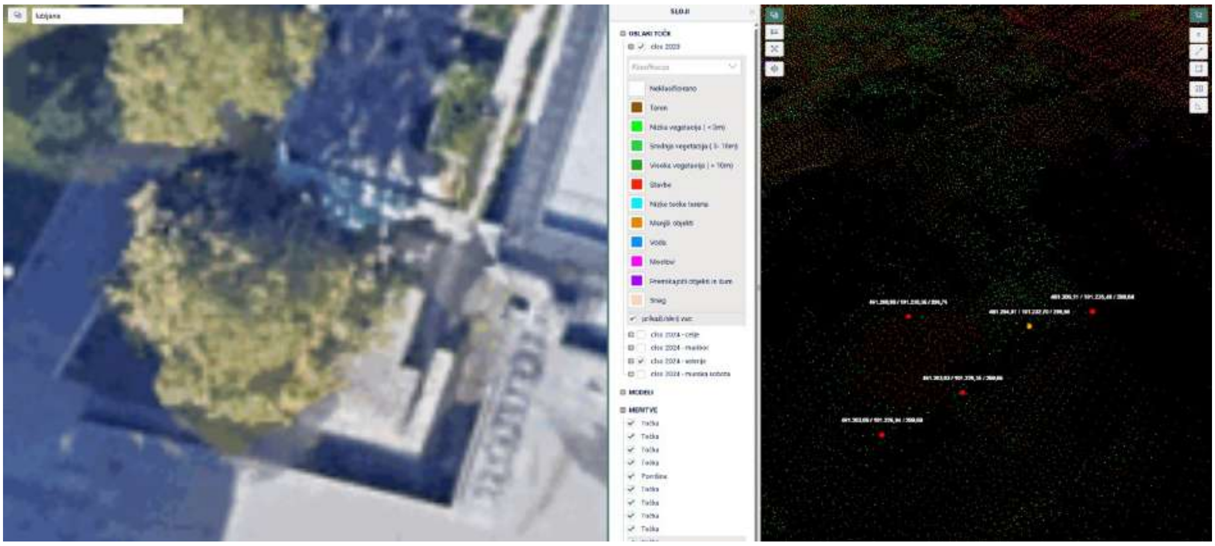


Figure 26. Using the CLSS viewer to create control points for the other fragments of the wall

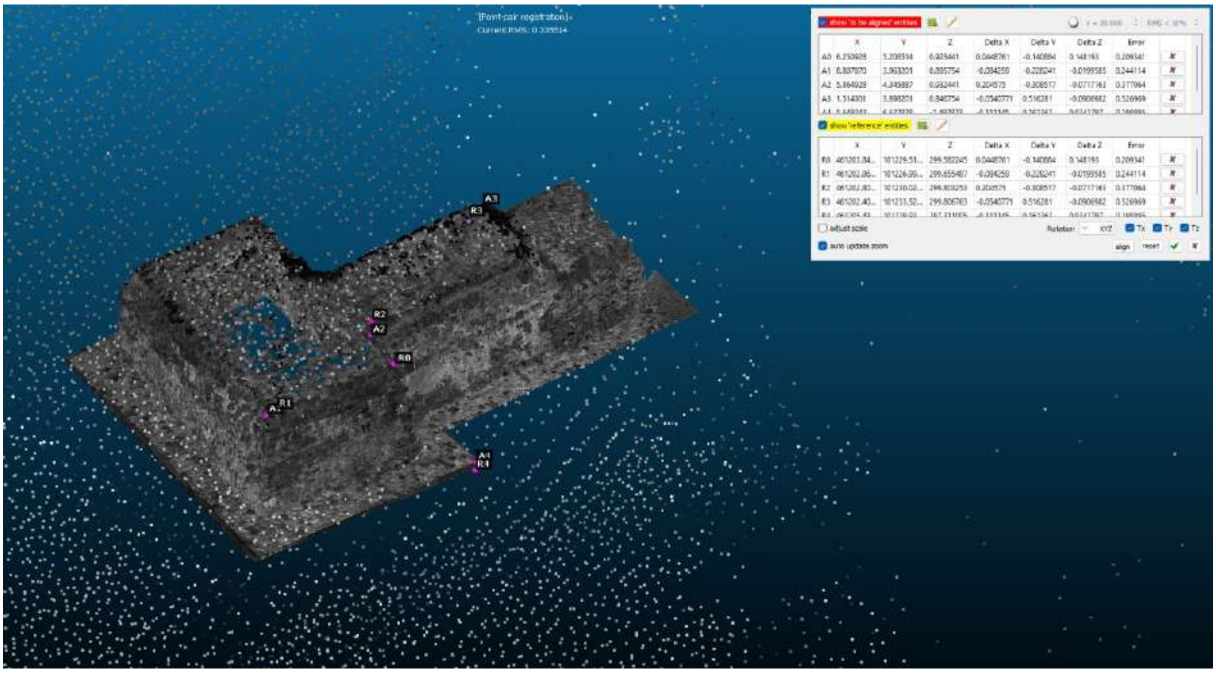


Figure 27. Achieved alignment of the fragment near the Presidential Palace, EW1 inside CloudCompare.

Praetorian City Gate, EW3

In the case of the Praetorian City Gate we use the same method, extracting the coordinates of the four corners of the wall in the WGS84 / D96 format and use this point list as reference inside CloudCompare (see Figure 28,Figure 29).

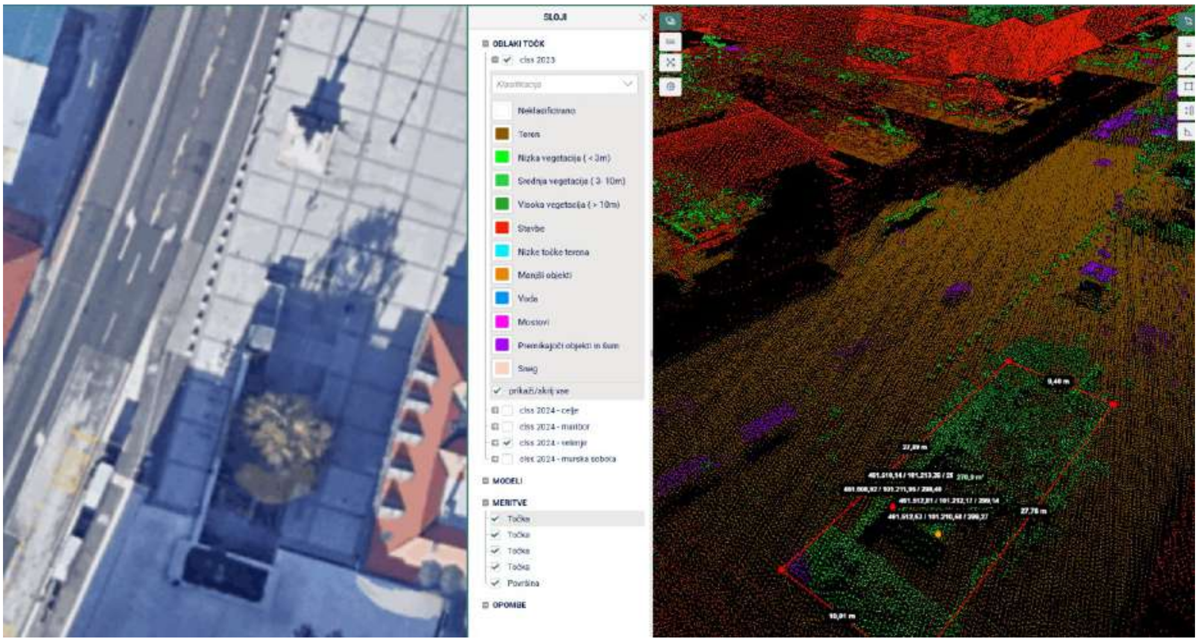


Figure 28 Using the CCLSS viewer to create control points.

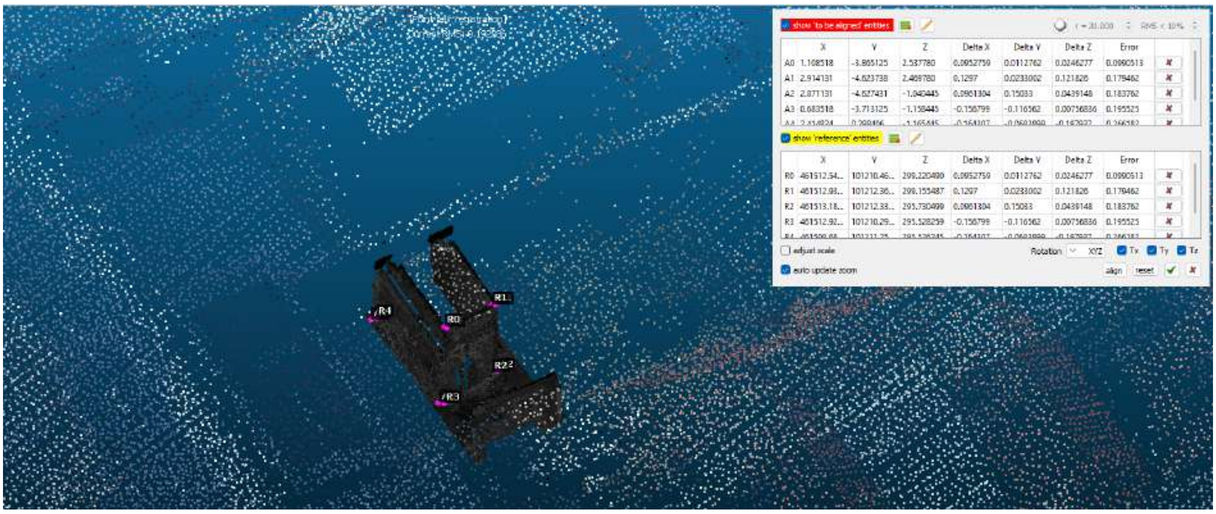


Figure 29 Achieved alignment of the Praetorian City Gate, EW3 inside CloudCompare.

Remnant near the houses in the southern part of the wall, EW4

The EW4, since we don´t have a point cloud dataset, will be of an inferior accuracy and this will be reflected in the associated meta-data. Otherwise, the process used was the same, see Figure 30.

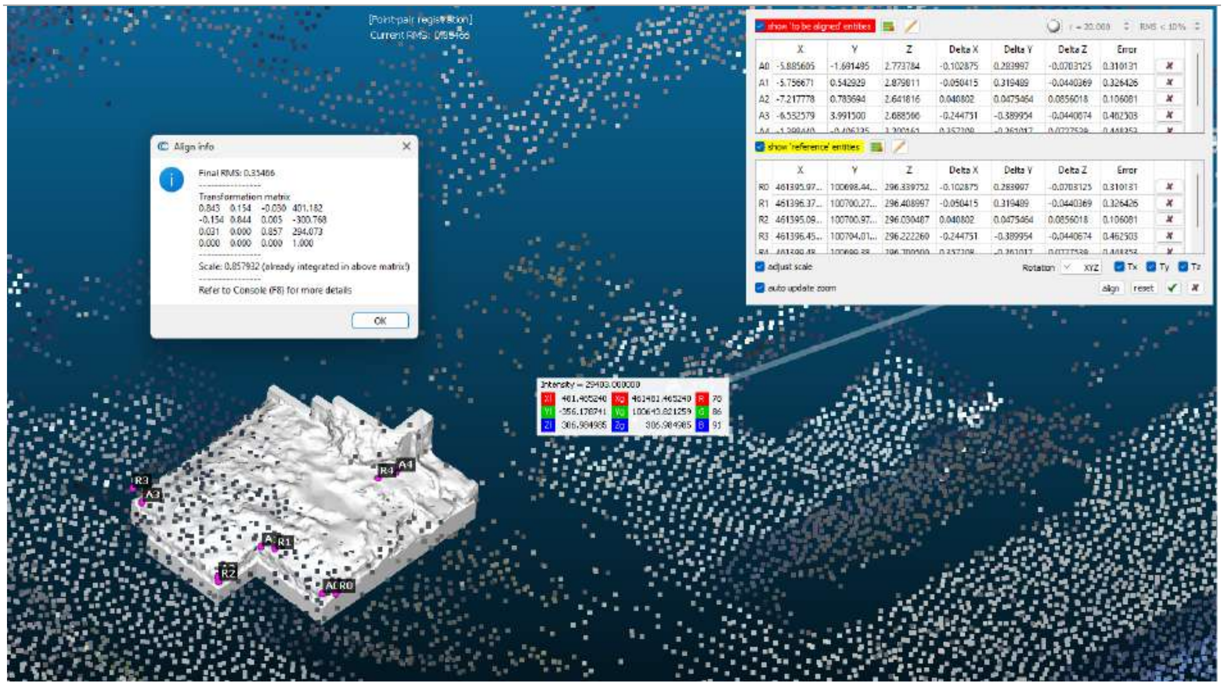


Figure 30. The cross-referencing of the EW4 fragment in CloudCompare.

Southwestern corner, EW5

In the Southwertern corner of the wall, EW5, the process used was the same, see Figure 31.

Figure 31. The cross-referencing of the EW5 fragment in CloudCompare.

Inside of the Lapidarium, EWL – EWM

For the Lapidarium we could reference to the dense cloud that was produced in 2022. See the sequence of Figure 32,Figure 33,Figure 34 andFigure 35 for the process of referencing. The capturing of the outer points, as detailed in Figure 78 of the appendix Inside of the Lapidarium, EWL - EWM was essential for this.

Figure 32 Previously obtained coloured point cloud dataset of the southern section.

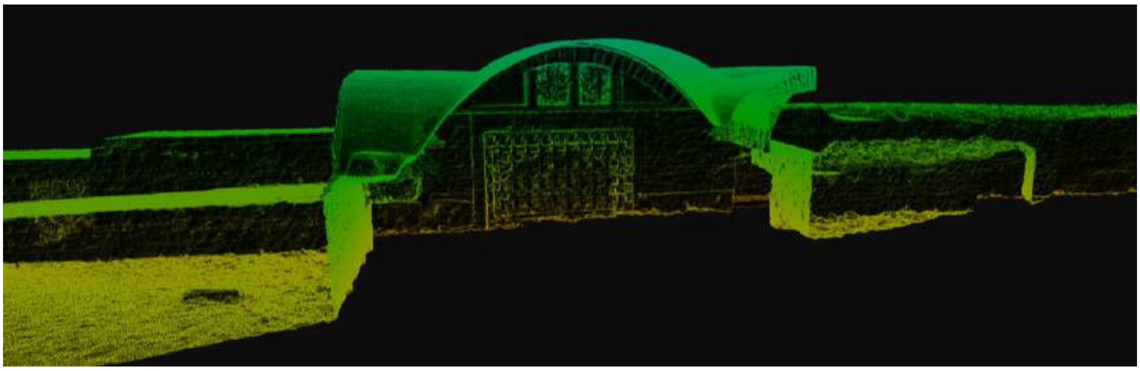


Figure 33 Sectioning the point cloud to reveal the missing interior of the Lapidarium

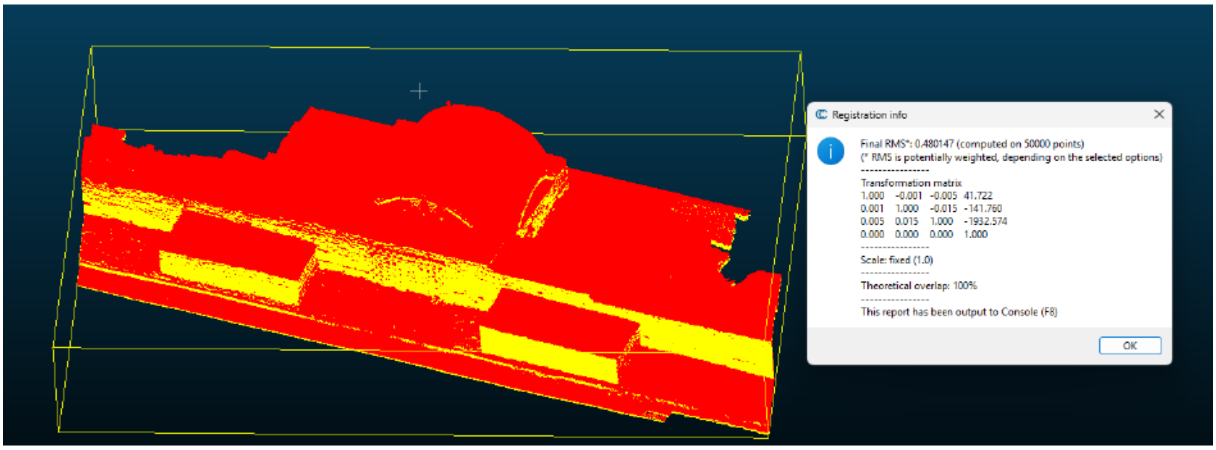


Figure 34 Using CloudCompare to perform the alignment of the interior of Lapidarium with the previously produced point cloud with all the Wall on Mirje.

Figure 35 The Lapidarium LIDAR interior dataset after manual cleaning and stitching to the outside in the correct geographical position.

3.2 Tridimensional mesh creation: Scan-to-MesHBIM

This chapter describes a robust workflow for converting reality-capture datasets, originating from laser scanning and photogrammetry, into IFC-compliant BIM models suitable for heritage documentation and digital project management. The process leverages mesh-based modelling as an intermediary, facilitating the conversion of complex, irregular heritage geometries into structured BIM data formats that can be recognized by industry-standard software.

We can see in the Figure 36 the process used to model BIM objects from reference point cloud objects.

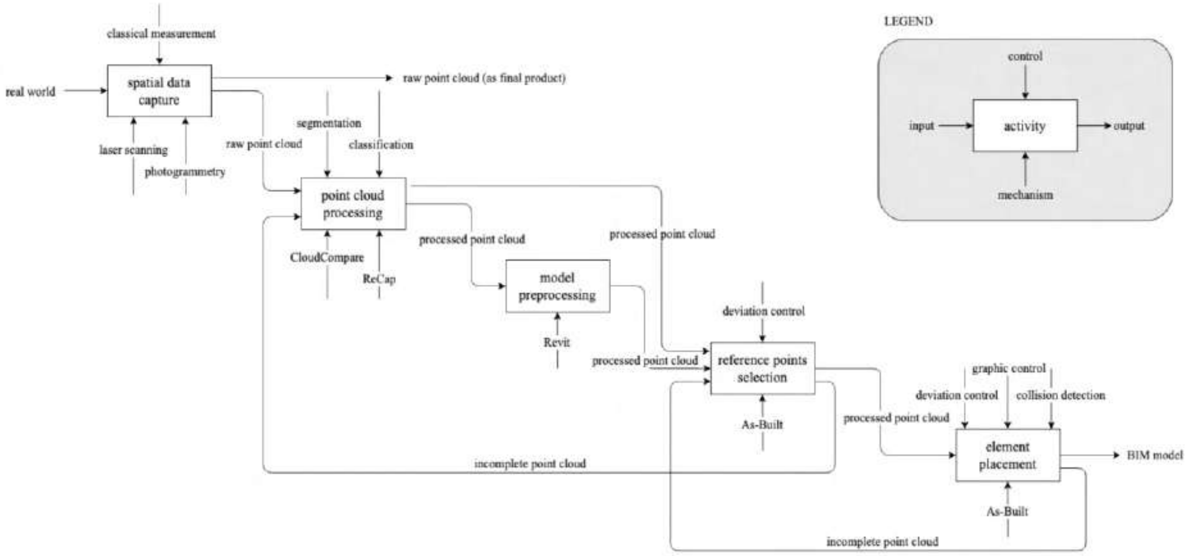


Figure 36 IDEF0 diagram of conversion from the material world to BIM model [48].

While HBIM is recognised as a suitable system for managing heritage projects, the modelling task itself is described as laborious, difficult, and time-consuming. This is partly due to the complex characteristics of historic buildings with their extended time of use, repurposed structures, reused materials, shape variations, diversity of fabrics, historic-constructive phases, and pathologies like cracks or humidity. Furthermore, BIM software tends to be complex, and many heritage stakeholders (e.g., historians, restorers, monument managers) lack the technical training for BIM modelling, preventing their full participation in the HBIM process. Historians and archivists, who handle documentation, typically cannot manipulate HBIM models[9]. In this sense we will apply a methodology that is almost automatic, to facilitate future additions to the model.

There were two different approaches described in the literature:

- one is more optimized towards FEM analysis and transforms a dense point cloud into a simplified IFC description slicing of the point cloud. These slices are then extruded up to the next one and capped on both ends. that aims at reconstructing the geometry of the solid This slicing process aims to reconstruct the geometry of the solid and to obtain a simplified IFC description of a dense point cloud describing a historic building [49], departing from the previously developed python libraries of the Cloud2FEM procedure [50]. This approach is based on the idea previously exploited in the Cloud2FEM procedure, which also utilizes slicing for generating voxelized FE models.

- the other methodology described by Muñoz-Cádiz et al.[51] makes specific use of Poisson surface reconstruction to generate highly accurate mesh models from point cloud data. Poisson reconstruction is an advanced algorithm that constructs a smooth, closed surface from oriented point samples, such as those collected via laser scanning or photogrammetry. Unlike simpler triangulation approaches, the Poisson method processes all input points simultaneously and is robust against data noise, filling gaps and generating watertight meshes ideal for heritage architectural modelling [52]. It works by mathematically "filling in" gaps in the input point cloud based on the surrounding geometry and the orientation of surface normals. Rather than only connecting directly observed points (like Delaunay triangulation), Poisson reconstruction approaches the problem as a global, volumetric calculation: it solves for a surface that best fits the spatial gradient field implied by all the oriented points and estimates where the surface should continue even where the direct data is incomplete [52].

In the Scan-to-MesHBIM workflow, the Poisson reconstruction stage plays a crucial role in transforming raw point clouds of complex historical ceilings into continuous, analysable geometric models. This step is especially valuable for heritage documentation, where original structures often feature irregularities and incomplete scan coverage. By producing a seamless, high-fidelity mesh that accurately represents both visible and occluded surfaces, Poisson reconstruction provides a solid geometric foundation that can later be enriched with semantic and historical information within the HBIM environment, thereby supporting analysis, conservation, and knowledge transfer [51].

We ended up choosing the second approach, due to the perceived improved time processing geometry (there is no need for a plane / points interaction to create the slices which will be the base of the 3D, as described in the previous case. In this case the methodology Scan-to-MesHBIM [51], is applied, creating a semi-automatic workflow between several programs, illustrated in **Error! Reference source not found.**. It consists of five major stages, each utilizing specialized software tools to refine, annotate, and segment 3D mesh data for eventual export to openBIM formats. These stages encompass data capture, initial and auxiliary modelling, mesh editing, feature remeshing, and BIM integration. By carefully sequencing automated and semi-manual procedures, the pipeline achieves a balance between modelling efficiency and geometric and semantic accuracy:

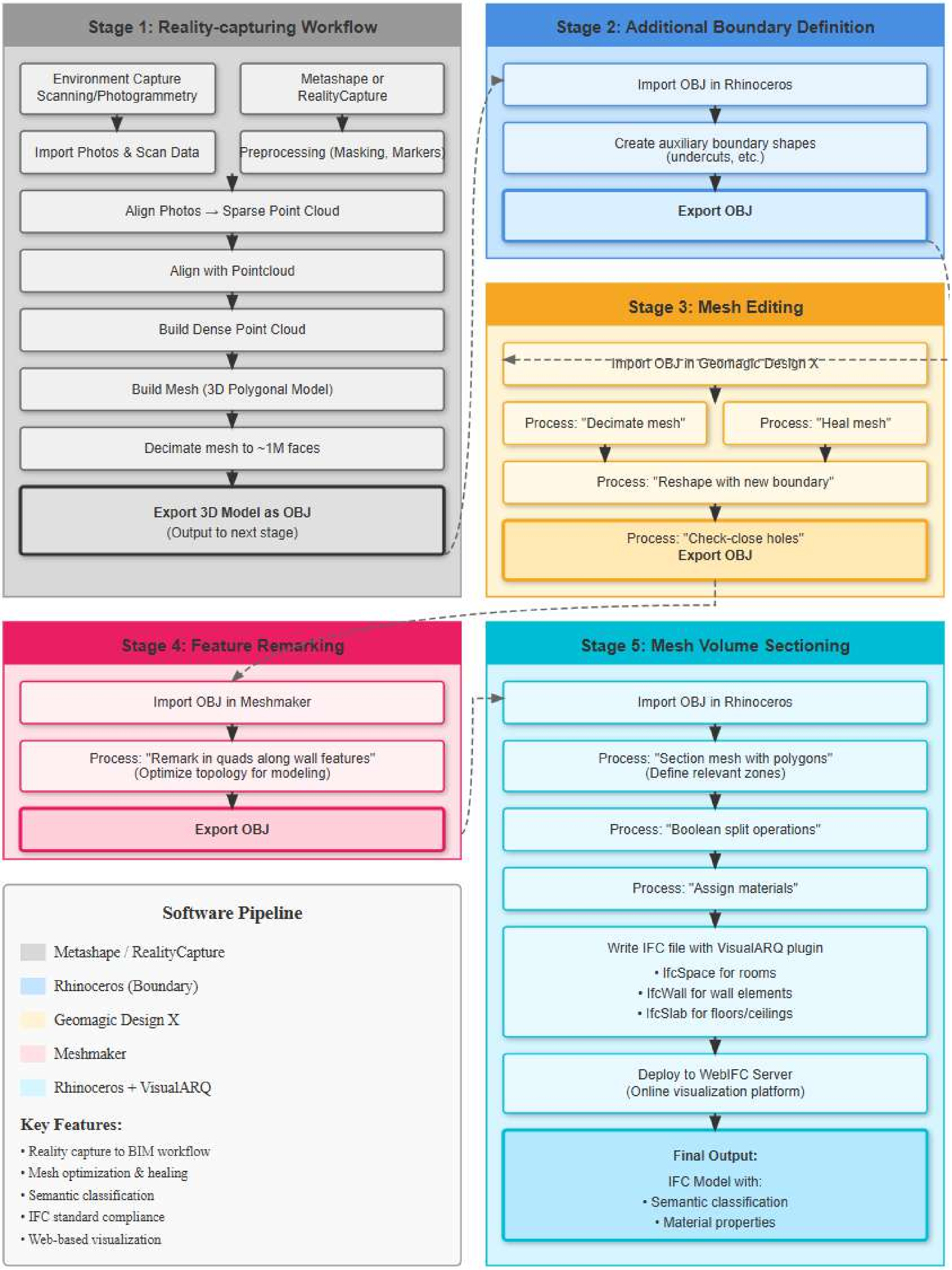


Figure 37. Developed workflow pipeline that allows the meshes to be converted to IFC compliant shapes.

Stage 1: The process begins with the capture of environmental geometry, as described on chapter 3.1, through terrestrial laser scanning (TLS) and photogrammetry. Images and scan data are brought into tools such as Metashape or RealityCapture, where preprocessing steps like masking and marker placement are performed. After aligning photos and scan data to generate a sparse point cloud, alignment with ground or project control points is conducted. A dense point cloud and subsequently a high-density mesh are constructed. For efficient processing and file management, the mesh is decimated to fewer than one million faces before being exported as an OBJ file.

