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COMPETENCE CENTRE FOR THE CONSERVATION OF CULTURAL HERITAGE

D4.4 Report on pilots

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Colophon

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List of acronyms and abbreviations

- 4CH: Competence Centre for the Conservation of Cultural Heritage
- BIM: Building Information Modelling
- CC: Competence Centre
- CH: Cultural Heritage
- D: Deliverable
- GNSS: Global Navigation Satellite System
- HBIM: Heritage Building Information Modelling
- ICP: Iterative Closest Point
- KB: Knowledge Base
- NURBS: Non-Uniform Rational Basis Splines
- SLAM: Simultaneous Localization and Mapping
- UAV: Unmanned Aerial Vehicles
- WP: Work Package

Definitions

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Executive summary

The Competence Centre for the Conservation of Cultural Heritage (4CH) project is a project approved in January 2021 within the DT-TRANSFORMATIONS-20-2020 call of the Horizon 2020 Framework Program of the European Community. Its objective is to design and prepare a European Competence Centre (CC) for the Conservation of Cultural Heritage that will work proactively for the preservation and conservation of Cultural Heritage (CH).

The main high-level issues addressed by the project include the organisation and services of the CC, which will operate by providing expertise and advice based on the most advanced standards, procedures and protocols for 3D digital documentation. In particular, this document provides a report on key examples of Cultural Heritage case studies addressing diverse needs. The methodology and solutions proposed for each pilot project will serve as examples to be applied to other cases.

1. Introduction

1.1 Objectives and structure of the deliverable

Deliverable 4.4 presents the implementation of the workflows developed in Work Package 4 and the sequential simulation through pilot cases that serve as demonstrators of success stories for validating the 4CH Competence Centre structure and activities. This report describes the selected pilot cases and their implementation by explaining the conditions, solutions and lessons learned.
This Deliverable is the final result of the Work Package 4 “Service deployment system” activities. The whole of Work Package 4 on pilots made full use of the 4CH project requirements and fields of activity (WP1), structure (WP2) and platform (WP3) to define the services that the Competence Centre will offer. Deliverable 4.4 covers the work developed in Task 4.4 “Implementation of workflows and simulation through pilot cases”. The Task started on month 19 (July 2022) and ended on month 36 (December 2023). It was led by the Cyprus Institute (CY) and involved the following partners:

- PIN SOC.CONS. A R.L. - SERVIZI DIDATTICI E SCIENTIFICI PER L'UNIVERSITÀ DI FIRENZE (PIN)
- Visual Dimension bvba (VD)
- Leica Geosystems AG (LEICA)
- IRON WILL (IRONWILL)
- ALMA MATER STUDIORUM - UNIVERSITA DI BOLOGNA (UNIBO)
- ATHINA-EREVNITIKO KENTRO KAINOTOMIAS STIS TECHNOLOGIES TIS PLIROFORIAS, TON EPIKOINONION KAI TIS GNOSIS (ATHENA)
- Istituto Centrale per il Catalogo Unico - Direzione (ICCU)
- Michael Culture Association (MICHAEL)
- INCEPTION S.r.l. (INCEPTION)
- INSTITUTUL NAȚIONAL AL PATRIMONIULUI (INP)

Deliverable 4.4 fulfils the following Project Objectives:

- Project Objective 3 - Increasing and enhancing the digitisation of Cultural Heritage to support conservation.
  The overall objective is to increase the digitisation of Cultural Heritage assets at a quality that supports conservation and preservation. This will be achieved by supporting cultural institutions and SMEs undertaking digitisation projects to identify and implement key standards, guidelines, benchmarks and methodologies that meet their needs and the solutions required. This objective will be achieved through tasks carried out in WP4, such as: developing guidelines and procedures to implement relevant standards and protocols needed to produce rich 3D documentation of monuments and sites, and to support the Heritage Digital Twin concept; promoting state-of-the-art 3D ICT technologies for the preservation and conservation of European Cultural Heritage; testing workflows on heritage assets selected according to different states of conservation, needs and exploitation purposes; developing plans and strategies for capacity building of CH institutions, including staff training (upskilling and retraining) using different modalities.

- Project Objective 4 - To develop best practices to make full use of CH data for the benefit of the Cultural Heritage sector and in other domains.
  This objective aims to develop best practices that maximise the impact of digital transformation in the Cultural Heritage sector by supporting the latest trends in CH valorisation. Increasing the volume and quality of digitised content for conservation purposes opens up new opportunities for data creation and reuse – from co-creation and co-curation to storytelling, visualisation, gamification, virtual and augmented reality applications. This objective will be achieved through the tasks implemented in WP5 on data management policies, and access to specific services developed in WP3 and WP4. The improvement of human capital skills, also part of the project Objective 3, is addressed in WP4.

- Project Objective 5 - To define the operational, financial and legal conditions for the creation of the Competence Centre.
  This objective aims to define the operational framework for the 4CH Competence Centre. It will assess a number of conditions ranging from its organisational structure, governance, funding and business plan with the aim of establishing the conditions for its sustainability.

In order to test the workflows of the Competence Centre and to define the relevant CC components and bodies to be activated, case studies of cultural heritage monuments and sites were selected according to different states of conservation, needs and exploitation purposes.

1.2 Working methodology

A common working methodology has been defined for Task 4.4. participants to exchange inputs and outputs and to have the same strategy for the implementation of the pilot projects.
The working methodology has been used to select the study cases, to identify the state of the art of each Cultural Heritage asset, the relevant best practices, the digital technologies and their possible use for the selected CH assets, the risks related to conservation and preservation and, finally, to propose the best solutions to manage and present the results obtained. The methodology consists of the following steps:

1. The first step was to define criteria for the identification, description and selection of the pilot cases. A list of criteria was identified and shared among the Task 4.4 participants.
2. Based on the selected criteria, Task 4.4 participants proposed one or more pilot cases to be developed.
3. The next step was to frame (outline?) the pilot cases and identify their objectives according to the 4CH Competence Centre structure.
4. Each pilot has implemented its methodology and workflow according to the purpose of the case study.
5. Each pilot case team assessed the best platforms and the most appropriate digital solutions to publish the pilot projects for visualisation, sharing and collaboration purposes.
6. After the publication, each pilot project was structured according to the 4CH metadata schema and aggregated in the 4CH Knowledge Base. For this step, Task 4.4 actively collaborated with WP3.
7. Each pilot project was presented through public demonstrations.
8. Finally, the results of the pilot cases contributed to establishing the frame of the 4CH CC in terms of strategies and best practices for the services to offer for Cultural Heritage assets conservation, preservation and valorisation.

1.3 Criteria for the selection of the pilot cases

The 4CH pilot cases are experimental projects designed to test methods, strategies and technologies for the conservation, preservation and valorisation of Cultural Heritage as part of the future activities of the Competence Centre.
Based on the results of D4.1 “Report on standards, procedures and protocols”, three main objectives have been identified for CH digitisation: i) intervention, ii) knowledge and iii) valorisation. Each objective can in turn have further sub-objectives. For example, intervention, maintenance and restoration could be the reason for digitising a cultural asset; knowledge, research and documentation could be the idea behind the process; finally, valorisation, tourism or gamification could be the reason for a digitisation project.
These objectives guided the definition of criteria for the selection of representative case studies and led the development of the pilot projects.

Indeed, as a first step, a list of criteria was drawn up for the selection of case studies that would comply with these objectives and with the three pillars of the 4CH project (conservation, preservation and valorisation). Table 1 lists the criteria identified for the selection of the case studies and their explanation.

Pilot cases Criteria	
Risks/ damages	The current situation of a CH asset helps to assess the urgency of working on a particular case study. For the development of this criterion and the methodology to be followed for this assessment, please refer to D1.4.
Geographic coverage	This criterion refers to the geographical locations where Cultural Heritage is found or preserved.
Type	Cultural Heritage is a broad and diverse concept encompassing various tangible and intangible elements. For a definition of the CH typology, please refer to D1.4 (Task 1.2) for the identification of the asset within the developed Risk Matrix.
Data Accessibility	This criterion refers to how easily data can be accessed, retrieved, used and reused by CH professionals or organisations and systems, taking into account security, usability and transparency.
Community Interest	This criterion refers to the attention or involvement of a group of people who share common characteristics, goals or geographical proximity towards a particular cause. Community interest is based on the collective attention and involvement of people within a community in matters that affect their common interests. Community interest may not necessarily align with national or international interest.
National Interest	This criterion refers to the attention given to a particular CH asset by the Nation in which the asset is located.
International Interest	This criterion refers to the collective interest and commitment of several countries or international organisations to a CH asset of recognised global value.
Comparability	This criterion involves the capacity to compare the characteristics of this Cultural Heritage asset with others. It represents the ability to meaningfully and consistently evaluate, assess, or analyse other cultural assets based on the selected CH case study.
Formalised/ not-formalised Heritage	Formalised Heritage refers to cultural assets that have undergone official processes of recognition, preservation, and documentation.

	They are often officially protected, regulated, and managed by governmental bodies, cultural institutions, or other recognised authorities. Non-formalised Heritage refers to Cultural Heritage assets that may be culturally significant to some communities but have not undergone formal processes of recognition or preservation.
Income	This criterion refers to the income generated by a Cultural Heritage asset, which contributes to the economic development of the place where it is located and even to its conservation and promotion, thus ensuring its preservation and valorisation.
Management status	This criterion refers to the policies and systems in place to manage and safeguard a cultural asset. It may integrate a variety of strategies (e.g. conservation, community involvement, education and sustainable development approaches) to preserve its cultural diversity and identity.
Ownership	This criterion refers to a complex concept involving legal, ethical, and cultural considerations (e.g., international conventions, heritage protection laws, repatriation or restitution agreements) and different stakeholders (state ownership, private ownership, and community ownership). For this reason, addressing ownership issues in the context of preservation, conservation and valorisation activities is crucial and is linked to the needs of the users of the CH (see D1.4 for more on user needs).
Annual visitors	This criterion refers to the number of visitors per year to which the Cultural Heritage asset is exposed. A further assessment is provided by the segmentation of the visitors (if available) and an analysis of their (possible) impact on the CH asset and society.
Feasibility	Feasibility refers to the possibility of successfully carrying out or achieving a pilot case for a specific CH asset.
Accessibility	This criterion refers to the possibility of accessing the Cultural Heritage asset for the development and implementation of the task.
Legal/ Protection status	This criterion refers to the legal and protection status of a cultural asset, which may vary between countries and regions according to the recognised value of the Cultural Heritage asset.

Table 1. Criteria for the selection of case studies for the development of pilot projects

Based on the above criteria, four case studies have been selected to demonstrate the 4CH approach to the implementation of workflows for the conservation, preservation and valorisation of Cultural Heritage assets. The case studies have been selected to cover a diverse historical periods and different heritage typologies in different locations across Europe and the Mediterranean:

- Agios Ioannis Lampadistis Monastery, Cyprus
- Shatby Necropolis of Alexandria, Egypt
- Saint Laurentius Church of Ename, Belgium
- Villa Aldrovandi Mazzacorati, Italy

In the following section, a description of the four case studies and the implementation of the related pilot projects will be presented, highlighting the digital technologies used and the solutions proposed for the objectives identified.

2. Pilot Case 1: From HBIM to stakeholders. A collaborative virtual environment for risk assessment, conservation and valorisation at a UNESCO World Heritage Site. The Agios Ioannis (Saint John) Lampadistis Monastery, Cyprus

2.1 Methodological workflow for the CyI pilot cases implementation

The Cyprus Institute has designed a methodological workflow for the implementation of the pilot cases under its responsibility. In particular, the methodological pipeline focuses on the development of collaborative solutions for risk assessment, conservation, and valorisation of Cultural Heritage assets. Such a methodology involves careful planning of all the steps that make up the pipeline and consideration of the various factors and actors that contribute to the well-being of a CH asset.
The methodological workflow established for the development of the pilot cases consists of four main steps (figure 1). Starting with the framing and description of the Cultural Heritage Asset, it is possible to make an initial assessment of the site, including the threats and damages to which the site is exposed. This step is followed by digital documentation and data curation, and the

subsequent implementation of conservation, preservation or valorisation solutions. These steps are all propaedeutic to the establishment of a Heritage Asset Management strategy that will allow for the effective monitoring and welfare of the site. The workflow developed is proposed as a roadmap for the activities and services that the Competence Centre will provide in the future for conservation, preservation or valorisation purposes.

Figure 1. The methodological workflow designed for the implementation of the Cypriot pilot cases

2.2 Agios Ioannis Lampadistis Monastery

The Agios Ioannis Lampadistis Monastery was selected as a pilot case on the basis of several criteria, such as its importance as a cultural heritage site, the typology of the building, its geographical location, its state of conservation and the nature of the threats to which the site is exposed. In particular, the aim of this pilot case is to demonstrate the application of a digital workflow for the implementation of a collaborative virtual environment for risk assessment, conservation and valorisation.

2.2.1 Description of the case study

Saint John Lampadistis Monastery is located in the Troodos Mountains of Cyprus, near the village of Kalopanayiotis. It is nestled on the eastern slope of a deep ravine formed by the river Setrachos in the Marathasa valley (figure 2). The building is a complex of three churches with the oldest dating back to the 11th century. The church is a prime example of Byzantine architecture, featuring characteristic elements such as domes, frescoes, and intricate stone carvings. The construction method is a load-bearing rubble masonry of local limestone with wooden reinforcements. The church complex is covered by a saddleback timber roof with flat hooked tiles, a common architectural element of all the so-called Troodos Painted Churches. The interior is composed of a significant interior decoration of Byzantine and post-Byzantine frescoes and paintings, a unique built-in wooden iconostasis *templon* and a variety of mediaeval graffiti witnessing the passage of worshippers through time. As part of one of the largest groups of churches and monasteries of the former Byzantine Empire, all decorated with frescoes that testify to the variety of artistic influences over 500 years, this site is among the ten monuments on the UNESCO World Heritage List[1] and under its legal protection at the international level. The local management of the site is under the Department of Antiquities of Cyprus, specifically under the direct supervision of the Curator of Ancient Monuments and the Director of the Department of Antiquities, and the Church of Cyprus. In addition, the Troodos Villages Community is one of the stakeholders involved in the promotion of the area, which is experiencing increasing tourism development. The site continues to be used as a place of religious practice, with an exponential increase in the number of visitors, thus on the one hand preserving its original function and constituting a living monument, and on the other hand being exposed to various anthropogenic threats in addition to the natural ones. Therefore, due to its location and its complex materiality, the monastery is affected by various natural hazards (e.i., water infiltration, climate change effects) and anthropogenic hazards (i.e., increasing tourism), whose damages need to be assessed, monitored and mitigated for the conservation and preservation of the asset.

Figure 2. Views of the Agios Ioannis Lampadistis Monastery

2.3 Pilot case implementation

2.3.1 Aims and approach

Due to the identification of the above-mentioned risks affecting the site, the aim is to develop a dynamic digital solution. This solution can be actively updated and managed to provide critical

1 https://whc.unesco.org/en/list/

information throughout the building's lifecycle. It will be integrated into web-based platforms offering a more readily available approach and a wide range of data for the conservation and preservation of the CH asset.
For this reason, the Cyprus Institute has developed an HBIM model that serves as a tool for the digital documentation and data curation of the site, and as a collaborative virtual environment for risk assessment, conservation and valorisation.
The HBIM approach developed for this pilot case is presented in the following diagram (figure 3) and consists of three main parts (starting from the bottom of the figure):

1. The Documentation Process
2. The Authoring Process
3. The Integration with Collaborative Platforms

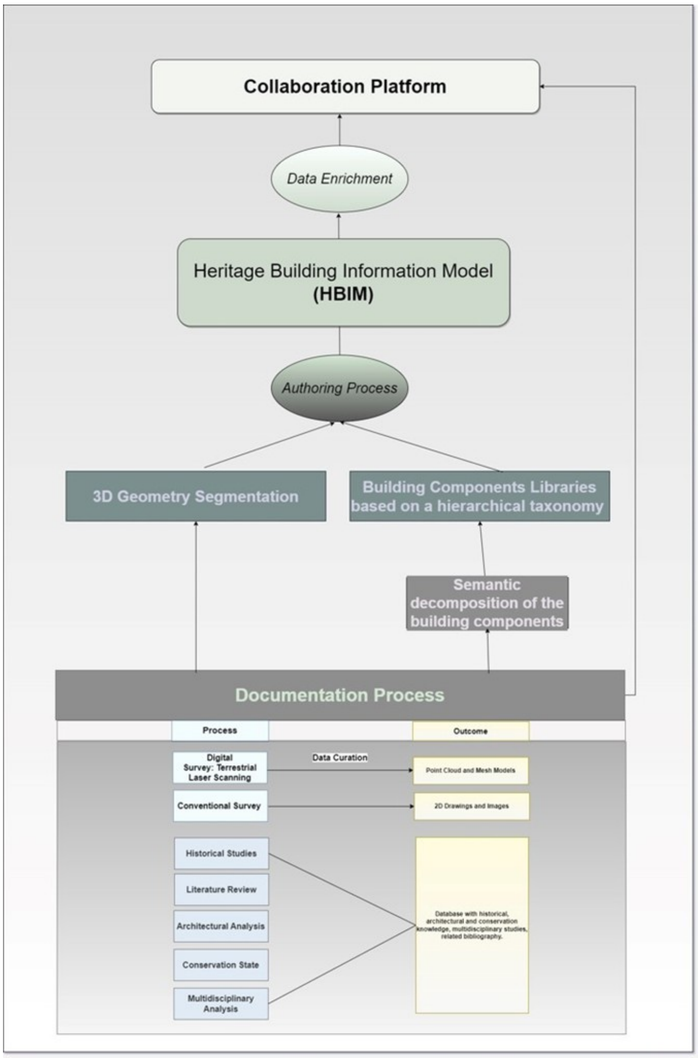


Figure 3. The HBIM methodology developed for the pilot case

2.3.2. The Documentation Process

The Documentation Process consists of two phases. The first one deals with the survey of the structures carried out using either digital documentation processes or conventional surveys. The second one involves the historical studies and architectural analysis of the Cultural Heritage asset.

Digital and Conventional Survey

Regarding the Digital Documentation Process, a Terrestrial Laser Scanning survey was carried out using a phase shift laser scanner with a certified accuracy of 5 mm at 5m. An aerial image-based survey was also completed using a UAV Platform. The flight plan was implemented to achieve a forward and lateral image overlap of ~80% and an average Ground Sampling Distance (GSD) of ~2 cm. This process only covered the roof part of the monument.
Furthermore, a survey with conventional methods took place to obtain complementary measurements. Archival data from previous surveys, provided by the Cyprus Department of Antiquities, were integrated to complete the dataset of the documentation process. The outcome of this process provided a variety of file formats (i.e., PLY, e57, STL, JPEG and DWG) that had to be further processed to become resourceful and manageable for the HBIM authoring process (figure 4).

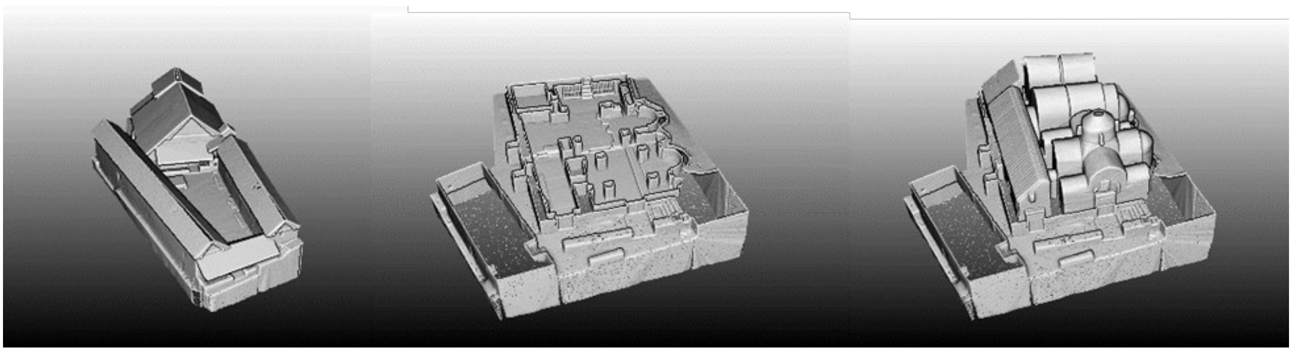


Figure 4. Mesh Models of the Agios Ioannis Lampadistis Monastery

Historical studies and Architectural Analysis

The study of the monument's historical context and conservation history was crucial to understanding its architectural evolution, as the church complex is the result of many transformations that took place over the centuries. The first Church was constructed in the 11th century and it was dedicated to Saint Herakleidios. The Saint John Lampadistis Chapel was added in the 12th century next to the first church. In the 13th century, the two churches were covered with a common saddleback roof.[2] In the 15th century, the Narthex and the Latin Chapel were constructed and until the 18th century, the Church Complex had formed its present-day tripartite

2 The particular roof of the monastery may have answered a specific climate need in the past (heavy snow), which nowadays does not affect the site anymore.

character and its external appearance of a large building covered with a timber roof. In the most recent years, two restoration projects took place in 1951 and 1955 (Limbouri-Kozakou 2018). These interventions were part of the same conservation plan which restored the timber roof and waterproofed several parts of the building. In addition, during these restoration phases, new elements were added to the building including the bell tower, the buttresses of the Narthex's west wall and the pediment between the timber roof of the Latin Chapel and the Saint John Lampadistis Chapel. Consequently, the historical evolution of the Church defined its current spatial segmentation which was a key factor for the HBIM model data structure and model segmentation (figure 5).

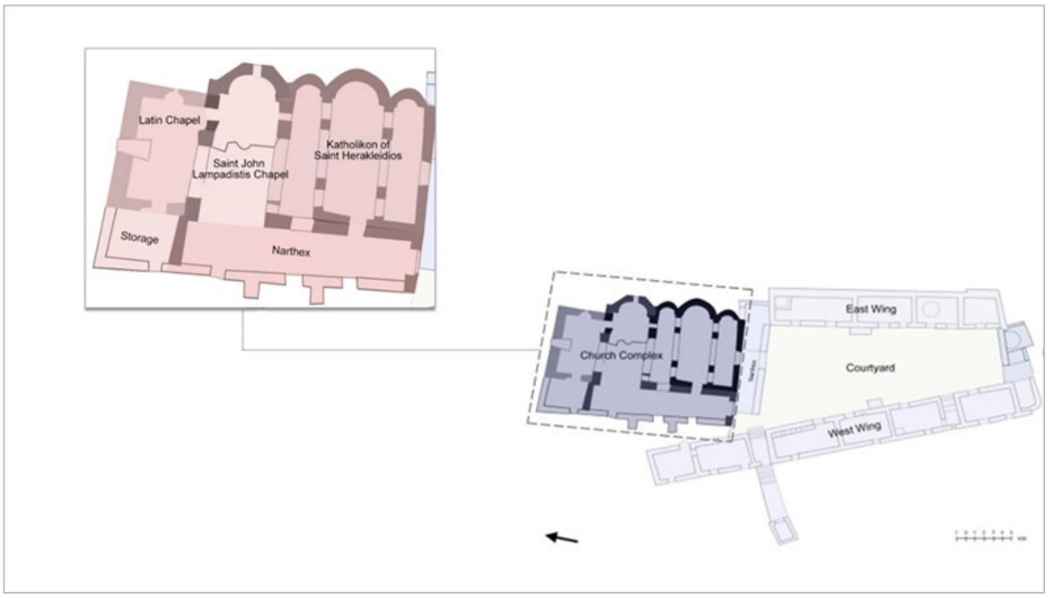


Figure 5. Space segmentation

Furthermore, the detailed architectural analysis aimed at understanding the technical-constructive techniques by studying surveys and historical data and adopting approved heritage vocabularies of Byzantine architecture. The main building typologies found in the monument are:

- The cross-in square Church of Saint Herakleidios, where the arches supporting the dome are carried on pillars, and barrel-vaults run lengthways covering the four corner bays and
- the barrel-vaulted structures of the Saint John Lampadistis Chapel and the Latin Chapel where the vaults are based on longitudinal walls, set along the vault axis (Papageorgiou 2007).