Stage 2: This intermediate stage involves importing the mesh OBJ into Rhino, where users create auxiliary boundary shapes (see Figure 38), often to represent complex undersides or additional segmentation needed for later processing. These boundaries are exported out for further use in mesh editing and sectioning (see Figure 39).

EWM – Meshing the old dataset

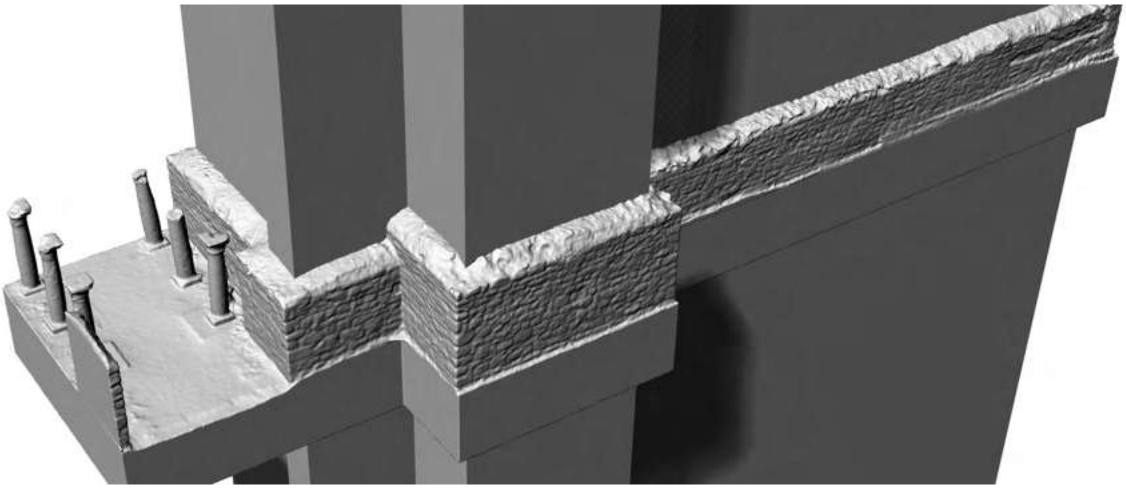


Figure 38. Boolean disjunction of the Mesh model of the Section 7 of the Wall on Mirje (Peristyle passage) with auxiliary polygon. In this case the separation of the Emplekton (inner core) from the outer layer is being performed.

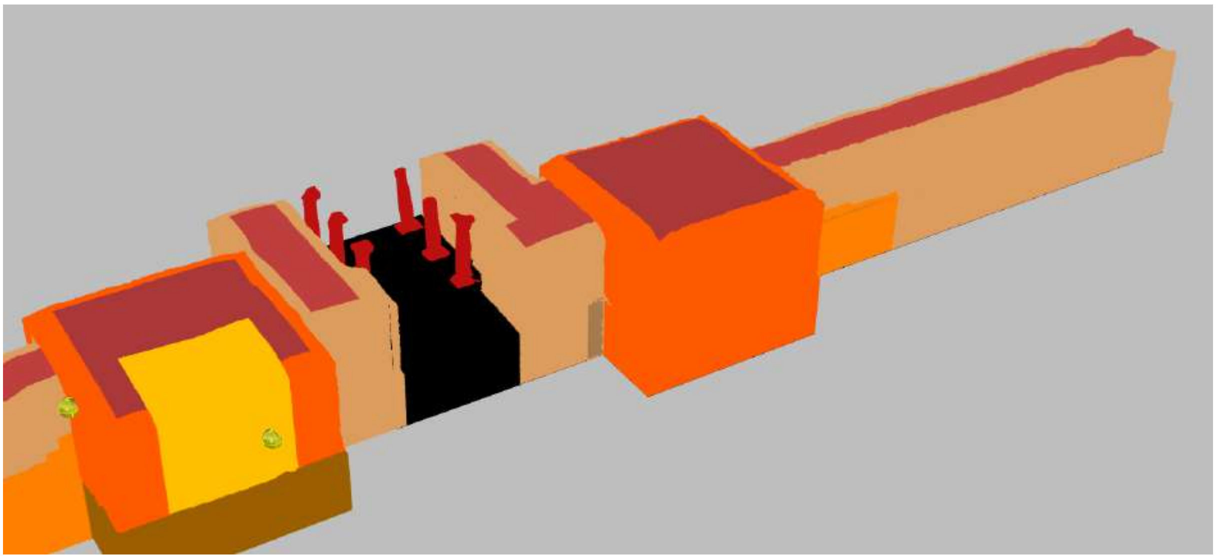


Figure 39. The Section 7 of the Wall on Mirje colour coded according to significant semantic and structural elements and sub-elements.

Stage 3: The OBJ mesh is next imported into Geomagic Design X. Here, the workflow focuses on decimating the mesh further if needed, healing mesh errors, reshaping geometry to fit newly defined boundaries from Rhino, and checking for residual holes. The clean, edited mesh is exported as an OBJ file for remeshing.

Stage 4: Feature remeshing is performed in Meshmixer (or with tools like Instant Meshes) where meshes are recomputed in quads (or, if necessary, triangles) along wall features and other critical components. This step enables better structuring of meshes for subsequent BIM conversion, preserving edge flow and reducing self-intersections. The remeshed OBJ is again exported, although sometimes problems may arise, as seen bellow.

Remnant near the houses in the southern part of the wall, EW4

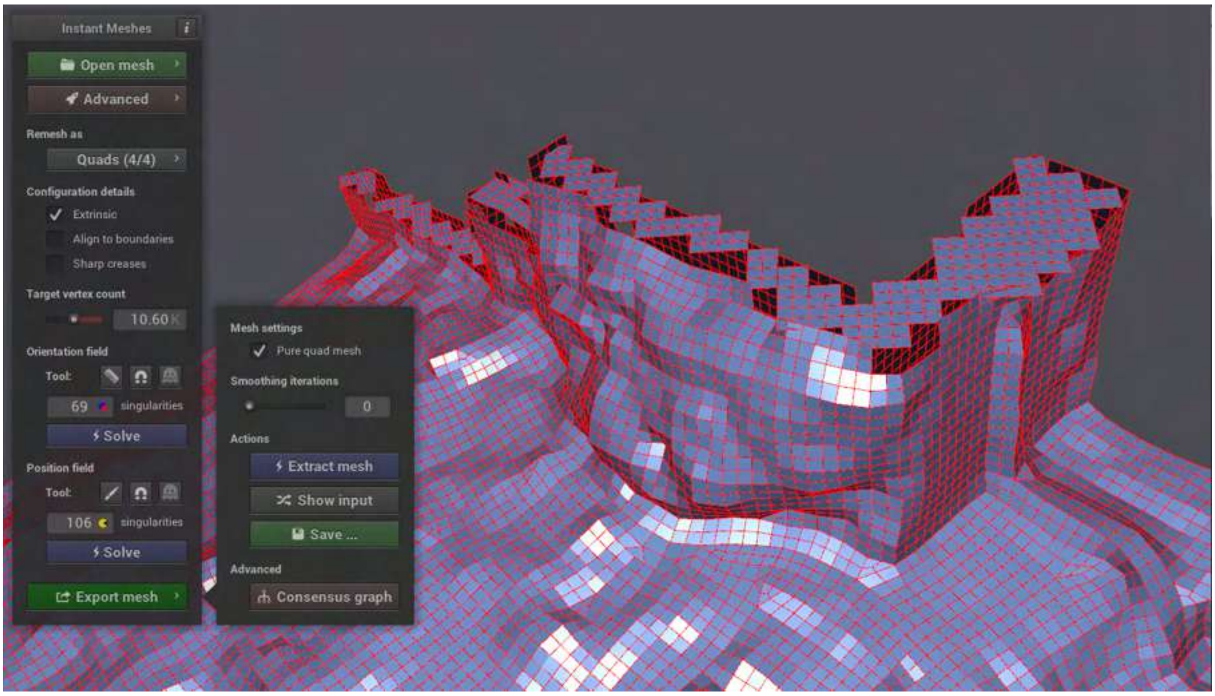


Figure 40. Areas where the field cannot be cleanly followed to create valid quads

Instant Meshes (Figure 40) uses field-guided parametrization to generate quadrilateral meshes (in this case 4-RoSy, 4-PoSy, which means 4-fold rotational and positional symmetries, failing less on complex organic meshes like the ones we are dealing with (allows directions to rotate 90° and still be considered aligned, instead of the 180° of a 2-RoSy field). This involves aligning a 4-directional (cross) field over the surface, which guides the generation of quads. However, some surfaces (especially with high curvature, topological complexity, or sharp features) do not admit a globally smooth, orthogonal cross field without introducing singularities, or non-integrable field directions areas, which causes holes or self-intersections in the output mesh. In these cases, we must resort to a traditional triangular mesh as seem on Figure 41.

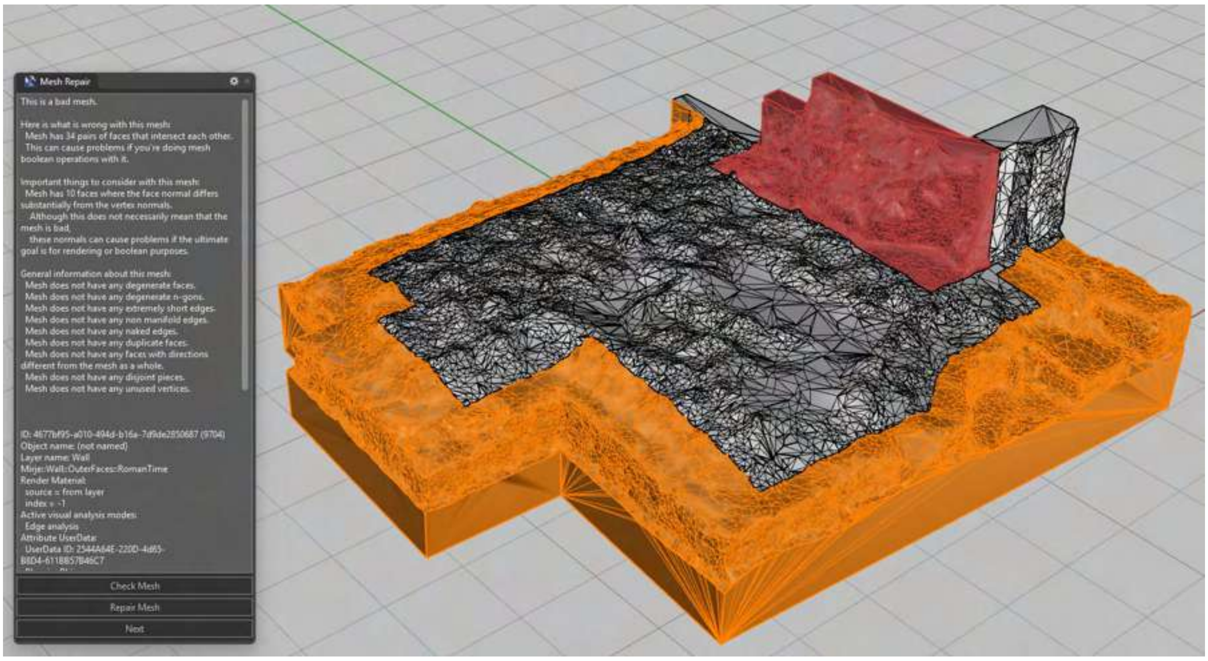


Figure 41. With the triangulated faces we can produce closed meshes, despite still having self-intersections. This mesh produces a 5.52MB IFC, so it is acceptable for the next stage of the process, the IFC creation.

Stage 5: In the final stage, remeshed OBJs are brought back into Rhino (with the VisualARQ plugin). Here, the mesh is split into sections with polygons corresponding to architectural or historically significant segmentation[16] (see Figure 42, Figure 43) Boolean splits, semantic annotation, and the assignment of BIM metadata are performed. The result is then written as an IFC file using VisualARQ and can be served via a webIFC-enabled server, making the data accessible within contemporary openBIM workflows.

[16] For instance, segmenting through the line of pebbles done by Schmidt, so that the roman mortar and the originally placed stones (if we can trust that this was actually the process) can be logged in a different object that the modern mortar.

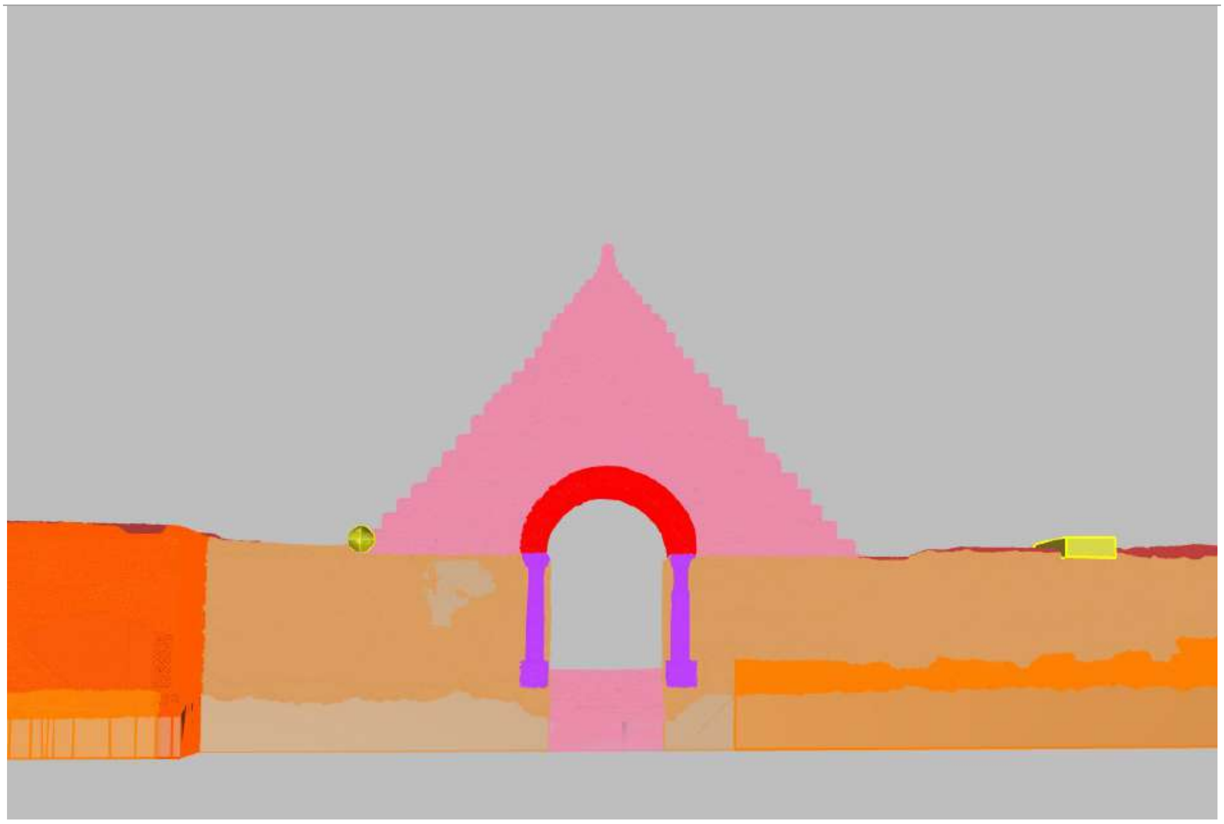


Figure 42. The wall segmentation was done as if supporting the pyramid stones itself. This still has to be further studied, if the characteristical emplekton typology is present in this area and if not, the segmentation must be corrected. This is also the subject of the study by Bosilijkov et al. [53]

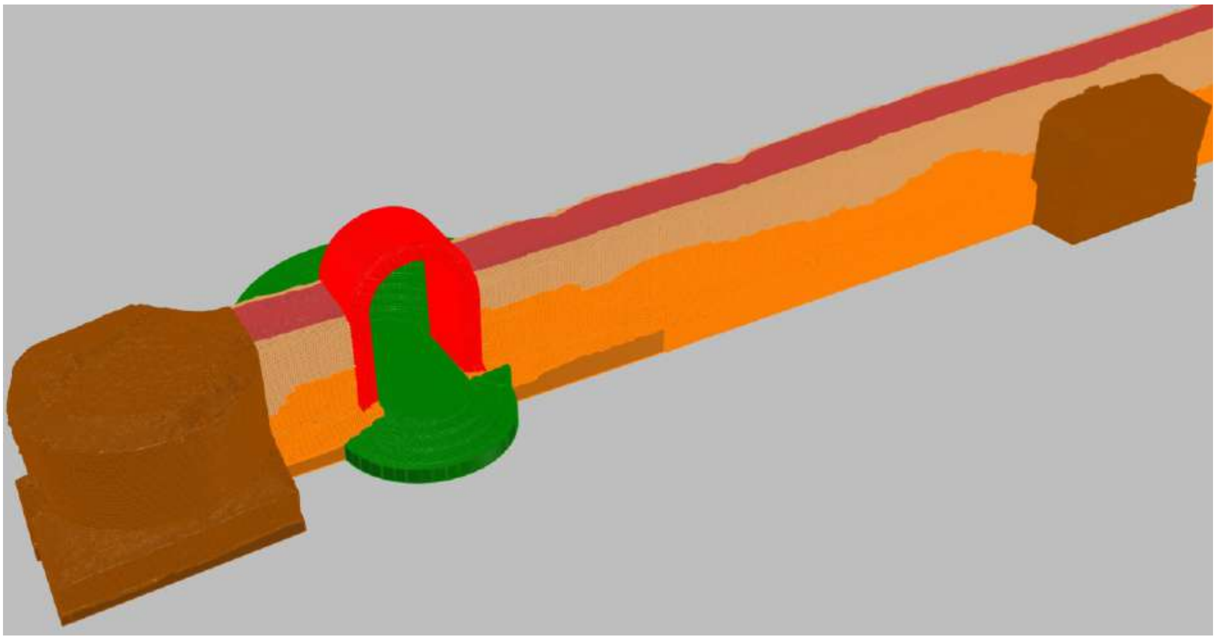


Figure 43. Example of the resulting semantic partitioning of the geometry producing watertight volumes

Now that we have created the simplified meshes from the original point cloud and photogrammetric data, we can use the VisualARQ plugin to allow native Rhino objects to be IFC-writeable.

The VisualARQ plugin acts as a bridge between Rhino's powerful freeform modelling capabilities and BIM workflows by making it possible to convert Rhino geometry - including mesh data generated from point clouds and photogrammetry - into BIM-ready objects that can be exported as IFC files. This ability is especially useful in heritage and scan-to-BIM projects, where many existing building elements have complex or irregular shapes that cannot be accurately described with standard parametric forms. With VisualARQ, users can assign BIM properties (such as element type, function, material, and classification) directly to mesh objects or convert them into VisualARQ native objects, such as walls, slabs, or custom parametric components. This not only gives semantic structure to geometry derived from reality capture but also ensures these elements are recognized as valid building objects in downstream BIM applications.

VisualARQ's built-in IFC import, and export tools are a key benefit for collaborative digital workflows. Once mesh or surface data has been structured and annotated with BIM information within Rhino, VisualARQ allows for seamless export of these objects to IFC 2x3 or IFC4 formats. This ensures interoperability with other AEC software platforms (such as Revit, Archicad, or Tekla), supporting openBIM standards.[17]

In summary, VisualARQ transforms mesh-based or freeform geometry into useful, information-rich BIM assets within Rhino, making such data fully compatible with the IFC standard. This process supports efficient documentation, enhances project collaboration, and preserves valuable geometric and semantic detail, which is crucial for heritage maintenance, or any situation where complex real-world forms need to be integrated into the BIM ecosystem.

This multi-stage workflow successfully bridges the gap between reality-captured data and usable BIM models. The approach ensures complex, historic geometries can be faithfully reconstructed, segmented, and semantically enriched, making them accessible in digital heritage and architectural projects.

Key benefits of this pipeline include the preservation of geometric detail through careful mesh processing, the flexibility to refine and annotate models at each step, and the interoperability achieved by using open formats like OBJ and IFC. Critical considerations throughout the process involve managing mesh complexity (to ensure performance and compatibility), maintaining coordinate consistency, and ensuring semantic accuracy when translating raw geometry into BIM-ready assets. Looking ahead, further automation, for instance, using scripting for mesh processing, batch metadata assignment, or even semi-automated boundary generation, could significantly reduce manual workload

[17] For more information visit https://www.visualarq.com/

and error rates. Improved algorithms for mesh healing, remeshing, and semantic segmentation would further streamline the workflow.

Ultimately, such structured and transparent methodologies are vital for collaborative heritage and BIM projects, enabling multidisciplinary teams to contribute, review, and reuse both geometric and semantic data. This ensures that digital models are not only accurate representations of the material world but also rich resources that support long-term conservation, analysis, and knowledge sharing.

3.2.1 Exceptions

As any good methodology, there are cases where it is not possible to adhere to it. We want to create a workflow that provides the best time / quality ratio, rather than being consistently using the same method, so manual or semi-manual modelling in architectural BIM tools becomes preferable when the automatic mesh creation (from point cloud or photogrammetry, or a hybrid dataset, is problematic, as described in the 3.1.1 Inside of the Lapidarium, EWL - EWM) creates a problematic mesh, which would take a long time to heal.

Inside of the Lapidarium, EWL - EWM

With traditional point cloud reference-based modelling users can precisely retrace geometry using reference points from scans, ensuring both sides connect properly and using the idea of "average point position" they can simplify a lot of the complexities while still respecting the original elements segmentation. Solid modelling (with control over wall thickness, connections, voids) guarantees watertightness and clean BIM integration. It allows for purposeful geometry correction and semantic labelling that automatic meshing can't reliably achieve for complex heritage interiors.

In Figure 44 we can see the result of the juxtaposition of the MeeshtoBIM model with the traditionally BIM modelled Lapidarium visualized in the developed server solution. There are a few centimetre-level gaps between both methodologies, but this is because the geo-positioning of the Lapidarium, being manually done, has a lower accuracy than the MeshtoBIM segments.

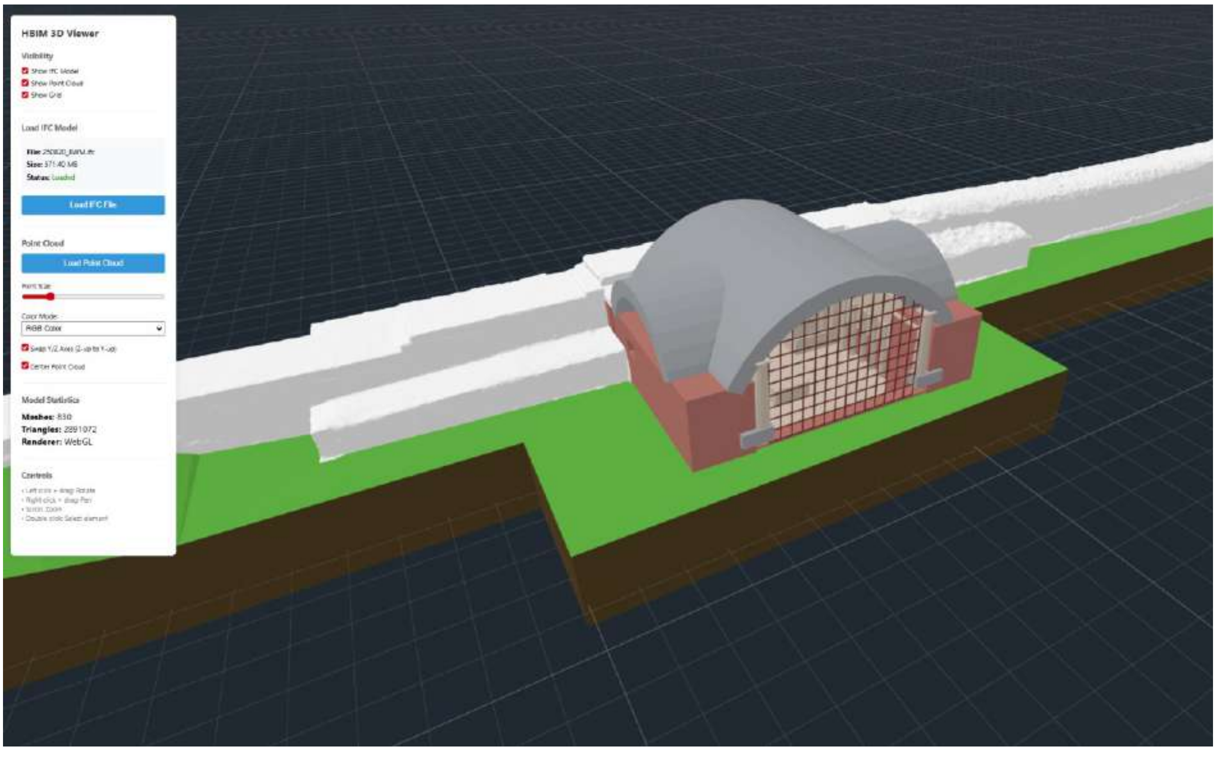


Figure 44. Juxtaposition of the MeeshtoBIM model with the traditionally BIM modelled Lapidarium.

Modelling the Pyramid – EWM

In the case of the pyramid, we will employ a similar workflow of the Cloud2FEM developed by Castellazzi et al. [22] but we will use the Contour function of Rhino progressing in the Z axis. This is done to perform future structural tests on this part of the structure, to make sure that the part of the wall (or Emplekton infill) below the pyramid is stable. See the original mesh model in Figure 45 and the new FEM ready model in Figure 46.

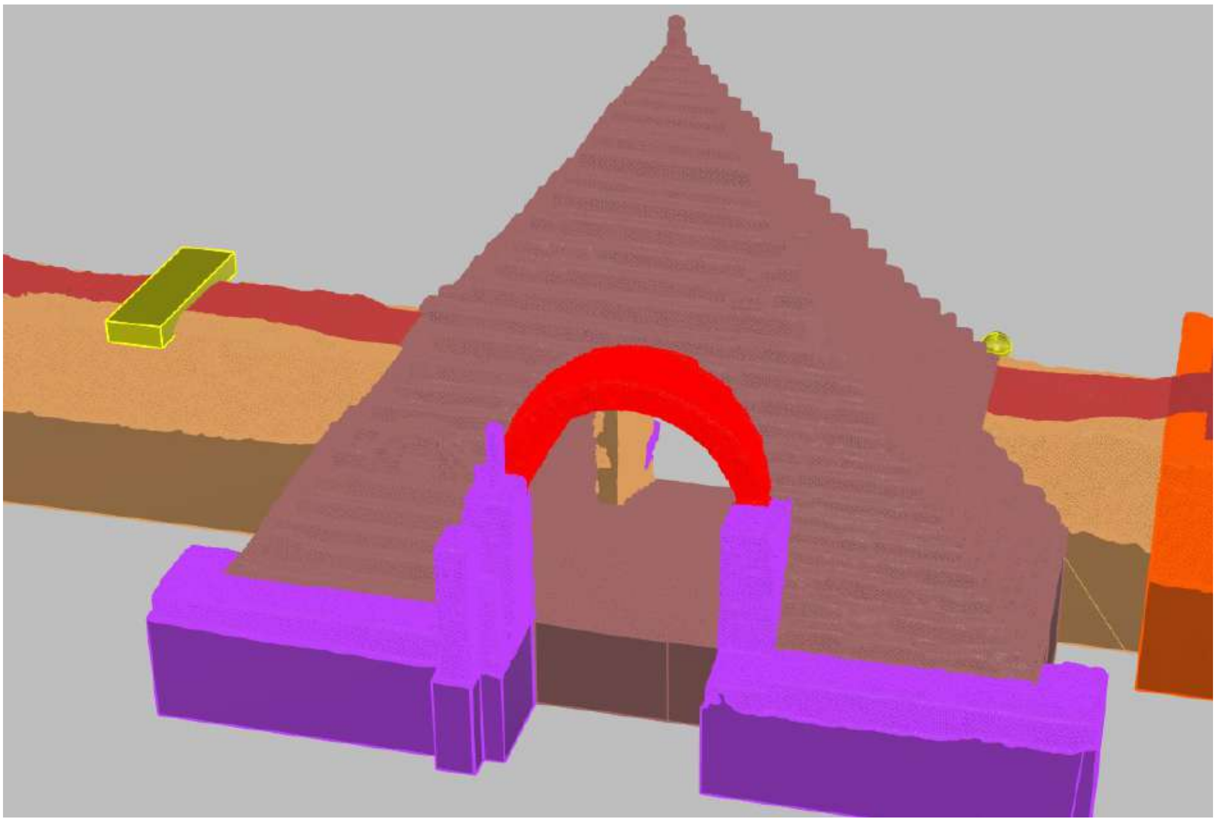


Figure 45. The initially processed high-density mesh of the point-cloud dataset.

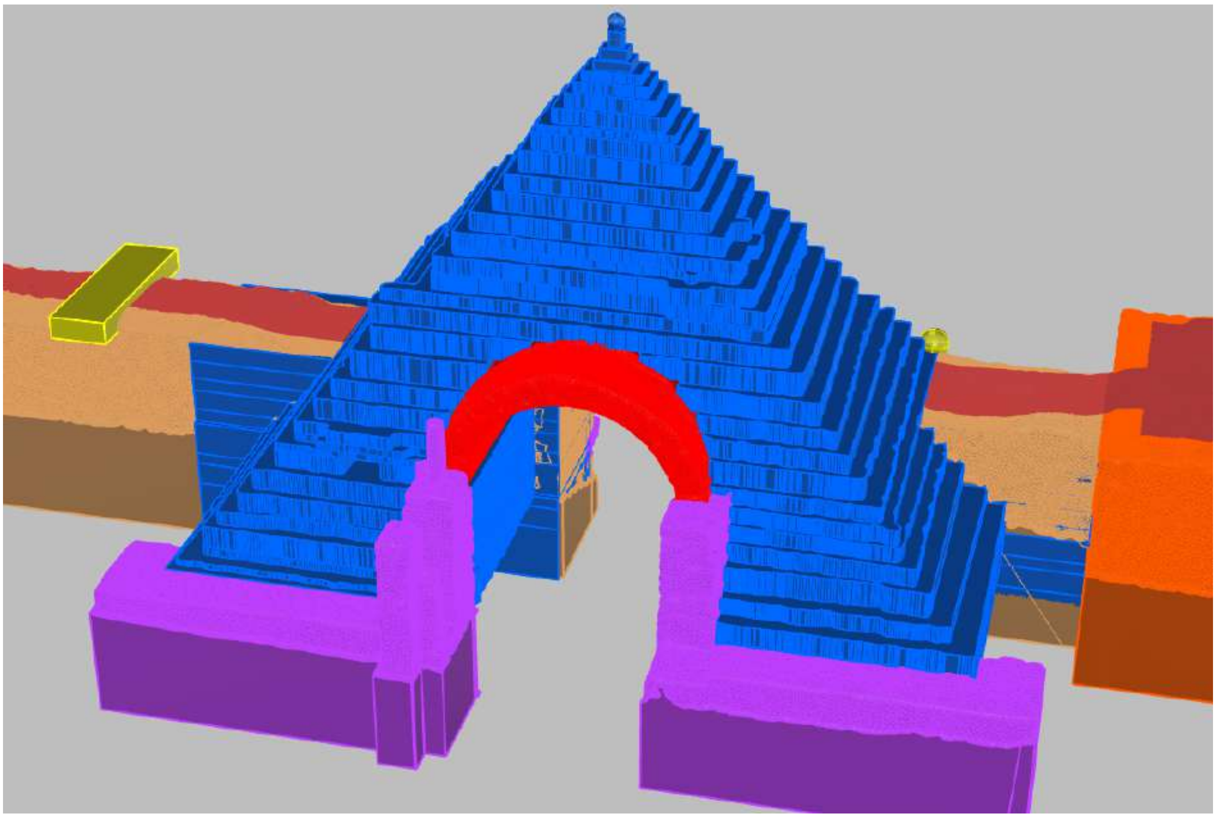


Figure 46. The BReps derived from the vertical contours of the 27 levels of the pyramid.

3.3 Linked Data

Alongside scan-to-mesh techniques, this work also relies heavily on the principles of Linked Data. This chapter introduces the foundational concepts of Linked Data, including RDF, ontologies, and SPARQL. The final section explores how Linked Data is applied in the context of built cultural heritage, with a particular focus on the Cultural Heritage Markup Language (CHML) [54] as a primary example. The core ideas behind the Semantic Web closely align with those of Linked Data, so presenting these topics within a Semantic Web framework can make them more accessible. While there are varying perspectives on how Linked Data and the Semantic Web relate, this thesis takes the view that Linked Data provides the structural foundation necessary for the Semantic Web, and that the information accessible through Semantic Web queries is, in essence, linked data.[55]

3.3.1 Resource Description Framework

The rise of the internet has greatly enhanced the way documents and data are shared and how people collaborate worldwide. A major factor behind the rapid growth of the web is its openness, allowing anyone to publish virtually anything they wish. This freedom to contribute, has fuelled the web's remarkable expansion. However, for information to be exchanged efficiently, whether on the traditional web or the Semantic Web, it must be structured according to agreed-upon international standards and protocols. Here, “information exchange” refers to the methods and frameworks for sharing data, rather than the content itself, as human interpretation can always vary.

Anyone developing or using Linked Data applications must understand the foundational principles that underpin these systems. As the W3C’s Semantic Web page notes, the ultimate aim of the Web of Data is to empower computers to perform more meaningful tasks and to build systems that foster trustworthy interactions online. With the world moving towards greater automation and interconnected information sources, computers and algorithms are increasingly responsible for handling data. Since effective communication is central to the internet, it is crucial to have a universal framework that enables all participants to interact seamlessly.

Yet, computers struggle to interpret the nuances of natural language as humans do. While people can effortlessly grasp the meaning of complex statements, machines find this task extremely challenging. To bridge this gap and create a network that both humans and computers can understand, information must be presented in two formats: one that is readable by people, and another that is interpretable by machines. The machine-readable format forms the backbone of the Semantic Web and is standardized as the Resource Description Framework (RDF). Today, RDF is widely adopted for representing, managing, and linking data on the web, either by enhancing existing web pages to integrate with the Semantic Web, or by building new applications that need to access, interpret, and exchange data stored on remote servers in an unambiguous way.

3.3.2 AI and Semantic Web Technologies: A Growing Symbiosis

As artificial intelligence continues to advance rapidly, its integration with semantic web technologies is becoming increasingly important. AI systems can harness the structured, machine-readable data from frameworks like RDF to improve their understanding, reasoning, and decision-making processes.

Through linked data access and interpretation, AI algorithms achieve superior performance in data integration, knowledge extraction, and automated reasoning across multiple domains. Semantic web technologies empower AI to clarify ambiguous concepts, resolve unclear references, and link related information, resulting in more reliable and context-aware AI applications.

The Semantic Web's interconnected data structure offers significant advantages over isolated datasets by providing richer context and relationships for AI algorithms to utilize:

- Contextual Understanding: Deep learning models particularly benefit from semantically structured data, enabling them to identify patterns, relationships, and hierarchies more effectively.

- Improved Decision-Making: AI systems can make better-informed choices by navigating linked data networks, understanding semantic connections, and evaluating contextual factors.
- Semantic Search and Reasoning: AI enables more precise search capabilities by interpreting user intent and context, delivering results that are semantically, not just textually, relevant.

This convergence creates a powerful combination: the Semantic Web establishes a structured data foundation that AI algorithms can intelligently process to uncover deeper insights and extract more meaningful information. Together, they form the basis for smarter, more interoperable, and more efficient digital ecosystems.

3.3.3 Uniform Resource Identifiers and Literals

When working with small datasets and a limited number of participants, representing information as triples is straightforward and effective. However, scaling this approach to the size of the entire web introduces new challenges. One common issue is that different people may use different terms to refer to the same concept; this can be resolved by explicitly declaring their equivalence. The problem becomes more complex when the same term is used to describe different things, which may differ subtly or significantly. For example, if two individuals named 'Jeroen' have each written a 'Thesis', it becomes unclear which person or thesis is being referenced.

To address this ambiguity, the system uses Uniform Resource Identifiers (URIs), which serve as unique, global references for specific resources—whether entities or relationships. By pointing to a resource's unique URI, different users or websites can be certain they are referencing the exact same thing. URLs, commonly used to access websites, are a specific type of URI that not only identify a resource but also provide its location and access method.

In addition to URIs, there are also value Literals, which represent information included directly in the graph but not linked to an external web resource. Literals can be simple data types like strings or numbers, or more specialized types associated with particular formats. In RDF triples, the subject and predicate are always identified by URIs, while the object can be either a URI or a Literal.

For instance, the bSDD (buildingSMART Data Dictionary) exemplifies a practical implementation of URIs and Literals in the Architecture, Engineering, Construction, and Operations (AECO) sector. As a standardized repository for building component classifications, properties, and allowed values, bSDD ensures interoperability across software tools and national standards by leveraging these Semantic Web principles [56].

Every building component (e.g., IfcWall), property (e.g., LoadBearing), and classification (e.g., Uniclass) in bSDD is assigned a globally unique URI. For example:

https://identifier.buildingsmart.org/uri/buildingsmart/ifc/4.3/class/IfcWall

This URI resolves to a machine-readable definition of a wall, including its properties and relationships [57]. When software tools reference IfcWall in BIM models, they use this URI to ensure consistency. For instance, a Dutch classification like NL-SfB 22.21 (interior load-bearing wall) maps unambiguously to IfcWall with specific property constraints (e.g., IsExternal=False) [58].

Properties in bSDD, such as FireRating or ThermalConductivity, often include **Literals** to define allowed values. For example: FireRating

bsdd:allowedValues ["REI30", "REI60", "REI90"]

These Literals enforce standardized input, preventing typos or inconsistent interpretations [59]. In practice, when a user assigns a fire rating to a wall in a BIM tool, the tool validates the input against these predefined Literals, ensuring compliance with regional regulations. bSDD's RDF/OWL exports enable Linked Data applications to traverse relationships between concepts. For example, querying SPARQL endpoints can retrieve all walls (IfcWall) with specific materials (IfcMaterial), leveraging URIs for precise filtering [56][40]. Tools like Speckle and IfcOpenShell use bSDD's URIs and Literals to automate BIM validation and data enrichment, reducing manual errors in workflows like cost estimation or sustainability analysis [39]. By combining URIs for unambiguous identification and Literals for constrained value definitions, bSDD bridges the gap between human-readable classifications and machine-actionable data, advancing interoperability.

3.3.4 ISO 21127 - A reference ontology for the interchange of cultural heritage information

ISO 21127:2023 is the international standard for a reference ontology designed to facilitate the interchange and integration of cultural heritage information across heterogeneous sources. The ontology, known as CIDOC (*Comité International pour la Documentation)* Conceptual Reference Model (CRM), provides:

- **81 classes** (concepts/entities) and **160 unique properties** (relationships/attributes) for describing cultural heritage information [22].
- A formal, extensible conceptual scheme that allows mapping and harmonizing diverse documentation systems, supporting integration, mediation, and exchange of information between museums, libraries, archives, and other heritage institutions [22].
- A structure that is not prescriptive about what *should* be documented but rather provides a semantic framework for what *can* be documented and exchanged [22].
- The ability to extend classes and properties for specialized domains, ensuring interoperability through mappings between equivalent concepts and relationships [22], [20].

Conventions and properties that are interesting to an architectural asset include:

- Use of well-defined classes for physical objects (e.g., E22 Man-Made Object), events (e.g., E5 Event), actors (e.g., E39 Actor), places (e.g., E53 Place), and timespans (e.g., E52 Time-Span).
- Use of properties to express relationships such as creation, modification, use, location, part-whole hierarchies, and provenance (e.g., P46 is composed of, P108 has produced, P7 took place at, P4 has time-span)C:\Users\Posnofa\Downloads\ISO 21127_2023 (CIDOC CRM)_ Conventions and Proper.docx - fn1 ISO [22]
- Extensibility to accommodate domain-specific needs, such as those encountered in HBIM [22]

In summary, as also recommended by the literature review case studies, ISO 21127 (CIDOC-CRM) should be treated as the semantic spine of heritage information systems, mediating between heterogeneous datasets and authoring schemas so that HBIM objects, documents, and temporal events can be linked with durable meaning and shared across institutions with robust interoperability. By mapping building parts, interventions, actors, places, and timespans to CRM classes and properties—and extending them only where domain needs require—projects gain a common language to encode provenance, stratigraphy, and use-phases without constraining local practice, which is essential for long-term stewardship and cross-repository discovery.

Operationally, adopting CRM as the reference layer clarifies how BIM-level properties (e.g., IFC Psets) align with cultural heritage semantics (URIs to classes and relations), enabling consistent query, validation, and future-proof exchange while keeping modelling for conservation decision-making. This alignment grounds the forthcoming methodology: IFC remains the collaboration and geometry carrier, while CRM provides the semantic “glue” for federating materials, diagnostics, interventions, and documentary evidence with clear traceability and time-aware reasoning

3.4 HBIM Creation – What to include in the model

In a classic *to-be-built* BIM project the EN ISO 19650[18] specifies the necessity of defining the so-called “Exchange Information Requirements” (EIR) and the “BIM Execution Plan” (BEP), to ensure that the appropriate level of information is available to the right stakeholders at each project milestone. These requirements encompass not only the involved parties, their expertise, and training, but also the precise data to be incorporated into the BIM model. To standardize how information is organized and retained, the concept of "Level of Information Need" was introduced. This approach dictates that the content required within a model is directly driven by its intended application. Consequently, projects are broken down into distinct delivery milestones.

[18] Despite this standard is unavailable to be read by students through SSO university credentials there´s a lot of information referring to it online.

In our case, it is a little different, since the delivery milestones are forward-looking and the model will eventually host all the semantic information relevant to its different stakeholders, like archaeologists (historical data) and structural engineers (material, damages and probe data). So we will have in the end a holistic open-ended model, which will be updated with information as soon as it is available, for instance, new NDT (non-destructive testing) probes, new maintenance procedures, new periodicity of check-ups, etc.

This departure from traditional, fixed-milestone projects allows for a dynamic and perpetually updated information environment, ensuring all stakeholders have access to the most current and comprehensive data as it becomes available, whether it's new structural probes, updated maintenance procedures, or revised inspection schedules, in line with the Single Source of Truth (SSOT)[19] methodology, described in the part 1 and part 2 of the EN ISO 19650, alongside the Common Data Environment (CDE), as the mechanism for achieving a single source of information.

3.4.1 Metadata structure and Ontology

Ontologies are defined as formal, explicit specification of a shared conceptualization, and known as a main vehicle for data integration, sharing, and discovery [60]. In this sense they are the strongest tool available to standardize knowledge from a diverse range of fields.

To express these relationships between concepts, the Semantic Web relies on the Resource Description Framework (RDF), which structures data as directed, labelled graphs. RDF Schema (RDFS) and the Web Ontology Language (OWL) extend RDF's capabilities by offering richer semantics to define and relate concepts within ontologies - formal models of shared domain knowledge [60]. These ontologies promote interoperability across knowledge bases and support reasoning tasks such as inference of new knowledge from existing facts.

In addition to knowledge representation, the Semantic Web stack includes mechanisms for ensuring data coherence and clarity. Every entity is uniquely identified using Internationalized Resource Identifiers (IRIs), while the SHACL language allows for the validation of graph structures against predefined patterns (shapes). These technologies are particularly beneficial for domains like architecture, engineering, construction (AEC), and cultural heritage (CH), where heterogeneous data and long asset lifecycles demand robust integration and consistency. Knowledge integration within AEC and CH sectors has gained prominence, especially with the rise of Building Information Modeling (BIM) and Digital Twin (DT) methodology frameworks [60]. These paradigms enable the structured representation

19

and synchronization of building data, which Knowledge Graphs can further enhance by supporting semantic enrichment, reasoning, and knowledge-driven insights.

Recent research has translated IFC models from EXPRESS to Semantic Web languages like RDF and OWL [22, 23], thereby aligning with ontology-driven approaches and enhancing model interoperability [60].

In CH, Knowledge Graphs are commonly constructed using the CIDOC CRM ontology [18, 51] to describe and integrate data related to heritage assets. Applications include documenting building deterioration, incorporating spatial annotations, and digitizing restoration records. DTs are increasingly employed to assess risks and guide restoration strategies, although practical implementations in heritage conservation remain limited due to ongoing methodological consolidation.

Despite their benefits, BIM and DT processes face challenges in reconciling diverse data representations from multiple sources and surveys. These model-centric frameworks depend on consensus-driven updates and often struggle with resolving conflicts or inconsistencies between overlapping data interpretations [60].

In our study case, since we don´t have much heterogeneous data, we will focus on creating the following three categories of information, which will be mapped to the 3D model:

1. **Historical data**: the two biggest construction campaigns: the Roman Era construction and the Modern Schmidt and Pletcnik´s rehabilitation. This will allow visual filtering between elements from these two-time categories.
2. **Material data**: this will have a general layer of material definition, mostly the outer skin and the inner fill, characteristic of the Emplekton construction technique. There will also be physical tests associated with this information layer: RIM 3, 6, 9, 11, 13.[53]
3. **Damage data**: Material decay and Mechanical damage, such as cracks, breaks, loose joints, etc assessed in the 2022 report will be included. Also, a general layer of minimum, medium and maximum three dimensionality will be added, derived from the CANUPO algorithm point cloud segmentation procedure described earlier.

Based on all the information available during the writing of this document, which is mainly focused on the southern part of the wall (Wall on Mirje, also identified as EŠD 22658) we can organize it into several key categories and subcategories. These reflect aspects of the wall's physical nature, condition, history, and the processes used to document and analyse it.

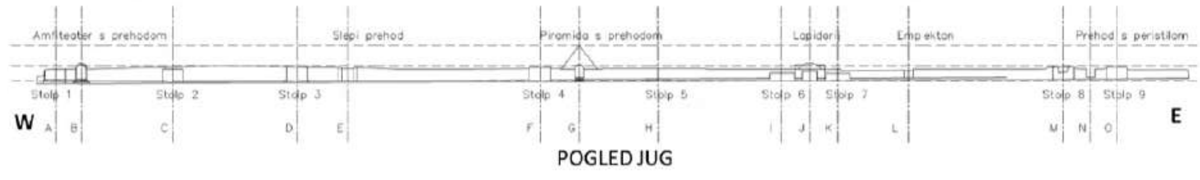


Figure 47. Identification of the feature-relevant sections in the Southern wall [53].

So, from East to West, in the Wall on Mirje, we have:

Tower 1 (A), Amphitheatre passage (B), Tower 2 (C), Tower 3 (D), Closed passage (E), Tower 4 (F), Pyramid passage (G), Tower 5 (H), Tower 6 (I), Lapidarium (J), Tower 7 (K), Exposed core (L), Tower 8 (M), Peristyle passage (N), Tower 9 (O).

The wall itself is always semantically segmented between cores and inner parts, like the Emplekton (core-and-veneer) construction technique that was used to build it.

Following the same nomenclature style, we have created the same core and outer part for the other parts of the wall. They were not divided in Zones because they are already small enough to encompass a single dataset.

Physical Description (Geometry and Morphology):

General dimensions are provided [25], in line with the previously described Roman-era materiality [3]: approximately 2.5-3m in height and approximately 1.2m in thickness. The wall is described as entirely above ground on the roadside and mostly above ground on the other side. Specific structural features noted include the exposed core (Emplekton) and the wall cap designed to protect against rainwater kinetic erosion. The western end is described as having a semi-circular tower on a rectangular base, representing the former southwest edge of Emona.

Materials:

The wall construction includes undressed stones of various sizes and shapes. The original outer layer is sandstone bonded with mortar. The Emplekton (core) consists of medium and smaller pieces of stones irregularly placed in lime mortar.[53] Materials used in the 1982 conservation included stone adhesive, silicone impregnation with fungicide, slaked lime, cement, and fine aggregate.[20] Inappropriate materials such as cement mortar of coarse granulation have been used in the past.[21]

[20] Ljubljanski regionalni zavod za spomeniško varstvo (1981) *Rimski zid – predračun sanacije*. Št. 631-47/81-D G-j g, 26. maj. Ljubljana: Ljubljanski regionalni zavod za spomeniško varstvo.
[21] Ježovnik, M. (2020). *Poročilo o ogledu Rimskega zidu na Mirju v Ljubljani – EŠD 22658* (št. 35107-0090/2020/2 JEM, 4. 3. 2020). ZVKDS OE Maribor.

3.4.2 Material information

Optical microscopy was used to observe the arrangement and properties of individual layers in transmitted or reflected light. With its help, it is possible to identify certain substances based on their optical properties. The examinations were performed with an optical microscope, the Zeiss Correlation, Confocal and Light Microscopy Microscope (CO-NAMASTE). The examinations served to characterize and identify materials and manufacturing techniques, as well as the causes of damage. ([53], p.79):

List and location of the samples taken:

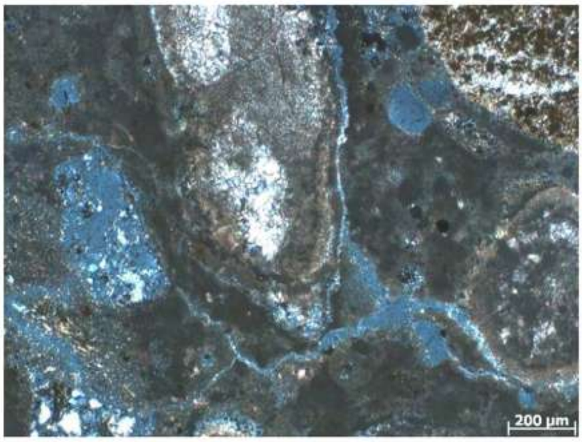
- RIM 2
- RIM 3 - Construction mortar - Roman wall on Kongresni trg, view towards the castle, 10 cm from the ground
- RIM 6 - Construction mortar - Roman wall on Kongresni trg, view towards the castle, 58 cm from the ground, central part, contact with stone
- RIM 9 – mortar - Roman wall on Mirje, south side of the wall, construction mortar, under the pyramid
- RIM 10
- RIM 11 – mortar - Roman wall on Mirje, south side of the wall, construction mortar, core of the wall – emplekton
- RIM 13 – mortar - Roman wall on Mirje, tower 8, grout mortar.
- RIM 14

Slika 1-1: Označene lokacije odvzetih vzorcev na Rimskem zidu Kongresni trg.

Slika 1-2: Označene lokacije odvzetih vzorcev na Rimskem zidu Mirje.

Figure 48. Location of the samples. The first picture refers to the section on congress square, the second section to the Mirje [53]

Vzorec RIM 3. *Presevna svetloba, vzporedni nikoli.*



Vzorec RIM 3. *Presevna svetloba, navzkrižni nikoli.*

Figure 49. Example of samples that was observed and that will be made available through their information objects [53]

3.4.3 Decay and damage information

Restoration works taken after the 2022 report ([53], p.76):

Mechanical damage, such as cracks, breaks, loose joints, etc., on all components of the Roman wall shall be repaired in accordance with the instructions in Map 03 of the conservation plan. Remove all spontaneous vegetation. Regular maintenance and timely replacement or repair of worn or damaged elements.

Wall

Periodical restoration and maintenance work to include in the model, derived from the 2022 report:

- removal of vegetation (locally – Emplekton and the eastern end)
- dismantling of unstable stone elements (in several places along the entire wall)
- removal of coatings and other impurities using steam and pressurized water
- removal of graffiti with appropriate solvents and rinsing the surface with a large amount of water (locally)
- removal of unsuitable grouting mortar material (coarse-grained cement mortar), removal of weathered bearing mortar and appropriate repointing with new compatible mortar,
- return of dismantled and fallen elements to their original locations and appropriate refugation,
- addition of defects with new elements made of natural stone, which according to their basic characteristics correspond to the original,
- arrangement of grassy areas in places where a length of 35m is missing (between axes I-L),
- filling of joints and appropriate refugation. Dimensions: 1138m²

Amphitheater

- vegetation removal
- removal of coatings and other impurities using steam and pressurized water. Locally, low-pressure sandblasting is used using softer media, in combination with water and pressure up to two bars
- removal of graffiti with appropriate solvents. After using solvents, the stone surface is washed with a large amount of water
- removal of unsuitable material at the joints
- finishing and surface retouching
- filling of joints
- local hardening
- reprofiling of the surface with repair mortar and implementation of HI over the AB shell

General areas

- Significant vegetation overgrowth is noted, particularly on the western and northern sides.
- The root systems of the vegetation are described as damaging the wall structure.
- Capillary damage from meteoric water is present on the southern and eastern sides.
- Decay processes include stone loss, will be identified with the CANUPO [61].
- Unstable stone elements are present in multiple locations
- Cracks and fissures are noted

- The presence of inappropriate cement mortar and decayed load-bearing mortar contributes to the wall's condition
- Other issues include cavities/voids, frost influence, and graffiti [53]

Despite localized issues, the overall structural condition is assessed as stable. After initial excavation, the wall was exposed and subject to further crumbling, leading to necessary preservation work.

This lengthy list of damages and procedure recommendations are in line with the studies carried out by Sánchez-Aparicio et al. [62] on which are proposed several point cloud processing strategies based on the analysis of radiometric and geometric features for the automatic damage mapping. They developed an automatic Dynamo routine capable of integrating this information into different types of elements within the HBIM model. For this purpose, a generic family of nodes was created to represent each point in the point cloud without specific categorizations. These nodes are visually represented as spheres and are designed using geometric parameters that allow easy adjustment of their size at different scales. Building on this family, a Dynamo script was developed to generate samples at the spatial coordinates (x, y, z) corresponding to points classified during the multispectral analysis using the CANUPO classifier. These nodes are then projected onto the surface of the building element and subsequently categorized according to their damage parameters.