Apart from the vaulted structures of the Church, another key element of the building is the timber roof (figure 6), both regarding its construction and its morphology. The timber roof was analysed

and broken down into its subsystems as it is composed of an internal and an external construction system. The internal roof system is seated on the side structural walls, transferring the roof load to the walls while the external part is covered with hooked flat tiles (Kypridemos 2016).
The detailed study and understanding of the building's morphological elements provided the knowledge to build a comprehensive database of the structural systems, the architectural elements and their relationships.

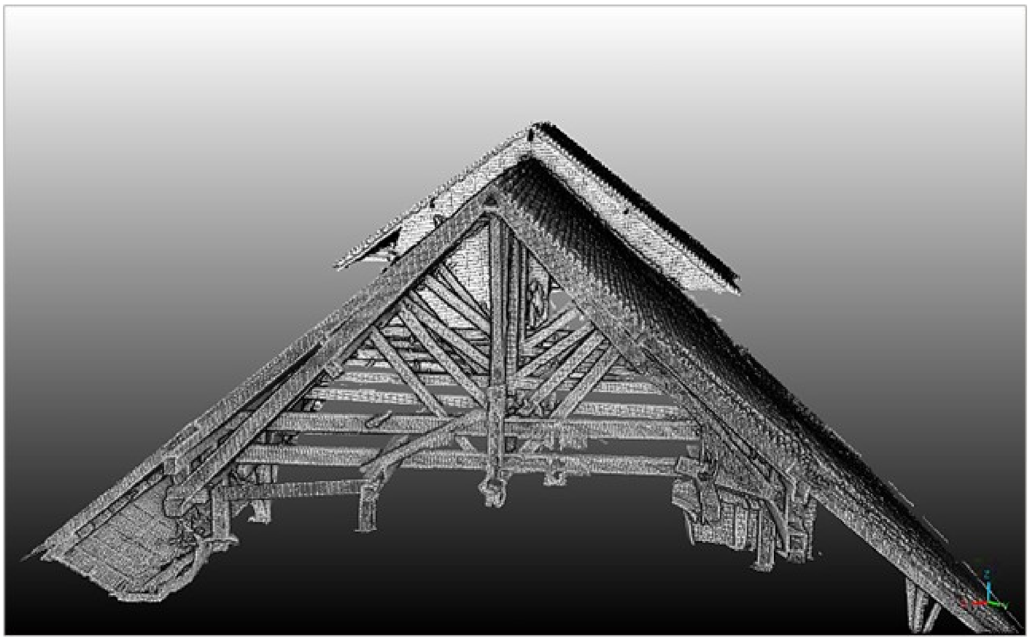


Figure 6. Point Cloud of the timber roof

2.3.3 The Authoring Process

Buildings of historic architectural styles often include highly complex geometries. The Saint John Lampadistis Church complex combines a set of curved geometries that present many irregularities due to the alterations of the initial design, the deformation of the load-bearing components and the degradation of the materials. Also, considering that the common BIM authoring tools are designed to address the needs of contemporary construction and include libraries of commercial products, the creation of features of specific architectural styles and periods requires a more complex and time-consuming modelling process to accurately represent the solid geometry (Woodward & Heesom 2019). Another challenging part of the authoring process was the combination of the different technologies. The variety of file formats coming from different software and areas of study can lead to compatibility issues, especially when transferring data between different software solutions. Moreover, when it comes to large-size files, the performance can be decreased significantly and geometrical details can be lost.

Taking into consideration the above-mentioned challenges and after testing different software (proprietary and free), a package of software solutions was chosen as more suitable for this pilot case:

- The point cloud and the mesh models were processed in *JRC 3D Reconstructor*[3], *CloudCompare*[4] *and MeshLab*[5] until a good quality of digital representation is achieved
- *Faro As-Built Modeler*[6] was used for the extraction of 2D drawings, profiles and orthophotos from the point clouds which combined with the 2D drawings obtained from previous surveys contributed to a more accurate decoding of the building's geometry
- *RecapPro (Autodesk)*[7] was used for the mesh model segmentation into semantic areas (figure 7)
- *Open Buildings Designer (Bentley)*[8] was used for the development of the Building Components Libraries, the creation of the 3D volumetric geometry and the export of the IFC model, an open international data exchange format that is ISO-certified[9]
- *SimpleBIM*[10] was used for the Data Enrichment of the IFC model through the creation of a customised template which hosted the additional datasets
- Prior to the authoring process, it is required that the building is broken-down into its architectural components, by performing a sort of reverse engineering (De Luca et al. 2006; Santagati et al. 2021). The architectural analysis that took place during the documentation process provided a detailed catalogue of the building components along with their semantic definition and the description of their physical characteristics. This catalogue was used to create a hierarchical taxonomy which assigns the building components to classes with common attributes and identifies their relationship. The developed classification system was built following international building classification standards such as Omniclass[11], which classify the building elements by their appearance and unique functional information.

3 https://gexcel.it/en/10-software/jrc-3d-reconstructor
4 https://www.danielgm.net/cc/
5 https://www.meshlab.net/
6 https://knowledge.faro.com/Software/As-Built/As-Built_Modeler
7 https://www.autodesk.com/products/recap/overview?panel=buy&us_oa=dotcom-us&us_si=b2f89383-2f80-493d-af8c-8273eed3e0f8&us_st=recap%20pro&term=1-YEAR&tab=subscription&plc=RECAP
8 https://www.bentley.com/software/openbuildings-designer
9 https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/
10 https://simplebim.com/
11 https://www.csiresources.org/standards/omniclass

Both the Building Components Libraries and the volumetric 3D geometry developed in the authoring BIM tool (*Open Buildings Designer*) follow this classification system, allowing the association of the graphical and non-graphical information up to the Object level (figure 8).

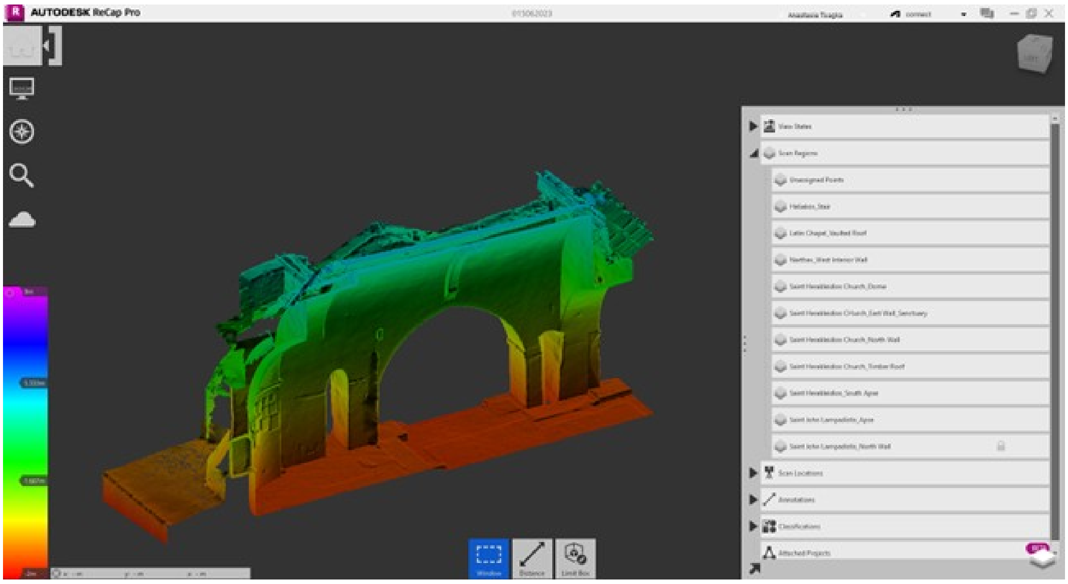


Figure 7. The mesh model segmentation into semantic areas in *RecapPro*

Figure 8. HBIM of the Agios Ioannis Lampadistis Monastery

<u>Data Enrichment</u>

The HBIM model was converted into an IFC file. To ensure that the HBIM serves as a useful tool during a conservation project, the IFC file was used to generate a more enriched BIM dataset. For this, a customised template was created containing property sets that can accommodate a wider range of information such as historical events, state of conservation, risk assessment (linked to the Risks Map developed by the Cyprus Institute within Task 1.2), intangible aspects, links to external collaborative platforms and repositories (figure 9).

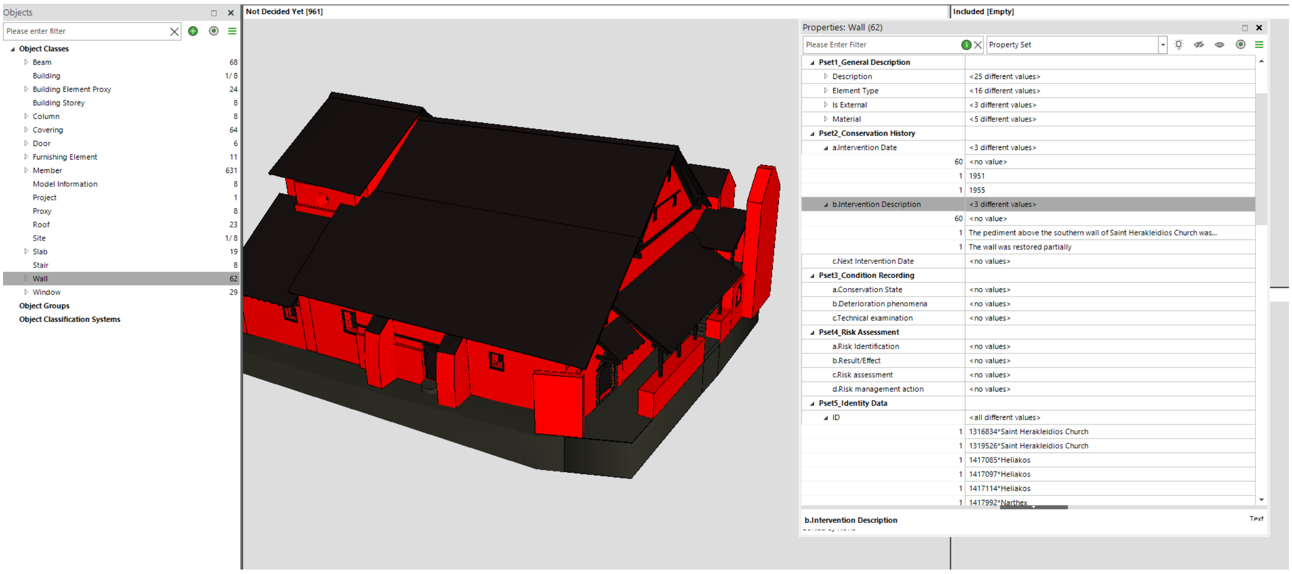


Figure 9. Creating new Property Sets in the IFC model for data enrichment

2.3.4 The Integration with Collaborative Platforms_

As per the implemented workflow, to provide direct access to the HBIM database to stakeholders involved in the technical analysis of the asset, the model was published at the Inception Core Engine (ICE) Viewer[12], an open-standard Semantic Web platform, compatible with the IFC data schema, developed within the H2020 "Inception project" (Maietti et al. 2022) and adopted as the 4CH project. Since the HBIM model was developed in accordance with the specifications and the guidelines developed in the 4CH project, the integration into the Inception platform was smooth and successful. The result is a web HBIM model that provides access to all the information stored in the BIM dataset. The Inception interface allows the selection of geometric elements, filtering them by space or by classification system, and provides access to related metadata up to an object level (figure 10).

12 https://thinice.arch.unife.it/Platform/ModelDetails?name=Saint-John-Lampadistis-Church-Complex&scope=general

Since the Inception platform can incorporate additional material related to the Heritage Asset, the model was linked to historical images and text descriptions detailing the monument's conservation history (figure 11).

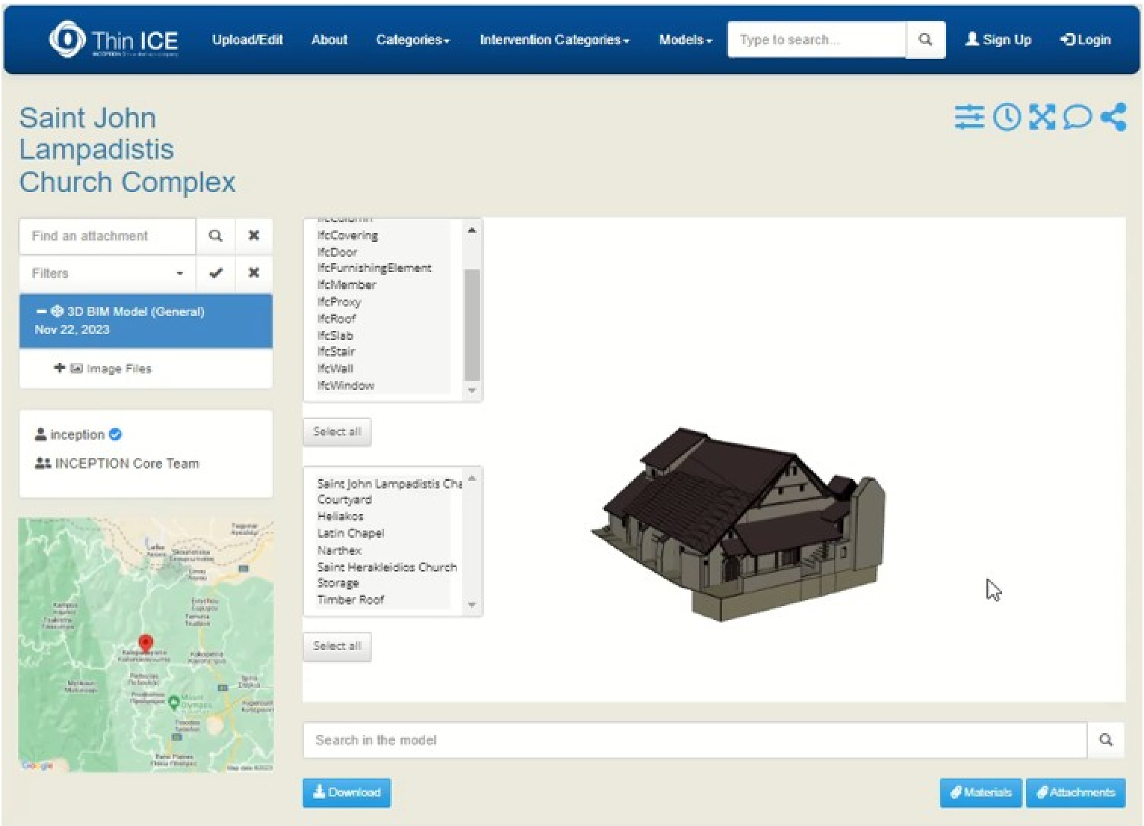


Figure 10. The HBIM model at the Inception Core Engine

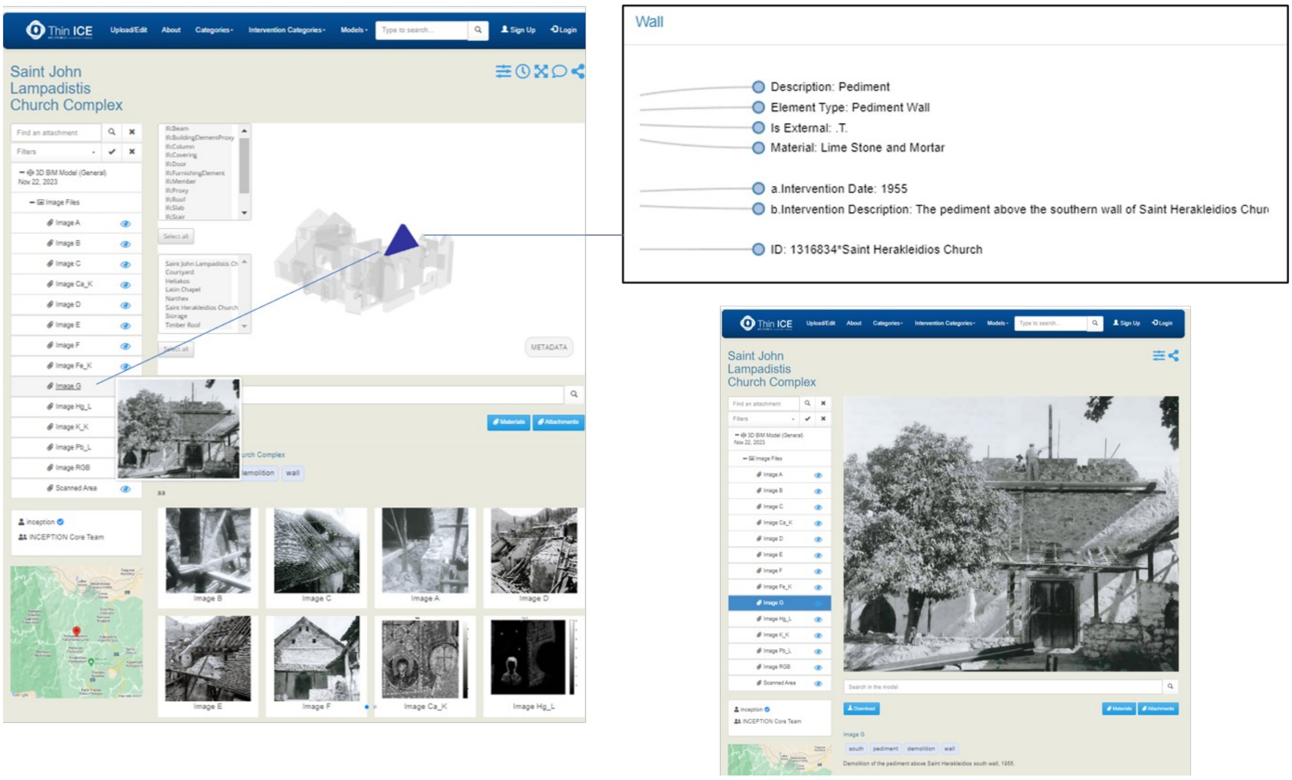


Figure 11. Integration of conservation data

Another useful dataset that is provided through the web HBIM model is the virtual representation of the building’s spaces. The model’s segmentation into building spaces facilitates the end-user’s navigation in the Inception interface and provides a more comprehensive dataset about the monument’s historical evolution and architectural analysis. Each building space corresponds to a virtual element that contains information about the building’s construction date, building typology, architectural morphological elements, intervention dates and intervention descriptions (figure 12).

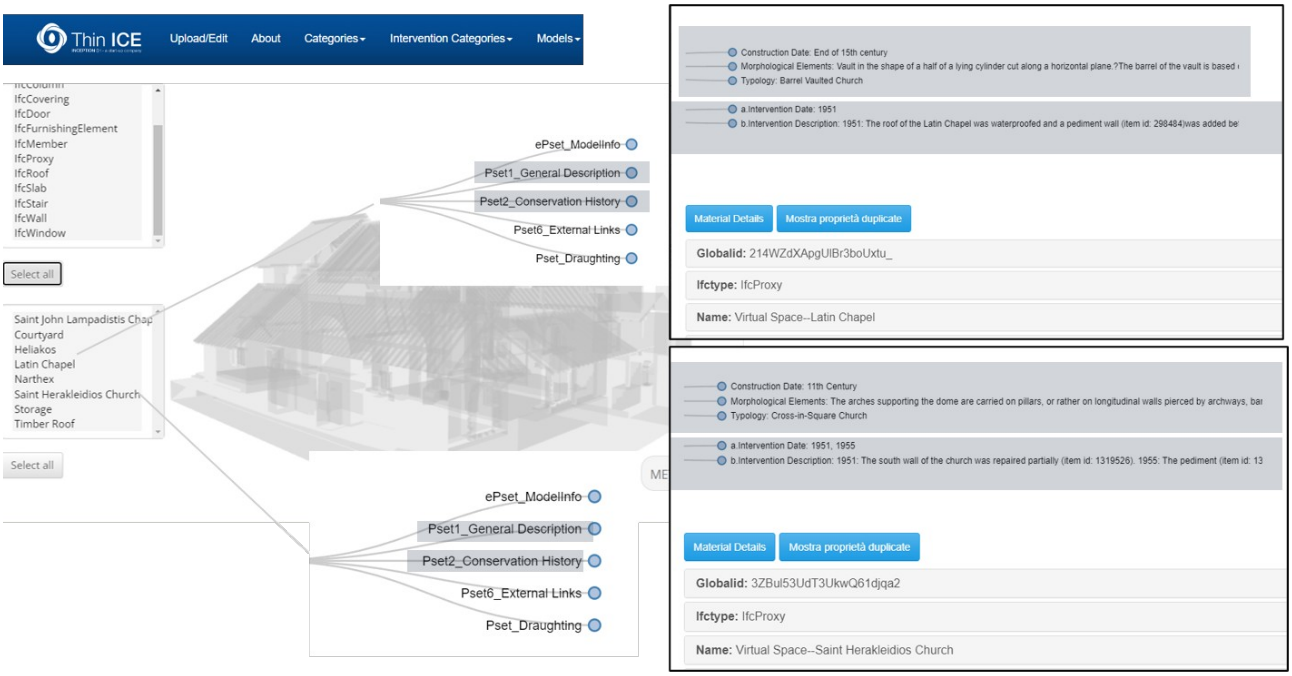


Figure 12. Architectural and conservation metadata connected to the building's spaces

The Agios Ioannis Lampadistis Monastery is connected to many stories and narratives that are part of its intangible heritage. These aspects are of high importance to be present in the HBIM, as they contribute to the monument's significance and heritage value. For instance, around the conch that hosts the reliquary with the Saint John Lampadistis skull, there are inscriptions written in the "karamanlidika" language (Irakleous & Bakirtzis 2020). For this reason, the graphical representation of the conch in the BIM model contains a hyperlink that directs to the related literature (figure 13).