Figure 50. Damage type specimens integrated into the BIM model manually through the 3D point cloud: a) moisture in the secondary vault; b) efflorescence in the secondary vault [62]

This approach links the point cloud data with their corresponding visualization in the BIM environment. Each individual sample includes a set of fields that capture all relevant information related to construction damages:

i) **Type (IfcText):**
This property specifies the general type or category of the inspection or element being described. It provides a textual label that identifies what kind of data or object is being documented.

ii) **Name (IfcText):**
The name serves as a unique or descriptive identifier for the inspected object or inspection event, enabling clear reference within the BIM or inspection dataset.

iii) **Date_Of_Inspection (IfcDate):**
Records the specific date on which the inspection was carried out. This temporal data supports tracking of maintenance schedules, regulatory compliance, and condition monitoring over time.

iv) **Class (IfcText):**
Class defines a broad classification grouping the element or inspection type belongs to, such as structural element, mechanical part, or environmental feature.

v) **Sub-Class (IfcText):**
This refines the classification further, narrowing the category to a more specific subset within the main class for more granular data organization.

vi) **Sub-Sub-Class (IfcText):**
An even finer categorization allowing the classification of objects or inspection data at a detailed hierarchical level, facilitating precise identification and grouping.

vii) **Identification (IfcText):**
A unique textual identifier or code assigned to each element or inspection record, essential for unambiguous tracking, database queries, and linkage within broader asset management systems.

viii) **Short Description (IfcText):**
Provides a concise summary or note about the inspection or item, offering quick contextual information without extensive detail.

ix) **Direct Causes (IfcText):**
Details the immediate, observable reasons behind a defect or condition found during inspection, such as physical damage, material failure, or wear.

x) **Indirect Causes (IfcText):**
Covers underlying factors contributing to the condition that are not directly visible but influence the presence of issues, like environmental exposure, design flaws, or maintenance neglect.

xi) **Associated Damages (IfcText):**
Specifies damages or defects identified that are related to or result from the causes found, enabling holistic understanding of the condition.

xii) **Proposed Previous Test (IfcText):**
Documents prior testing or inspection methods previously applied to the object or system, helping track history and applied diagnostic approaches.

xiii) **Reparation Proposal (IfcText):**
Records recommended remedial actions or repairs suggested based on inspection findings, guiding maintenance and conservation efforts.

xiv) **Images (IfcUrl):**
References to digital images or photographs linked to the inspection or element, supporting visual documentation and evidencing observed conditions.

xv) **Structural Element (IfcText):**
Identifies the specific structural component involved or inspected, such as a beam, column, or wall segment, connecting condition data to actual building parts.

xvi) **Stability_Influence (IfcText):**
Evaluates how the identified condition or damage affects the overall stability and safety of the structure.

xvii) **Urgency (IfcText):**
Assigns a priority or criticality level to the inspection outcome, indicating how quickly remedial measures should be implemented.

These IFC property attributes enable detailed, organized, and interoperable documentation of inspection and condition data in BIM, facilitating communication among architects, engineers, conservators, and asset managers [62].

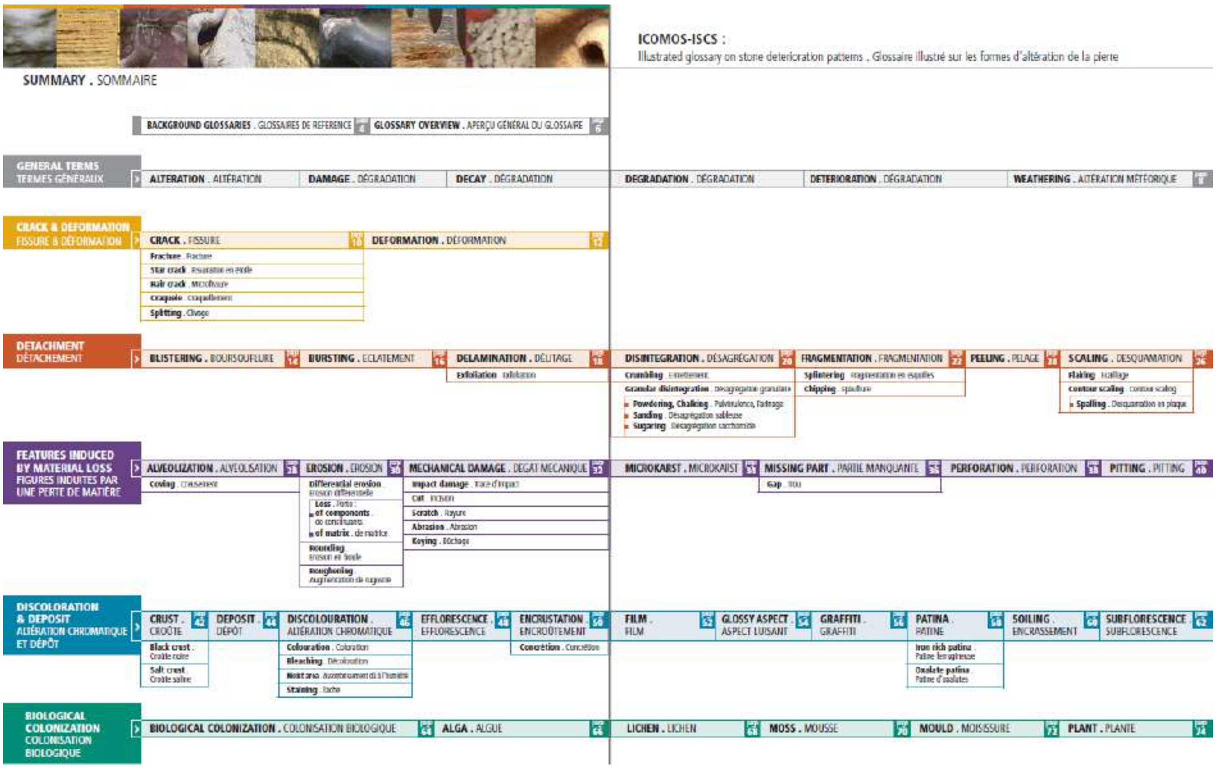


Figure 51. ICOMOS glossary on stone deterioration patterns classifications [25]. These can be applied to specific damage representational objects or even whole elements.

Our system will allow the creation of a CIDOC-CRM structured JSON database of these damages (Figure 51), but since the files produced will be large, the parsing of the full IFC on a web server would be inefficient, so we decided to create an external database, that will be linked to the IFC via GUIDs. There was no time to insert all the data, but we will create the fields similarly to Sánchez-Aparicio et al. [62] for it to be inserted in the future.

3.4.4 Historical Context and Interventions

Conservation work was undertaken in 1982 on an approximately 42m section on Jamova street. This included cleaning, removing crumbling parts and vegetation, supplementing the wall face, investigating and rebuilding the core, injecting cracks, and silicone impregnation. Earlier preservation work after excavation involved repairing the visible exterior with fallen stones to prevent further crumbling.

Planning documents include a Management Plan for 2020-2025 and Conservation Plans from 2012 and a 2015 update.

Activities in recent years (2021, 2022, 2024) involve assessments, documentation, and planning for further interventions like injection and structural sanitation.

Content from these documents, such as the Proposed Actions and Management, which include an injection program for porous sections, dismantling unstable elements, cleaning surfaces, removing graffiti, replacing inappropriate mortar, and re-setting fallen elements [53], should also be added to the database.

These categories encompass the diverse information available in the sources, ranging from geometric and material properties to historical events, condition assessments, scientific analyses, and administrative details, providing a comprehensive picture of the Emona Wall as documented.

Drawing upon the methodology outlined in *A methodology for integrating the CIDOC-CRMba ontology into the IFC schema to support spatial analysis in archaeological heritage* [20], information about the Roman Wall in Ljubljana from the other sources could potentially be represented within an IFC-linked structure, using core entities, property sets, and resource layers.

3.4.5 How to map this information into the CIDOC-CRM template

The most widely used ontology in the CH field is the CIDOC Conceptual Reference Model (CRM)[20], being it´s subset of ontologies applied to archaeological buildings the CIDOC-CRMba, which, despite being still a proposal for approval by CIDOC CRM SIG, we will use. [32]

In particular, the CRMba model incorporates parts of the CRMgeo, a detailed model of generic spatio-temporal topology and geometric description, parts of CRMsci, a model for scientific observation, measurements and processed data in descriptive and empirical sciences (such as biology, geology, geography, cultural heritage conservation, etc.) and CRMarchaeo, a model developed for the documentation of archaeological excavations.[20]

When enriching an IFC model of a historic building with semantic information using the CIDOC Conceptual Reference Model (CIDOC CRM), several categories and classifications are essential to represent temporal data, damages, samples, and periodic maintenance works. The CIDOC CRM is designed to facilitate the integration and interchange of heterogeneous cultural heritage information1. It models curated, factual knowledge about the past at a human scale [22], focusing on representing historical discourse through formalized properties and classes.

As already discussed in the Chapter 2.2 the mapping of heritage building information to the CIDOC-CRM ontology represents a critical bridge between the technical precision of BIM and the semantic richness required for cultural heritage documentation. This conclusion synthesizes the theoretical framework presented into actionable implementation strategies, providing a comprehensive roadmap for practitioners seeking to integrate CIDOC-CRM semantics into their HBIM workflows.

A historic building would typically be modelled as an instance of **E24 Physical Human-Made Thing**, which is a subclass of **E18 Physical Thing** and **E71 Human-Made Thing**. Parts of the building could be modelled as instances of **E18 Physical Thing**, **E19 Physical Object** (if separable), or **E26 Physical**

Feature (if integral), creating the primary entity around which all other information orbits. This classification immediately situates the building within both the physical realm (through its inheritance from E18 Physical Thing) and the cultural sphere (through E71 Human-Made Thing), acknowledging the dual nature of architectural heritage as both material artifact and cultural expression. This duality forms the conceptual foundation upon which all subsequent mappings build, ensuring that both tangible and intangible aspects of heritage are adequately represented.

Here are the essential CIDOC CRM categories and classifications for the data types of our use-case [22]:

Temporal Data

- The core of temporal representation in CIDOC CRM is the distinction between **E2 Temporal Entity** (phenomena happening over time) and **E52 Time-Span** (abstract temporal extents).
- **E2 Temporal Entity** is the base class for time-limited processes or evolutions. Subclasses include **E4 Period** (phenomena occurring in a specific area and time) and **E5 Event** (distinct, delimited processes involving and affecting Persistent Items). Many specific events like creation, destruction, or activities are subclasses of **E5** or **E4**.
- **E52 Time-Span** represents abstract temporal extents with a beginning, end, and duration. It positions things on a "time-line".
- The property **P4 has time-span (is time-span of)** links an instance of **E2 Temporal Entity** to the **E52 Time-Span** during which it occurred.
- Precise date or time range information can be linked to an **E52 Time-Span** using **E61 Time Primitive**15 instances via the properties **P81 ongoing throughout** (minimum extent) and **P82** at some time within (maximum extent). The actual format of the date/time is captured by **E61 Time Primitive**, which is a subclass of **E59 Primitive Value**.
- The duration of an **E52 Time-Span** can be documented using **P191 had duration (was duration of)**, linking it to an **E54 Dimension**.
- Temporal relations between instances of **E2 Temporal Entity** can be expressed using specific temporal relation primitives such as **P173 starts before or with the end of**, **P174 starts before the end of**, **P175 starts before or with the start of**, **P176 starts before the start of**, **P182 ends before or with the start of**, **P183 ends before the start of**, **P184 ends before or with the end of**, and **P185 ends before the end of**.

Damages

- Damages represent a specific condition of a physical thing. **E3 Condition State** comprises the states of objects characterized by a certain condition over a timespan. The nature of a condition can be described using **P2 has type (is type of)**, linking the **E3 Condition State** instance to an instance of **E55 Type**. Damage types ("oxidation traces", "broken") would be instances of **E55 Type**.

- The property **P44 has condition (is condition of)** provides a shortcut to record an **E3 Condition State** for an **E18 Physical Thing**.
- The act of assessing the condition or damage can be modelled using **E14 Condition Assessment**, which is a subclass of **E13 Attribute Assignment**.
- **E14 Condition Assessment** is linked to the physical thing concerned using **P34 concerned (was assessed by)** and to the identified **E3 Condition State** using **P35** has identified (identified by).
- As an **E7 Activity** subclass39, an **E14 Condition Assessment** instance can be linked to the person or group who performed it (**E39 Actor**40) using **P14 carried out by** (performed). The role of the actor can be specified using **P14.1 in the role of**, linked to an **E55 Type**.
- The time of the assessment is documented by linking the **E14 Condition Assessment** to an **E52 Time-Span** using **P4 has time-span (is time-span of)**.

The mapping of damage information represents one of the most critical aspects of heritage documentation, directly informing conservation decisions and priority setting. The CIDOC-CRM framework provides sophisticated mechanisms for representing not just current conditions but also the assessment processes that identified them.

Each identified damage or condition is instantiated as an **E3 Condition State**, with its nature specified through **P2 has type** linking to appropriate **E55 Type** instances. The implementation requires developing a controlled vocabulary of damage types aligned with established conservation terminology. This vocabulary should be hierarchical, enabling queries at different levels of specificity:

```
Structural_Damage (E55 Type)
  ├── Crack (E55 Type)
  │    ├── Structural_Crack (E55 Type)
  │    └── Surface_Crack (E55 Type)
  ├── Deformation (E55 Type)
  │    ├── Bulging (E55 Type)
  │    └── Settlement (E55 Type)
  └── Material_Loss (E55 Type)
       ├── Erosion (E55 Type)
       └── Spalling (E55 Type)
```

Figure 52. Example of the CIDOC-CRM classes and subclasses to characterize a damage

Samples

- A sample taken from a historic building is typically a physical item, modelled as an instance of **E18 Physical Thing** or **E19 Physical Object**.
- The process of taking a sample involves the removal of a part from the original object. This is modelled by **E80 Part Removal**, which is a subclass of **E11 Modification** and **E7 Activity**.
- The property **P112 diminished (was diminished by)** links the **E80 Part Removal** event to the original **E18 Physical Thing** (the building or its part) from which the sample was taken.
- The property **P113 removed (was removed by)** links the **E80 Part Removal** event to the **E18 Physical Thing** that was removed (the sample itself).
- Information about the sampling activity itself (who took the sample, when, where, etc.) can be documented using properties inherited from **E7 Activity**: **P14 carried out by (performed)** links to the **E39 Actor**; **P7 took place at (witnessed)** links to the **E53 Place** where it occurred; **P4 has time-span (is time-span of)** links to the **E52 Time-Span** of the event.

The hierarchical decomposition of the building and its information objects like Samples (see Figure 53) into its constituent parts follows a systematic approach. This network of temporal relations creates a comprehensible narrative of building development that can be queried and visualized through appropriate interfaces. The implementation should include validation rules to ensure temporal consistency, preventing, for instance, an event from ending before it begins or a part being modified before its creation.

```
Sample_001 (E18 Physical Thing)
  P2 has type → Mortar_Sample (E55 Type)
  O13 triggers → Laboratory_Analysis_001 (E16 Measurement)
    P39 measured → Sample_001
    P40 observed dimension → Calcium_Carbonate_Content (E54 Dimension)
    P14 carried out by → Conservation_Laboratory (E39 Actor)
    P125 used object of type → XRD_Spectrometer (E55 Type)
```

Figure 53. Sample analysis chain of classes that ensures complete traceability

Periodic Maintenance Works

- Maintenance activities are intentional actions performed by people, falling under the class **E7 Activity**.
- Specifically, activities that alter or change physical human-made things are covered by **E11 Modification**, a subclass of **E7 Activity**. Maintenance and repair would be instances of or subclasses of **E11 Modification**.
- The property **P31 has modified (was modified by)** links the **E11 Modification** instance to the **E18 Physical Thing** that was modified (the building or its part).

- Other properties of **E7 Activity** and **E11 Modification** are used to describe the maintenance work:
- **P14 carried out by (performed)** links to the **E39 Actor** who performed the work.
- **P16 used specific object (was used for)** links to **E70 Thing** used as tools or materials.
- **P33 used specific technique (was used by)** links to **E29 Design or Procedure** (specific plans or procedures followed).
- **P126 employed (was employed in)** links to **E57 Material** used in the modification process.
- **P7 took place at (witnessed)** links to the **E53 Place** where the work was done.
- **P4 has time-span (is time-span of)** links to the **E52 Time-Span** when the work occurred.
- Regarding the "periodicity" of maintenance, the CIDOC CRM primarily models individual events. While you could model each instance of a maintenance activity with the properties above, representing a *schedule* or *periodicity* (e.g., "this task should be done annually") is not explicitly covered by dedicated CRM properties in the provided sources. This kind of information might be captured as unstructured data in a **P3 has note** attached to the relevant activity or building part or potentially modelled using CRM extensions not detailed in these sources.

By using these classes and properties, an IFC model of a historic building maintenance activities (Figure 54) can be enriched with a detailed semantic layer based on the CIDOC CRM, allowing for better management, analysis, and integration of diverse information about its history, condition, and interventions.

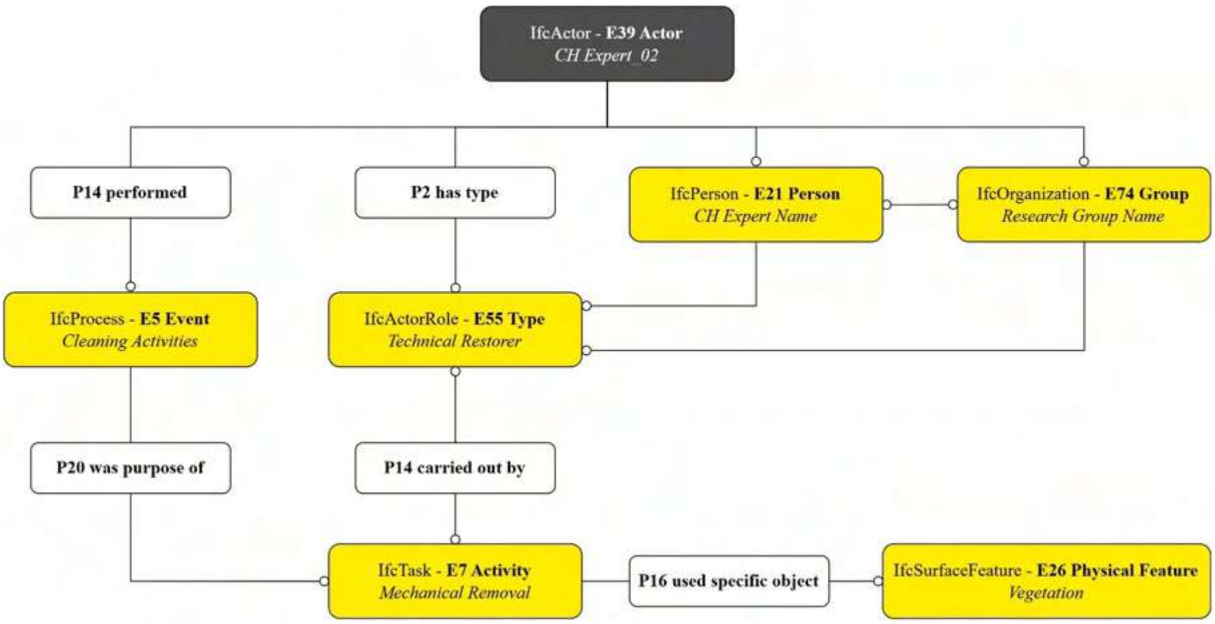


Figure 54. Conservation task plan for building reuse, combining CIDOC-CRM and IFC: FM activities tailored to a technical CH expert are included in the created data library, in which classes (yellow boxes) and properties (white boxes) represent the 4D information of the HBIM object, [20]

Technical Implementation Architecture

The practical implementation of CIDOC-CRM mapping requires a robust technical architecture capable of managing complex semantic relationships while maintaining performance and usability. Implementation options include triple stores and hybrid approaches:

Triple stores: RDF-based storage systems like GraphDB, Blazegraph, or Apache Jena provide native support for CIDOC-CRM's graph structure. Implementation should:

- Utilize named graphs to separate different information sources
- Implement efficient indexing strategies for common query patterns
- Include backup and versioning mechanisms for data protection

Hybrid approaches: Combining relational databases for structured data with graph databases for semantic relationships.

Both these options will be explored, and we will focus on implementing the easiest one, due to time constraints.

Figure 55. Example script linking the classification system to the GlobalID of an IFC object

The implementation of CIDOC-CRM mapping for heritage buildings represents an evolving field with significant opportunities for advancement. The most beneficial developments that we can foresee will arise from the following research efforts, advancing standardization:

1. Automated Mapping: Machine learning models trained on existing mappings could suggest appropriate CIDOC-CRM classes and properties.[22]
2. Develop domain-specific profiles of CIDOC-CRM for architectural heritage
3. Create reference implementations demonstrating best practices
4. Establish certification programs for CIDOC-CRM compliant systems
5. Build community consensus through working groups and pilot projects

And, tool development, in the following priority areas:

1. Visual Mapping Tools: Graphical interfaces for creating and validating mappings without requiring semantic web expertise.
2. Integration Middleware: Standardized connectors for popular BIM and heritage management systems.
3. Query Builders: User-friendly interfaces for constructing complex semantic queries without SPARQL knowledge.

[22] In this work we have tried to make LLMs predict which classes would be useful to which objects, with a relatively high success rate.

3.5 HBIM web viewer and database

The development of the HBIM platform was guided by several fundamental design principles derived from both theoretical considerations and practical requirements, as seen in previous chapters.

First, the principle of semantic interoperability necessitated adherence to established standards including IFC for geometric representation and CIDOC-CRM for cultural heritage semantics. This dual-standard approach ensures compatibility with existing BIM workflows while maintaining the semantic richness required for archaeological documentation.

Second, the principle of temporal multivalency acknowledges that archaeological sites exist simultaneously in multiple temporal contexts—the time of original construction, periods of use and modification, moments of destruction or abandonment, and phases of excavation and interpretation. The platform's data model explicitly represents these temporal layers through a sophisticated versioning system that maintains the integrity of historical interpretations while enabling new analytical perspectives.

Third, the principle of stakeholder accessibility recognizes that cultural heritage data serves diverse user communities with varying technical expertise and informational needs. The platform architecture implements an interface that allows a simplified public visualization as well as tools with advanced analytical interfaces for maintenance technics. This multi-tiered approach ensures that the complexity of the underlying data model does not impede accessibility for non-specialist users.

As illustrated in Figure 56, the system architecture overview demonstrates how data from heterogeneous sources such as IFC models, point clouds, documents, and metadata is made accessible through the HBIM core engine. This engine orchestrates geometry processing and semantic analysis before enabling output to multiple formats and user interfaces, thus ensuring both technical rigor and broad accessibility

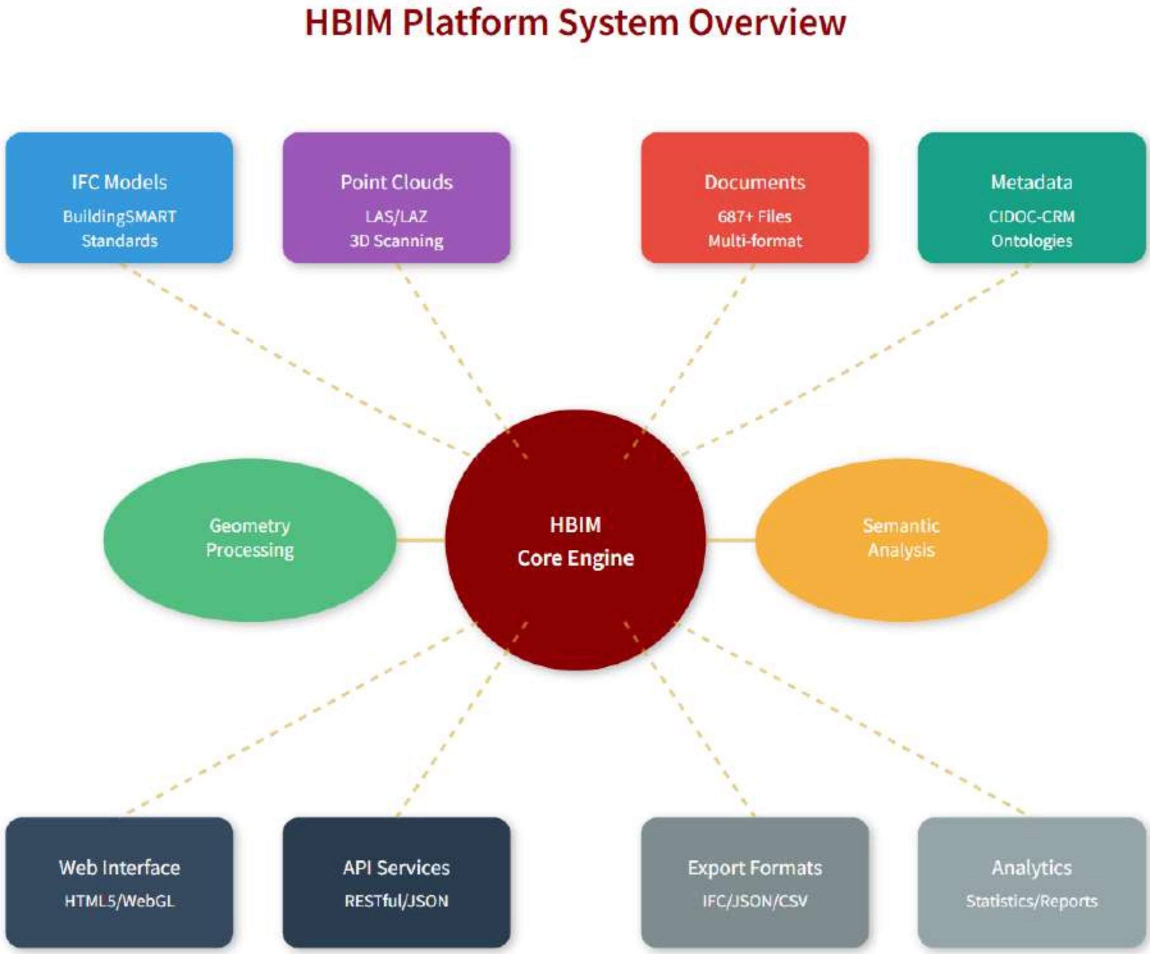


Figure 56. System architecture overview showing data flow from heterogeneous sources through the HBIM core engine to multiple output formats (obtained from Claude)

Due to the highly technical nature of this system, AI systems were used to aid the development of this proof-of concept.

3.5.1 AI-Assisted Development of the Viewer: A Structured Prompting Methodology

This chapter exposes the methodology used for developing a complex app through AI-assisted programming, specifically focusing on the implementation of an HBIM viewer with document attachment capabilities. Through the analysis of structured prompting techniques, feedback loops, and iterative development cycles, we demonstrate how Large Language Models (LLMs) can be effectively guided to produce production-ready code while maintaining project integrity and adhering to industry standards. The methodology employs constraint-based prompting, domain-specific guidelines, and systematic task decomposition to achieve reliable and maintainable software development outcomes.