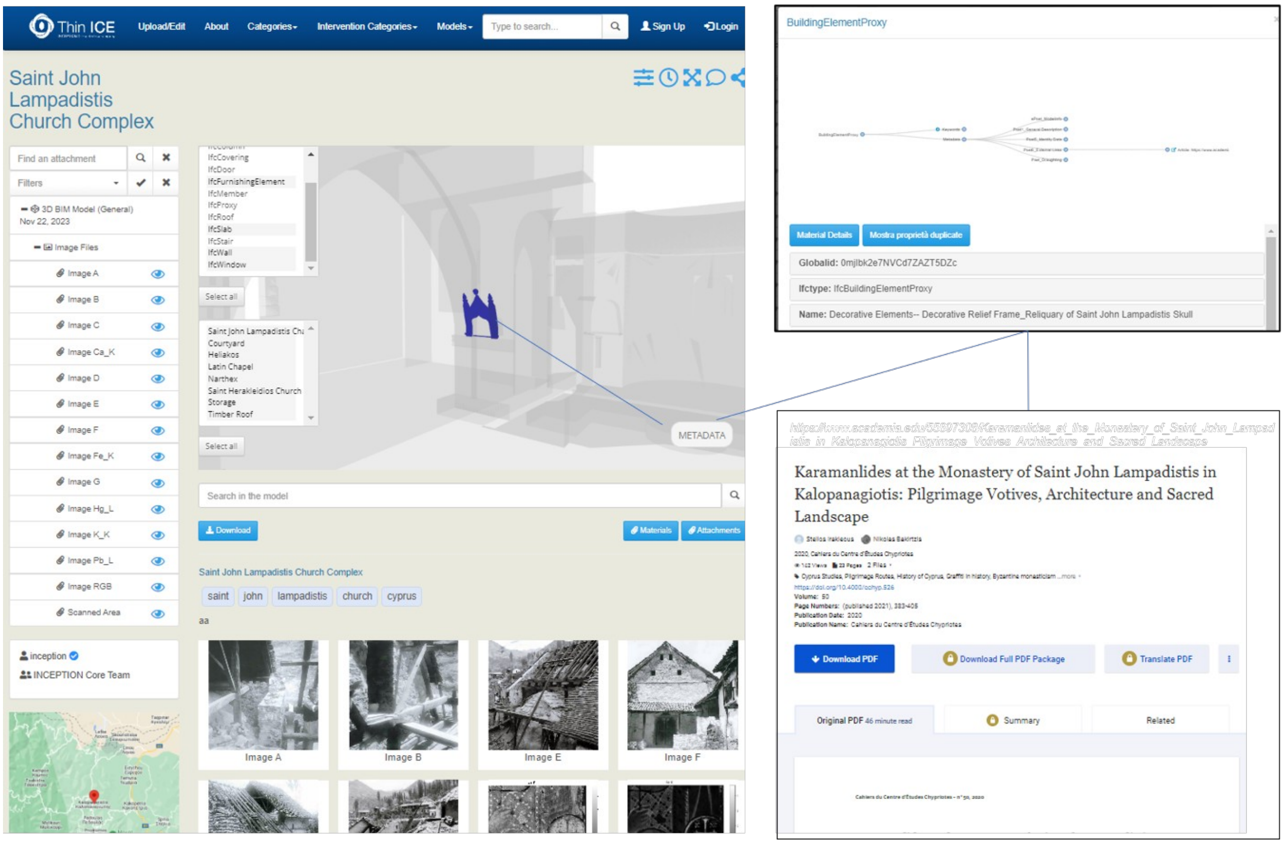


Figure 13. Capturing the intangible aspects of CH assets

Following the workflow for the implementation of a collaborative virtual environment, another solution has been implemented to manage the digital replica of the site and give access to a wider public both for conservation and valorisation purposes. The mesh model was loaded in the 3DHOP viewer[13], an open-source framework for the creation of interactive Web presentations of 3D models equipped with interactive tools and annotations (Potenziani et al. 2015).
Furthermore, a 360° panoramic of the monastery provides a virtual tour for the site valorisation and promotion.[14] All these solutions are interoperable and they are linked both to the HBIM model and the 4CH Knowledge Base. The various digital representations deliver a set of information that contributes to different areas of study and analysis, allowing a more comprehensive understanding of the heritage asset and facilitating better decision-making during the conservation process (figure 14).

13 https://3dhop.net/; https://apacwebstorage.hpcf.cyi.ac.cy/threedimensionalmodels/4CH/3DHOP.html
14 https://apacwebstorage.hpcf.cyi.ac.cy/panoramas/360/Lampadistis/index.htm

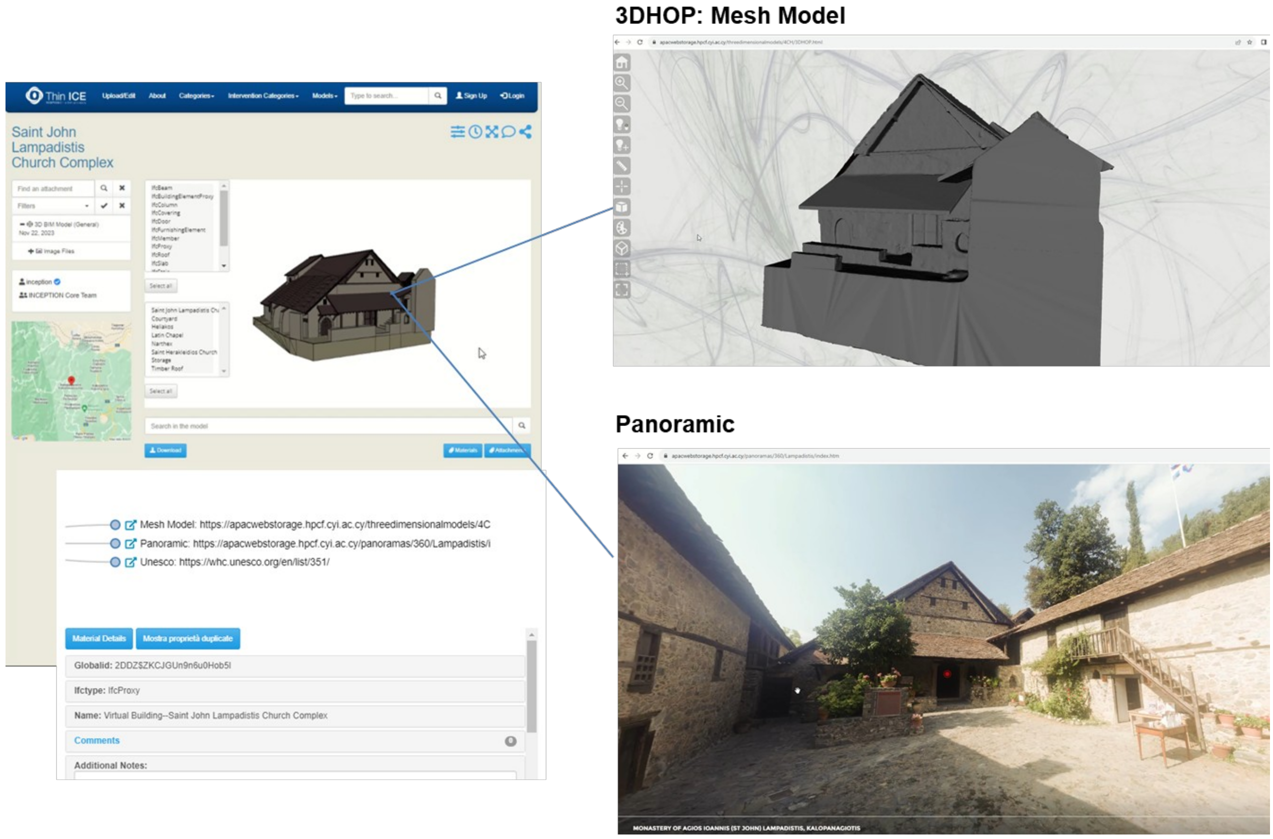


Figure 14. Access to different digital representations of the heritage asset

The Inception web platform sets the framework to support multidisciplinary collaboration through BIM, with access to data and related documentation. It serves as a trustworthy and comprehensive source of knowledge for the monument for the various stakeholders, to collect, manage and disseminate information for the different areas of study of historical buildings. Therefore, data from multidisciplinary analyses, such as X-ray fluorescence (XRF) and Dendrochronological investigations that took place in various parts of the monument are integrated into the BIM model through the Inception platform (figure 15).

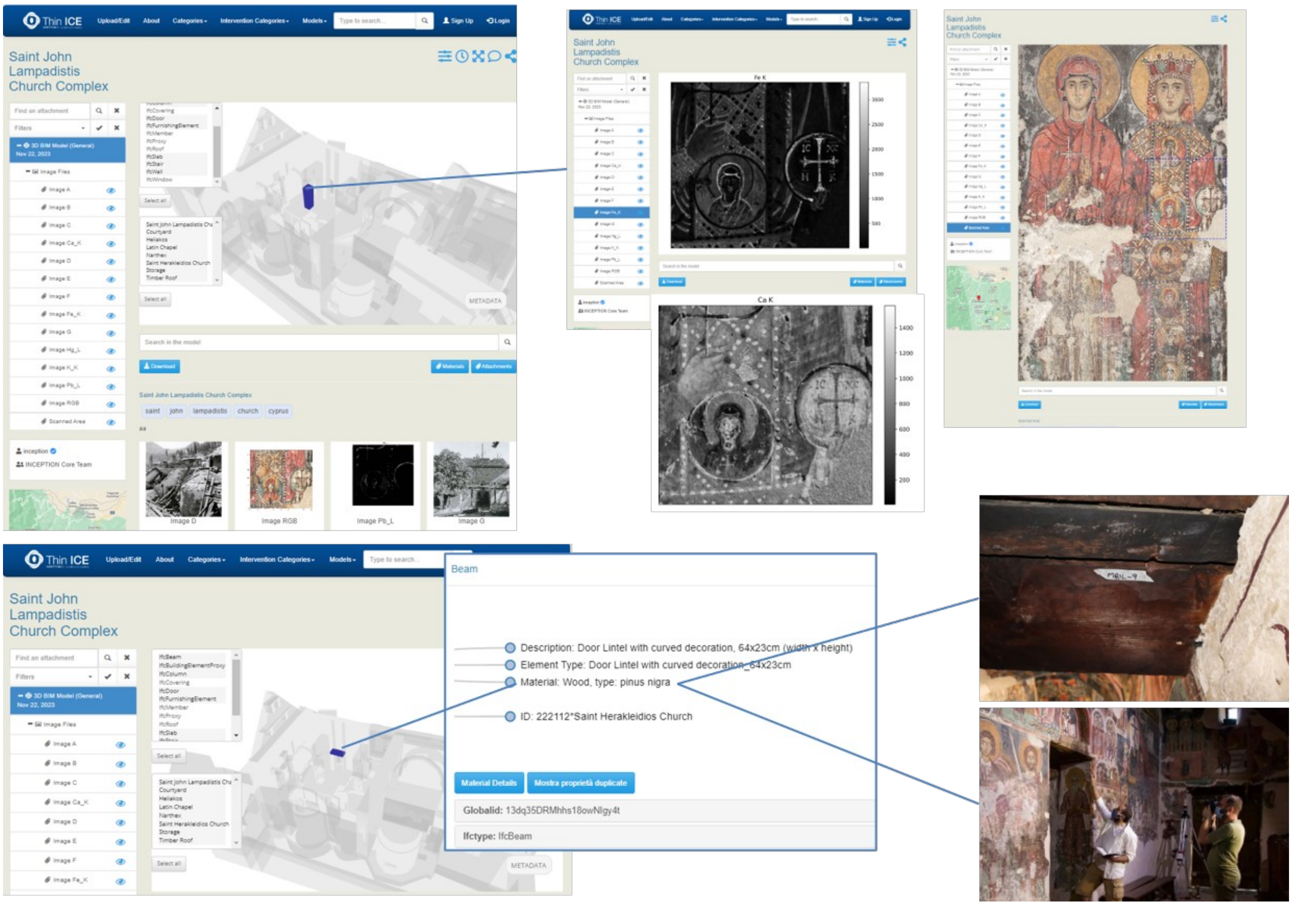


Figure 15. Integration of multidisciplinary studies

The Monastery of Agios Ioannis Lampadistis is a living monument where numerous events, natural and anthropic, continuously happen. Therefore, it should be regularly monitored and its digital representation should be constantly updated with new inputs. As a result, the workflow developed and tested for this pilot case, brings the concept of the Digital Twin closer, with the HBIM serving as a tool for on-site condition assessment and asset management. Indeed, such a tool facilitates not only the monitoring of the heritage asset but also provides a rich dataset for better decision-making in conservation maintenance planning, preservation, and valorisation strategies.

3. Pilot case 2. A digital workflow for conservation, preservation and valorisation. The Shatby Necropolis of Alexandria, Egypt

3.1 Methodological workflow for the CyI pilot cases implementation

As mentioned above, the Cyprus Institute has developed a methodological workflow for the implementation of pilot cases under its responsibility, which can serve within the future Competence Centre as a roadmap for the activities and services that the centre will provide for all types of Cultural Heritage assets. Indeed, the methodological workflow is perfectly adapted to different types of assets, with different geographical locations, needs and exposure to different types of hazards. Thanks to the developed circular workflow (figure 1), the future Competence Centre will provide stakeholders with solutions for the preservation of CH assets and the continuous monitoring of their well-being. In general, the workflow aims at developing collaborative solutions for risk assessment, conservation and valorisation of Cultural Heritage assets. In particular, with regard to the following pilot project, special attention has been paid to the digital documentation phase of the workflow, linking this step of the workflow and its activities also to the standards and guidelines for CH digitisation implemented within Task 4.2. Indeed, this step of the workflow is essential for the implementation of digital solutions for conservation, preservation and valorisation, as well as for supporting the Heritage Digital Twin concept.

3.2 The Shatby Necropolis of Alexandria

The Shatby Necropolis of Alexandria was selected as a pilot case based on several criteria from those established for Task 4.4. The importance and uniqueness as a Cultural Heritage site, the archaeological typology, the geographical location and, above all, its state of conservation and the serious threats and damages to which the site was exposed, led to the selection.

3.2.1 Description and Historical Background

The case study concerns the Hellenistic necropolis situated in Alexandria, Egypt. The use of the necropolis seems to have started at the end of the 4th century BC, a mere two decades after the city's foundation by Alexander the Great, a populous cosmopolis of more than 500.000 inhabitants. The cemetery's occupants were the Greeks of Alexandria, including the first generation of immigrants from Macedonia, Thessaly, Crete, Cyrenaica and Asia Minor. This makes it the earliest surviving funerary complex in Alexandria and a site of considerable uniqueness. The necropolis was constituted of a vast network of underground corridors, galleries, chambers and multi-chambered complexes (*hypogea*). In the past, the necropolis spanned an area of approximately 30.000 m². Regrettably, the greater part of the archaeological zone has been obliterated by the expansion and urban development of the city, already since the later Ptolemaic period (2nd-1st century BC). The current area of the Hellenistic necropolis occupies approximately 3500 m², and it is situated at the heart of modern Alexandria, in the present-day area of Shatby, not far from the Bibliotheca Alexandrina (figure 16).

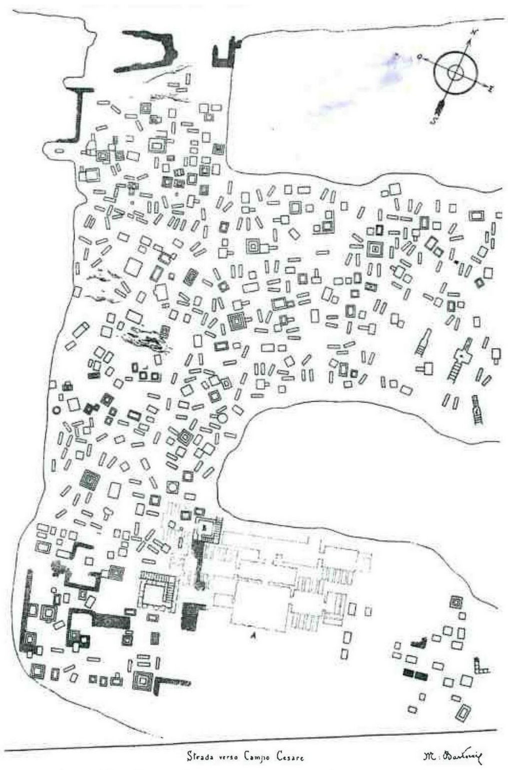


Figure 16. Extension of the necropolis at the beginning of the 20th century.

The archaeological interest in the area of Shatby goes back to the last quarter of the 19th century with no organised excavations. Giuseppe Pugioli and Alexandre Max de Zogheib were among the early local explorers. Even Heinrich Schliemann, the notorious excavator of Troy, would sporadically dig in Shatby during 1888. More organised investigations in the area of Shatby began by the turn of the 20th century, by Giuseppe Botti, the first director of the Graeco-Roman Museum. Investigations were interrupted by Botti's death in 1903, but continued by Evaristo Breccia, his successor in the directorship of the Museum. Breccia systematically excavated the necropolis from 1904 to 1910 (Breccia 1905; Breccia 1912 - see reference section). During that period, the excavated area was preserved as a visitable archaeological site (figure 17).

Figure 17. A view of a *hypogeum* of the Shatby necropolis as seen in an old photograph at the time of the discovery

Unfortunately, in the period following the discovery, the site met its gradual deterioration, being exposed to weather conditions and invading waters from underground. Furthermore, rain caused soil concentrations from the excavation to spread across the area, resulting in the invasion of the archaeological site in the form of mud. The underground structures of the necropolis were therefore covered under a thick layer of water, debris and dump (figure 18). Such a situation transformed the site into a neglected place both for visitors and archaeologists.

Figure 18. View of the mud invading the archaeological area (left); view of the chambers invaded by waters from underground and dump (right)

Partial rescue excavations were made by the Egyptian Antiquities Service in the early 1990s, and by the Augsburg University during 2010-2013. Nevertheless, they were the only exceptions in this course of oblivion and decay.
In 2020, the Archaeological Society of Alexandria sponsored by the A.G. Leventis Foundation and under the concession of the Ministry of Tourism and Antiquities of Egypt, initiated a project ("The Alexandrian Necropolis Project") for the complete revisiting of the necropolis, involving the Cyprus Institute due to its expertise and role as a reference for the East Mediterranean. The Cyprus Institute further implemented the aforementioned workflow developed for the previous pilot case, especially for the (digital) documentation part, including the logistics of a mobile laboratory for digital documentation in the East Mediterranean and beyond (Koutoupas et al. under review).

3.2.2 Objectives of the 'Shatby Necropolis' pilot case

The site, its characteristics and its peculiar situation in terms of hazards and damages affecting Cultural Heritage is an ideal pilot case to test and simulate a digital workflow aimed at Cultural Heritage conservation, preservation and valorisation and the activities that the Competence Center will develop. In particular, for the specific pilot case, the digital workflow application aims to achieve several objectives:

- First of all, the complete digital documentation of the site, utilising advanced 2D and 3D imaging technologies and selected applications of spectral and technical photography, aims at creating a detailed 3D model that captures the site's current condition and state of preservation. Such a digital model provides improved and detailed documentation of the site compared to the past and incomplete 20th-century plans. Furthermore, the digital documentation of the site enables the identification of all alterations (both natural and human-made) that have occurred at the site since its discovery, at least as captured by the 1900s plans. For instance, a crucial part is the tracing and preservation of the almost faded painted decoration of the funerary complex due to its bad conservation state.

- The complete scientific digital documentation of the site aims to provide an invaluable record that allows for monitoring any threats the site has to confront in the present and the near future. That can be used for monitoring the site's state of conservation over time.

- Finally, the digital documentation aims at the production of digital solutions for the site's valorisation and promotion.

3.3 Implementation of a 'digital' workflow for conservation, preservation and valorisation

3.3.1 Compatibility with 'Standards and Guidelines to CH digitisation' (T4.2)

An important step in implementing the digital documentation part of the workflow, especially for the current pilot case, is compatibility with standards and guidelines for Cultural Heritage digitisation. Indeed, in the context of digitisation, criteria and recommendations are crucial to ensure the long-term preservation, accessibility and interoperability of (digital) cultural heritage assets. Therefore, following the Standards and Guidelines for Cultural Heritage digitisation developed within the 4CH project (Task 4.2), the implementation of the current pilot case started with the definition of the general objectives of the Cultural Heritage digitisation project. Based on the general objectives that a digital documentation process should address, such as for intervention purposes, knowledge enhancement or valorisation, the digital documentation aims to create an accurate 3D model of the Alexandria Necropolis site. This model is intended for documenting and analysing its exposure to risks, monitoring its state of conservation for maintenance and restoration purposes, collecting data for further research on the site, and creating digital media for its valorisation, including the promotion of tourism (table 2).

Intervention	Maintenance, Restoration
Knowledge	Research, Documentation
Valorisation	Tourism

Table 2. General and specific aims addressed by the digital documentation and the implementation of the Alexandria Necropolis pilot case

Task 4.2 emphasised the importance of developing a workflow and defined the 4CH project's contribution to the 3D digitisation process by dividing it into three parts: data capturing, data processing and data storage and access. In line with the recommendations on standards and best practices for 3D digitisation developed by the above-mentioned task, this pilot case shows, in relation to the data acquisition phase, how different techniques and methodologies can be integrated and used for the digital workflow process. Indeed, an important element is the documentation of the entire digitisation process, including equipment specifications, workflow diagrams and software used. For this reason, this report presents the selection of digitisation equipment that complies with established standards and ensures that the chosen technology provides high-resolution data, accuracy and compatible formats for long-term preservation. Specifically, the integration of Terrestrial Laser Scanning and Terrestrial Photogrammetry has been selected for the current pilot project. In addition, archaeological literature, legacy data and previous conventional surveys have been collected, digitised and integrated as a source of information. The subsequent phase involves digital data processing to generate high-quality point clouds, mesh models (i.e., 3D models) and data for the aforementioned purposes.
Storage and access also play an important role in ensuring long-term preservation and eventual migration to new formats or repositories. In particular, the choice of platforms is another key issue

in ensuring access and interoperability: this needs to be done by assessing who the users of the case study are and what their needs and expectations are. Such a choice, using different systems and platforms, guarantees access to the content for the relevant audience and promotes interoperability.
Therefore, for the data storage and access phase of the Shatby necropolis, several digital solutions have been implemented and made available, through the use of viewers and platforms, for the storage, access, management and analysis of the digital dataset representing the archaeological site for its conservation, preservation and valorisation (table 3).
Ensuring that the pilot case conforms to established standards and guidelines for cultural heritage digitisation will contribute to the preservation and accessibility of a valuable cultural heritage asset such as the Alexandria Necropolis.

Data capture	Laser scanning, Photogrammetry
Data process	Point cloud modelling, 3D object modelling, Technical drawing, Texturing, Rendering
Data storage and access	Viewers and platforms

Table 3. Standard and guidelines for Cultural Heritage digitisation (D4.1 'Report on standards and guidelines'). On the right, the features that characterise the Alexandria Necropolis pilot case

3.3.2 Digital documentation

As mentioned above, in this pilot case, various techniques and methodologies were integrated and applied to the data acquisition process of the archaeological excavation and all its associated data. Advanced 2D and 3D imaging technologies, as well as selected applications of spectral and technical photography, were used for the complete digital documentation of the site. Detailed documentation was necessary to provide a detailed/comprehensive record of the monument and to enhance the rather incomplete documentation from the 1900s. Digital documentation of the site was also necessary to identify any changes, both natural and human-made, to the site since its discovery, at least as recorded on the 1900s plans.
Digitisation of archival data, including archaeological studies and old images, was also used as a source of information, along with previous conventional survey studies provided by the Archaeological Society of Alexandria. High-resolution 3D scanning provided detailed and accurate representations of the remains and the surrounding landscape, preserving them in a digital format that could be used for multiple purposes. The result was a large dataset for documenting the current structure and geometry, as well as the state of conservation due to exposure to various risks.

<u>Data capture</u>

The primary objective of the 3D documentation of the Shatby necropolis was to obtain precise and accurate geometry and capture detailed textures at a high resolution. Therefore, an integrated approach of Terrestrial Laser Scanning and Terrestrial Photogrammetry was chosen (Figures 19, 20). Specifically, the laser scanning data is used to create a high-fidelity geometry, and the photogrammetric data is used to produce high-resolution texture maps. Two field surveys were required to complete the data acquisition process: the first took place in May 2022 and the second in January 2023. A Faro S150 laser scanner was used to collect a total of 332 scans to cover the entire archaeological area. To maintain data uniformity, various settings and resolutions were used to capture different areas and details of the large site. In addition, over 5000 photographs were taken using a Canon 80D equipped with a Canon EF 24-105 lens to create the 3D textured model (Table 4).

Fieldwork	Date	Area 3D documented	Laser scanner	3D scans	Camera	Photographs
20 days	May 2022	~3200 m²	Faro S150	332 scans	Canon 80D + Canon EF 24-105 lens	5898 photos
5 days	January 2023					

Table 4. Technical specifications of the data capturing phase: these summarise the date and duration of the fieldwork campaigns, the area digitally documented, the technology and tools used and the results obtained

Figure 19. 3D documentation using laser scanner technology


Figure 20. Photogrammetric documentation of the site

Data process

According to the workflow described in the 4CH guidelines for the 3D digitisation process, the subsequent part consists of data processing. For the current pilot case, the data obtained during the data capturing phase were processed according to the following pipeline:

- Laser scanning data processing
- Photogrammetric data processing
- Integration of the two resulting datasets

Specifically, the laser scanning data was first processed in Autodesk Recap[15] software and aligned using cloud-to-cloud registration (Figure 21). The completed point cloud was then cleaned and exported as an E57 file format for import into further data processing software. In parallel, the photogrammetric data was first processed in Photoshop Lightroom[16] to ensure uniform lighting and white balance correction across all the photographs in the dataset. The corrected images were then imported and processed in Reality Capture[17] software. The laser scanning results were then imported into Reality Capture software to align and integrate them with the photogrammetry data already processed in the same software. This pipeline was designed to achieve the highest accuracy of 3D model geometry, using the high-quality mesh obtained with the scanner data and

15 https://www.autodesk.com/products/recap/overview/
16 https://www.adobe.com/ie/products/photoshop-lightroom.html
17 https://www.capturingreality.com/

the high-quality texture generated by photogrammetry. The resulting high-resolution textured mesh of the site consists of a large dataset of 1 billion triangles made up of 4081 parts. The texture layer consists of 59 textures with a resolution of 8192×8192.

Figure 21. Views of the point cloud of the site obtained in *Autodesk Recap*

Due to the size of the resulting output, the 3D model was optimised by implementing two key strategies. First, the mesh was sub-sampled to reduce the number of polygons to 25 million polygons. Second, the high-resolution textures were projected from the high-definition model to the simplified version. By using this process, the geometrical details of the high-definition model are effectively preserved in the textures' information in the form of depth maps (figure 22). The resulting model is an accurate and manageable dataset for carrying out any analysis and developing several solutions for the conservation, preservation or valorisation of the site.

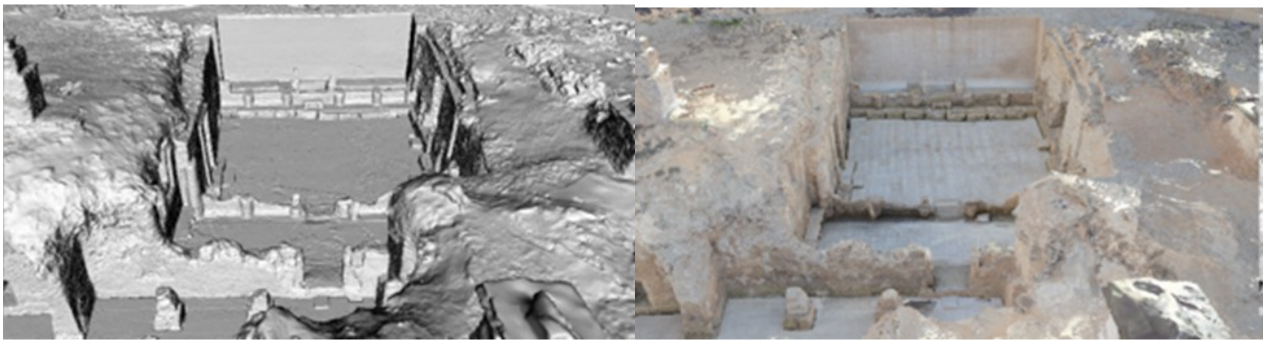


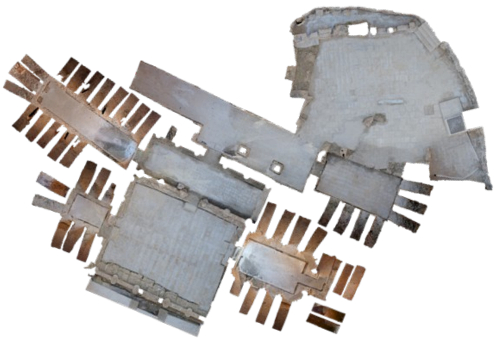
Figure 22. View of the mesh (left) and of the textured model (right) of the Shatby Necropolis

3.4 Conservation, Preservation and Valorisation Solutions

3.4.1 Data storage and access

In line with the recommendations on standards and best practices for 3D digitisation, the final step in the digital workflow is data storage and access.

The 3D model itself is an ideal platform for accessing information and for studying and analysing the site. The first result is the production of new, updated, precise and accurate data from the 3D model for the analysis of the site. For example, the 3D model of the Hellenistic necropolis was used to produce ortho-projections of the site, which were then traced in AutoCAD[18] to create plans and sections (figure 23). In this way, a 3D model allows conservation specialists and site managers to extract data and define tailored actions to conserve and restore areas of the site that are vulnerable to potential damage from various hazards.



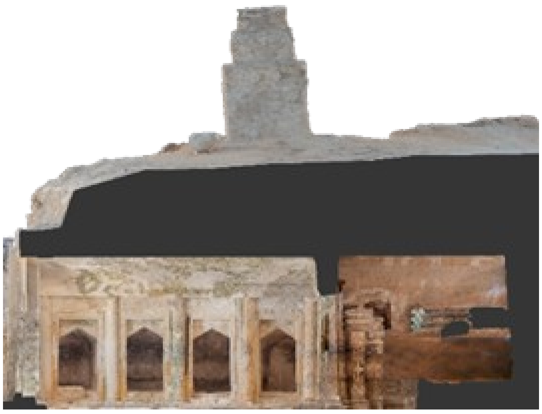


Figure 23. 2D orthophoto of the plan (left) and an orthophoto section (right) of the site

In this particular case, plans and sections extracted from the 3D model of the site were also used for comparison with the old data. Due to the accuracy of the digital documentation, the new data allowed the identification of measurement errors in the old plans of the site and improved the knowledge of the archaeological asset (figure 24).

18 https://www.autodesk.com/products/autocad/overview/

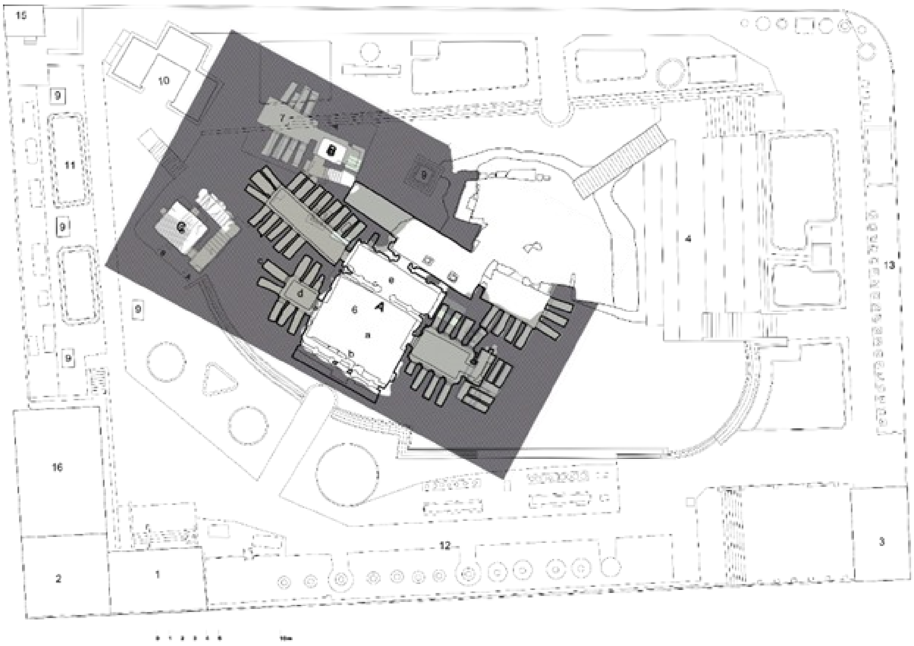


Figure 24. Superimposition of the old plan with the new one obtained from the 3D model.

Conservation and preservation solution with Potree[19] viewer

Furthermore, following the digital workflow, once the digital model of the site has been obtained, various digital solutions have been implemented through the use of viewers and platforms to store, access, manage and analyse the digital replica of the site for various purposes. In the case of the Shatby necropolis, a research and analysis solution for the conservation and preservation of the site was implemented using Potree, a free and open-source WebGL-based point cloud viewer for large point clouds. For visualisation in the point cloud viewer, the model was transformed into a Potree-compatible format using a programming compiler. The 3D model was then uploaded to the viewer. Afterwards, the viewer was embedded into the CyI DIOPTRA[20] web storage for online visualisation and interaction of the 3D model in web browsers (figure 25).

19 https://potree.github.io/
20 https://dioptra.cyi.ac.cy/

Figure 25. Visualisation of the Alexandria necropolis in Potree within the CyI DIOPTRA digital library

This solution, specifically designed for researchers and specialised users and stakeholders, such as architects and engineers of the institutions responsible for the protection of the archaeological site, allows professionals to manage and analyse the 3D model and monitor the state of the archaeological site, as well as develop customised plans for risk mitigation, conservation and restoration of the site. Indeed, this specific digital solution offers several options for visualising and analysing point clouds in web browsers. Users can navigate the point cloud, measure distances and angles, heights, areas and volumes, clip the limit box to view only a section of the cloud and extract sections and plans (figure 26).

Conservation and preservation efforts can benefit from the use of 3D models by providing a comprehensive view of the site's condition, making the conservation process more efficient and cost-effective. The 3D model embedded in such a platform facilitates the study and continuous monitoring of the site's conservation status, for example, as in the current pilot case, by analysing and mapping the damages and discolouration caused by the site's frequent submersion in water or assessing the structural integrity and deterioration of the stone.

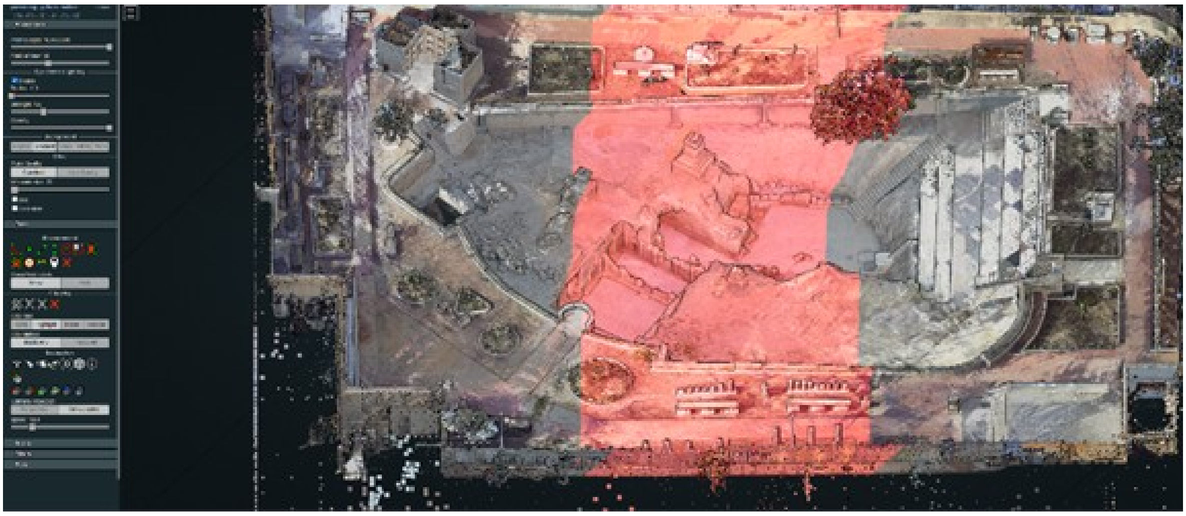


Figure 26. Analysis of the site through the use of the Potree measurement tools

Valorisation solution with 3D Vista[21] viewer

Another digital solution was implemented for the Hellenistic necropolis of Alexandria. In this case, the development of a 360° panoramic image and interactive tour showcases the multidisciplinary work carried out to document and preserve the site, as well as to enhance and promote it.
Virtual tours are immersive digital tools that allow users to visit virtual locations accessible from any computer or mobile device, providing a simulation of being on the site. In addition, information can be linked to these virtual tools to facilitate the user's understanding of the environment shown. The reconstruction of this environment is based on the integration of a series of 360° panoramic images that allow a complete visualisation of the space generated by specialised software.
Renderings of the 3D model were used to create the virtual tour of the Shatby Necropolis. Firstly, 3D modelling software (e.g., Autodesk 3D Studio Max[22]) was used to remove unwanted geometry, such as vegetation and surrounding modern buildings, from the previously obtained 3D model. The 3D model was then placed in a larger 3D environment with a verisimilar environment texture, properly lit and rendered as a panoramic image. Each rendering was then separately enhanced in Adobe Photoshop. In 3D Vista, the renderings were stitched together and hotspots were overlaid to navigate the space and simulate the tour. Once the 3D panoramic tour was created, various data were integrated into the 3D Vista software to create an interactive 360° panoramic tour of the site. Multidisciplinary information was added to the panoramic tour. Figure 27 shows the construction of the scenes in the back-end through the integration of different data, such as 2D drawings and plans from surveys provided by the Archaeological Society of Alexandria, literature, ancient sources, excavation diaries and texts from archaeological studies, and old images from archival data, to create storytelling about the archaeological site of Shatby Necropolis.

21 https://www.3dvista.com/en/
22 https://www.autodesk.com/products/3ds-max/overview/

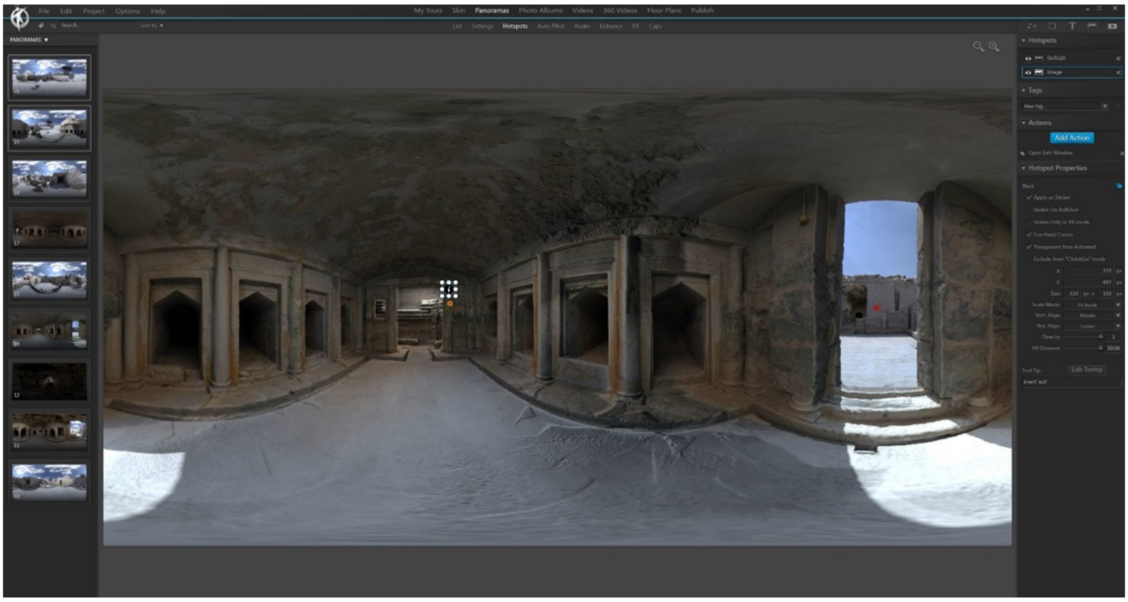


Figure 27. The back-end of the 3D Vista software for the implementation of a panoramic tour

This digital solution allows the public to take a virtual tour of the site, accompanied by multidisciplinary information, activated by clicking on the hot spots (pop-up information with images and descriptions) installed in the scene. The 360° panoramic image and the interactive tour integrate aspects of the monument that go beyond its morphological characteristics, such as the state of conservation (e.g., conservation activities, state of the art, risks), the historical information of the monument (e.g., archaeological excavations) and the 3D documentation carried out for the purposes of documenting the heritage and its conservation, valorisation and promotion. In addition, the 3D panoramic tour also offers an augmented visit with respect to the "real" one, since some parts of the site are inaccessible to visitors and are only available in the virtual tour (for example, the internal part of the loculi with human remains and artefacts can be visited as it was before the final removal).

Furthermore, beyond the valorisation objective, this type of digital solution, displayed in the newly established Shatby archaeological site information centre and online, allows the wider public to access and acquire knowledge and be educated about the site, thus promoting its future preservation (figure 28).

Once the digital solution was implemented, the 360° interactive tour was published in the CyI DIOPTRA[23] digital library.

23 https://dioptra.cyi.ac.cy/

Figure 28. The virtual tour of the 3D reconstructed site

Both the Shatby Necropolis and the Ayios Ioannis Lampadistis Monastery applications were eventually incorporated into the 4CH Knowledge Base for retrieval via the 4CH (future Competence Centre) platform (figure 29). Indeed, storage in a digital repository facilitates the organisation and management of the vast amount of data and information, streamlines the research process and promotes sharing and collaboration among the scholars involved. It also ensures the accessibility and long-term preservation of the cultural heritage, guaranteeing its up-to-date study, monitoring and conservation.

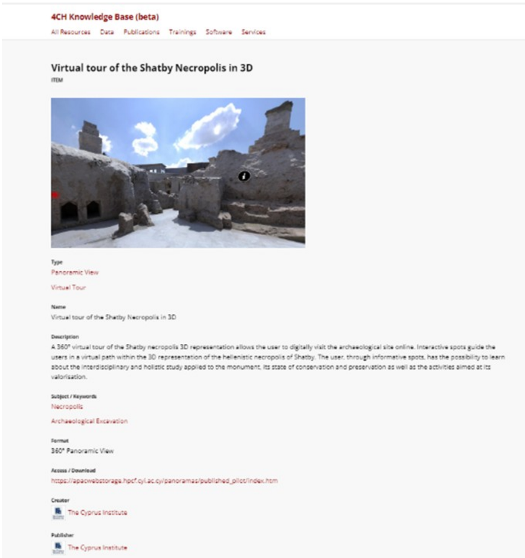


Figure 29. The digital solutions incorporated in the 4CH Knowledge Base

3.4.2 Mitigation Strategies and Actions

This is the last - but not the final - step of the workflow developed for the implementation of the CyI pilot cases. In fact, after providing detailed digital documentation and digital solutions aimed at the well-being of the CH assets, the pipeline returns/circle back to the stakeholders and site managers. It assists them in planning mitigation strategies and actions for the conservation, preservation and valorisation of the site, maintaining continuous monitoring through a circular digital workflow.
Indeed, as in the case of the Shatby necropolis, several conservation, preservation and valorisation actions have been carried out, bringing numerous benefits to the revitalisation of the site. Cleaning, restoration and maintenance of the ancient remains have been completed, as well as an up-to-date archaeological survey for monitoring its state. In addition, the conservation and preservation works have solved the problem of water and soil infiltration, guaranteeing the stability of the structures and their conservation, as well as improving the experience of visitors to the site. In addition, the development of digital multimedia experiences in the information centre and online has enhanced the visitor experience (figure 30).

Figure 30. The new set of the Shatby Necropolis site after the conservation and valorisation works and the inauguration to the public

4. Pilot case 3: Saint Laurentius Church of Ename, Belgium

This pilot concerns the Saint Laurentius Church of Ename in Belgium. The pilot project has been implemented by Visual Dimension to demonstrate the digital technologies and the solutions adopted to visualise hypotheses on its former structure in the period around 1000 AD while preserving its current physical state. In particular, the pilot case demonstrates the implementation of a workflow for the creation and re-use of relevant data and their links with the monument documentation, with an additional application to valorisation, storytelling and education by virtual reality reconstructions.

4.1 Virtual reconstructions of monuments and their importance for conservation and restoration

3D models and virtual reality have been used since many years (at least, since the last decade of the 20th century) to display the hypothesised original shape of monuments and sites, now destroyed, damaged or heavily changed. The main goal of this work concerns their valorisation, to explain to the public how the monument appeared in the past and – in some cases – its history, visualising the stages of its shape. The same methodology has been applied to other significant archaeological items, such as statues, artefacts and even human remains. In both regards such reconstructions may also have a value for scientific research: often research papers include drawings of the pristine appearance of archaeological assets as resulting from investigations, to accompany and illustrate the results. However, due to the prevailing technique for publications, in most cases still conceived on paper or on its digital equivalent, a digital document mimicking paper (for example PDF), reconstructions are published in most cases as static and bi-dimensional, although the use of a multimedia apparatus including 3D models is gaining consensus, relying on online publication with attached material.

When the reconstruction concerns minor details of an artefact, for example the missing part of the hand of a statue or a small part of the façade of a monument, some people use (perhaps improperly) the term “digital restoration”, which instead should be preferably reserved to the restoration of born-digital material. Possibly this terminology is used in these cases to propose the virtual reconstruction of small details as an alternative or a preliminary study for their actual physical restoration.

The use of virtual reconstructions in archaeology dates back to the last decade of the 20th century, when 3D computer graphics became more largely available. A milestone for these applications was the publication of the book *Virtual reality in Archaeology* (2000), which summarised the state of the art at the time[24]. Since then a huge number of virtual reconstructions[25] has been published to illustrate to visitors the probable shape of a monument in the past or, less frequently, to accompany scientific work on the same topic.
This research field filled a gap between “interpretive restoration”, as Eugène Viollet le Duc named its rebuilding of parts of the walled city of Carcassonne in the years 1852-1879, and the reaction of many architects and architectural historians who promoted “conservative restoration”, i.e. the

24 J.A. Barcelo, M. Forte and D.H. Sanders (2000) *Virtual Reality in Archaeology*, BAR Publishing, https://doi.org/10.30861/9781841710471
25 Google scholar reports about 74,000 results for the search “virtual reconstructions archaeology”, and 255,000 if the search is extended to “virtual reconstructions cultural heritage”, which of course includes the above.

consolidation of the architectural or archaeological remains, “as is”, i.e. in their current state. This controversy was still open when Arthur Evans carried out the excavation at Knossos in 1900-1931 and decided to ‘restore’ the Bronze Age palace, in use from around 1900 to 1350 BC, using modern building materials. Also this decision was subject to strong criticism as the shape imagined (and physically built) by the archaeologist and by the architects collaborating to the reconstruction was broadly (and in some cases freely or abusively) inspired by the supposed shape of the monument in the Bronze Age, and some important details were invented from scratch.

The topic was addressed by the publication of the *Athens Charter* (1931) and, in a conclusive mode, by the *Venice Charter* (1964), which indicated precise rules for the conservation of monuments. However, the discussion did not end, with the argumentation that the Venice Charter was biased by “Modernist pre-conceptions”. Later on, the issue was revisited by the *Nara Document* (1993), which focused on and further explored the concept of “authenticity”. However, the discussion did not end, because of the different intrinsic nature of monuments in different parts of the world, which opened a debate still affecting international heritage organisations such as UNESCO and ICOMOS. It was marked by the Timbuktu world heritage site partial reconstruction, approved by UNESCO, while, on the contrary, the reconstruction of the Bamyan Buddhas in Afghanistan destroyed by Talibans in 2001 was halted by UNESCO, so now only the visual documentation of the two statues exists.