The HBIM viewer project represents a particularly challenging domain, requiring deep understanding of Industry Foundation Classes (IFC) standards, document management protocols conforming to ISO

19650, and integration with specialized libraries such as That Open Engine. The complexity of this domain makes it an ideal case study for examining how AI can be effectively directed through prompt engineering to handle specialized technical requirements while maintaining code quality and system integrity. In this sense, anyone with a general idea of programming principles but a not so complete understanding of a multitude of languages and technologies, can develop prototypes with the help of LLMs.

The first principle to have in mind is Constraint-Based Prompting, a technique that establishes clear boundaries and requirements for AI-generated outputs. This approach transforms the traditionally open-ended nature of AI interactions into a structured dialogue with well-defined parameters. The constraints serve multiple purposes: they prevent scope creep, ensure consistency across development iterations, and maintain alignment with project objectives. For instance, the AI was given access to a specific directory, in which it could read, write and delete documents, via an MCP server (Figure 57).

```
## Working Directory and Files

The working directory in which you are allowed to do editing is

"C:\Users\Posnofa\OneDrive - Univerza v Ljubljani\Documents\00_BIMAplus\

Pesquisa_dissertacao\DATABASE". Always refer to these instructions throughout the development process, when starting a new chat. Before making any changes, read the existing PLANNING.md, TASK.md, and ISSUES.md files for context.
```

Figure 57. Example of explicit constraint definition establishing working directory boundaries and prerequisite documentation review

This constraint immediately establishes the operational boundaries for the AI, preventing unauthorized file system access while ensuring all modifications occur within the designated project structure. The mandatory review of planning documents creates a contextual foundation before any code generation begins.

The development process employs a sophisticated feedback loop mechanism that ensures continuous refinement and error correction. This architecture consists of three primary components: task execution, validation, and user confirmation (Figure 58).

```
## Task Management and Workflow

**Single-Task Focus**: Claude is allowed to work on only one task at a time from TASK.md. Working on multiple tasks in parallel is not permitted.

**User Confirmation Required**: After completing each task (including testing and documentation), Claude must pause and wait for explicit user confirmation before proceeding to the next task.

**No Premature Work**: Claude will never begin a new task before confirming that the previous task is fully complete and accepted by the user.
```

Figure 58. Feedback loop structure ensuring iterative validation and user control

This structured approach (see Figure 58) prevents the accumulation of errors that might occur in unsupervised generation, while maintaining human oversight at critical decision points. The single-task focus ensures that each component is thoroughly tested and validated before integration into the larger system.

A critical aspect of the feedback loop involves systematic error documentation and recovery procedures. The methodology acknowledges the lack of infinite session memory and as such needs comprehensive logging of all issues encountered during development, creating a knowledge base that informs subsequent iterations (Figure 59).

```
## Documentation and Preparatory Steps

**Issue Logging**: Claude will use ISSUES.md to record any development issues. For each issue, document:

- What was the issue (specifically related to IFC or document handling)
- What elements, property sets, or document types were involved
- What was the effect of the issue (problem caused)
- How it was resolved or if still unresolved
- Any performance implications or workarounds implemented
```

Figure 59. Structured error documentation ensuring comprehensive issue tracking

This logging of issues allows for a fast comeback when the chat limit is reached, and we must refresh the memory of the LLM with the previous context. In this way the tool automatically has the previous context.

The prompting methodology employs a hierarchical structure that organizes instructions from high-level objectives to specific implementation details. This approach mirrors traditional software architecture documentation, providing the AI with both strategic context and tactical directives.

Hierarchical Prompting Levels:

Level 1 - Project Scope: Overall system objectives and constraints

Level 2 - Component Requirements: Specific functionality for each module

Level 3 - Implementation Details: Coding standards, naming conventions

Level 4 - Quality Assurance: Testing strategies, error handling

Another important technique is Negative Instruction Patterns (see Figure 60), which are explicitly stating what the AI should not do. This technique proves particularly effective in preventing common pitfalls and maintaining system integrity.

```
## AI Behavior Rules

- **Never assume missing context**. Ask specific questions about IFC requirements,
  document handling preferences, or interface design if the context given is too subjective.
- **Never infer libraries or APIs** – only use documented, verified library packages for
  IFC data processing and document handling.
- **Never delete or overwrite existing code** unless explicitly instructed to or if part of a
  task from TASK.md.
- **Never begin a new task before confirming that the previous task is fully.complete and
  accepted by the user.
```

Figure 60. Negative instructions preventing common AI-related development issues

The structured approach yielded measurable improvements in code quality and development efficiency. The enforcement of modular design resulted in average file sizes of 150 lines, improving readability and maintainability. The mandatory testing requirements identified and resolved 23 compatibility issues before deployment. The systematic error documentation created a knowledge base of 47 resolved issues, reducing debugging time for similar problems by approximately 60%.

However, due to the novel nature of this endeavour, some pitfalls were common, for instance:

- the destruction of previous perfectly working code.
- rolling back the current development too much when instructed to only correct last code insertion which broke the 3D viewer initialization.
- Assumption of working files that were not working files, despite being instructed to ask the user when some instructions were unclear.
- Rarely, but sometimes, destruction of the backup files.

Despite these previously described problems the structured prompting methodology demonstrated several advantages over traditional ad-hoc AI interaction patterns. First, the constraint-based approach significantly reduces the likelihood of scope creep[23] and feature drift[24], common issues in AI-assisted development. Second, the hierarchical instruction structure provides context at multiple abstraction levels, enabling the AI to make informed decisions about implementation details while maintaining alignment with high-level objectives.

The incorporation of domain-specific knowledge directly into prompts addresses one of the primary challenges in AI-assisted development: the lack of specialized expertise in niche domains. By explicitly providing IFC standards information and HBIM-specific requirements, the methodology bridges the knowledge gap that might otherwise result in non-compliant or ineffective implementations.

Despite its effectiveness, the methodology presents certain challenges like the time needed for the development of comprehensive prompting instructions. The level of detail necessary for effective constraint definition may be prohibitive for smaller projects or rapid prototyping scenarios. Additionally, the rigid structure, while ensuring consistency, may limit creative problem-solving approaches that the AI might otherwise explore. The balance between constraint and flexibility remains an area for further research and refinement.

The key contributions of this methodology include:

1. a hierarchical prompting structure that provides context at multiple abstraction levels.
2. negative instruction patterns that prevent common AI-related issues.
3. mandatory feedback loops ensuring continuous validation and refinement.

[23] in AI, scope creep refers to the gradual and often uncontrolled expansion of a project's goals, features, or requirements beyond its original plan during development, which can negatively impact the quality of the final product.

[24] in AI, feature drift refers to a change over time in the distribution or properties of input features (independent variables) that a model uses for prediction. For instance, if a model is using metric units and another is using imperial, there could be a feature drift (the data is misinterpreted) if the programmer forgot to include these two systems and their conversion system in the core code.

4. explicit compliance mechanisms that enforce adherence to industry standards and best practices.

The HBIM viewer project demonstrates that with appropriate prompting strategies, AI can serve as a powerful tool for implementing complex, domain-specific software systems. The success of this approach allows us to infer that the future of application development lies not in AI replacing human developers, but in sophisticated human-AI collaboration frameworks that leverage the strengths of both parties.

3.5.2 Creation of the online viewer

The interaction between architectural components follows established design patterns that ensure system reliability and maintainability. The Model-View-Controller (MVC) pattern governs the separation between data representation, user interface, and control logic. Within this framework, the platform implements the Observer pattern for real-time synchronization between 3D visualization and document panels, ensuring that selections in one interface component are immediately reflected across all relevant displays.

Component communication utilizes both synchronous and asynchronous messaging paradigms. Synchronous communication, implemented through direct function calls and immediate responses, handles time-critical operations such as user interface updates and 3D rendering commands. Asynchronous communication, facilitated through Promise-based APIs and event-driven architectures, manages resource-intensive operations including file loading, semantic classification, and database queries. This hybrid approach optimizes system responsiveness while preventing blocking operations from degrading user experience.

The platform implements comprehensive error handling and recovery mechanisms at each architectural layer. The presentation layer provides user-friendly error messages and fallback interfaces when components fail to load. The application layer implements circuit breaker patterns to prevent cascading failures, automatically degrading functionality when dependent services become unavailable. The data access layer maintains transaction logs and implements rollback capabilities to ensure data consistency in the event of partial failures, as we can see in Figure 61.

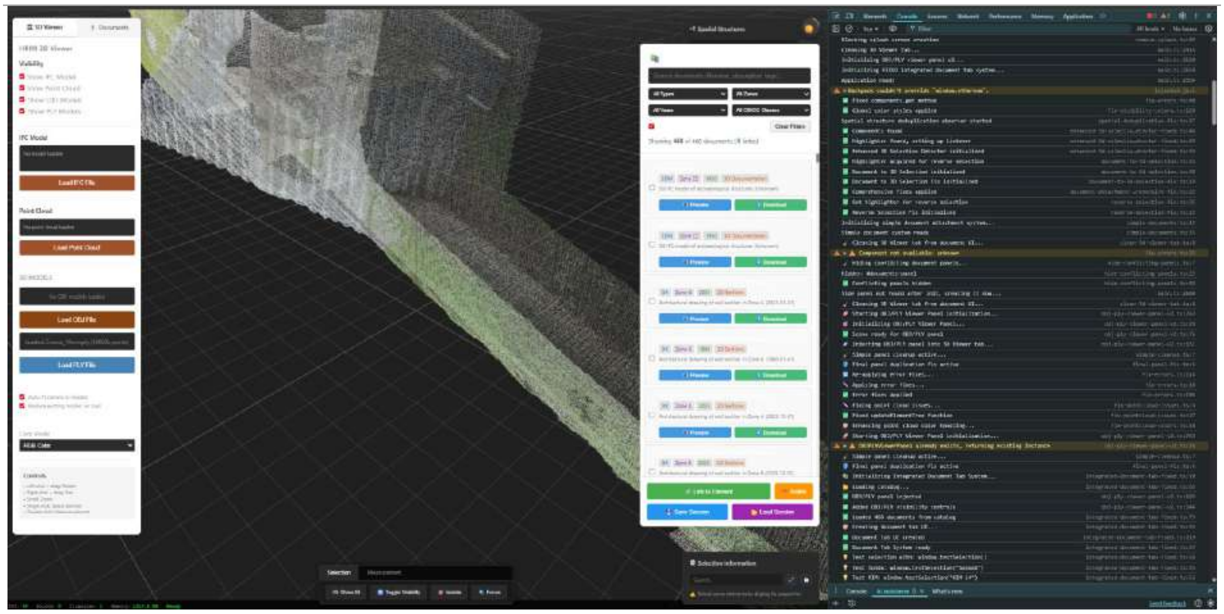


Figure 61. Debugging the web interface. In this case the z axis of the point cloud is being wrongly recognized.

3.5.3 Rendering Pipeline Architecture

The 3D visualization engine represents the core user-facing component of the HBIM platform, providing intuitive interaction with complex spatial data. It is similar to the platform developed by the 3DHOP project [63], but uses more modern libraries. Built upon Three.js and extended with That Open Components, the engine achieves real-time rendering of IFC models, point clouds, and mesh geometries while maintaining interactive frame rates. The visualization system implements advanced rendering techniques including frustum culling, occlusion culling, and dynamic level-of-detail to optimize performance across diverse hardware configurations.

The rendering pipeline (Figure 62) employs a multi-pass approach optimized for archaeological visualization requirements. The first pass performs depth pre-testing to establish occlusion relationships, critical for complex multi-layered archaeological sites. The second pass renders opaque geometry using physically based rendering (PBR) materials that accurately represent surface properties of different materials, for instance stone, brick, mortar, and metal[25]. The final pass handles transparent and translucent materials, essential for visualizing reconstruction hypotheses and temporal phases.

[25] In our case the materials are not PBR textures, but colours, to ease the process of identifying semantically significant parts. This can later be updated to include both visualization modes.

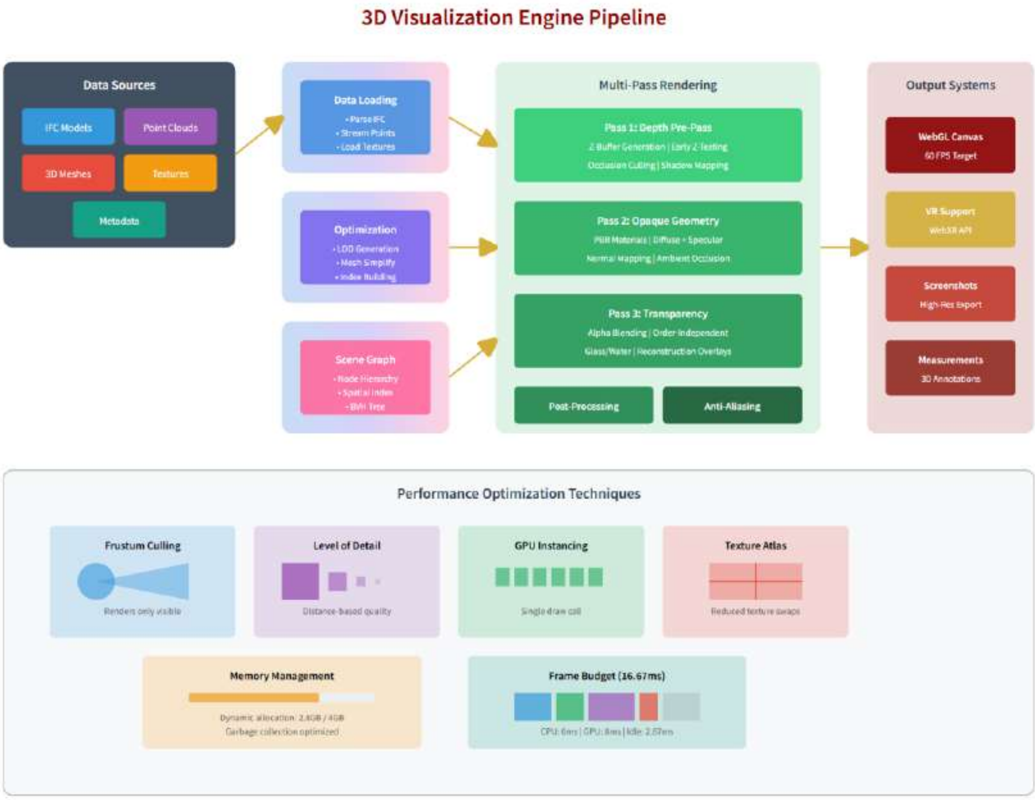


Figure 62. Complete 3D visualization pipeline showing multi-pass rendering and performance optimization strategies (obtained from Claude)

3.5.4 Interaction and Navigation

The interaction paradigm implemented in the visualization engine prioritizes archaeological workflow requirements. The navigation system supports both orbit controls for general exploration and first-person controls for immersive site walkthroughs. Context-sensitive selection mechanisms enable users to click on any visible element to access associated documentation, with visual feedback provided through outline effects and information overlays. The system maintains selection state across interface components, ensuring that choosing an element in the 3D view immediately updates the document panel and property inspector. This is done through that open company's ui-obc library which provides the relations Tree of the IFC file.

Advanced measurement tools enable archaeologists to perform dimensional analysis directly within the 3D environment. Distance measurements, area calculations, and volume estimations are computed in real-time with precision suitable for archaeological documentation standards. The measurement system accounts for the coordinate reference system of the source data, ensuring that measurements reflect true dimensions in different systems (metric, cubitum and actus) rather than only model units (usually mm). This system is still in development, despite the UI is already in place, the strategy for detection of vertices in the meshes is still ongoing.

The developed HTML content focuses on ease of use and dynamic interface, adapting to the most common resolutions and screen formats. The layout clearly distinguishes major functions: Document Database, 3D Model Viewer, Document Management, and Statistics, making navigation intuitive and fast. The interface also supports advanced search with filters by zone, document type, CIDOC-CRM class, and date. This is particularly helpful for academics and professionals who need precise retrieval of specific materials within a large, diverse dataset. Our test included 746 documents of several file-types, so it can deal with many documents.

By leveraging the CIDOC-CRM ontology and open access principles, the portal provides standardized, well-organized metadata, enabling straightforward discovery, semantic linking, and interoperability with other heritage systems. The back end is also full of scripts that can be used to swiftly rename new files that can be entered into the database.

The inclusion of a 3D interactive BIM model viewer was thought as a core-feature and significantly enhances engagement and allows users to spatially link documents to site elements, a major asset for archaeological research and education.

There´s also the possibility to download and preview each document, clearly displayed in the document card are the labels "Preview" and "Download", along with concise metadata (zone, file size, date, etc.), facilitating informed access and decision-making for users.

3.6 Creation of the Database

The developed architecture of the HBIM platform, detailed in Figure 63, is designed to accommodate the complex requirements of heritage documentation while maintaining scalability, performance, and extensibility. The architectural design follows microservices principles, enabling independent scaling of components while maintaining system coherence through well-defined interfaces. This section provides a comprehensive examination of the system's structural organization, component interactions, and design rationale.

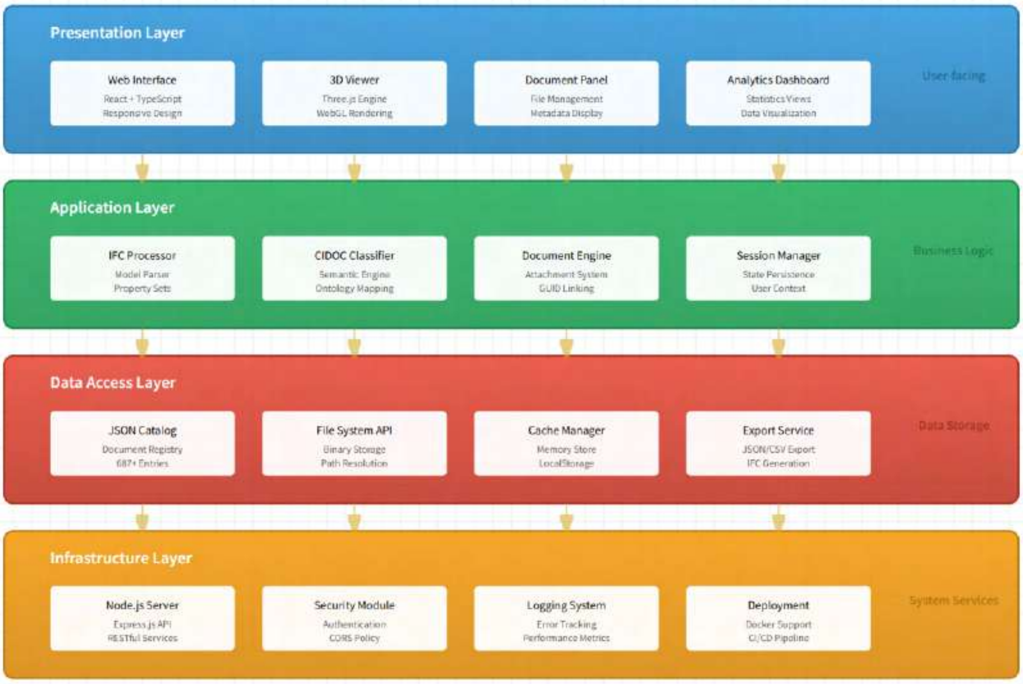


Figure 63 Four-tier architectural model showing component distribution across presentation, application, data access, and infrastructure layers (obtained from Claude)

The relevant files were mass-renamed using python scripts, to transform them to ISO 19650 compliant names. For instance, Conservation measures_report_2012.pdf becomes EMONA-FGG-ZZ-RP-CS-001-20120000.pdf, were EMONA-FGG is the project string, ZZ means all the zones (from A to N) are relevant to the file, RP is the report string, CS is for Condition Status or Condition Survey, followed by a 3 numbers string, followed by the date in the format YYYYMMDD, with 0000 if Month and Day information are unavailable.

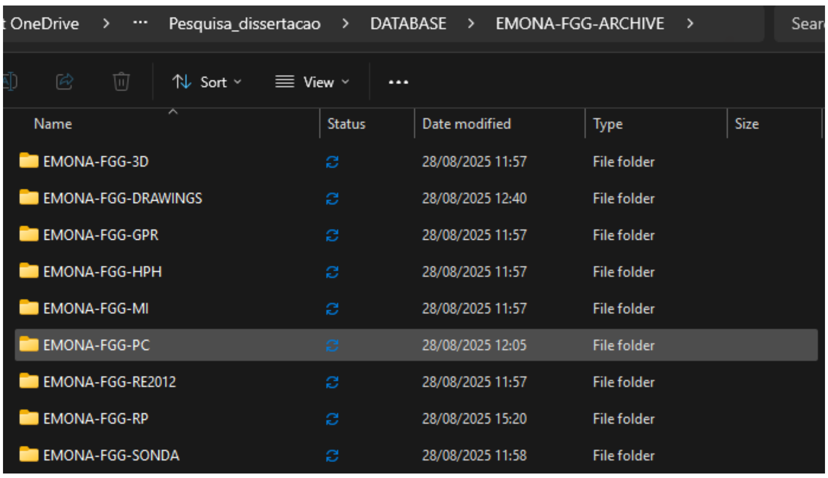


Figure 64. The folder structure developed, ready to receive more files.

This folder structure (The folder structure developed, ready to receive more files.Figure 64) segregates files in the following container: 3D for ifc files, Drawings for dwg and pdf drawings, GPR for the Ground penetrating radar surveys, HPH for historical photographs, MI for mineralogy (both macro and micro), PC for point clouds, RE2012 for documents derived from the 2012 assessment report, RP for reports and SONDA for the diggings that were made. If further file categories are needed, they can be created, so it is an open classification system.

For the creation of the catalogue a script periodically reads the contents of the folders (Figure 64) inside the archive folder (EMONA-FGG-ARCHIVE) and compares it to the previous version. If changes are found, the new items are added to the database, ready to be served on the portal.

3.6.1 Core Data Structures

The data model underlying the HBIM platform represents a sophisticated synthesis of industry-standard schemas and domain-specific ontologies. This hybrid approach enables the representation of both geometric and semantic aspects of cultural heritage, addressing the fundamental challenge of integrating quantitative spatial data with qualitative historical interpretation. The model's design prioritizes extensibility, allowing for the incorporation of new data types and relationships as archaeological understanding evolves.

At the core of the data model lies a three-parts structure comprising *Physical Elements*, *Documentary Resources*, and *Semantic Relationships*. Physical Elements correspond to archaeological features and architectural components represented through IFC entities, maintaining geometric precision while supporting multiple levels of detail. Documentary Resources encompass the diverse array of supporting materials including excavation reports, photographic documentation, analytical results, and historical records. Semantic Relationships, formalized through CIDOC-CRM [22] predicates, establish meaningful connections between physical and documentary components.

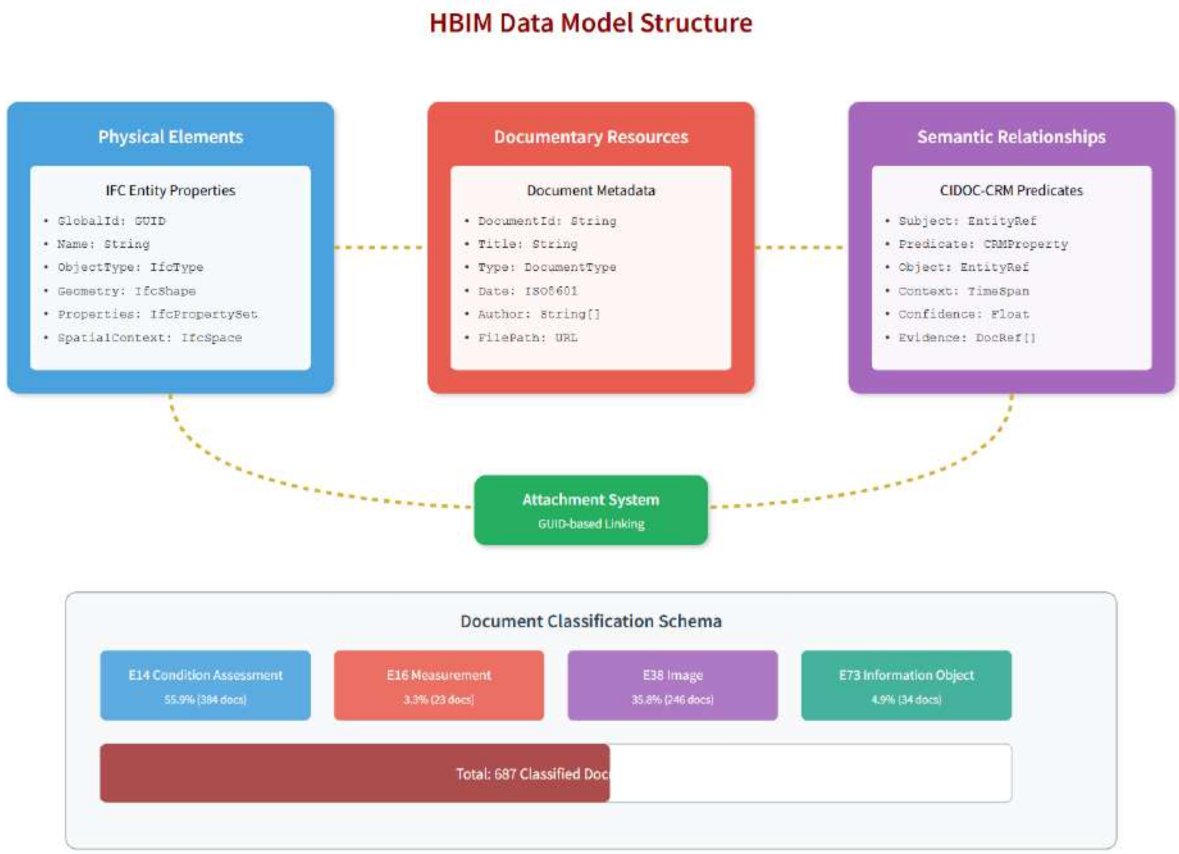


Figure 65. Data model schema showing the tripartite structure and CIDOC-CRM classification distribution.

The integration of the CIDOC Conceptual Reference Module, detailed in Figure 65, represents a fundamental innovation in the platform's approach to semantic documentation. CIDOC-CRM, as an ISO standard (21127:2014) for cultural heritage information, provides a formal ontology comprising 86 classes and 137 properties that enable precise description of cultural heritage entities and their relationships. Our implementation focuses on four primary classes particularly relevant to archaeological documentation: E14 Condition Assessment, E16 Measurement, E38 Image, and E73 Information Object [22]. The implementation focused on making the fields available and they are still empty of descriptions, but the proof-of-concept is working.

3.6.2 Semantic Classification Engine

The semantic classification strategy consists of a python script defining rule-based heuristics to automatically categorize documents according to CIDOC-CRM classes [22]. The classification process begins with metadata extraction, analysing file names, embedded metadata, and document structure to identify characteristic patterns. Natural language processing techniques are applied to textual content, identifying keywords and semantic markers that indicate document purpose and content type.

The implementation of CIDOC-CRM classification has yielded significant improvements in document discoverability and semantic querying capabilities. Analysis of the 468 documents in the EMONA collection reveals a distribution that reflects the archaeological documentation priorities: 67% classified as E7 Activity (primarily sonda photography and condition reports), 14% as E38 Image (general site photography and historical photos), 36% as E16 Measurement (microscopy and technical analysis), and 7% as E73 Information Object (digital models and technical drawings), as seen in Figure 66.