Since the nineties of the 29th century the increasing availability of computer graphics and its applications to reconstructions allowed the creation of a huge number of virtual reconstructions where it was uneasy to identify the ones based on solid scientific bases and the purely imaginary others. This aspect was pointed out in research papers published at the beginning of the 21st century[26], including one[27] proposing that virtual reconstructions should be curated in a way similar to the curated edition of ancient documents. This paper is still one of the most cited studies on the matter. The issue was definitely addressed by the London Charter (2005)[28], which dictates the requirements for a virtual reconstruction to be considered as scientifically based. In sum, the London Charter requires quoting the reference to the background studies on which any virtual reconstruction should be based. This corpus must be available for inspection by scholars. Imaginary reconstructions – for example to explain monuments to visitors when there is no sufficient background research – may be used, but must be qualified as such. The forthcoming use of Artificial Intelligence to create virtual reconstructions may obscurate the reasoning that lead to them, and paves the way for rediscussing the requirements of the London Charter.

26 Many of such papers are included in the proceedings of the VAST Conference held in 2000 and published in 2002: F. Niccolucci (ed.), 2002. *Virtual Archaeology: Proceedings of the VAST Euroconference, Arezzo 24-25 November 2000* BAR Series 1075

27 Among the papers presented at the VAST Conference, the most quoted one is: B. Frisher, F. Niccolucci, N. S. Ryan and J. A. Barcelo “From CVR to CVRO: the past, present, and future of cultural virtual reality”, *Virtual Archaeology: Proceedings of the VAST Euroconference, Arezzo 24-25 November 2000* BAR Series 1075 pp. 1-12. It set the scenario for the London Charter, see below

28 https://www.london-charter.org/

The above summary excursus on the history of virtual reconstructions explains why this topic belongs to the 4CH scope, although without a primary importance. A result of 4CH is the possibility to link any virtual reconstruction of a heritage asset – in 3D, VR or AR – to its supporting documentation, availing of the 4CH Knowledge Base which can contain (and link) all the related information, such as the artistic, architectural, historical and cultural one. Under this regard, it is probably the first effective implementation of the London Charter, because up to now the background documentation was stored – when the Charter was implemented – either narratively or in a separate database[29]. This was the main motivation to explore virtual reconstructions in the present pilot.

However, for the sake of explanation, the background information is reported here in a narrative way. Similarly, no authoritative sources are cited for the background information, replacing them with references to reliable and checked Wikipedia pages that quote relevant publications.

4.2 Historical and archaeological context of the Saint Laurentius in Ename

In this section we will briefly summarise the historical background of the Saint Laurentius Church in Ename, Belgium, in a narrative way as already mentioned. This short report – or an extended version of it – should be included in the background information supporting the reconstruction, as it justifies some design decisions: for example it explains, among others, why some details are compared with Byzantine art located elsewhere and with Byzantine famous people, a relationship which a superficial consideration of a church built in Belgium might erroneously consider as spurious. However, the detail of such supporting historical information might well go beyond this summary: the KB infrastructure offers, instead, connections to unlimited background documentation. As already mentioned, links to Wikipedia are provided here as a shortcut for the pilot, to be replaced with richer quotations of research material.

Although the river Scheldt was the formal border between Flanders (part of the French kingdom) and the Ottonian Empire[30] at the end of the 10^{th} century, relations between the two sides were friendly in the second half of the 10^{th} century, as there were several family ties between the ruling people of both regions and empires.

29 This is the case, for example, of the virtual repositioning of Vasari's *Last Supper* painting, presently in the Santa Croce Museum in Florence, in its original location in the refectory of the Murate Convent: see N. Amico, F. Niccolucci "The Murate Project and Vasari's Last Supper," 2018 *3rd Digital Heritage International Congress (DigitalHERITAGE) held jointly with 2018 24th International Conference on Virtual Systems & Multimedia (VSMM 2018), San Francisco, CA, USA, 2018*, pp. 1-4, https://doi.org/10.1109/DigitalHeritage.2018.8810037. The related database on the online DBMS based on ResourceSpace contains all the background information.

30 https://en.wikipedia.org/wiki/Ottonian_dynasty

When the Flemish count Baldwin IV[31] came of age at fourteen years old (end of 993), he decided to reorganise the military structure of Flanders. One of the most important aspects of this reorganisation was the creation of new strongholds along the river Scheldt, at Tournai, Petegem and Ghent. The new stronghold in the county of Petegem, at the place which is now the city of Oudenaarde, was facing the new trade settlement of Ename[32] (founded around 965 by Godfrey of Verdun[33]).

This new stronghold invoked a firm response from the Ottonian side when Emperor Otto III came of age (fourteen) in the summer of 994 and decided to build an unprecedented stronghold in Ename[34] and turn the trade settlement into a well-established border town. A major stone keep with a palace building was built by the riverside, while two stone churches were erected, one at the trade settlement and one at the rural settlement. The latter is still standing while other buildings collapsed and have been excavated in one of the most extensive excavation campaigns in Flanders. Both the keep (as a military innovation) and the standing Saint Laurentius church have unique Byzantine elements.

This Byzantine influence finds its origins in the *Renovatio Imperii Romanorum*[35], the goal of the Ottonian Empire to become the renewed Roman Empire, which of course clashed with the Byzantine Empire, the continuation of the Roman Empire in the East. The Ottonian emperors not only clashed with the Byzantine colony in Southern Italy[36] but also tried to assimilate and mimic Byzantine culture and habits. This led to the marriage of Otto II with Theophano[37], a Byzantine princess, and the planned marriage in 1002 of their son Otto III with another Byzantine princess[38] (unfortunately, he died while his bride was on her way to Italy). Theophano was only twelve when she married Otto II, and only twenty-three when her husband died, forcing her to rule the Ottonian Empire, making her the first empress in Western Europe. She died unexpectedly at the age of thirty-one in Nijmegen, in the presence of her son Otto III, around the time he turned eleven years old. Otto III was raised by his mother, although she had to rule the vast Ottonian Empire. He spoke fluent Greek and historical documents show a profound veneration for his mother.

Theophano had a huge impact on Western European culture by establishing links with Byzantine culture and knowledge. The fact that this culture and knowledge was present in southern Italy greatly facilitated this transfer, as Byzantine craftsmen from that region worked on many new building sites throughout the Ottonian Empire.

31 https://en.wikipedia.org/wiki/Baldwin_IV,_Count_of_Flanders
32 https://enamearound1000.wordpress.com/2022/12/28/a-city-in-the-making-ename/
33 https://en.wikipedia.org/wiki/Godfrey_I,_Count_of_Verdun
34 https://en.wikipedia.org/wiki/Ename#Middle_Age
35 https://en.wikipedia.org/wiki/Renovatio_imperii_Romanorum
36 https://en.wikipedia.org/wiki/Catepanate_of_Italy
37 https://en.wikipedia.org/wiki/Theophanu
38 https://en.wikipedia.org/wiki/Zo%C3%AB_Porphyrogenita

Around 994, Otto III[39] had a chapel[40] built in Nijmegen[41] to commemorate his mother. The chapel was dedicated to Saint Nicholas, one of the Byzantine saints that Theophano introduced to Western Europe. Around the same time, the small trade settlement of Ename was upgraded significantly (figure 31) to counter the increased military pressure from Flanders and the French Kingdom. A massive stone keep – one of the biggest in Western Europe – was built to protect the enlarged trade settlement, along with a palace building and two churches in stone.

Figure 31. Ename around 1020[42]

The new Saint Laurentius church[43] in the rural settlement got an exceptional double east choir, which experts interpreted as a ceremonial coronation church: during a massive gathering, typically on a special day such as Easter, Pentecost or Christmas, the emperor went in procession from one church to the other, where he was crowned in the upper east choir. As this church was part of the transformation of Ename from a small trade settlement into a well-defended border town, a ceremonial coronation could be used as a show-off towards the potential aggressor on the other side of the river.

39 https://en.wikipedia.org/wiki/Otto_III,_Holy_Roman_Emperor
40 https://nl.wikipedia.org/wiki/Sint-Nicolaaskapel_(Nijmegen)
41 https://nl.wikipedia.org/wiki/Valkhof
42 https://en.wikipedia.org/wiki/Ename
43 https://en.wikipedia.org/wiki/Saint_Laurentius_Church

Otto III died unexpectedly in January 1002, at the age of 21 years old, without a successor. Several elements lead us to believe that the Saint Laurentius church was not yet finished at that time. Several successors to the imperial throne were competing, but none had sufficient support all over the empire. Only by 1014, the Frankish king Henry II[44] succeeded in being crowned as emperor. The tensions between Flanders and the Ottonian Empire had not diminished over time, resulting in attacks in 1007 and 1020 of the army of Henry II on Ghent, one of the main strongholds of the Flemish count. The creation of a new wall painting in the Saint Laurentius church of a Maiestas Domini in Byzantine style (see below) suggests that the ceremonial coronation of Henry II in Ename took place in the summer of 1020, in a period which is compatible with the most probable dating interval of the wall painting[45].

Hence, the influence of the Byzantine culture on the Ottonian Empire and on the border town Ename, which was built under direct imperial imperatives, can still be witnessed in this Flemish village within the extant Saint Laurentius church[46] and the excavated keep at 600 m of the church. Since Otto III ordered this church to be built only a few years after the death of his mother Theophano, it is not surprising that there are possible links with Theophano in Ename. The additional Byzantine wall painting in the Saint Laurentius church in 1020 shows the continuation of the Byzantine influence in the Ottonian Empire, probably also through Byzantine artists from southern Italy.

The Ename keep was conquered and destroyed by the Flemish count in 1033 and the region around Ename became part of Flanders in 1047. The trade settlement shifted towards the new trade settlement of Oudenaarde, created by the Count of Flanders. In 1063, the Ename realm was donated to a new abbey, founded by the Count of Flanders, and the proto-city of Ename became an abbey village. The Saint Laurentius church was way too big for the small village population and was turned into a pilgrimage church, as it was located on the road network to Compostela, the *Camino de Santiago*. The abbey maintained the church but did not change it structurally, so the Byzantine wall paintings were hidden under layers of whitewash or wooden covering and were preserved.

Stability problems of the church tower initiated in 1990 a set of intense research campaigns, revealing the hidden treasures. Between 1999 and 2002, a major restoration and excavation project was executed with European funding, restoring the original structures and wall paintings. In this way, the church is a very rare and nearly intact relic from the Ottonian period 1000 years ago, but at the same time it is an operational church with a very dedicated community, cherishing this hidden pearl of Ottonian art and Byzantine influences.

44 https://en.wikipedia.org/wiki/Henry_II,_Holy_Roman_Emperor
45 For the sake of conciseness we do not include here the details of such dating and its confidence interval. They should however be included in the knowledge base.
46 https://commons.wikimedia.org/wiki/Category:Sint-Laurentiuskerk_(Ename)

4.3 The pilot case

4.3.1 The 3D model

The 3D model created shows the virtual reconstruction of the church in 1020, the year the church was most likely used for the ceremonial coronation of Emperor Henry II. Although a laser scan of the church interior and exterior is available, we have chosen not to use this scan for two main reasons.

The first reason is that the entire church has been surveyed in the highest detail, and these plans already contain an interpretation of all the features encountered during the survey. In other words, the survey was a much better source to decide which features belonged to the phase of 1020, having also precise measurements and levels, even in the most unreachable areas of the church (for example the attics).

The second reason is that many small errors were made during the restoration process (figure 32). The problem, unforeseen at the time, was that Ottonian building techniques are pretty much unknown in detail: hence it would have required time to study and understand them and apply them correctly, but the strict timing assigned to the restoration project did not allow for that. For example, the church revealed that there are three different ways to build Ottonian windows, which were completely undocumented at the time of the restoration. Even during the creation of the virtual model, extensive study has been made to fully understand the building techniques for the windows. This knowledge has been applied in the creation of the model and is documented in this pilot project.

So, the 3D model of the church in 1020 has been created through Blender, based on the precise measurements of the survey. The additional advantage of hand modelling this model is that we could prove that the builders were using Roman feet as the standard measure, not the Carolingian foot or some local standard. This was to some extent logical, as Otto III, who commissioned the church, was passionate about the *Renovatio Imperii Romanorum*, the recreation of the Roman Empire. Due to this discovery, we found out that other structures in Ename had measurements in Roman feet: for example, the keep of the stronghold measures exactly 60 by 120 Roman feet, while the three rows of parcels of the trade settlement are exactly 100 Roman feet wide.

Figure 32. The current east choir vs. the east choir of the digital twin (1020)

An additional advantage of the modelling approach (instead of a laser scanning approach) is that all elements were structured properly from the beginning.

In other words, the 3D model is a mixture of building elements that are present in the restored church, elements that have changed or are hidden in the current church plus elements that have disappeared and can be reconstructed through interpretation of the remaining traces. This means also that we have re-interpreted several physical reconstructions of the restoration, as better and more profound study allows us to come up with better interpretations.

We believe that a platform such as the 4CH Knowledge Base could be used to document such interpretations as they are fundamental knowledge about the monument to be preserved. This also holds for intangible heritage information, which is nowadays acknowledged to be an inseparable component of heritage assets. Such background information will be stored together with other knowledge about the monument in a holistic way, using appropriate formats for each one.

4.3.2 Valorisation of the monument: the interactive VR model

We have chosen to make an interactive real-time visualisation[47] of the virtual reconstruction of the Saint Laurentius church and its environment, use several storytelling techniques and integrate interactive visualisation of the different stages of digital wall painting restoration[48]. As there is too much uncertainty over some parts of the wall paintings, we have chosen to show the wall painting

47 https://www.youtube.com/watch?v=olHAliHbCgc
48 https://www.youtube.com/watch?v=K6KgtvyVWBg

remains, what can be reconstructed with sufficient certainty (in white lines), and what can be only imagined (in red lines).

The interactive model is still a research model, where 3D is mainly used to test out the virtual reconstruction. For example, we use an avatar of 1,7 m in height to verify the scale and ergonomics of the reconstructed environment (figure 33).

Figure 33. Use of an avatar for verifying ergonomy and object sizes

In the example below (fig. 34), the 3D visualisation (sight line analysis) shows that the ciborium is probably too high. After studying the size ratios and structural composition within 11th-century ciboria, we made some changes that show that the wall paintings at the top of the windows (see figure 33) can be much better seen now (figure 34). This kind of paradata needs to be stored, linked to the east choir.

Figure 34. Sight line analysis shows the original ciborium model (top) needs to be smaller (bottom)

The interactive VR model can already be used for VR storytelling, especially in the mode of a guided virtual tour. This virtual reconstruction of the Saint Laurentius church was presented in the church itself on August 17, 2023 (figure 35).


Figure 35. Presentation of the “Saint Laurentius church in 1020” in the church itself in Ename


Figure 36. Showing iconography in the VR application, next to the object itself

For this presentation, we added an additional storytelling tool[49] to show historical iconography in context (figure 36). In this way, a closer match can be obtained between the iconography and the VR presentation, providing a richer storytelling experience.

4.2.3 The Byzantine wall paintings

Another important aspect of the digital reconstruction is the study and a digital extrapolation of the possible original colours of the wall paintings. The current wall paintings have been restored by two different teams in three restoration campaigns. Based on the conclusions of these restoration experts, and with the support of the Museum for Byzantine Art in Thessaloniki, we hope to have enough information about such the wall paintings to be able to show it in the virtual reconstructions. This activity will probably take place in 2025, as funding for it still needs to be secured.

For the moment, we have made preliminary studies that help assess the complexity of this task. These studies are recorded and presented in this pilot project. The final results concerning the wall paintings will be produced by expert restorers.

The *Maiestas Domini*

This wall painting is a fresco and sits on the arcade between the upper east choir and the central nave (figure 37). This arcade and its wall paintings were bricked up and have been discovered while checking the structure of the church tower in 1992, due to appearing cracks.

49 https://youtu.be/hlBZCzfKB_g

Figure 37. The Maiestas Domini fresco has been found on the upper east choir arcade

The wall painting is only partial (figure 38) due to the collapse of the arcade around 1172, when the church burned down completely. During the restoration of the church around 1175, the *Maiestas Domini* fresco was covered by a layer of plaster on which a new secco painting was made depicting Christ taken from the cross, with angels surrounding the scene.

Figure 38. Christ is surrounded by a Byzantine *quadrifolium*, the eagle depicts John the Evangelist

This Maiestas Domini fresco has been declared by experts as having a clear Byzantine style (for example, the use of a *quadrifolium* instead of the typical mandorla). "The blue colour is lapis lazuli, most likely coming from the East, similar to others used during the same period. They were applied in fresco and in secco (figure 38).

The Maria *Hodegetria*

This wall painting in the right blind niche on the west side of the west choir (figure 39) has been identified as a Byzantine Maria *Hodegetria*[50]. This depiction of Our Lady was very popular as it was the most important relic in Constantinople, believed to be the original painting of Maria by Luke the Evangelist. The relic disappeared during the sacking of Constantinople in the fourth Crusade (1204).

In the second blind niche at the right of the Maria Hodegetria, another live-size wall painting is faintly visible. We can assume that all blind niches were filled with similar wall paintings. The similarity of this group of blind niches with a *Deesis*[51] is striking (and has a clear link to the Byzantine artists in the south of Italy). The central blind niche is supposed to be a little bigger (not

50 https://en.wikipedia.org/wiki/Hodegetria
51 https://en.wikipedia.org/wiki/Deesis

implemented in the physical restoration) and is probably linked to a throne (of which the possible bottom part has been found in the excavations, see section on throne below). In the possible Deesis configuration, the other niche next to the throne would be occupied by John the Baptist.

Figure 39. The west choir has eleven blind niches that contain wall Byzantine paintings

The original Maria *Hodegetria* relic in Constantinople showed a life-size standing Our Lady. Later copies show her half-size or sitting. We made a line drawing of the Maria *Hodegetria* of Torcello (Venice) and superimposed this line drawing on the Ename wall painting to give an idea of the size and presence of the wall painting in its blind niche (figure 40).

As an Ottonian emperor ruled over both the State and the Church, the west choir of an Ottonian church symbolises the power over the State and the east choir the power over the Church (figure 41).

Figure 40. The Maria *Hodegetria* wall painting with the Torcello Maria *Hodegetria* superimposed

Figure 41. Virtual reconstruction of the west choir with throne and Maria *Hodegetria* wall painting

4.2.4 The church interior

The Imperial Throne

The west choir in a double choir Ottonian church symbolises the worldly power of the Ottonian rulers and is said to contain a throne that is similar to the throne of Charlemagne. The hypothesis that this west choir contains a throne is supported to a certain extent by the presence of two stone foundation blocks that are integrated into the wall (figure 42, figure 43) and the original height at which the blind niches start. Assuming that a potential throne would start (for aesthetic reasons) at the same height as the blind niches (see virtual reconstruction in figure 44 and 45), we see that there is only a 2 cm difference between this height (112 cm) and the height of the throne of Charlemagne in Aachen (114 cm). Unfortunately, other archaeological traces in that area have been destroyed by later activities.

Figure 42. Excavations of the west choir revealed two foundation stones


Figure 43. These foundation stones could be part of a throne


Figure 44. Virtual reconstruction of the west choir

Figure 45. Virtual reconstruction of the throne

For the throne, we have not created an identical copy of the throne of Charlemagne, as the throne consists of thin marble slabs that have been taken from Jerusalem. Instead, we have taken 10 cm stone slabs of German red sandstone, inspired by the royal throne from Mainz[52]. We have kept the general structure of the Aachen throne platform but in a closed form (as the open form of the Aachen throne probably only emerged when Charlemagne was declared a saint and people would crawl under the throne to get its power). The bottom part of the steps aligns with the stones found in the excavation. As in Aachen, there are six steps, and the wooden footrest acts as the seventh step. The throne has a long cylindrical cushion as can be seen on nearly all iconography of thrones (as is the wooden footstep). The throne virtual reconstruction exemplifies well the different degree of reliability in the global virtual reconstruction: this part is more conjectural than others as evidence shows the presence of a throne but gives no hint on its material.

The Altar Screen

All Mediaeval churches were divided by a choir screen into a public part and a holy part, dedicated to the mass. This separation was made by curtains, as is still the case in some Orthodox churches (figure 46). The central curtain only opened at the moment of the consecration[53]. The raised ambo[54], from where the Scriptures were read, was situated in the enclosed area in front of the

52 https://www.academia.edu/2170630
53 https://en.wikipedia.org/wiki/Anaphora_(liturgy)
54 https://en.wikipedia.org/wiki/Ambon_(liturgy)#History

altar. We think this choir screen was made from wood, as it left no archaeological traces (for the ciborium, it is quite certain from the archaeological remains that it was made in wood). However, other churches provide historical and archaeological evidence for the form and placement of the choir screen[55].

Figure 46. Overview of the church, divided into two distinct zones by the altar screen

All this information, and much more, is integrated into the 3D model. It gives an idea about the kind of information linked to digital reconstructions of monuments so that this information can be shared by the research and cultural heritage community.

4.4 Pilot case implementation

4.4.1 The HBIM model

The 3D model of the virtual reconstruction has been re-used and transformed into an HBIM model (figure 47) with excavation (figure 48) and restoration (figure 49) images linking to the model.

55 https://www.campus-galli.de/portfolio/chorschranken_holzkirche/

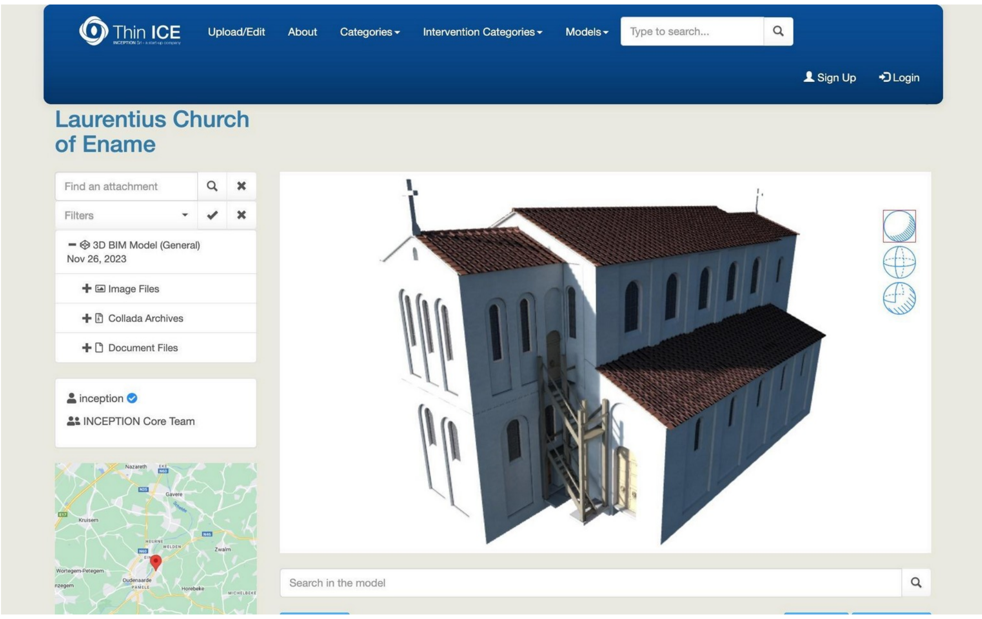


Figure 47. The 3D model of the digital twin is re-used as HBIM model

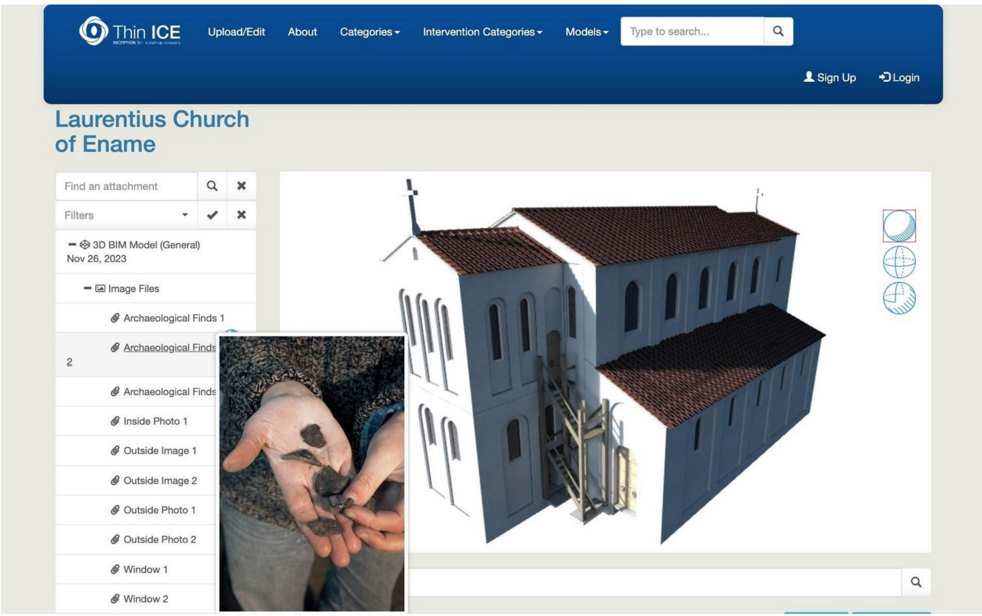


Figure 48. Excavation images are linked to the HBIM model (molten glass of the windows)

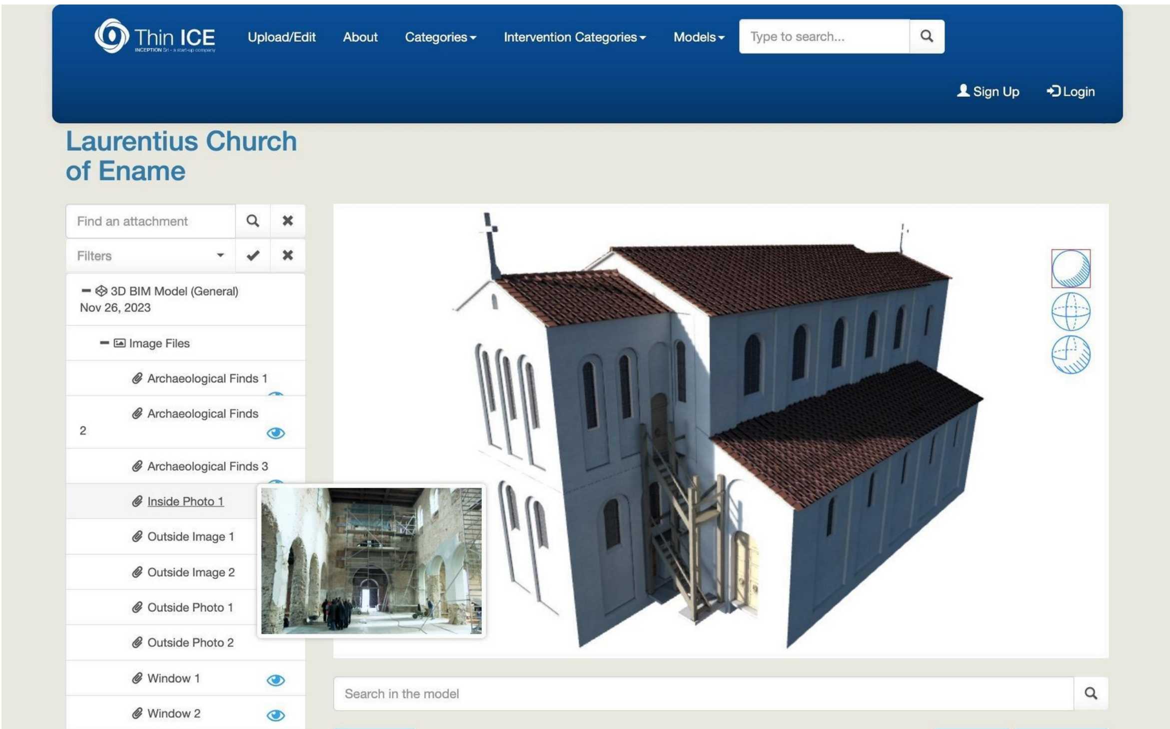


Figure 49. Restoration images are linked to the HBIM model

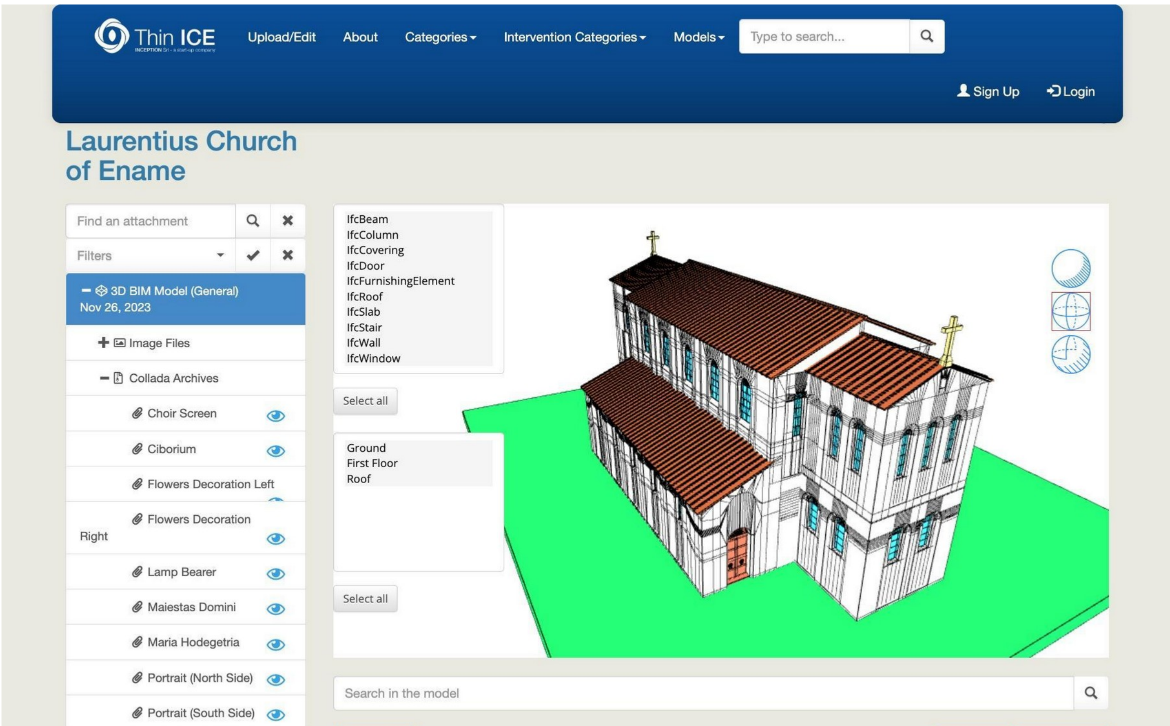


Figure 50. The structured HBIM model

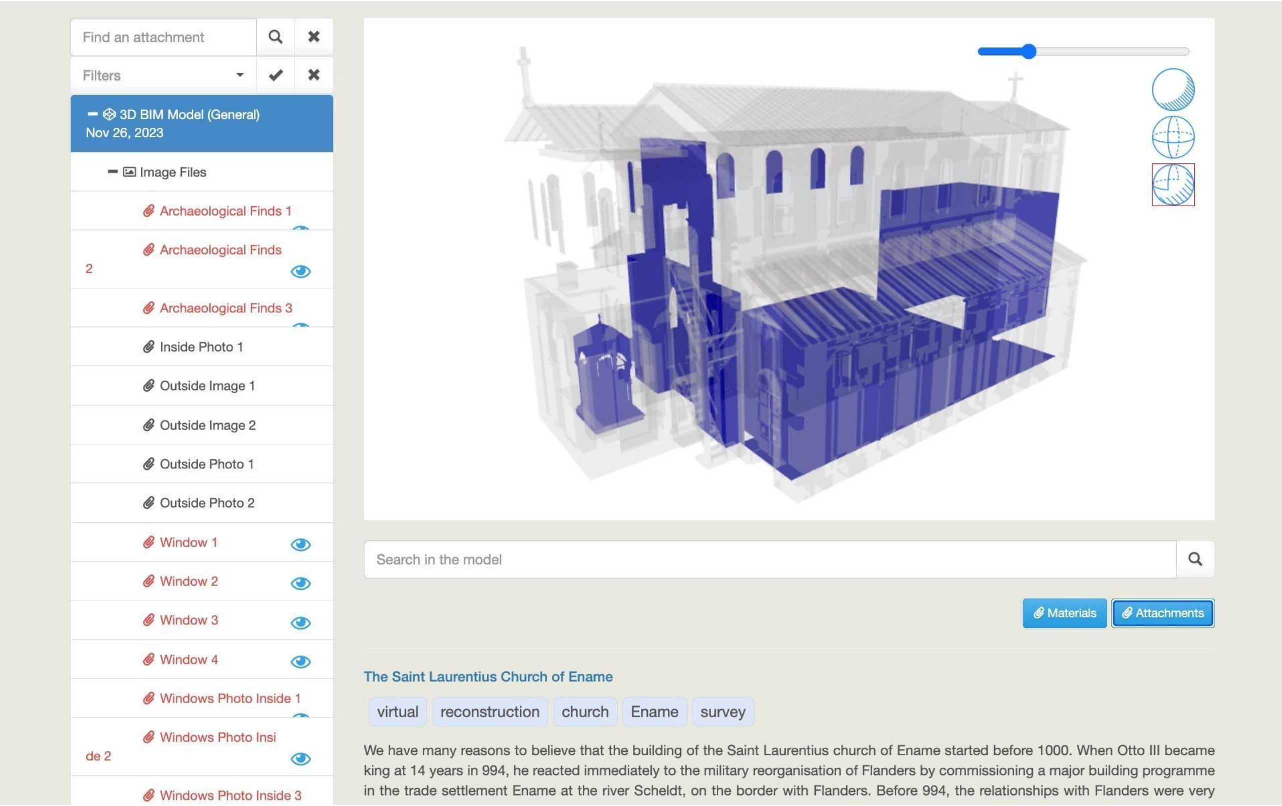


Figure 51. Interactive elements of the HBIM model that contain additional information

A number of HBIM elements (figure 50) were made interactive (figure 51) to connect additional information, reports, restoration and excavation photographs. For example, the survey of the church during restoration revealed three different techniques to build windows. We have documented them in a PDF document (titled “Construction techniques in Ottonian buildings: the “Saint Laurentius church of Ename in 1020”) that is attached to the upper windows in the HBIM model. We briefly provide a part of that information here.

The Saint Laurentius church of Ename has been built most probably between 996 and 1002. It was part of a major building campaign that turned the small local trade settlement (founded around 965) into an important Ottonian frontier town at the river Scheldt.

The restoration of this church in 1999-2002 has allowed us to get an unprecedented insight into the building techniques of Ottonian buildings, due to the exceptional level of preservation of the Ottonian parts of the building plus the very detailed survey and study of these remains.

One of the totally unknown building techniques is the creation of the upper windows of the central nave. As one wants to optimise the amount of light through these windows, they are not only exceptionally large for a Romanesque building but have a special construction. This has not only been found in this Saint Laurentius church but can also be observed in other famous Ottonian buildings such as the Saint Michael church in Hildesheim (and studied during its recent restoration).

This construction has been interpreted as a two-step technique (figure 52) that allowed in the first step (dark grey in the image below) put supports (red lines) to sustain the centrings to build the arches of the window, while the final shape of the window (see below) is created by filling in (indicated in light grey) the sloped sections after removal of the centring supports. This concept was not understood during the restoration phase due to lack of time and study, resulting in an incorrect restoration of the bottom inside part of the window.

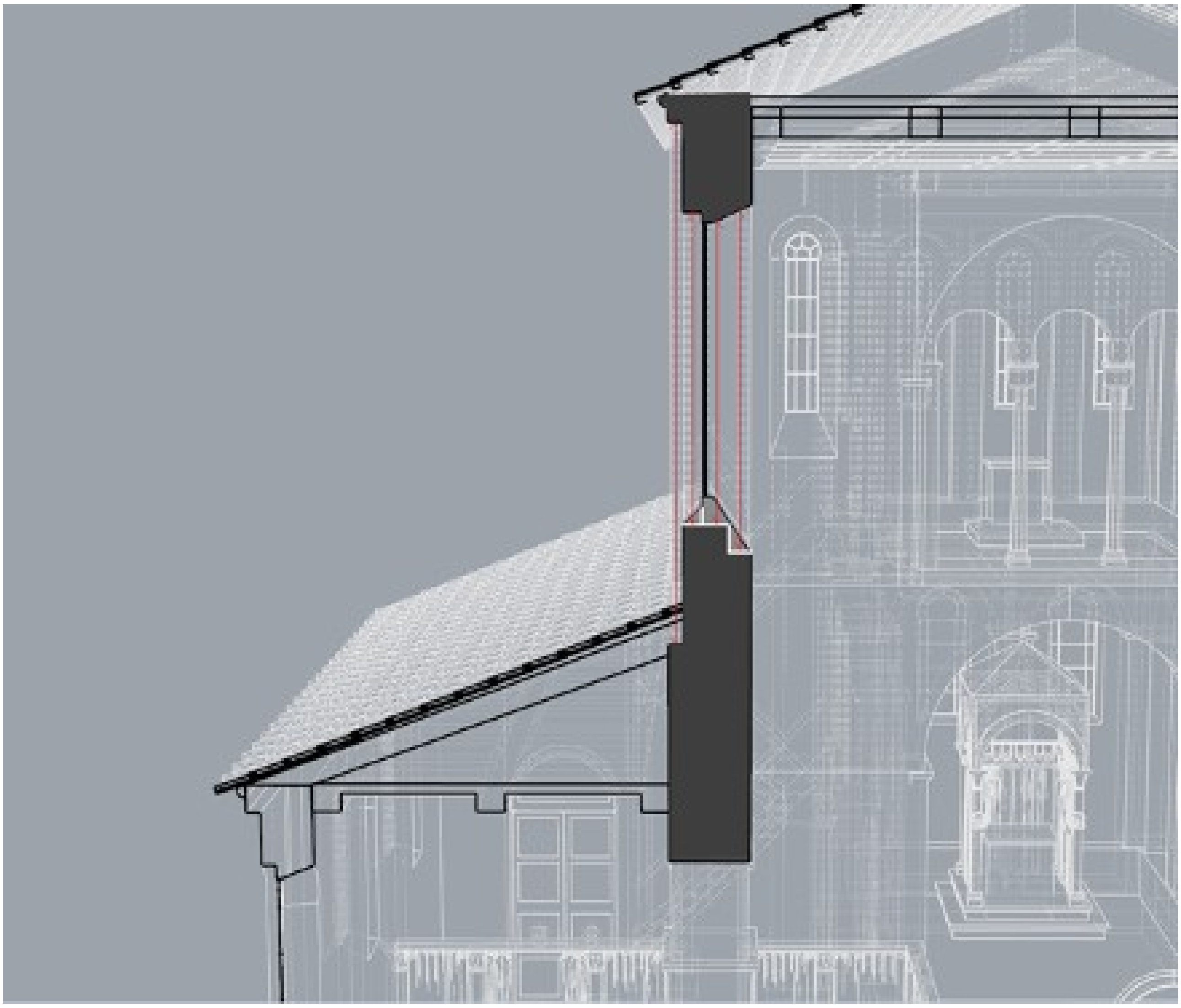


Figure 52. Construction method for the upper windows

The resulting shape of the window can be seen in this virtual reconstruction on the inside (figure 53) and the outside (figure 54) of the church. After construction, the limestone has been plastered both on the inside and on the outside. The original outside plaster is still visible on the attics of the side naves. The remaining inside plaster has been preserved and documented, and the inside of the church has been plastered, based on all knowledge available at that moment (hence a couple of errors, as indicated above).

During the restoration phase, all inside plaster has been removed, revealing the structure of the construction. This structure has been meticulously surveyed both on the inside and on the outside. The current windows are smaller than the original windows as the slope of the roof of the side naves has been raised.

Figure 53. Resulting virtual reconstruction of the inside of the upper windows


Figure 54. Resulting virtual reconstruction of the outside of the upper windows

4.4.2 The visualisation of the HBIM model

As the 3D model in the Inception platform is not linked to laser scan data, adaptations have been made to provide shading for the 3D model (laser scan data have its own, natural shading). After some testing, the best solution appeared to be backing the light conditions of the VR model (figure 55).

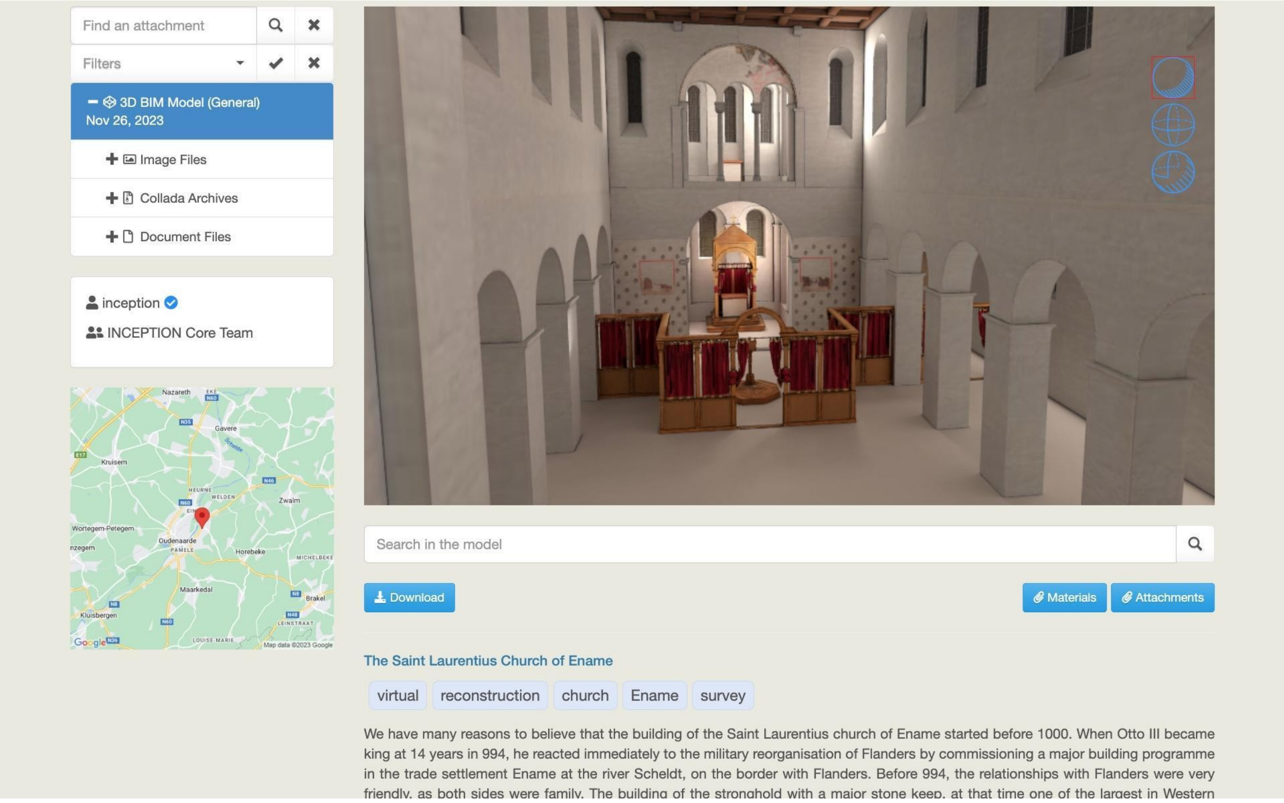


Figure 55. Visualisation of the interior of the 3D model

This visualisation has also allowed us to show the restoration studies (figure 56) and link descriptive text to the HBIM object of the arcade (figure 57).