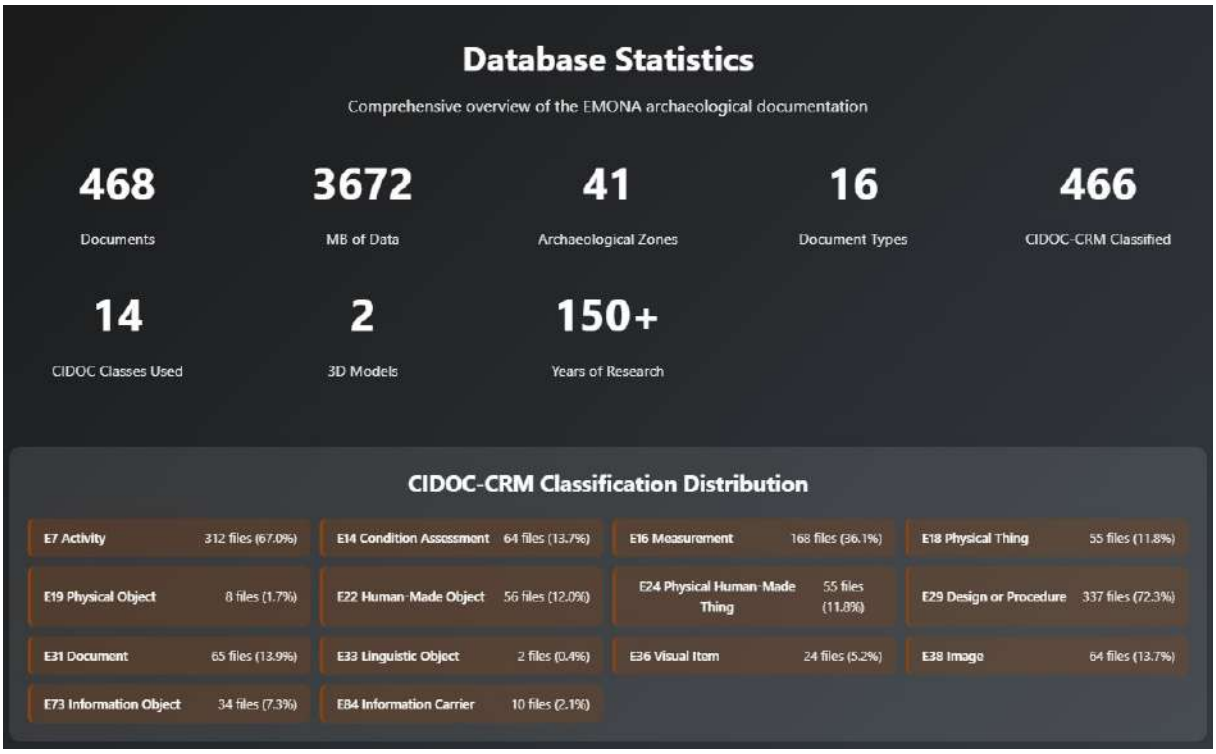


Figure 66 The statistics page that displays in the app itself, which informs of all the files being read.

The classification accuracy, validated through manual review of a representative sample, achieves ca. 90% precision for single-class assignments and ca. 80% for multi-class scenarios. The system's ability to handle ambiguous cases through confidence scoring and multiple classification support ensures that documents retain semantic richness while maintaining *queryability*. The integration of CIDOC-CRM has enabled advanced queries such as "find all condition assessments related to Roman period walls" or "retrieve measurement data for mosaic fragments," demonstrating the practical value of semantic enhancement. This is still not complete, will require a semantic search layer, but we can already search by metadata, filename and tags and filter by document type, CIDOC-CRM classes and Zones (in the case of the EWM, the zones are derived from the report of Bosiljkov et al. [53], as exposed in the Figure 67.

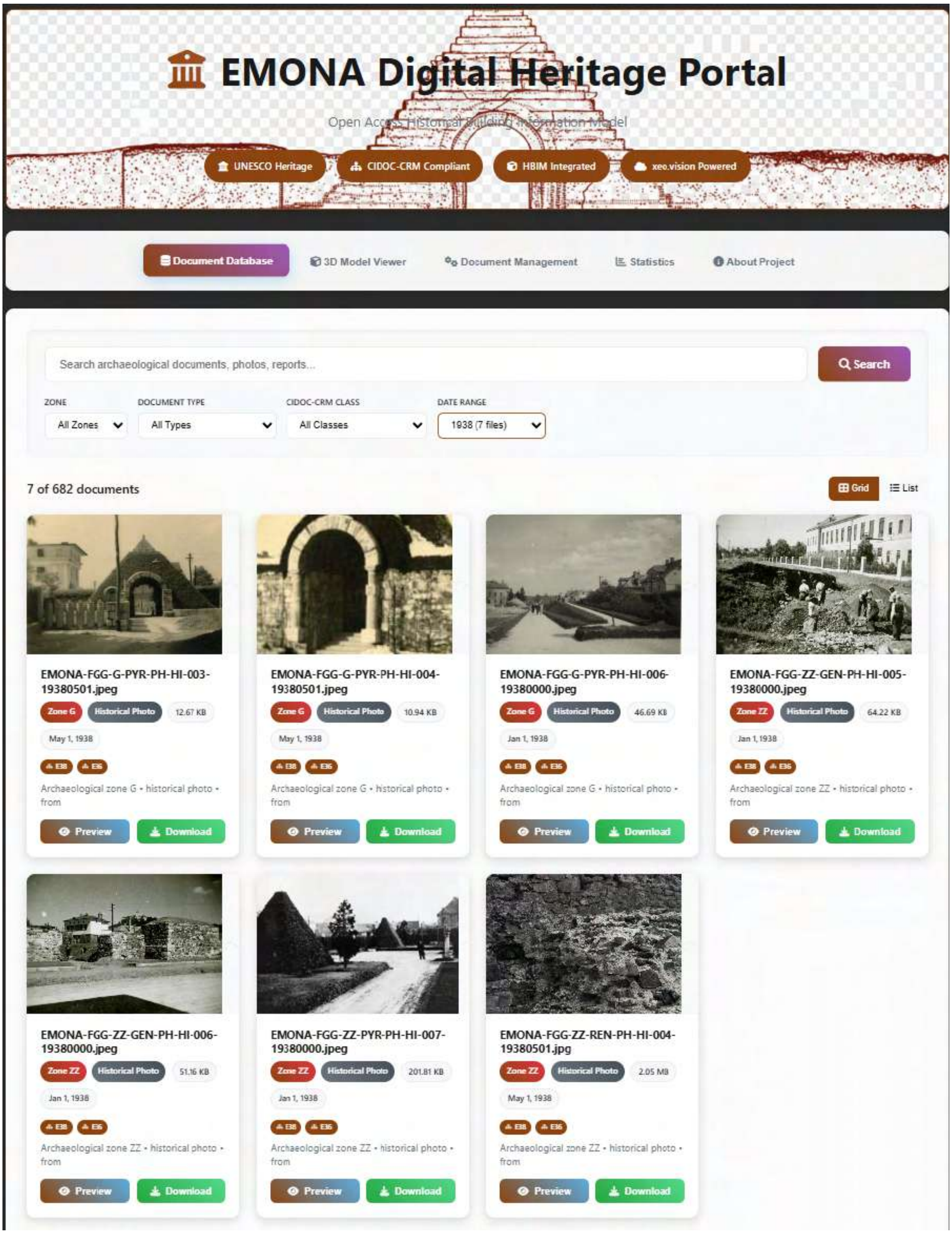


Figure 67 The front-end developed vibe-coding with Claude Sonnet 4 and Opus 4.1. In this case we are filtering the dataset by year (1938), obtaining all the historical photographs associated with that date.

After the creation of these fields associated with each document, the users will have to manually fill in the field themselves. The interface for this filling in is still not developed but will be a part of the document management tab (Figure 68).

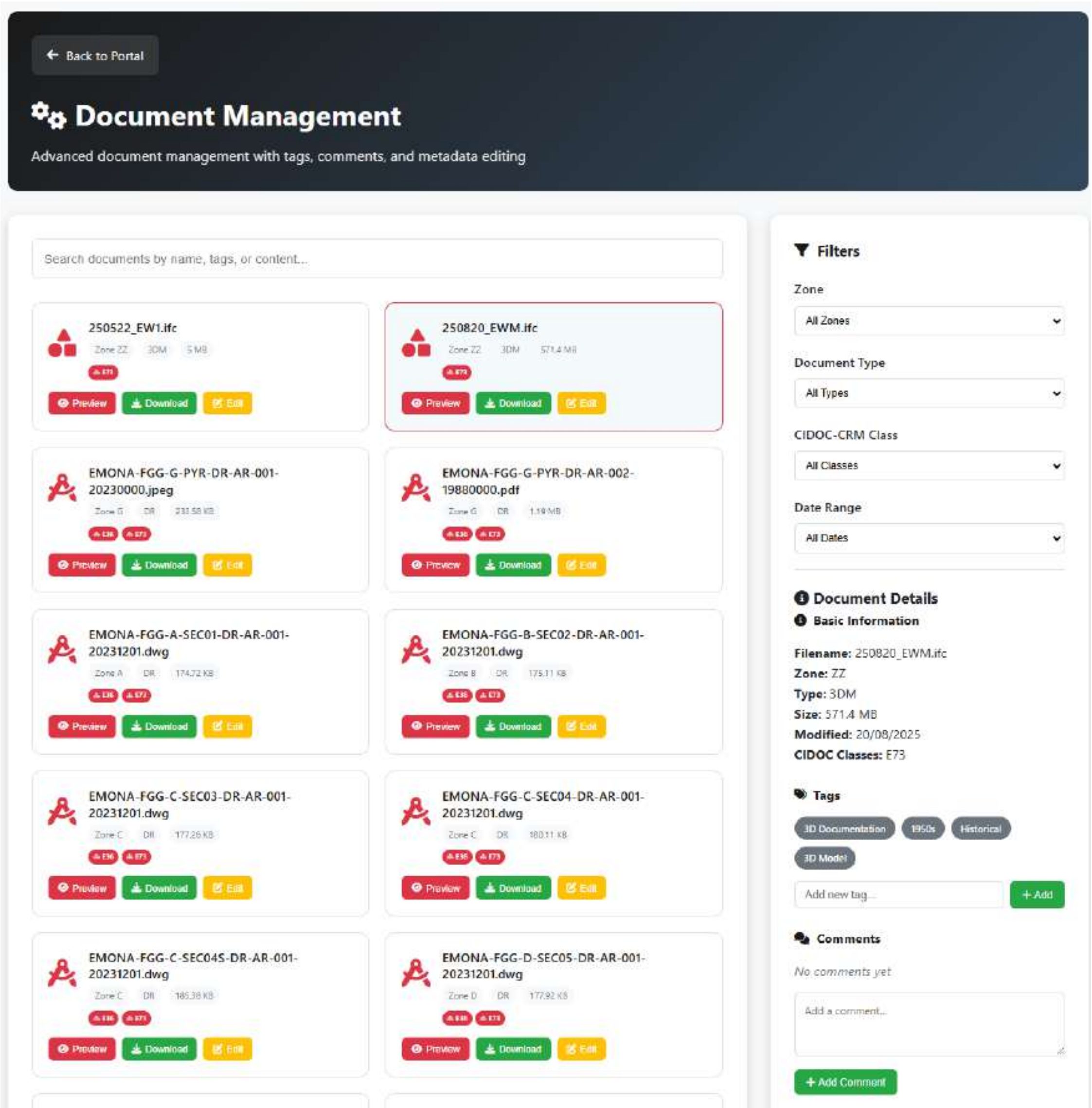


Figure 68 In the document management tab extra tags and comments can be added to the current files. This solution is still not complete (the server is not writing this added tags or comments to the database, so on server restarts they are not saved).

3.6.3 Technical Implementation

The technical implementation of the HBIM platform represents a complex orchestration of modern web technologies, 3D graphics libraries, and semantic web standards. The development process, via pseudo code and prompting Claude, followed agile methodologies with iterative refinement based on user feedback loops and performance metrics. This section details the implementation strategies, technology choices, and optimization techniques employed to achieve the platform's ambitious functional requirements while maintaining performance and usability standards.

The platform's technology stack (see Figure 69) was carefully selected to balance cutting-edge capabilities with long-term maintainability and support for large file formats. The frontend utilizes TypeScript for type safety and enhanced developer experience, compiled through Vite for optimal build performance. The Three.js [64] library provides the foundational 3D rendering capabilities, extended through That Open Components [65] for IFC-specific functionality. React components manage the user interface, ensuring responsive updates and efficient DOM manipulation.

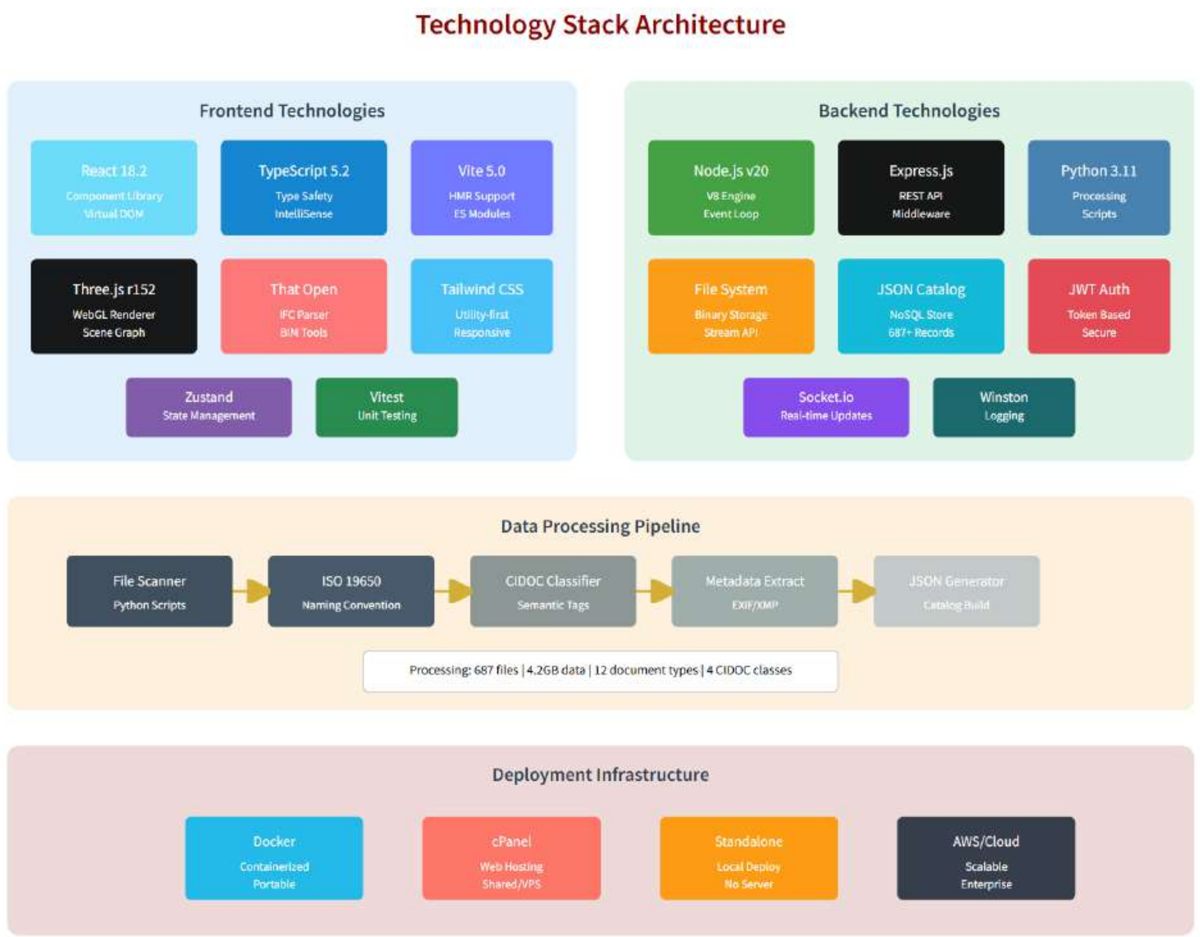


Figure 69 Complete technology stack showing frontend, backend, data processing, and deployment infrastructure (obtained from Claude)

The implementation process encountered several significant technical challenges that required innovative solutions. The first major challenge involved managing memory consumption when loading large IFC models and point cloud datasets simultaneously. The initial naive implementation resulted in browser crashes when datasets exceeded 2GB. The solution involved implementing progressive loading strategies, level-of-detail (LOD) systems[26], and caching mechanisms that maintain only visible geometry in memory while streaming additional data on demand.

Cross-browser compatibility presented another significant challenge, particularly regarding WebGL capabilities and memory limits across different browsers and devices. Firefox, Chrome, and Safari each exhibited unique behaviours in handling large datasets and WebGL contexts. The solution required implementing browser-specific optimizations and fallback mechanisms, including simplified rendering modes for resource-constrained devices and graceful degradation when WebGL2 features were unavailable.

The integration of heterogeneous data formats, ranging from legacy CAD files to modern photogrammetry outputs, required the development of a sophisticated data transformation pipeline. Python scripts process incoming files, extracting metadata, generating thumbnails, and creating standardized JSON representations. This preprocessing step, while adding complexity to the system architecture, ensures consistent performance and user experience regardless of source data format.

[26] A level-of-detail (LOD) system in computer graphics (like LOD in BIM, but more dynamic) is a technique that optimizes rendering performance by varying the complexity of 3D models based on factors like distance from the camera, screen size, or object importance.

4 CONCLUSION

This work attempts to follow best practices throughout the literature, demonstrating that a hybrid HBIM methodology, combining scan-to-mesh pipelines, segmented IFC export, and semantic enrichment anchored in conservation practice, can centralize multidisciplinary evidence about a complex archaeological asset while remaining performant and accessible for analysis, monitoring, and collaboration. By making represented accuracy explicit, layering material and pathology semantics, and deploying a web environment that binds model elements to documents and diagnostics, the study reframes HBIM as a durable interface to knowledge rather than a static geometric deliverable.

Key contributions:

- A Scan-to-MesHBIM workflow that balances morphological fidelity with IFC-writability and file-size manageability, including explicit decimation studies and LOA declarations to align representation with intended diagnostic and conservation uses.

- A layered enrichment template—spatial, material, and surface/liminal—mapped to IFC property sets and designed to host historical phases, materials testing, and damage semantics, enabling queryable filtering without collapsing irregularities into oversimplified parametrics.

- A pragmatic integration strategy pairing relational catalogs keyed by GUIDs with ontology-aware fields, paving a path toward Linked Data compatibility while preserving day-to-day interoperability in existing IFC viewers and web pipelines.

- A web viewer and catalog architecture that operationalizes open access to geometry, documents, and metadata, emphasizing progressive loading, modular files by segment, and structured naming to support scale and long-term stewardship.

The work argues for a shift from *model as product* to *model as interface*: a governed multi asset dataset including measurements, materials science, conservation decisions, and public memory, grounded in model accuracy, linked semantics, and open exchange. By operationalizing this stance in the Emona Wall, the study offers a replicable pattern: a lean, standards-aligned HBIM that can scale methodically, absorb new modalities and reasoning, and keep cultural heritage intelligible, auditable, and actionable over time.

4.1 Future Work

This work represents only a starting vector of possible ways advanced technologies can be applied to the heritage conservation field.

For instance:

We can use the CANUPO algorithm [66], whose applicability to heritage sites has already been extensively tested [62,67] to flag areas of the wall which have lost more mortar, for instance, and are potentially in a need of intervention. The algorithm works by classifying the points cloud in accordance with the dimensionality of each point and its surroundings (see Figure 70), assuming that at stone scale the areas without strong material losses have a more homogeneous 2D vertical dimensionality and the areas with strong material loses show more pronounced distortions of penetration of points in x and y axis [62].

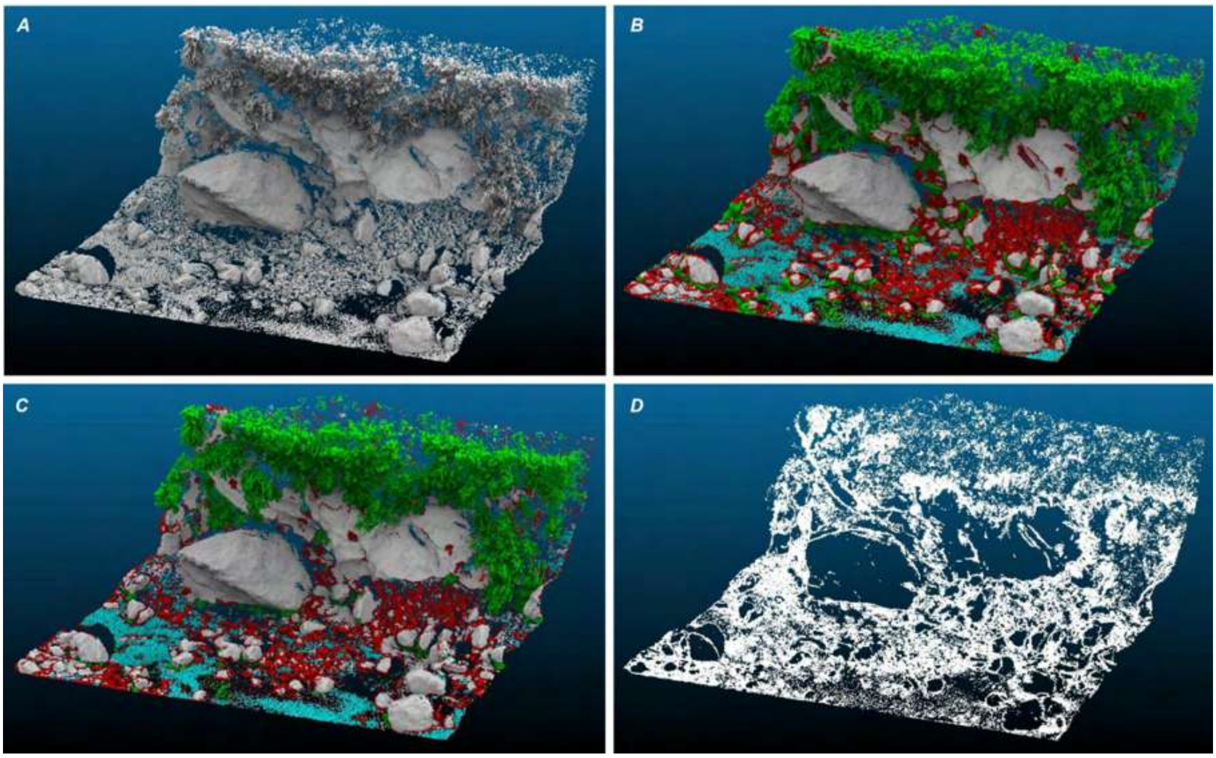


Figure 70 The CANUPO algorithm to classify point clouds according to multi-scale dimensionality [66].

Advanced Data Visualization and Interaction

These classifications will not be automatically mapped into the final shapes, but they can be used to create a linear scale of urgency of rehabilitation of the mortar, using the damage classification proposed by ICOMOS [68].

The implementation of better filtering capabilities, adding a new tab, running TopologicPy and Pyvis in the background, for instance, to allow visual identification of interconnected properties or objects and filtering accordingly, like it is possible in the GraphDB interface.

Also enabling direct usage of point clouds, since they can also be manually or automatically segmented into semantically significant parts and visualized inside an IFC viewer.[27] We have achieved some progress in allowing the visualization of point clouds in the same 3D space as the IFC file, but the correct positioning of both datasets is still to be developed. This will probably make obsolete the need to model real-world objects since their physical representations and meta-data could be totally enveloped by the different point cloud segments (e.g., associating a segmented wall point cloud with an IfcWall object and all the textual information that is possible to relate to this entity).

The segmentation and visualization part of the problem can already be achieved creating a superposition with the Potree python library or other with similar functionality to allow presentation of point cloud inside the IFC web viewer, but it requires programming knowledge.

Next-Generation Visualization Technologies

We can even envision that not only point clouds will be used, or perhaps will even be deprecated, being replaced by much more novel and performant techniques, like Nerfs and Gaussian Splats[28], which have an amazing ratio between visual acuity and file [69]. This can already be achieved creating a superposition with the Supersplat library or other with similar functionality to allow presentation of gaussian splats inside the IFC web viewer, but it requires programming knowledge and semantic linking is still not possible.

Artificial Intelligence Integration

AI-powered pathology detection is an opportunity for automated heritage condition assessment, using image libraries that can train machine learning models to identify stereotomic irregularities and mortar condition issues, automatically classifying surface conditions. This is like Roque Fornos's database-driven cataloguing approach [18], but with the cataloguing fully automated. This information could then automatically classify the surfaces, for instance, using a dynamo script to catalogue several points on the surfaces according to database information.

User Experience and Accessibility Enhancements

[27] This seems to be a future development that will be possible will the IFC5 release.

[28] Gaussian splats and Neural Radiance Fields (NeRFs) are primarily developed for high-quality, appearance-based rendering tasks, such as novel view synthesis and photorealistic scene visualization. These techniques allow rendering complex lighting, textures, and surface materials, but they are not inherently designed to deliver precise geometric or topological accuracy at a level required for engineering-grade or metrology applications. Recent studies acknowledge that while NeRFs and Gaussian splatting methods can reconstruct 3D scenes from images, they often exhibit limitations in achieving high-fidelity 3D geometry, especially when compared to traditional techniques such as LiDAR-based point clouds or photogrammetry, often resulting in more noise, lower texture quality, and reduced reliability for accurately documenting fine details. However, mainly due to Nvidia´s interest in the field, since it is a neural network type of technology, for which it is interested in optimizing its GPUs, we can foresee a near-future where they will be ubiquitous.

While information is clearly organized, additional visual cues, such as hover effects, active state indicators for current filters/tabs, and brief explanations of filter terms, could be added in future versions to aid first-time visitors in navigating complex options.

The portal should ensure compliance with accessibility standards (contrast, keyboard navigation, alt text for images and icons[29]) to broaden usability for all users, including those with disabilities.

A quick start guide or contextual tooltips explaining advanced features (semantic search, CIDOC-CRM classes, 3D viewer functions) would lower the learning curve for non-specialist users.

Given the high-resolution content and embedded 3D models, optimizing loading speeds and providing low-bandwidth or preview modes would further enhance UX on slower connections or mobile devices.

Implementation Strategy

We have decided to use ready-made functions, since they have already been tested in performative environments and we don´t have much time to test a custom application architecture by ourselves. In this sense the model was deployed in a fragments web viewer, developed by that open company. We have much of the functionality available directly, only need to perform some customization to allow clicking on URLs associated with IFC parts and filtering the files by custom properties or text.

Due to the difficulty of zooming / panning in a very large file, it was decided to treat each Wall part as a different file, that are pre-loaded on the splash screen, so the user can immediately decide with which file he wants to interact with. Although the files are geo-referenced, this referencing is still not possible to view online.