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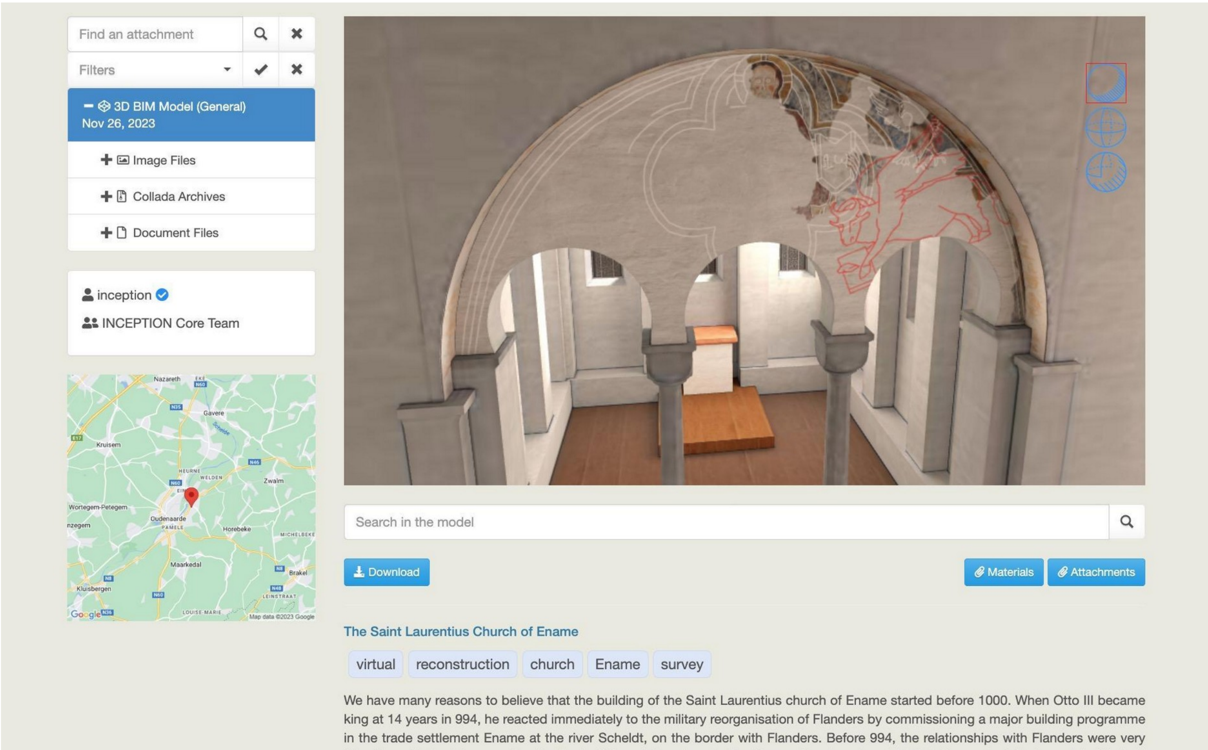

Figure 56. Visualisation of the digital restoration study

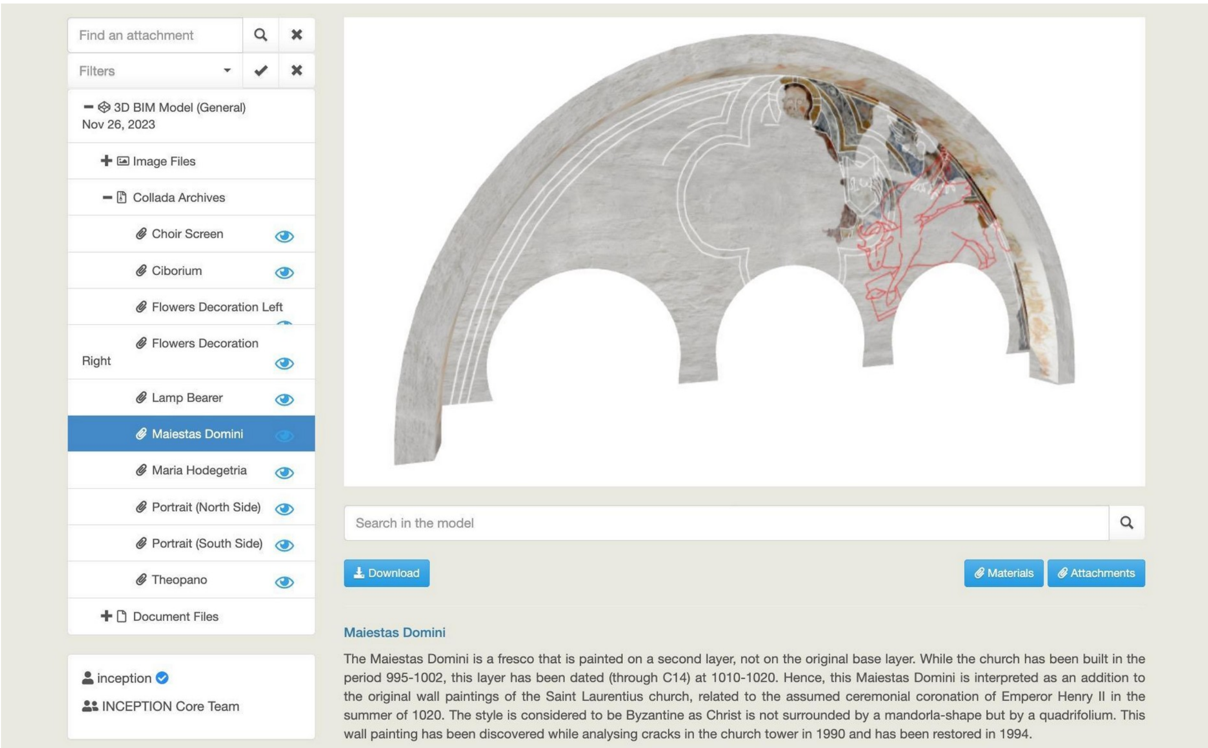

Figure 57. The arcade element contains the description of the Maiestas Domini

4.5 Lessons learned from the Saint Laurentius pilot case

By developing the pilot case it was clear that the 4CH solution provides substantial support to make it scientifically based, in addition to providing a flexible viewer. This aspect supports the validity of 4CH virtual reconstructions for the valorisation of heritage assets, because 4CH enables storing and linking to the 3D models all the related documentation in a straightforward and holistic way as recommended by the London Charter. At the same time, however, it provides the instruments to make available all the related scientific information, such as historical sources, architectural and materials analyses, the results of on-field activity, and more, including related research publications. Such background documentation linked to the monument and its 3D replica becomes easily consulted and referrable. As demonstrated by some aspects discovered during the digitalization of the Saint Laurentius church and mentioned above. this feature may support the use of 3D modelling as a research tool for historical assets, their conservation and restoration.

5. Pilot case 4: Villa Aldrovandi Mazzacorati, Italy

Villa Aldrovandi Mazzacorati is one of the pilot cases of the 4CH project for the implementation of standard workflows.
Aim of the pilot: Documentation and knowledge acquisition for intervention and restoration
Development: INCEPTION in collaboration with Geomax, part of the Hexagon Group – leading manufacturers of survey equipment, and the Cultural Heritage Sector of the Emilia-Romagna Region.

5.1 The history of the Villa and its role in 4CH

Villa Aldrovandi Mazzacorati, located just outside Bologna, is a striking example of neoclassical architecture. Initially a modest agricultural estate, its first significant transformation was under the stewardship of the Aldrovandi family around 1690, where it was expanded and embellished to better reflect the family's noble status. The architectural pinnacle of the estate came in the late 18th century. In 1763, a uniquely designed theatre was added, boasting two tiers of loggias supported by intricate caryatids, the handiwork of Petronio Tadolini. This was not just an aesthetic addition; it became a cultural cornerstone, influencing the evolution of Italian theatre. After the theatre, a second floor was integrated into the structure, amplifying its stature. Between 1770 and 1772, the villa was further enriched with neoclassical elements, primarily guided by the artistic vision of Filippo Tadolini. Transitioning to public ownership in the 20th century, the villa now serves a dual function as a historic monument and a practical facility. It houses offices and clinics for Bologna's health and social services, as well as a remarkable "Mario Massacesi" Historical Toy Soldier Museum, hosting over 12,000 toy soldiers dating from 1800 to the present. Today, Villa Aldrovandi Mazzacorati is gearing up to enter another transformative phase since an important restoration will be needed in a few years. Thus, it will benefit from becoming a pilot case for the 4CH project. The use case is focused on specific needs of architects, engineers and professionals involved in heritage buildings conservation and restoration. Major research questions and scenarios are related to the analysis of surface features combining it with the 3D modelling, as an innovative support for computing and designing restoration actions.

Figure 58. View of the exterior of Villa Aldrovandi-Mazzacorati (left) and the interior of its theatre (right)

5.2 Survey activities and goals

5.2.1 Designing the survey phase

Exteriors:
fixed station laser scanner survey (Leica RTC360) integrated with nadiral aerial photogrammetry + inclined camera (DJI Mavic Mini 3 Pro), ground photogrammetry (Sony Alpha 7 IV) and GNSS and TPS (Geomax Zenith60 - Zoom95). Ground and facade targets are used.

Interiors:
fixed station laser scanner survey (Leica RTC360) and internal slam (Leica BLK2GO) with ground photogrammetry integration for decorated/frescoed parts (Sony Alpha 7 IV). A comparative fixed station vs slam is also performed for interiors.

Figure 59. Schema of target positions for the exteriors (blu dots: targets for aerial photogrammetry; red squares: TPS positions; yellow triangles: targets for TLS and ground photogrammetry)

5.2.2 Main façade and the theatre

Requirements: 3D documentation with reliable metric information and high-resolution pictures.

The exterior of the Villa, with a particular focus on the main façade, and the unique theatre required an acquisition with a high-accuracy laser scanner. For that, the Leica RTC360 laser scanner has been used:

- 49 scans with the RTC360 for the exterior;
- 18 scans with the RTC360 for the theatre.

Furthermore, both the façade and the theatre have been enriched by a photogrammetric campaign of thousands of pictures:

- 1188 pictures from ground (Sony Alpha 7) and aerial (DJI Mini Pro 3) photogrammetry for the exterior of the building;
- 702 pictures from ground photogrammetry (Sony Alpha 7) for the theatre.


Figure 60. Point cloud from TLS with bubbles representing the scanning positions


Figure 61. Scanning operations inside the theatre

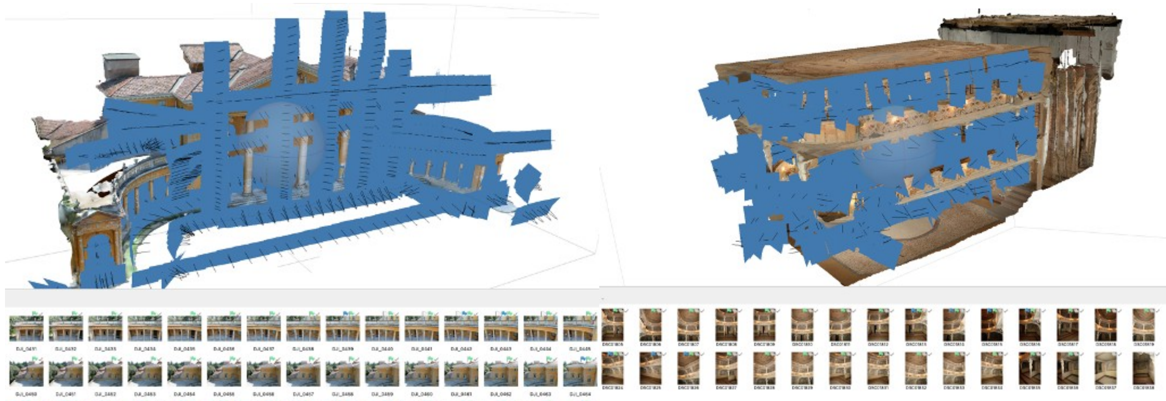

Figure 62. Point cloud from photogrammetry with estimated picture positions of the exterior of Villa Aldrovandi-Mazzacorati (left) and the interior of its theatre (right)

5.2.3 The interiors

Requirements: Capturing the current configuration for space management.

The interior of the Villa is currently allocated to several functions, including health services, the Toy Soldiers Museum and spaces dedicated to the municipal community. Thus, several modifications occurred during the last years and current plans do not reflect the current situation anymore. SLAM technologies can already be reliable enough for covering these purposes.
However, due to the extensions of the building, it has been divided into 18 different paths to be then integrated and registered in the overall survey.

Figure 63. Point cloud from the Leica BLK2GO in perspective view (left) and top view, with a bounding box extrapolating a horizontal slice of 10cm (right)

5.2.4 The garden and the roofs

Requirements: Integrating the survey of the complex with the roofs (missing from the ground survey) and documenting the overall condition of the surrounding garden.

The use of UAV and photogrammetry techniques is becoming more and more common for vast urban areas, with the possibility of capturing roofs and (partially) facades of buildings. Furthermore, algorithms are already capable of segmenting the point cloud (or mesh) into trees, buildings and ground, making the analysis even more immediate.
For this use case, 1553 pictures were taken, including:

- nadiral pictures for the entire area;
- tilted pictures around the buildings.

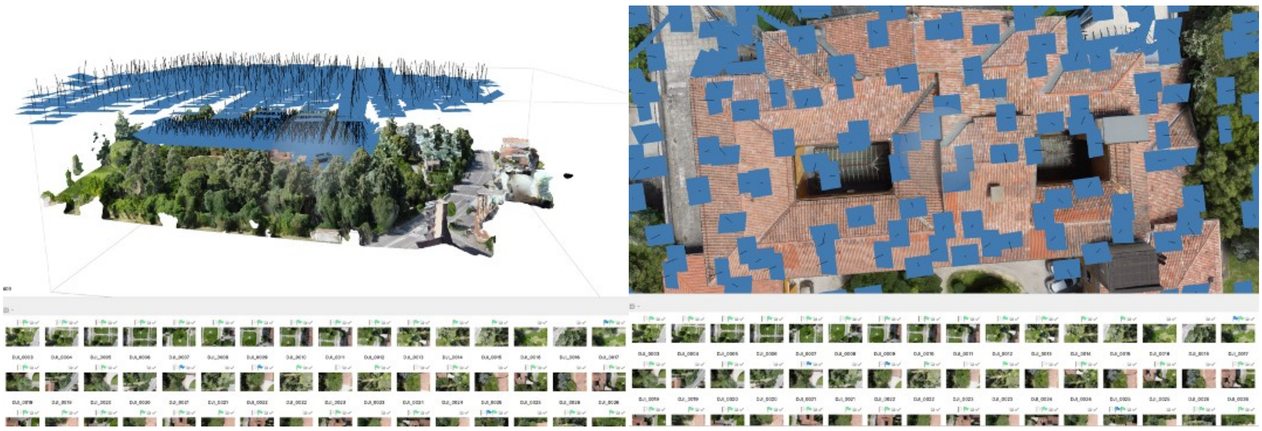

Figure 64. Textured mesh from photogrammetry with estimated picture positions of the exterior and the surroundings of the Villa (left) and a detail highlighting the pattern of the pictures (right)

5.2.5 Topography

GNSS and TPS data on ground and façade targets have been used for metric correction of aerial and ground photogrammetry as well as for registering it together with a laser scanner.

- 7 GNSS points to be used as Ground Control Point
- More than 150 TPS points for measuring targets, building features and garden elements

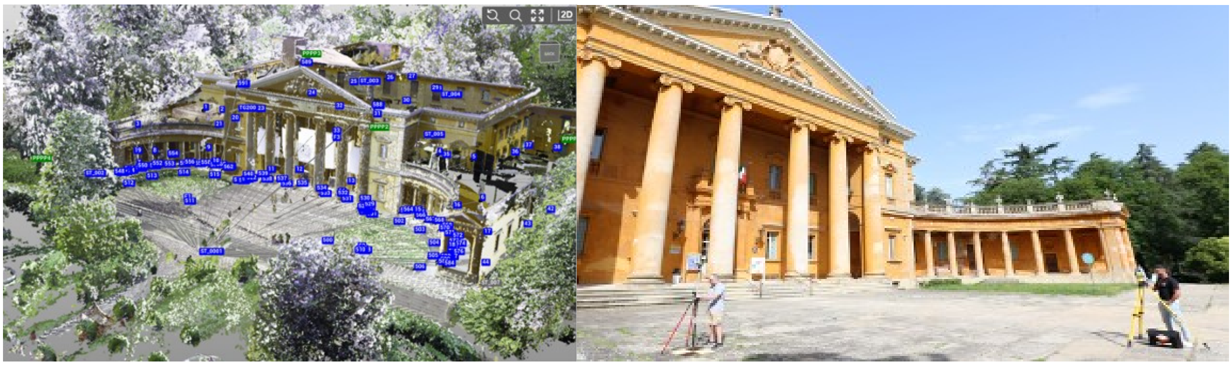

Figure 65. TPS measured points (left) and related on-field operations (right)

5.3 Data integration: building the overall point cloud

Both laser scanning measurements and photogrammetry campaigns required separate processing efforts. Currently, it's not yet common to fuse data at the early processing but data integration rather occurs at a later stage. However, the following measures have been adopted:

- the aerial and ground photogrammetry of the exterior have been processed using the topographic targets;
- topographic targets have been also used in the registration process of the RTC360 scans;
- the BLK2GO paths have been performed, as much as possible, as a closed paths connecting outside to inside environments to have overlaps with the RTC360 scans;
- the photogrammetry of the theatre has been processed using 3D coordinates of visible features from the scans as markers.

The resulting point cloud has been obtained by the registration of all the original scans based on targets and, where needed, fine-tuned with an ICP bundle adjustment. Scanner data have been preserved at their original density but saved in the .E57 open file format.
The file size of the overall point cloud comes very close to 75GB:

- 50GB of 67 RTC360 point clouds;
- 23GB of 18 BLK2GO point clouds;
- 1GB of 1 point cloud from photogrammetry.

At this stage, the overall point cloud has been also decimated and unified in order to be provided as a usable source for CAD drawings and BIM models.

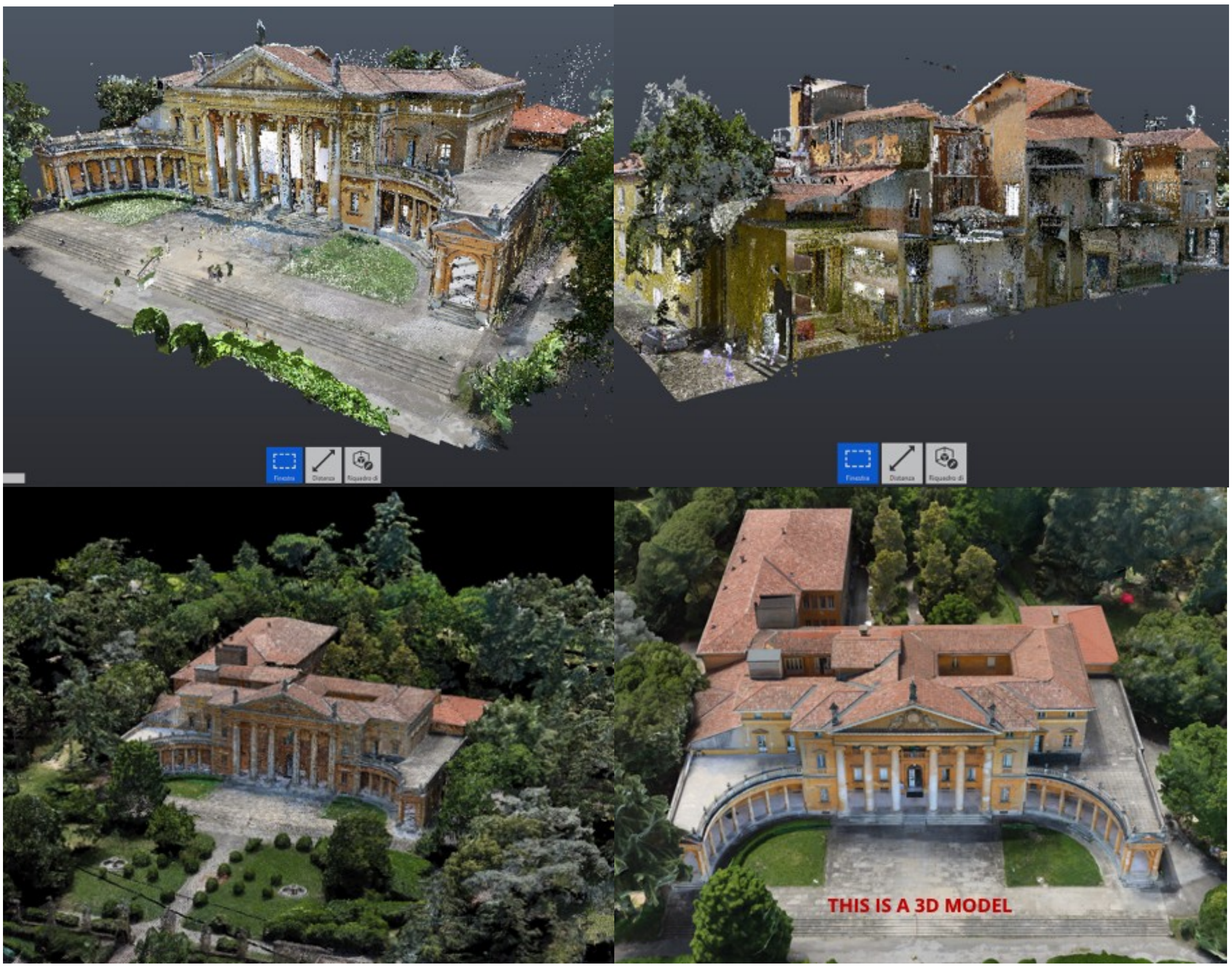

Figure 66. Point cloud of Villa Aldrovandi-Mazzacorati resulting from the integration of different data (top-left, top-right, bottom-left) and visualisation of the high-detailed textured model (bottom-right)

A point cloud is the common denominator for merging a survey that integrates both scanning and photogrammetry. While scanning produces point clouds, photogrammetry yields additional outputs like meshes and photo plans. However, to combine these datasets and find a common ground, utilising a point cloud is the most effective approach.
In the following pages we'll explore other (ongoing) outputs coming from this 3D digitization.
From point cloud: CAD drawings; H-BIM modelling; Primitive modelling.
From photogrammetry: Hi-res orthophotos; 3D model for online visualisation; Immersive VR environment.

5.4 Technical outputs

5.4.1 CAD drawings

Creating CAD drawings from the 3D survey of Villa Aldrovandi-Mazzacorati primarily involves a detailed and manual process where technicians used the 3D point cloud data as a reference.

Technicians indeed interpret this complex 3D information to accurately draw 2D lines and shapes, translating the intricate details of the building's architecture into coherent 2D CAD drawings. This transformation process is challenging, especially for culturally significant structures with non-standard components. While recent technological advances have enabled 2D drawing environments to handle large 3D point clouds and extract thin slices representing cutting planes, the automation of this process remains limited. Hence, much of the work relies on the skill and interpretation of the technicians to manually convert the 3D models into precise and usable 2D drawings. These 2D representations are essential for various purposes, including compliance with existing regulations and for easier visualisation, interpretation, and reproduction, such as printing on paper.

Figure 67. CAD drawing of the Grand Staircase of the Villa based on the overall point cloud (scanner + photogrammetry)

5.4.2 Primitive 3D modelling

In modelling Villa Aldrovandi-Mazzacorati's components like columns, the point cloud from 3D surveys is first transformed into a surfaced 3D model using triangular meshes. This process involves grouping point cloud vertices into triangles, creating a mesh that still carries the original data's noise. Noise filtering becomes more efficient due to the mesh's known surface topology. Handling discontinuities in the mesh, such as holes caused by occlusions or surface properties, involves identifying missing data areas and reconstructing them using algorithms that consider the curvature trends at the boundaries. Further cleaning of the mesh addresses issues like spikes and non-manifold edges using software like MeshLab. Additionally, primitive and NURBS modelling are applied for optimised, lightweight models that integrate missing parts, supporting both mesh and solid/surface models, crucial for accurately representing complex elements like columns in a manageable digital format.

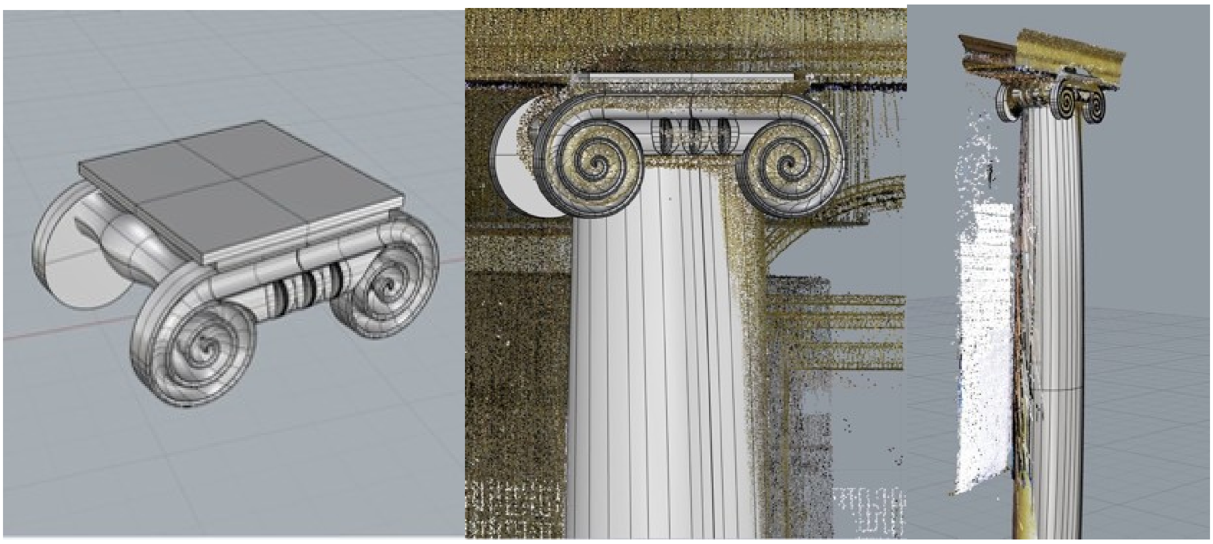

Figure 68. Primitive modelling of the columns of the Villa based on the overall point cloud (scanner + photogrammetry)

5.4.3 H-BIM modelling

The BIM modelling process for Villa Aldrovandi-Mazzacorati creates a detailed digital representation of the building, integrating physical and functional characteristics. This method, essential for architectural projects, is now adapted into H-BIM (Heritage BIM) for historical structures. BIM models combine geometrical data with information on materials, costs, and structural details. For restoration and maintenance, BIM is invaluable. It enables extensive collaboration across multidisciplinary teams, incorporating diverse data like point clouds and mesh models. This integration allows for precise simulations and management of restoration interventions, ensuring that each aspect of the building's heritage is accurately preserved. BIM also facilitates model checking for compliance with regulations and supports advanced structural analyses. These features are crucial for both preserving the historical integrity of the villa and maintaining its structural soundness, making BIM an essential tool in heritage conservation and management.

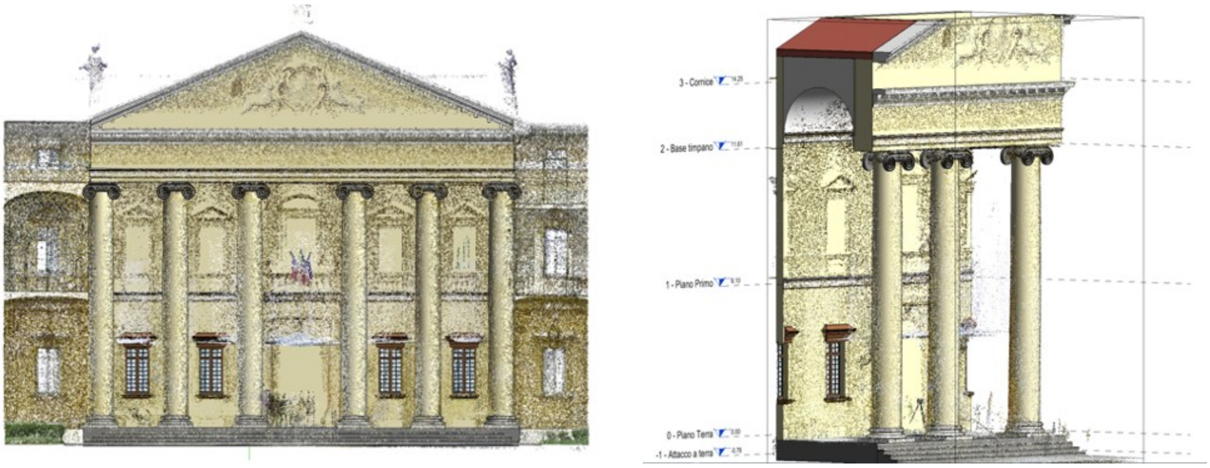

Figure 69. BIM modelling of the entrance porch of the Villa based on the overall point cloud (scanner + photogrammetry)

5.4.4 Hi-res orthophotos

The creation of high-resolution orthophotos from photogrammetry involves using modern rendering technologies to enhance low-complexity 3D geometry with 2D relief maps. These maps carry detailed topological features like bumps, cracks, and glyphs without the need for a massive amount of polygons in the 3D mesh, thereby maintaining efficiency. This is achieved through displacement maps, generated by specialised software that compares each texel on the simplified mesh against the original mesh, creating a 2D bitmap-based map. This approach takes advantage of modern graphics hardware while keeping resource requirements minimal. Additionally, the 2D data (photos) from the photogrammetry process are used to create orthophotos. These are geometrically corrected, or "ortho-rectified," images that represent the object from a viewpoint free of perspective or optical distortions. Orthophotos maintain a uniform scale and allow for accurate measurements. Traditionally used in the cultural heritage sector, orthophotos were once produced by correcting distortion in photographs. However, they are now more accurately and efficiently generated from 3D models, particularly those created using Structure from Motion (SfM) techniques, providing a precise and rapid means of documenting and analysing heritage sites.

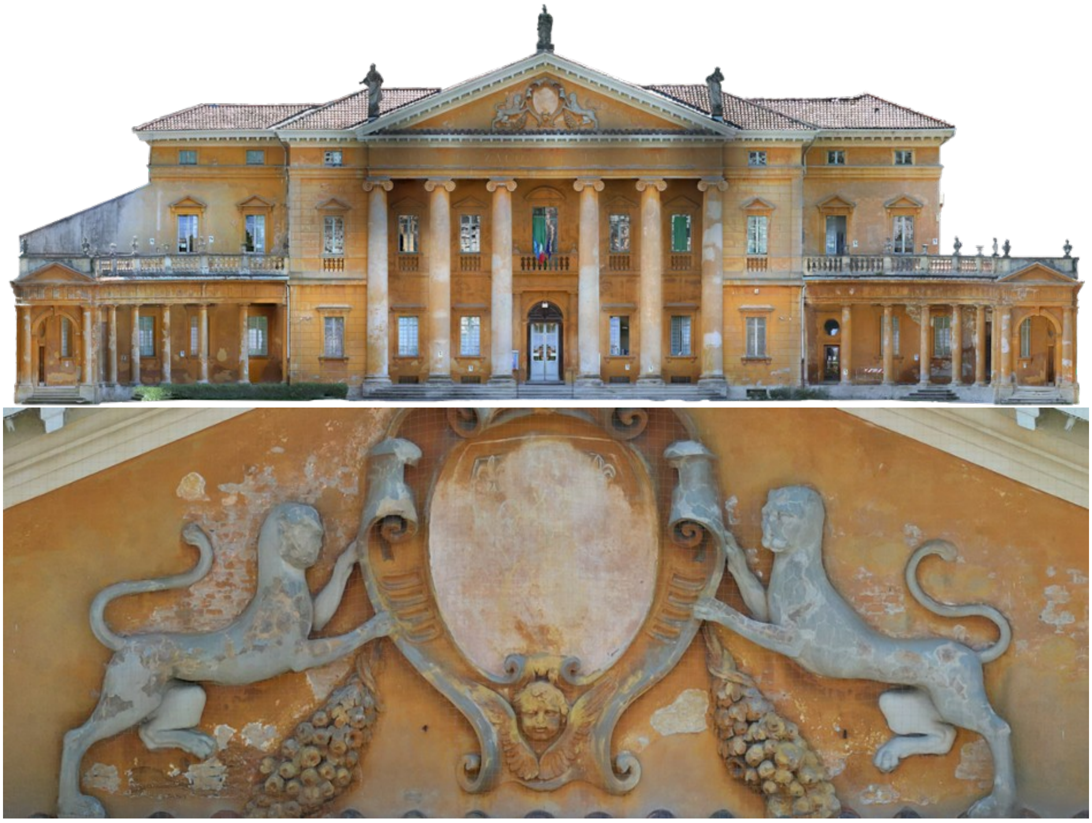

Figure 70. Hi-res orthophoto of the façade from photogrammetry (top) and an illustrative detail (bottom)

Figure 71. Hi-res orthophoto of the theatre from photogrammetry (left) and an illustrative detail (right)

5.5 Towards a wider audience

The data created from the 3D survey of Villa Aldrovandi-Mazzacorati can be repurposed for various applications, catering to a broader audience beyond architectural and conservation experts. One of the most engaging uses of this data is in creating immersive VR environments. By translating the detailed 3D models into virtual reality, a wider audience can experience the villa in a unique and interactive way. For instance, Villa Aldrovandi-Mazzacorati's VR experience was showcased to over 100 enthusiasts during the European Researchers Night in Bologna, allowing visitors to virtually explore the villa's intricacies and historical context, which enhances public engagement and education about cultural heritage.

Additionally, these 3D models can be made accessible online through specific viewers and platforms, like the INCEPTION platform. This online visualisation enables remote audiences to explore and interact with the 3D representations of the villa from anywhere in the world. Such digital accessibility democratises the experience of cultural heritage, making it available to a global audience, including educators, students, researchers, and history enthusiasts.

These applications exemplify how digital heritage data can be repurposed for educational and public engagement purposes, fostering a deeper appreciation and understanding of historical sites. By leveraging modern technology like VR and online platforms, cultural heritage sites like Villa Aldrovandi-Mazzacorati can reach and inspire a much larger and diverse audience.

Figure 72. VR immersive experiences during the European Researchers Night in Bologna on 29th September 2023

5.5.1 Immersive VR environment

Creating a VR immersive environment for Villa Aldrovandi-Mazzacorati involves optimising the 3D models for real-time rendering, a crucial step when using platforms like Twinmotion, based on Unreal Engine. The process starts by importing the detailed 3D models, such as those from CAD or BIM processes, into Twinmotion. These models often contain a high level of detail, which needs to be balanced against performance considerations for VR. Optimisation involves reducing the polygon count of the models to ensure smooth performance in VR without significantly compromising the visual quality. This is achieved by simplifying complex geometries and using lower-resolution textures where high detail isn't necessary. Additionally, Twinmotion's capabilities in handling lighting and materials are utilised to enhance the realism of the VR environment, creating a more immersive experience. In VR, it's crucial to maintain a high frame rate to prevent motion sickness; thus, the optimisation process focuses on streamlining the models and scene complexity to run efficiently on VR hardware. The result is an immersive, interactive VR experience that allows users to explore Villa Aldrovandi-Mazzacorati in a virtual space, balancing high-quality visuals with the performance demands of VR technology.

Figure 73. Visualisations of the VR immersive created for the theatre

Figure 74. Visualisations of the VR immersive created for the exteriors of the Villa

5.5.2 3D models for online visualisation: INCEPTION viewer

To visualise a 3D meshed model of Villa Aldrovandi-Mazzacorati online, it must be optimised for web rendering. This involves reducing the model's complexity to ensure it loads quickly and runs smoothly on various devices and internet speeds. First, the polygon count is reduced. High-resolution models are often too dense for efficient online viewing. Tools like MeshLab can simplify the mesh while retaining critical details. Next, texture resolution is adjusted. Large, high-resolution textures are downscaled to balance quality with performance. The model is then converted to a standard and web-friendly format (COLLADA in this specific case). Finally, the optimised model is uploaded to a platform capable of online 3D visualisation or into a storage space that can be accessed by the new INCEPTION viewer that has the capability of displaying content despite their location. The viewer has the ability to interact with the model – rotating, zooming, and exploring different aspects with ease. Through this process, the detailed 3D representation of Villa Aldrovandi-Mazzacorati becomes accessible and interactive for a global online audience, allowing for broader engagement and appreciation of the cultural heritage site.

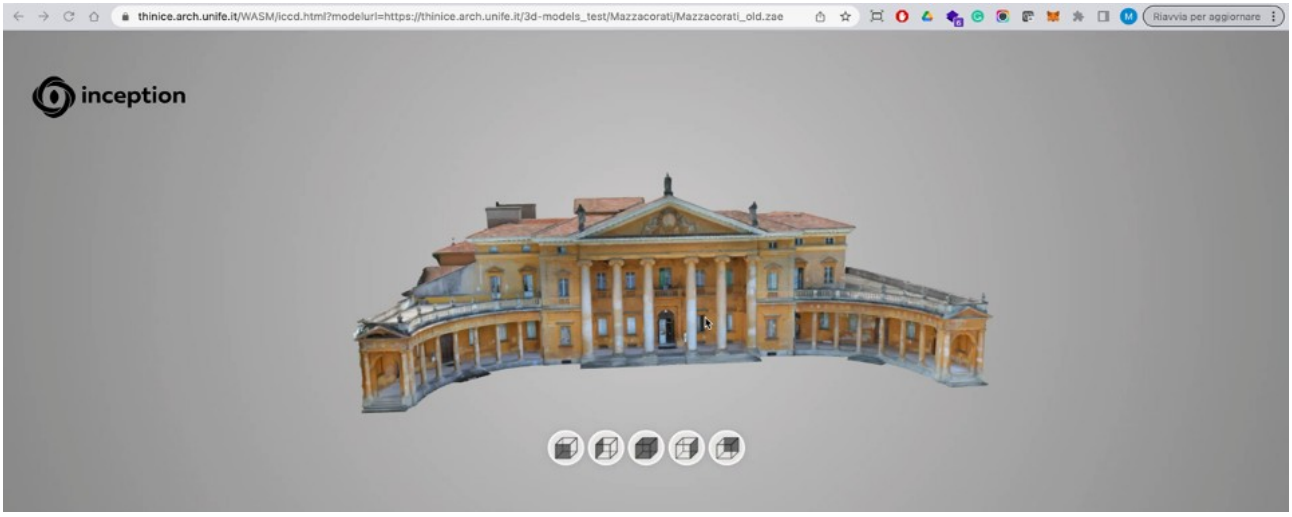

Figure 75. Visualisations of the Villa using the INCEPTION viewer

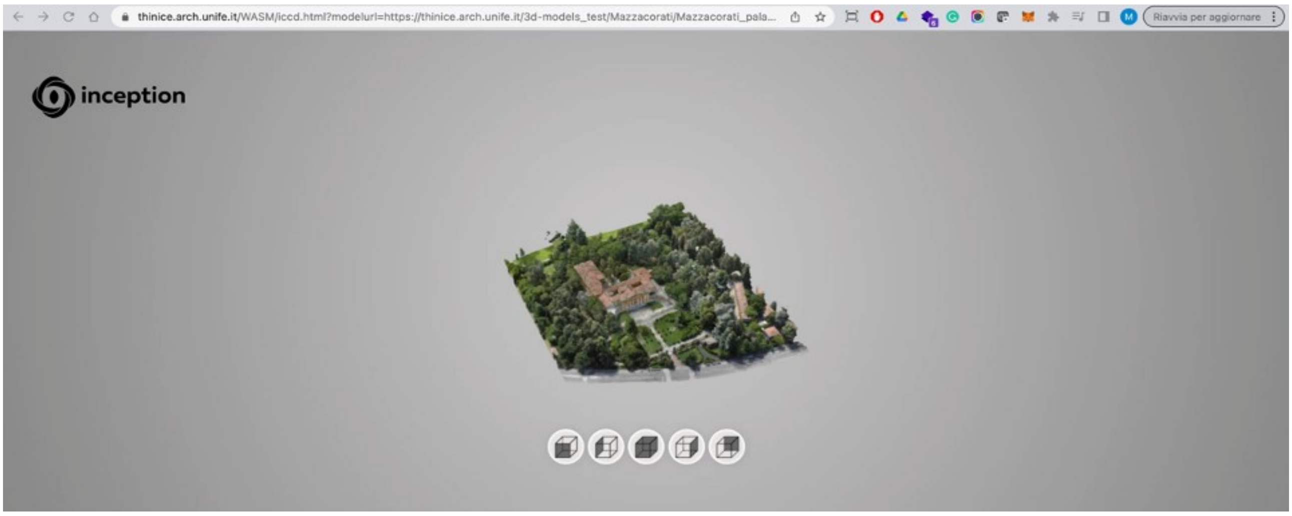

Figure 76. Visualisations of the exteriors of the Villa using the INCEPTION viewer

5.5.3 3D models for online visualisation: INCEPTION platform

Finally, as in the other pilot cases, the model has been uploaded to the INCEPTION platform for visualisation and interactive access to information related to its various parts/components.
The tools offered by the web platform integrated with the other 4CH tools provide a rich source of data and information on Villa Mazzacorati that can offer the various stakeholders a wide dataset for the valorisation of the asset, for the management of maintenance activities and for the planning of conservation and preservation interventions.
Figure 77 shows some examples of how to visualise the model and access the data.

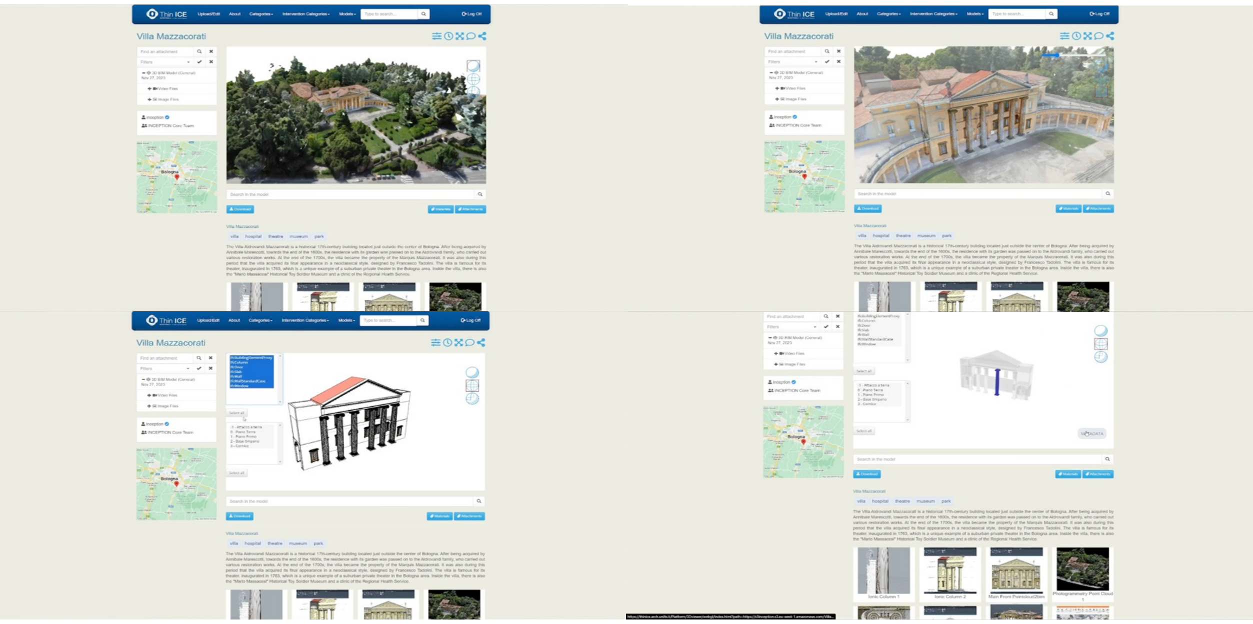

Figure 77. Visualisations different aspects of the Villa using the INCEPTION platform

6. Conclusions

This deliverable presents the implementation and application of the workflows developed in Work Package 4 through the simulation of pilot cases. The pilot projects served as demonstrators of success stories to validate the structure of the 4CH Competence Centre and its future activities.

The current report describes the selection of pilot cases, following the definition of specific criteria. These criteria were indeed useful to describe the main characteristics of the Cultural Heritage assets, to identify their state of the art, the risks related to their conservation and preservation, and any information related to their management status. They also served to analyse the compatibility of the aims of the pilot projects with the objectives of the 4CH project: conservation, preservation and valorisation. Finally, four case studies were selected to cover a diverse historical period and different heritage typologies in different locations, and to show the 4CH approach to implementing workflows for different objectives. The pilot projects were carried out to demonstrate whether the proposed workflows and methodologies were feasible and whether the digital technologies and solutions adopted were in line with the objectives of the Competence Centre in the field of preservation, conservation and valorisation of Cultural Heritage. Each pilot project has demonstrated, through the use of digital documentation techniques, the collection of data and how it can inform future conservation and preservation strategies or serve as a basis for valorisation activities. The pilot projects have also been instrumental in enabling experts and stakeholders to develop approaches and strategies, address challenges and establish best practices in the field of Cultural Heritage. They also contributed to the development of guidelines for the management of cultural heritage sites with different needs and exposure to different risks. Each pilot project focused on a defined purpose and developed a tailored strategy to meet the identified objectives and needs. The pilot cases demonstrated in practice, through a series of specifically designed features and services, how the use of the methods and technologies defined in the 4CH project can benefit the well-being of the various selected Cultural Heritage assets and, by extension, other similar sites and monuments. Indeed, throughout the results presented here, the pilot projects demonstrated the possibility of future applicability to other case studies within the future Competence Centre.

The use of 3D technologies underlined the importance of digital documentation and digital data for any kind of study, analysis, visualisation and management of CH assets. The reliability, high accuracy and speed of 3D documentation make them indispensable for a correct and complete documentation study, as well as for the valorisation of cultural heritage, especially in the case of heritage at risk.

The digital solutions proposed and adopted for the different objectives of the selected case studies were not without their pitfalls and needed to be tested before the best result could be achieved. In general, the pilot cases highlighted the need to develop integrated workflows by combining different technologies for documentation, as well as different digital solutions and software for

publishing and sharing the results with the community, whether for research, communication or education purposes.
The case studies highlighted how the use of visualisation experiences to promote and foster social inclusion or solutions for risk assessment, conservation, and valorisation, increase user engagement and support sustainability solutions and practices.
The workflows highlighted the importance of establishing mechanisms for updates based on continuous monitoring, technological advances, and evolving standards, as well as the importance of fostering collaboration with relevant stakeholders, including cultural institutions and preservation experts, to allow the reiteration of the workflow steps in a productive manner.
The results of the pilot cases contributed to establishing the framework of the 4CH CC in terms of strategies and best practices for the services to offer for Cultural Heritage assets conservation, preservation and valorisation.

7. References

Breccia, E. 1905. La Necropoli di Sciatbi. Primo Rapporto Provvisorio. BSAA 8, 55-106

Breccia, E. 1912. La Necropoli di Sciatbi. Catalogue general des Antiquités (Musée de Alexandrie), Cairo, vol. I-II

De Luca, L., Véron, P., & Florenzano, M., 2006. Reverse engineering of architectural buildings based on a hybrid modeling approach. Computers & Graphics, 30(2), 160–176. doi:10.1016/j.cag.2006.01.020

Irakleous, S., Bakirtzis, N., 2020. Karamanlides at the monastery of Saint John Lampadistis in Kalopanagiotis: pilgrimage votives, architecture and sacred landscape. Cahiers du Centre d'Études Chypriotes, (50), pp. 383-405.

Kypridemos, A., 2016. The Wooden Roofed Churches in the Troodos Mountains, Our Unique World Heritage [Research Thesis, Newcastle University], https://www.cy-arch.com/wp-content/uploads/2017/03/Kypridemos_Antonis_Dissertation.pdf

Koutoupas A., Orabi R., Loukas N., Bakirtzis N., Hermon S. (under review) The Digital Documentation of the Shatby Necropolis in Alexandria, Proceedings of the International Conference "Alexandria and Hellenism in Northern Egypt"

Limbouri-Kozakou, E., 2018. The restorations of monuments in Cyprus: from the establishment of the Department of Antiquities in 1935 until 2005, Cyprus Department of Antiquities, Nicosia

Maietti, F., Medici M., Bonsma P., Martin Lerones P., Ferrari F. (2022). Digital Technologies Towards Extended and Advanced Approaches to Heritage Knowledge and Accessibility. In Ugliotti, F.M., Osello A. (Eds.), Handbook of Research on Implementing Digital Reality and Interactive Technologies to Achieve Society 5.0. IGI Global. DOI: 10.4018/978-1-6684-4854-0

Papageorgiou, A., 2007. Η Μονή του Αγίου Ιωάννου του Λαμπαδιστού στον Καλοπαναγιώτη. Πολιτιστικό Ίδρυμα Τράπεζας Κύπρου, Ιερά Μητρόπολης Μόρφου σε συνεργασία με το Τμήμα Αρχαιοτήτων, Nicosia

Potenziani, M., Callieri, M., Dellepiane, M., Corsini, M., Ponchio, F., Scopigno, R., 2015. 3DHOP: 3D heritage online presenter, Computers & Graphics (ACM), Vol. 52, p. 129, https://doi.org/10.1016/j.cag.2015.07.001

Santagati, C., Papacharalambous D., Sanfilippo, G., Bakirtzis, N., Laurini, C., Hermon, S., 2021. HBIM approach for the knowledge and documentation of the St. John the Theologian cathedral in

Nicosia (Cyprus), Journal of Archaeological Science: Reports, vol. 36, p. 102804, DOI: 10.1016/j.jasrep.2021.102804

Woodward, A., Heesom, D., 2019. Implementing HBIM on conservation heritage projects: Lessons from renovation case studies, International Journal of Building Pathology and Adaptation, 39 (1), p. 96-114. https://doi.org/10.1108/IJBPA-06-2019-0054