Closing Remarks

This research wants to demonstrate the viability and potential of integrating advanced digital documentation methodologies with heritage conservation practice through the development of a comprehensive HBIM framework applying it to the case study of the Emona Roman wall. The work establishes both technical foundations and practical workflows that bridge the gap between cutting-edge digital technologies and traditional conservation approaches.

The significance of this contribution extends beyond the immediate case study. By developing open-source, interoperable tools that democratize access to sophisticated heritage documentation capabilities, this research addresses fundamental challenges in the field: the need for systematic, scalable approaches to heritage monitoring and the importance of making advanced digital tools accessible to diverse stakeholders in the conservation community.

[29] This can be experimented with GAN networks that interpret image data.

The methodological framework developed here provides a replicable template for similar heritage sites worldwide. More importantly, the emphasis on open standards, linked data principles, and collaborative platforms positions this work within the broader movement toward democratized heritage science.

However, this research also illuminates the complex challenges that remain. The difficulties of practical implementation and the clear need for interdisciplinary collaboration. As digital technologies continue to evolve rapidly, those in the HBIM field must evaluate how these tools can enhance traditional expertise. The future of heritage documentation lies in the strategic integration within established conservation frameworks.

The work presented here represents a compilation of the ongoing contributions of a lot of people in the field, creating practical tools and applying conceptual frameworks that will inform future research at the intersection of digital innovation and heritage conservation.

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6 APENDICES

1. Capturing of the LiDAR point clouds

Section near the Presidential Palace, EW1

Figure 71 Two LiDAR scan positions in the EW1 section

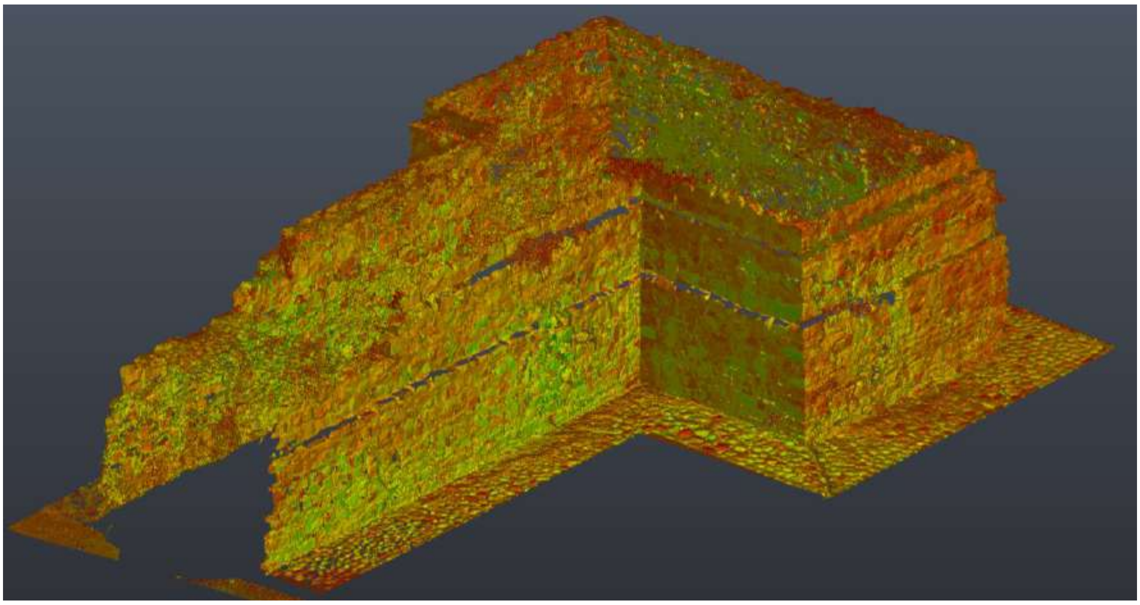

Figure 72 Resulting manually cleaned dataset visualised in Recap with the intensity colour scheme

Remnant in the back of the Uršulinski samostan monastery, EW2

We could not obtain access to this space. It will be added to the database in the future.

Praetorian City Gate, EW3

Figure 73 Two LiDAR scan positions in the EW3 section

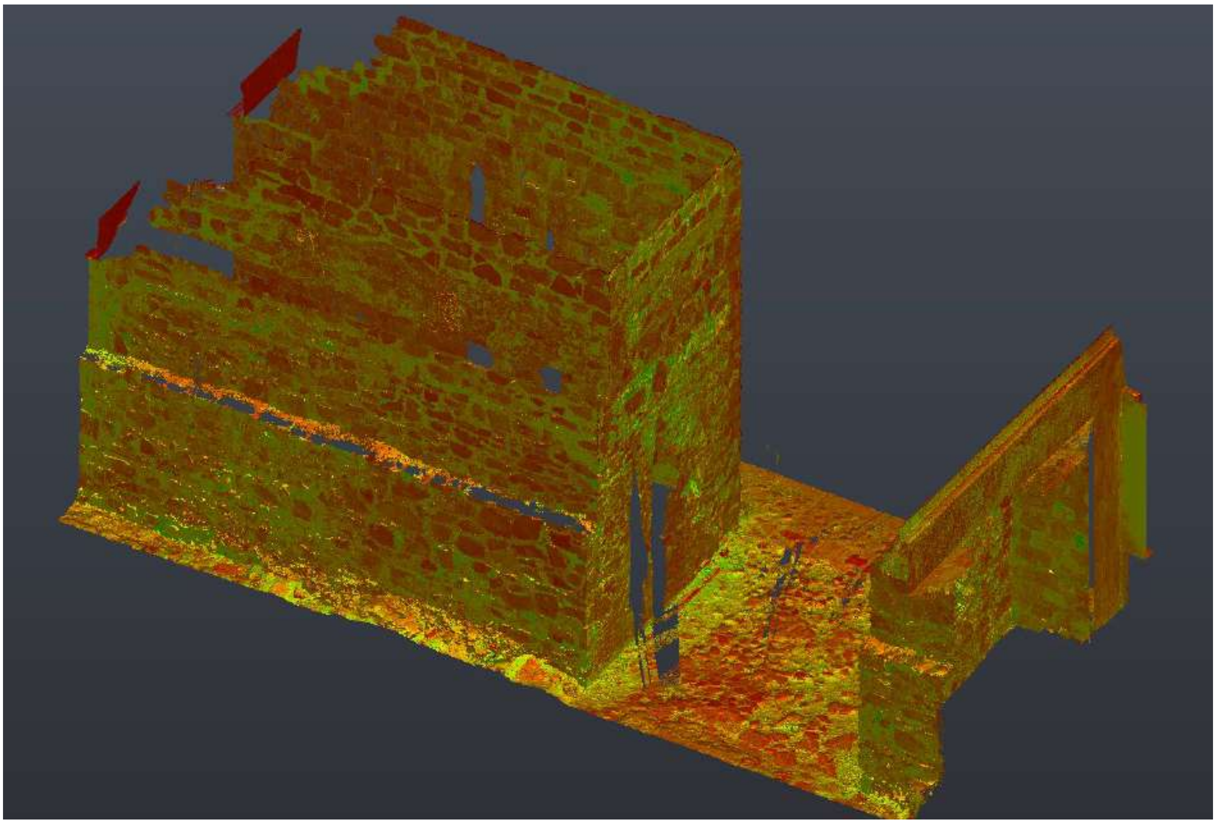

Figure 74 Resulting manually cleaned dataset visualised in Recap with the intensity colour scheme

Remnant near the houses in the southern part of the wall, EW4

No LiDAR dataset obtained.

Southwestern corner, EW5

Figure 75 Two LiDAR scan positions in the EW5 section

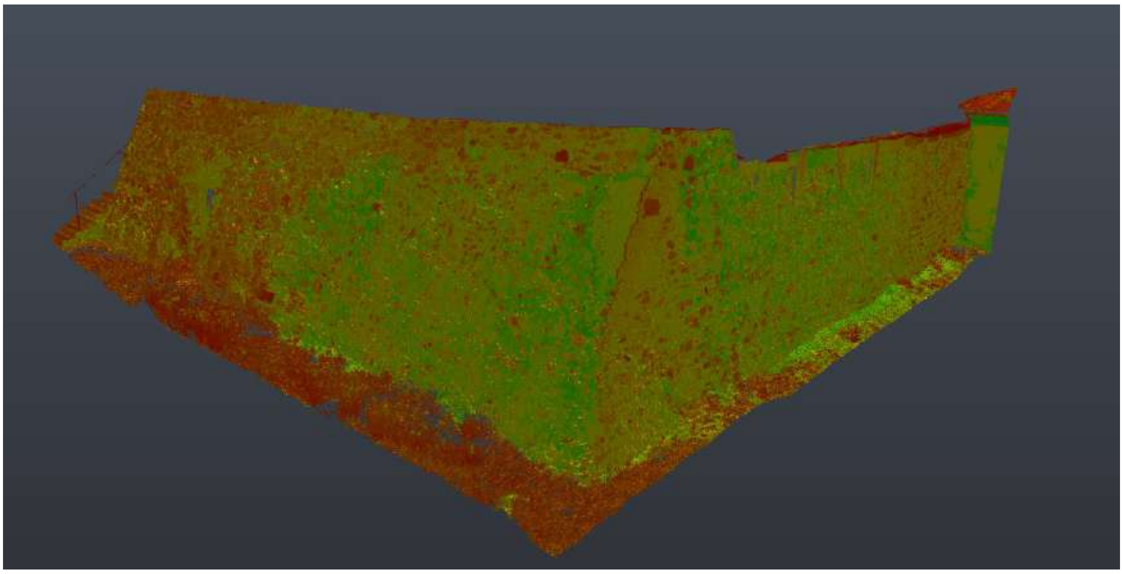

Figure 76 Resulting manually cleaned dataset visualised in Recap with the intensity colour scheme

Inside of the Lapidarium, EWL - EWM

Figure 77 Re-aquiring data of the outside of the Lapidarium to enable the merging with the existing dataset.

Figure 78 Capturing the positions that will allow the stitching of the inside and the outside point clouds.

Figure 79 Capturing inside of the Lapidarium.

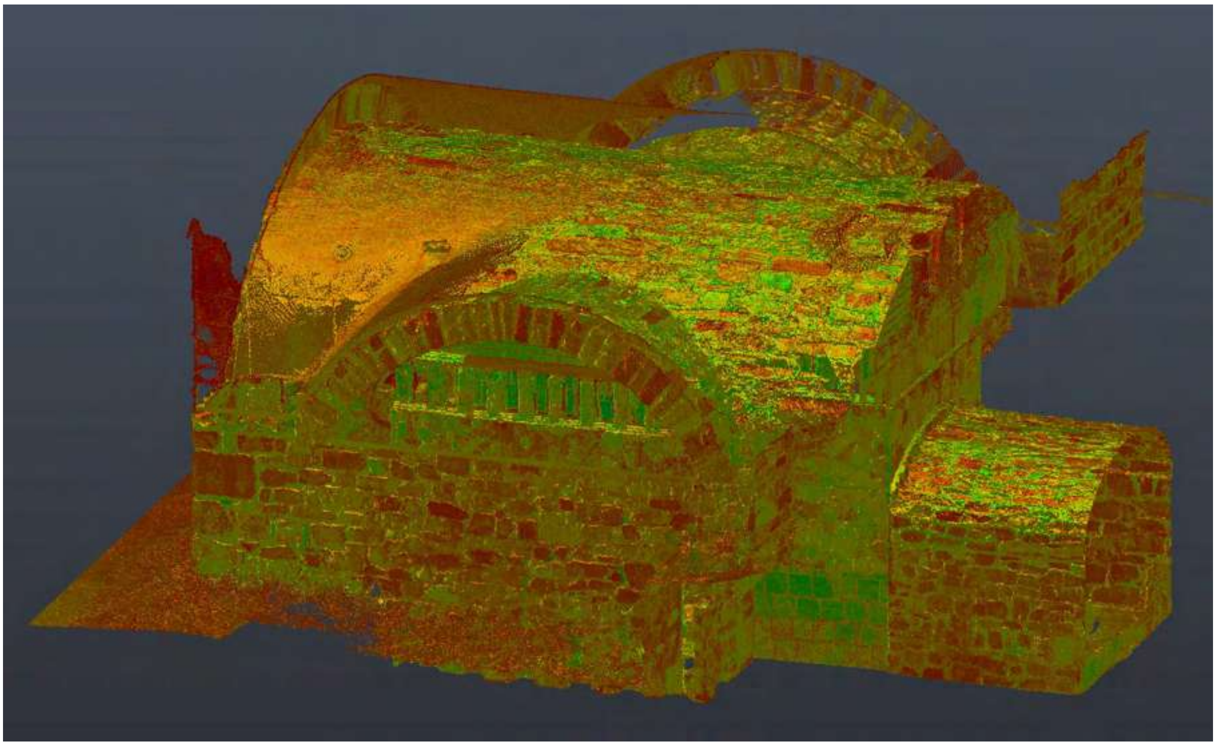

Figure 80 Resulting manually cleaned dataset visualised in Recap with the intensity colour scheme

2. Capturing of the photogrammetric dataset

Section near the Presidential Palace, EW1

Best Practices employed in the capturing of the photographs for the photogrammetry processing:

- Image Overlap: Maintain about 70-80% overlap between consecutive images to ensure sufficient common features are captured for robust matching and reconstruction.

Figure 81 Example of capture from the EW1 with 80% overlap

- Capture Variety of Angles: Take photos from multiple viewpoints and heights to improve 3D reconstruction from different perspectives, reducing blind spots.

Figure 82 Example of capture from EW1 with angle variance from the same position

- Avoid Reflective or Monochrome Surfaces: Shiny, transparent, or uniform single-color surfaces lack distinctive features and hinder accurate photogrammetry.

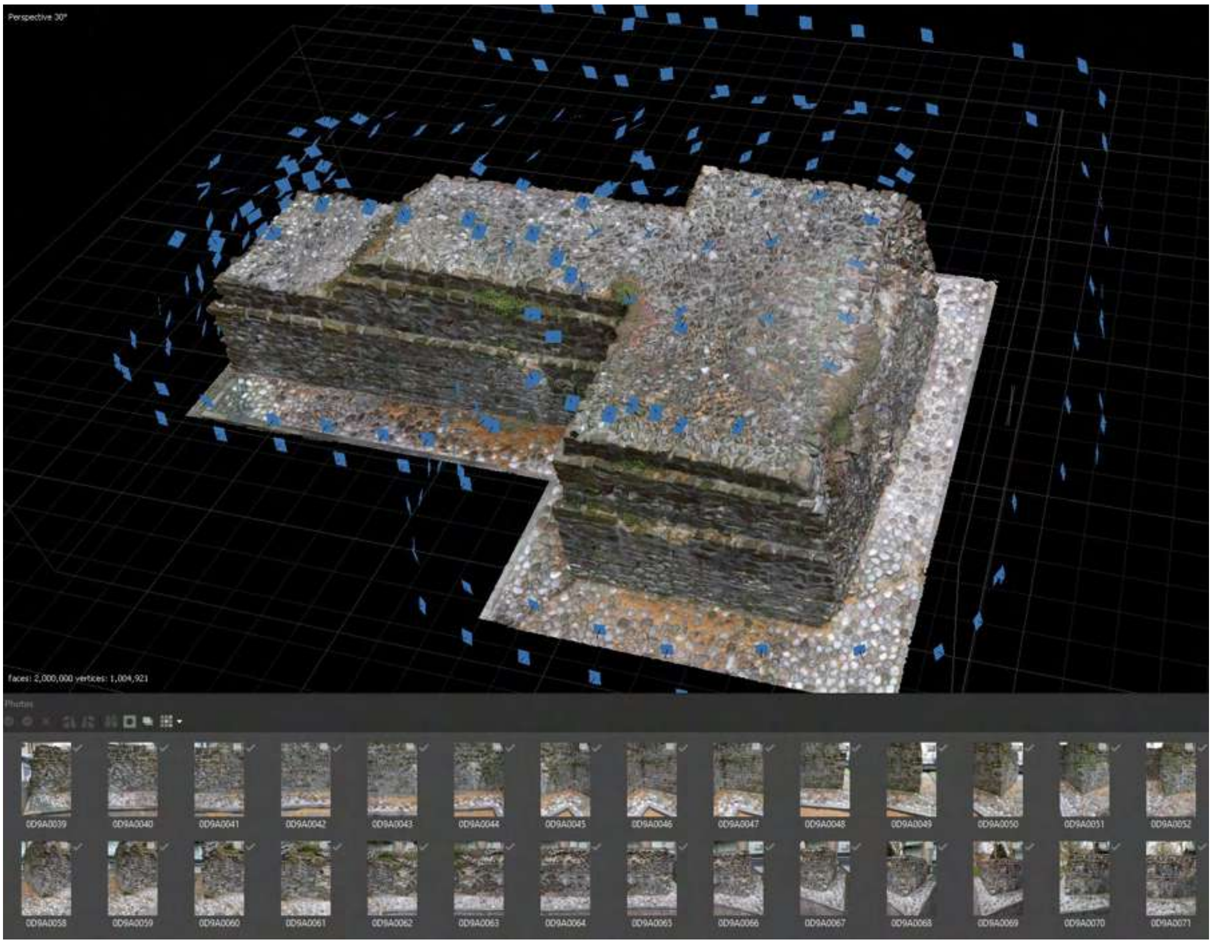

Figure 83 The Photogrammetric dataset of the EW1 processed in Metashape and decimated to 2M faces.

Remnant in the back of the Uršulinski samostan monastery, EW2

We could not obtain access to this space. It will be added to the database in the future.

Praetorian City Gate, EW3

Figure 84 Example of two viewpoints capture from the EW3 with 80% overlap

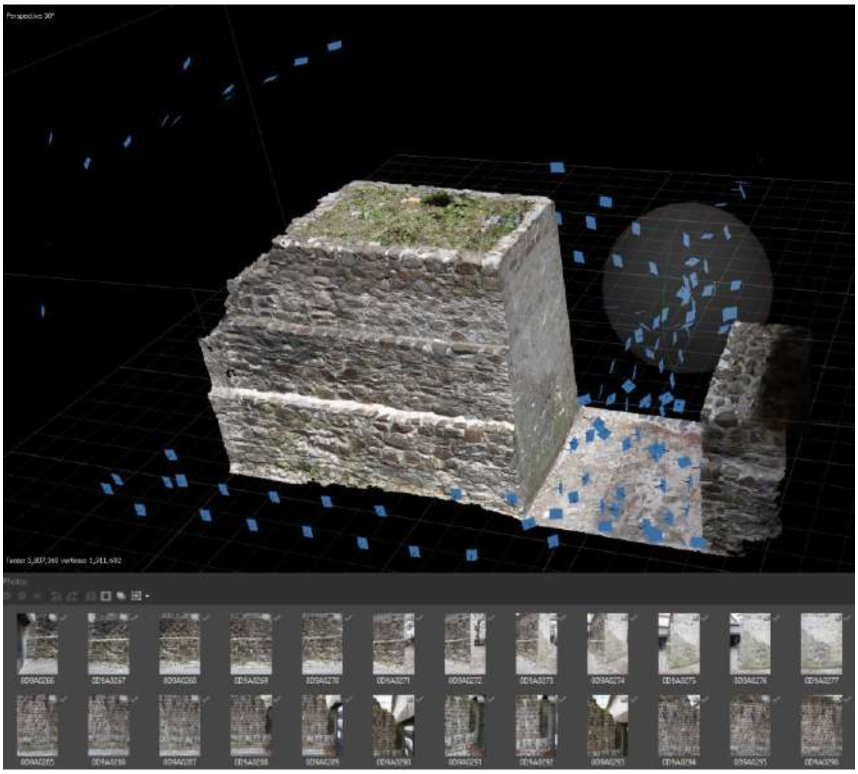

Figure 85 The Photogrammetric dataset of the EW3 processed in Metashape and decimated to 2M faces.

Remnant near the houses in the southern part of the wall, EW4

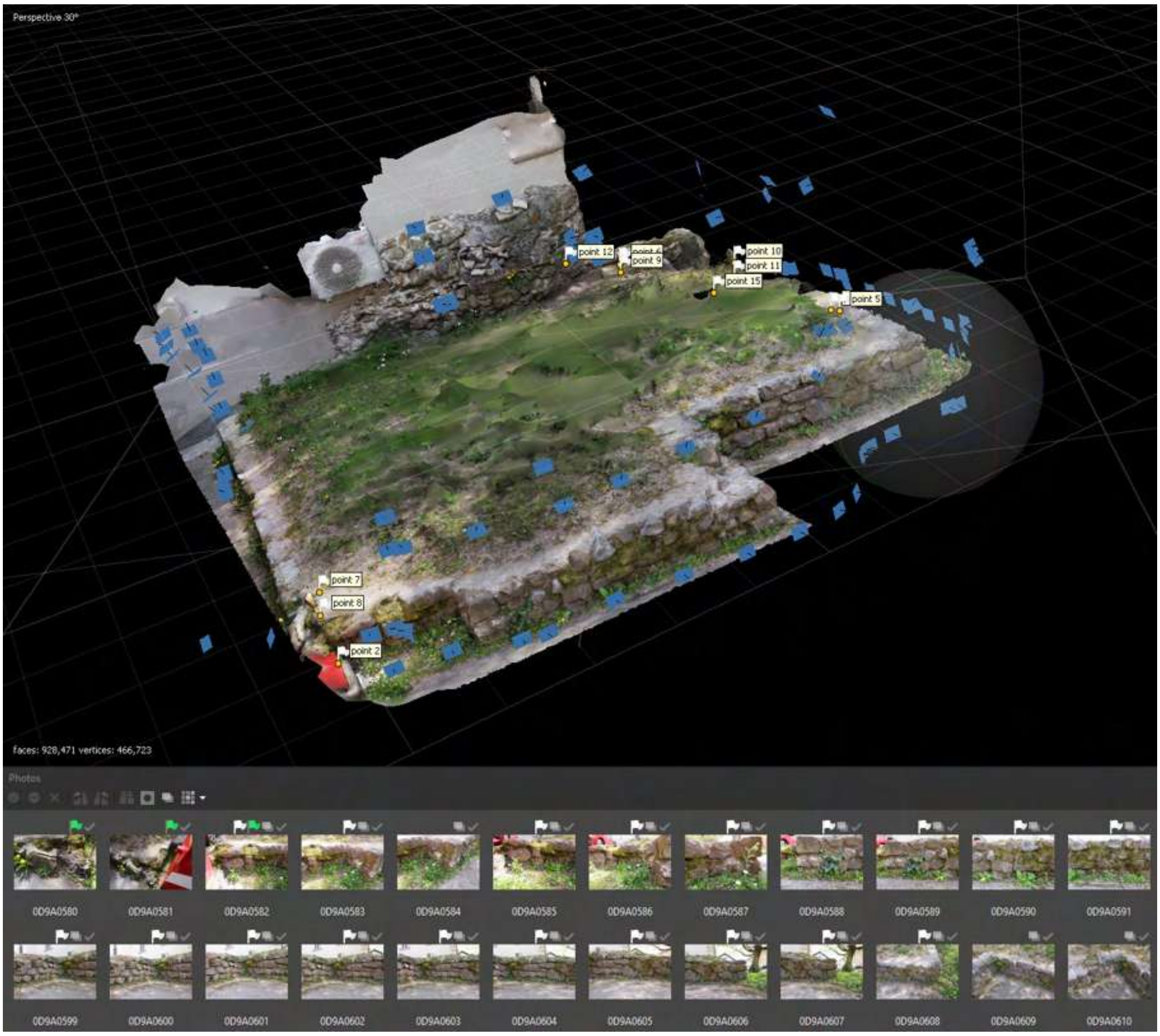

Figure 86 Photogrammetric dataset of the EW4.

This case se-study was only captured with photography by myself, and the quality of the assets is lower due to my inexperience. For instance, I had to manually add markers to some pictures because the algorithm was having difficulty matching the pictures, mostly because of orientation and capturing too near to the asset. There were cars parked around it so it was also a difficult capture.

Southwestern corner, EW5

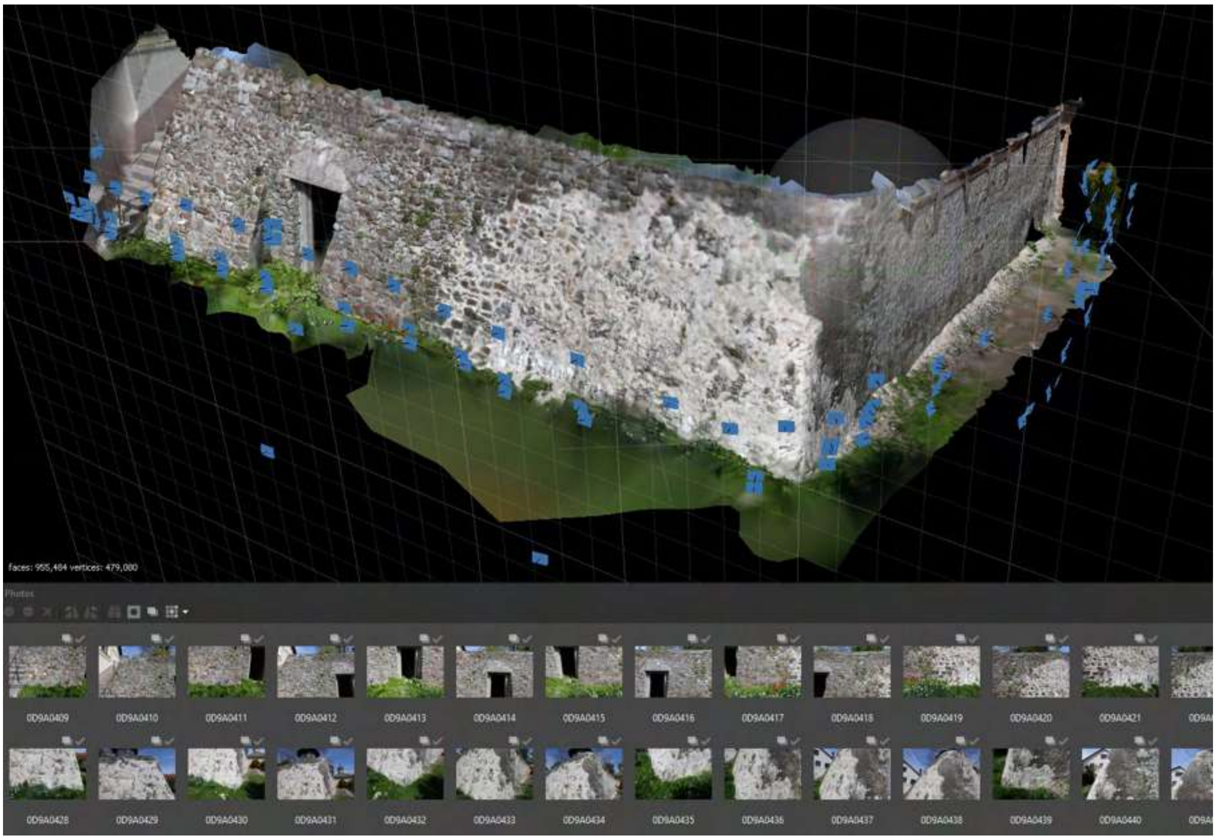

Figure 87 Alignment of the photogrammetric dataset.

In this case, due to the height of the wall, and the inaccessibility the pictures were only captured from the lower part of the wall, which created artifacts, like the sky being baked in the texture. This was manually cleaned in Metashape.

Inside of the Lapidarium, EWL - EWM

Figure 88 Calculating the dense point cloud derived from the photos taken inside the Lapidarium.

This process will allow us to filter the points by confidence level and achieve a better-quality mesh. As seen in the corpus of the thesis this turned out to not be enough to create a high-quality mesh. In this part of the model, it was less time demanding to model classically.

3. Timeline of the Renovation and Monumentalization of the Roman Wall at Mirje

This timeline is produced sourcing information from Bernarda Zupanek[7], Plesničar-Gec[3] and France Stele [70].

Before 1895:

- The Roman wall at Mirje is largely covered by earth, resembling a miniature, low mountain ridge with grassy slopes. It features niches (alcoves) used by local children for hide-and-seek or bonfires.
- During the life of J. W. Valvasor (1641-1693) the walls with towers on the exterior of Emona were still partially visible and his copper etchings (bakrorezl) also provide evidence of water in the northern ditches.

1895:

- An earthquake occurs, likely affecting the state of the Roman wall.

Late 19th - Early 20th Century:

- Across Europe, the perception of historical monuments changes, driven by the industrial age's transformation and degradation of the environment. Scientific approaches replace antiquarian ones, and stricter legislation for monument protection is introduced.
- Protective excavations around the northern gate began as early as 1890. In August and September of that year, digging a large canal from the Ljubljanica across Kongresni trg uncovered Roman antiquities, including Roman bricks, pottery lamp fragments, and the main Roman gate (Porta Praetoria) two meters below the surface in front of the Ursuline church and Wurzbach's/Zweyer's houseThe awareness of Emona as a valuable historical monument grows.
- The connection between Roman Emona and modern Ljubljana is strengthened through cartographic representations, such as Rutar's and Schmid's maps, which superimpose Emona's layout onto Ljubljana's.

First Decade of 20th Century (pre-1910):

- Major archaeological excavations of Emona begin under the leadership of Walter Schmid, revealing the southern part of the Roman city, including a section of the wall.

13 April 1910:

- During a visit to Ljubljana, Archduke Eugen of Austria is so impressed by Walter Schmid's archaeological findings that he decides to establish a "Museum Emonense".
- The Ljubljana City Council reserves/protects the entire complex south of Rimska cesta (Roman Road) for the excavation, research, presentation of Emona, and the planned Emona Museum, though the project is not realised.

1912:

- Anton Aškerc's poem "Attila in Emona" is published as a standalone book and in the newspaper *Ljubljanski zvon*, popularising the Emona narrative.

1913:

- Walter Schmid publishes *Emona*, a significant scientific work detailing his excavations of the southern part of the Roman city.
- Schmid reconstructs the excavated wall to a uniform height, reinforces it with an internal embankment, marks the boundary between preserved and reconstructed parts with pebbles, and protects the wall's crown with turf.

1914 - 1937:

- Matko Prelovšek serves as the head of the city construction office in Ljubljana, playing a decisive role in public works and supporting Jože Plečnik's urban projects.

1918:

- The Austro-Hungarian monarchy collapses.
- The Kingdom of Serbs, Croats and Slovenes is established, fundamentally changing Ljubljana's political and economic position. Ljubljana aims to expand economically southwards and becomes the political centre of Slovene identity.

1919:

- Dr. France Stele becomes the provincial conservator at the Monument Office in Ljubljana, responsible for the entire Slovene-speaking area within the newly formed Yugoslavia.

1920:

- Jože Plečnik returns to Ljubljana and begins teaching architecture at the newly established University of Ljubljana.

1920s - Early 1930s:

- The Roman wall at Mirje falls into disrepair due to inadequate repairs after Schmid's reconstruction.
- As Ljubljana expands, the city administration parcels out the area between Gradaščica and present-day Aškerčeva Street for private construction. The Roman wall becomes an obstacle to development and traffic.
- Parts of the citizenry advocate for the demolition of the wall, arguing it is scientifically unimportant, not authentic, and hinders urban development. A proposal for its removal is put forth in the municipal council and reported in *Slovenski narod*.
- France Stele strongly advocates for the preservation and restoration of the wall, believing its demolition would harm Ljubljana's reputation in the cultural world. He views the wall as a symbol of Emona, a valued ancient predecessor of Ljubljana, providing symbolic capital for the city's new political aspirations.
- The "Emona" tea series from Bahovec pharmacy becomes a successful brand, further cementing Emona's popularity.

1926:

- At the suggestion of the Conservation Society, the Ljubljana City Municipality decides to renovate the wall according to Plečnik's plans. This indicates France Stele has successfully enlisted Jože Plečnik.

1928:

- France Stele publishes the pamphlet "In Defence of the Roman Wall at Mirje in Ljubljana" (*V obrambo rimskega zidu na Mirju*), initially as articles in *Slovenec* (issues 163 and 164) and then as a standalone publication by the Monument Office.
- In this publication, Stele counters arguments for demolition, asserts the wall's authenticity and importance, and gathers support from prominent archaeologists and architects, including Fran Bulić, Nikola Vulić, Viktor Hoiller, Mihovil Abramić, Balduin Sario, Emil Reisch, Rudolf Egger, Walter Schmid, and Jože Plečnik (whose letter is cited).

- November 1928: The Ljubljana City Council discusses and officially approves the renovation of the Roman wall at Mirje according to Plečnik's plan, including the surrounding area.

1932:

- France Stele publishes "Ljubljana Castle: The Slovene Acropolis" (*Ljubljanski grad: slovenska akropola*).
- Jože Plečnik undertakes monument conservation work on Ljubljana Castle, supported by Stele.

1934:

- Masonry work on the Roman wall at Mirje, according to Plečnik's plans, finally begins after numerous debates.

End of 1936:

- Major works on the wall are completed.
- 13 October 1936: The technical committee of the Ljubljana City Council reports on the final arrangement of the Roman wall and the park between Mirje and the technical school according to Plečnik's plan.
- Plečnik's significant transformations include:
- Breaking two new passages through the wall to connect Snežniška and Murnikova Streets.
- Creating a park behind the wall with displayed ancient architectural elements.
- Building a lapidarium in the Emona side city gates.
- Planting a poplar avenue on the roadside of the wall.
- Placing eight massive conglomerate columns at the former main entrance to Emona, paving the entrance, and converting one of the Roman towers into a viewpoint.
- Erecting a turf-covered pyramid above the passage to Murnikova Street.
- Building two earthen pyramids on the inner side of the wall.
- A report in *Slovenec* notes that "traces of ancient Roman Emona are slowly rising, recalling to the present inhabitants of Ljubljana, Emona's successor, memories of the ancient glory and renown of our city."

1936-1938:

- The renovation of the southern Emona wall at Mirje is completed according to Plečnik's plans.

After World War II:

- Stricter criteria for the authenticity and presentation of historical monuments are adopted, leading to changes in Plečnik's design elements.
- The two pyramids at the main Roman entrance, which had started to decay, are removed.
- The turf covering the pyramid above the Murnikova passage is removed, revealing the stones beneath.
- The poplar avenue on the outer side of the wall is removed, initially cited as necessary due to its destructive effect on the wall's foundations, but later clarified as a decision by Dr. Jaro Šašel to achieve a "cleaner scientific interpretation" of the wall, making it appear less hospitable, as an ancient defensive wall would have been.
- The Roman wall is "black-boxed" into the broader heritage network of Emona, losing its distinct identity as a separate network.

15 August 1960:

- The District People's Committee, Department for Social Services, Section for Monument Protection, issues a document (No. 246/1960) outlining 17 points for radical changes to the wall's appearance, including the removal of the pyramid above the Murnikova passage and the lapidarium, aiming to bring the wall closer to its original Roman form. Many of these planned "protective works" are not implemented.

1963

- More than 100m of the northern wall beside the modern Trg republike was demolished, a process that took eight whole days even with modern resources.

- The northern gate was finally excavated in the **spring of 1963** during preparatory work for the new route of today's Slovenska cesta.

1977

- The first defensive ditch alongside the defensive wall was found during rescue excavations on the site of Cankarjev dom

Present Day:

- Some of Plečnik's solutions remain, though significant changes have been made to others, particularly the removal of the earth pyramids and the alteration of the Murnikova passage pyramid's appearance.

4. **Principal persons involved in the modern transformation of the Wall**

- **Jože Plečnik (1872–1957):** A highly influential Slovenian architect. He returned to Ljubljana in 1921 and began teaching architecture at the university in 1920. He was the key figure responsible for the radical and monumental redesign of the Roman wall at Mirje in the 1930s, intending to transform Ljubljana into a symbolic capital for Slovenes by incorporating classical and ancient elements into the urban landscape. His work on the wall was part of a broader "Plečnik's Ljubljana" project.

- **Dr. France Stele (1886–1972):** A crucial figure in modern Slovenian monument conservation. From 1919, he served as the provincial conservator at the Monument Office in Ljubljana, overseeing monument protection for the entire Slovene-speaking area in Yugoslavia. He was a staunch advocate for the preservation of the Roman wall at Mirje, actively campaigning against its demolition and enlisting the support of other experts and the public. He had a strong professional and personal relationship with Plečnik, often defending his (sometimes controversial from a conservation perspective) interventions. He envisioned Ljubljana as a classical city and the spiritual capital of Slovenes.

- **Walter Schmid:** An archaeologist who led the first major archaeological excavations of Emona in the first decade of the 20th century. His work uncovered the southern part of the Roman city, including the wall at Mirje. After his excavations, he reconstructed parts of the wall and envisioned the area as a large "Museum Emonense." He later became a professor of archaeology at the University of Graz.

- **Matko Prelovšek:** An engineer who served as the head of the city construction office in Ljubljana between 1914 and 1937. He held significant influence over public works in the city and was a key supporter and collaborator of Jože Plečnik, facilitating the implementation of many of Plečnik's urban projects, including the renovation of the Roman wall.

Other Mentioned Individuals:

- **Dr. Bernarda Županek:** The author of the text *Producing a Classical Past: Ljubljana, the Roman Wall at Mirje, and the Actor-Network Theory* [7]. She is a museum advisor and curator for antiquity at the City Museum Ljubljana.
- **Josip C. Oblak:** Mentioned for his memories of the Roman wall at Mirje before the 1895 earthquake and Schmid's research, describing it as an earth-covered "miniature mountain ridge" with "niches" used by children.
- **Archduke Eugen of Austria:** Visited Ljubljana on April 13, 1910, and, impressed by Walter Schmid's archaeological findings, decided to establish a "Museum Emonense."
- **Iva Curk:** An archaeologist who explains the problematic state of the wall in the expanding Ljubljana and later offers a different perspective on the removal of Plečnik's trees.
- **Dr. Fran Bulić:** A prominent Yugoslav archaeologist cited by Stele in his defence of the wall.
- **Nikola Vulić:** A professor of archaeology from Belgrade, cited by Stele in his defence of the wall.
- **Viktor Hoiller:** A professor of archaeology from Zagreb, cited by Stele in his defence of the wall.
- **Mihovil Abramić:** Director of the State Archaeological Museum in Split, cited by Stele in his defence of the wall.
- **Balduin Sario:** A professor of archaeology from Ljubljana, cited by Stele in his defence of the wall.
- **Emil Reisch:** A professor of archaeology from Vienna, cited by Stele in his defence of the wall.
- **Rudolf Egger:** A professor of archaeology from Vienna, cited by Stele in his defence of the wall.
- **Anton Aškerc:** A poet whose romance "Attila in Emona" was published in 1912, contributing to the popularisation of Emona.
- **Leo Bahovec:** The owner of a prominent Ljubljana pharmacy that produced the popular "Emona" tea series in the 1920s and 1930s.
- **Dr. Jaro Šašel:** An individual who, after World War II, advocated for a "cleaner scientific interpretation" of the wall, leading to the removal of trees planted by Plečnik along its outer side.

Archaeologists/Scholars cited by France Stele:

- **Fran Bulič** (msgr., leading Yugoslav archaeologist).
- **Nikola Vulič** (prof. of archaeology at the University of Belgrade).
- **Viktor Hoffiller** (dr., prof. of archaeology at the University of Zagreb, director of the National Archaeological Museum).
- **Mihovil Abramič** (dr., director of the State Archaeological Museum in Split, former director of the Archaeological Museum in Aquileia).
- **Balduin Sarija** (dr., prof. of archaeology at the University of Ljubljana).
- **Emil Reisch** (dr., director of the Austrian Archaeological Institute, prof. of archaeology at the University of Vienna).
- **Rudolf Egger** (dr., secretary of the Austrian Archaeological Institute, prof. of archaeology at the University of Vienna).
- **Guido Calza** (head of excavations in Ostia).

5. Timeline of the contemporary research carried out in the Southern Wall

- 11th February 2020: The "Poročilo o ogledu Rimskega zidu na Mirju v Ljubljani – EŠD 22658" was signed on this date by Miran Ježovnik and Srečko Štajnbahar.
- 4th March 2020: This is the date on the "Poročilo o ogledu Rimskega zidu na Mirju v Ljubljani – EŠD 22658"
- 28th June 2022: This is the date of an initial offer from UL FGG (reference number 401-1/2021-124a, mentioned in) for research on the Roman wall. The document "Ponudba_Rimski zid 28062022 pod.pdf" bears this date.
- 6th July 2022: This is the date of another offer from UL FGG (reference number 430-1373/2022-1, mentioned in) for research on the Roman wall. The document "Ponudba_Rimski zid 06072022.pdf" has this date, and this offer is referred to in the contract between the City Municipality of Ljubljana and UL FGG
- 1st November 2022: This is the deadline for UL FGG to complete the work on the Roman wall according to the contract
- 30th August 2024: The "Ponudba UL FGG injektiranje in preiskave - dvofazno.pdf" for injection and investigation works on the Roman wall at Mirje is dated this day.

6. Persons involved in the contemporary research carried out in the Southern Wall

Robert Klinc (author of "OBLAKI TOČK ZA UPORABO V INFORMACIJSKIH MODELIH GRADENJ (BIM)")

Uroš Jotanović (author of "OBLAKI TOČK ZA UPORABO V INFORMACIJSKIH MODELIH GRADENJ (BIM)")

Klemen Kregar (author of "OBLAKI TOČK ZA UPORABO V INFORMACIJSKIH MODELIH GRADENJ (BIM)")

Vlatko Bosiljkov (prof. dr., preparer of offers, Head of KPMK, and co-preparer of the "POROČILO O NALOGAH IN PREISKAVAH V OKVIRU PROJEKTA MATERIALNE IN KONSTRUKCIJSKE RAZISKAVE RIMSKEGA ZIDU S PREDLOGI ZA KONSTRUKCIJSKO SANACIJO" report).

Andreja Padovnik (asist. dr., co-preparer of the "POROČILO O NALOGAH IN PREISKAVAH V OKVIRU PROJEKTA MATERIALNE IN KONSTRUKCIJSKE RAZISKAVE RIMSKEGA ZIDU S PREDLOGI ZA KONSTRUKCIJSKO SANACIJO" report and natural science investigations).

David Antolinc (doc. dr., responsible person for the Faculty of Civil Engineering and Geodesy (UL FGG) in equipment offers, and co-preparer of the "POROČILO O NALOGAH IN PREISKAVAH V OKVIRU PROJEKTA MATERIALNE IN KONSTRUKCIJSKE RAZISKAVE RIMSKEGA ZIDU S PREDLOGI ZA KONSTRUKCIJSKO SANACIJO" report).

Tilen Turk (asist., mag. inž. kem. inž., co-preparer of the "POROČILO O NALOGAH IN PREISKAVAH V OKVIRU PROJEKTA MATERIALNE IN KONSTRUKCIJSKE RAZISKAVE RIMSKEGA ZIDU S PREDLOGI ZA KONSTRUKCIJSKO SANACIJO" report).

Petra Štukovnik (doc. dr., co-preparer of the "POROČILO O NALOGAH IN PREISKAVAH V OKVIRU PROJEKTA MATERIALNE IN KONSTRUKCIJSKE RAZISKAVE RIMSKEGA ZIDU S PREDLOGI ZA KONSTRUKCIJSKO SANACIJO" report and natural science investigations).

Franci Čepon (dig., co-preparer of the "POROČILO O NALOGAH IN PREISKAVAH V OKVIRU PROJEKTA MATERIALNE IN KONSTRUKCIJSKE RAZISKAVE RIMSKEGA ZIDU S PREDLOGI ZA KONSTRUKCIJSKO SANACIJO" report).

Matej Dolenec (izr. prof. dr., Head of the Department of Geology, mentioned in an offer).

Boštjan Rožič (prof. dr., Head of the KMPM laboratory, mentioned in an offer).

Mirana Ježovnik (preparer of the "Poročilo o ogledu Rimskega zidu na Mirju v Ljubljani – EŠD 22658" report).

Momo Vuković (akad.kipar, konservator-specialist, author of "Poročilo o nadaljevaljnem konservatorskem posegu na Rimskem zidu ob Jamovi ulici v letu 1982").

France Stele (dr., spomeniški konservator, author of "V OBRAMBO RIMSKEGA ZIDU NA MIRJU V LJUBLJANI").

Project and Institutional Leads:

Violeta Bokan Bosiljkov (Prof. dr., Dean of UL FGG, signatory of various offers and contracts).

Srečko Štajnbaber (prof., Head of ZVKDS OE Maribor, signatory of the Report on the visit to the Roman Wall at Mirje in Ljubljana – EŠD 22658

Zoran Janković (Mayor of Mestna občina Ljubljana, representing the client in a contract).

Jerneja Batič (Responsible representative for the client, Mestna občina Ljubljana, and contract caretaker).

Martina Lesar Kikelj (mag., Head of Restoration Centre for ZVKDS RC, signatory on a work order).

Nina Žbona (mag., Head of department for stone in stucco at ZVKDS RC, proposer for a work order).

Dinko Gregorim (dipl.iur., Head of Restoration Atelier, preparer and signatory of the 1981 estimate and contract).

Aleksander Bassin (Director, representing the client Ljubljana Regional Institute for Monument Protection in a 1981 contract).

Contributors and Historical Figures Mentioned:

Renato Angeloni (Acknowledged for participation in the 2018 survey campaign).

Ludovico Ruggeri (Acknowledged for participation in the 2018 survey campaign).

Ivan Šubic (Director of the State Vocational School, collaborated with Walter Schmid).

Iva Curk (dr., member of the supervising commission for the 1982 conservation work).

Ljudmila Plešničar (dr., member of the supervising commission for the 1982 conservation work).

Marijan Slabe (dr., member of the supervising commission for the 1982 conservation work and recipient of the 1981 estimate).

7. Defining a new measuring system that was significant for the romans

To create a custom measuring system using Roman units (cubitum = 444 mm, actus = 35.5 m) in an IFC file, follow this technical implementation framework:

javascript

```
// Roman unit conversions to meters

const romanUnits = {

  'cubitum': 0.444,    // Roman cubit (elbow to fingertip)

  'actus': 35.5         // Roman actus (120 Roman feet)

};
```

Added a unit system tracker to the app state:

javascript

```
const app = {

  // ... other properties

  measurePoints: [] as THREE.Vector3[],  // Store two points for measurement

  measureMode: false,                    // Toggle measuring mode

  unit: 'metric' as 'metric' | 'cubitum' | 'actus',  // Current unit system

};
```

Created a dropdown selector in the HTML interface:

javascript

```
<div class="section">

  <h3>Measure</h3>

  <button class="btn" id="measure-btn">Measure Distance</button>

  <select id="unit-select">

    <option value="metric">Meters</option>
```

```
    <option value="cubitum">Roman Cubitus</option>

    <option value="actus">Roman Actus</option>

  </select>

  <div id="measure-result"></div>

</div>
```

The measuring tool works in several steps:

Step 1: Activation

javascript

```
function startMeasure() {

  app.measureMode = true;

  app.measurePoints = [];

  updateStatus("Click two points to measure");

}
```

Step 2: Point Selection via Raycasting

javascript

```
function handleMeasureClick(event: MouseEvent) {

  // Convert mouse coordinates to normalized device coordinates

  app.mouse.x = ((event.clientX - rect.left) / rect.width) * 2 - 1;

  app.mouse.y = -((event.clientY - rect.top) / rect.height) * 2 + 1;



  // Create ray from camera through mouse position

  app.raycaster.setFromCamera(app.mouse, app.camera);



  // Find intersections with 3D objects
```

```
  const intersects = app.raycaster.intersectObjects(app.scene.children, true);


  if (intersects.length > 0) {

    const point = intersects[0].point;  // Get 3D intersection point

    app.measurePoints.push(point);


    // Add visual marker at clicked point

    const markerGeometry = new THREE.SphereGeometry(0.2);

    const markerMaterial = new THREE.MeshBasicMaterial({ color: 0xff0000 });

    const marker = new THREE.Mesh(markerGeometry, markerMaterial);

    marker.position.copy(point);

    app.scene.add(marker);

  }

}
```

Step 3: Distance Calculation

When two points are selected:

javascript

```
if (app.measurePoints.length === 2) {

  // Draw line between points

  const geometry = new THREE.BufferGeometry().setFromPoints(app.measurePoints);

  const material = new THREE.LineBasicMaterial({ color: 0xff0000 });

  const line = new THREE.Line(geometry, material);

  app.scene.add(line);
```

```
  // Calculate Euclidean distance
  const distance = app.measurePoints[0].distanceTo(app.measurePoints[1]);


  displayDistance(distance);
  app.measureMode = false;
}
```

Step 4: Conversion Logic

The key innovation is the conversion system:

```
javascript
function displayDistance(distance: number) {
  let displayValue = '';


  switch (app.unit) {
    case 'cubitum':
      // Convert meters to Roman cubits
      const cubits = distance / 0.444;
      displayValue = `${cubits.toFixed(2)} cubitus (${distance.toFixed(3)} m)`;
      break;


    case 'actus':
      // Convert meters to Roman actus
      const actus = distance / 35.5;
      displayValue = `${actus.toFixed(3)} actus (${distance.toFixed(3)} m)`;
      break;
```

```
    default:
      // Display in meters
      displayValue = `${distance.toFixed(3)} meters`;
  }

  // Update UI with result
  const resultDiv = document.getElementById('measure-result');
  if (resultDiv) {
    resultDiv.innerHTML = `<strong>Distance:</strong> ${displayValue}`;
  }
}
```

This approach maintains IFC schema compliance while enabling interoperability with major BIM platforms. For version control, document unit definitions in the IFC header and project metadata explicitly.

8. Quick Start Guide – How to run the application locally

Historic Building Information Modelling - Document Database & 3D Viewer

System Requirements

- **Node.js** version 16.x or higher (Download from nodejs.org)
- **NPM** (comes with Node.js)
- **Modern Web Browser** (Chrome, Firefox, Edge - latest versions)
- **Free Ports:** 3002 (Document Database) and 5177 (BIM Viewer)
- **RAM:** Minimum 4GB recommended
- **Storage:** 2GB free space for dependencies and cache
- **Extract Files**

Important: Extract the entire ZIP file to a location WITHOUT spaces in the path.

1 Recommended extraction location:

C:\xx\HBIM_Project\

2 Avoid paths with spaces like:

- C:\Program Files\HBIM Project\
- C:\Users\My Name\Documents\

3 Expected folder structure after extraction:

```
📁 HBIM_Project/ ├─ 📁 DATABASE/ │ ├─ 📁 emona-web-app/ │ │ ├─ 📁 server/ │ │ ├─ 📁 public/ │ │ ├─ 📄 start_server.bat │ │ └─
📄 package.json │ ├─ 📁 bimapp/ │ │ ├─ 📁 src/ │ │ ├─ 📁 dist/ │ │ └─ 📄 package.json │ ├─ 📁 EMONA-FGG-ARCHIVE/ │ └─ 📁
EMONA-FGG-3D/ └─ 📄 FIX_BIM_INTEGRATION.bat
```

Install Dependencies

First-time setup only! This step downloads required packages and may take 5-10 minutes depending on your internet connection.

1 Open Command Prompt as Administrator

- Press Win + X
- Select "Windows Terminal (Admin)" or "Command Prompt (Admin)"

2 Navigate to the project folder:

cd C:\xx\DATABASE

3 Install Document Database dependencies:

cd emona-web-app npm install

4 Install BIM Viewer dependencies:

cd ..\bimapp npm install

Success! If you see "added X packages", the installation was successful. You only need to do this once.

Launch the Applications

Two Launch Methods Available: Choose either the integrated launcher or individual platform launchers.

Option A: Integrated Launch (Recommended)

1 Navigate to the DATABASE folder

2 Double-click the batch file:

start_dev.bat

This will:

- Start the Document Database server on port 3002
- Launch the BIM Viewer on port 5177
- Test API connections
- Open your browser automatically

Option B: Individual Launch

- **Document Database**

1. Navigate to DATABASE\emona-web-app\
2. Double-click start_server.bat
3. Wait for "Server running on port 3002"

http://localhost:3002

- **BIM 3D Viewer**

1. Navigate to DATABASE\bimapp\
2. Run npm run dev
3. Wait for "Local: http://localhost:5177"

http://localhost:5177

Verify Installation

Document Database loads at http://localhost:3002 Documents are visible in the grid layout "3D Models" button appears in the interface BIM Viewer loads at http://localhost:5177

IFC files can be loaded in the viewer Document attachment panel is visible

All checked? Your HBIM system is ready to use!

- **Using the System**
- **Document Database Features**
- Browse 466+ archaeological documents
- Filter by CIDOC-CRM classification
- Search by tags and metadata
- Preview and download files
- Access 3D models via interface button
- **BIM 3D Viewer Features**
- Load IFC models (250820_EWM.ifc)
- Navigate with orbit controls
- Select elements for properties
- Attach documents to IFC elements
- Save/load attachment sessions

Quick Workflow:

1. Open the Document Database (http://localhost:3002)
2. Browse available documents
3. Click "3D Models" to open the BIM Viewer
4. Load an IFC model using "Load IFC" button
5. Click on 3D elements to select them
6. Attach documents from the side panel
7. Save your session for later

Troubleshooting

Port already in use:

If you see "EADDRINUSE" error:

taskkill /F /IM node.exe netstat -ano | findstr :3002 taskkill /PID [PID_NUMBER] /F

Node.js not found:

Install Node.js from https://nodejs.org/ (LTS version recommended)

Documents not loading:

Ensure the EMONA-FGG-ARCHIVE folder is in the correct location and contains the document files

3D Viewer not opening:

Check that both servers are running (ports 3002 and 5177) and no firewall is blocking them

IFC file won't load:

Try the smaller test file first (250820_EW1.ifc). Large files (>500MB) may take time to load

Browser compatibility issues:

Use Chrome, Firefox, or Edge (latest versions). Safari may have WebGL limitations