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(37th Cycle)**

**Application of Scan-to-BIM approaches to HBIM
digitisations in Architectural Heritage
environment for documentation, management and
conservation purposes**

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Abbreviations and acronyms

AEC: Architecture, Engineering and Construction
AGC: Automated Ground Classification
AI: Artificial Intelligence
AIA: American Institute of Architects
AH: Architectural Heritage
BH: Built Heritage
BIM: Building Information Modelling
BDS: Building Description System
BEP: Bim Execution Plan
BLM: Building Lifecycle Management
BSI: British Standards Institution
BOM: Building Object Model
CAD: Computer Aided Design
CDE: Common Data Environment
CH: Cultural Heritage
CIDOC: Intercultural Centre of Documentation
CIPA: Comité International de Photogrammétrie Architecturale
CRM: Conceptual Reference Model
CSF: Cloth Simulation Filter
CW: Continuous Wave
DL: Deep Learning
DSLR: Digital Single Lens Reflex
EIR: Employer's Information Requirements
FoV: Field of view
GCP: Ground Control Point
GNSS: Global Navigation Satellite System
GPS: Global Positioning System

GSA: General Services Administration
GSD: Ground Sampling Distance
HBIM: Heritage Building Information Modelling
HFOV: Horizontal Field of View
HMLS: Handheld Mobile Laser Scanning
ICCROM: International Centre for restoration of Built Heritage
ICOMOS: International Council on Monuments and Sites
ICP: Iterative Closest Point
IFC: Institution Foundation Class
IMU: Inertial Measurement Unit
ISO: International Organization for Standardization
LASER: Light Amplification by Stimulated Emission of Radiation
LiDAR: Laser Imaging Detection and Ranging
LOD: Level of Development
LOd: Level of Detail
LOD: Linked Open Data
LOE: Level of Evolution
LOG: Level of Geometry
LOK: Level of Knowledge
LOI: Level of Information
LOIN: Level of Information Needed
LOR: level of Reliability
LS: Laser Scanning or Laser Scanners
MDCS: Massive Data Capture System
ML: Machine Learning
MMSs: Mobile Mapping Systems
MPS: Model Progression Specification
MVS: Multi View Stereo
NIBS: National Institute of Building Science
NPS: National Building Specification
NURBS: Non-Uniform Rational B-Splines

OWL: Web Ontology Language
PAS: Publicly Available Specifications
PW: Pulse Wave
RDF: Resource Description Framework
RMSE: Root Mean Square Error
SfM: Structure from Motion
SLAM: Simultaneous Localization And Mapping
SPARQL: SPARQL Protocol and RDF Query Language
TLS: Terrestrial Laser Scanning
UAV: Unmanned Aerial Vehicle
UNI: Italian Standardization Body
VFOV: Vertical Field of View
VPL: Visual Program Language

Unless otherwise specified, the images are graphic elaborations by the author

Introduction

Research background and justification

Architectural Heritage (AH) management frequently encounters significant difficulties in documenting existing historical buildings, due to the lack or the loss of information, inefficient geometric representation, and unrecorded restorations over time. Moreover, the traditional methods for supporting evidence based on archival research and bidimensional deliverables have been proven to be time-consuming and incomplete; these inconveniences often lead to poorly planned interventions, loss of resources and increased costs for maintenance.

As the expected life cycle of the historical buildings to be maintained is considered potentially perpetual ([Quattrini et al., 2017](#)), their correct management has become nowadays even more important, with an increased need for reliable, strategic and structured tools capable of handling the complexity of historical assets ([Santagati et al., 2018](#)). From this point of view, three-dimensional digitisations, founded on a thorough knowledge of the buildings to be recorded, are ideal to fulfil the scopes of planned maintenance and potential restoration procedures.

In the last 15 years, especially in Europe, Cultural Heritage (CH) researchers became interested in the novelties introduced by **Building Information Modelling** (BIM), trying to extend its capabilities to existing buildings of historical value, with the name of **Heritage Building Information Modelling** (HBIM). As a derivation of BIM, HBIM as well is an object-oriented modelling solution, where the parametric models are composed by geometric elements and semantic attributes and constitute at the same time a computational and informative database ([Volk et al., 2014](#)).

The main advantage of using HBIM processes to manage a CH asset is that the model not only reproduces the aspect and the behaviour of the real structures, but it even contains a conceptual system of information inside the BIM environment. Another aspect appealing to CH management is the collaborative work among different professionals, enhancing multidisciplinary knowledge and skills during the whole process.

HBIM documentary connotation and the synergic concept combined together bring huge advantages to the management, conservation, and restoration of buildings of historical values ([Pocobelli et al., 2018](#); [Lopez et al., 2018](#); [Lovell et al., 2023](#)).

Whenever a HBIM process is based on the outputs of preliminary surveys carried out on the case studies with Massive Data Capture Systems (MDCSs), such as Terrestrial Laser Scanning (TLS) and/or terrestrial and aerial photogrammetry, this approach is called **Scan-to-BIM** ([Brumana et al., 2020](#)). This approach is strongly recommended in HBIM process, because is the most reliable, quick, efficient, non-invasive and cost-effective method for capturing the real surfaces of the assets, guarantee the maximum accuracy of the data and provide all necessary information for parametric modelling ([Aricò and Lo Brutto, 2022](#); [Costantino et al., 2021](#)). The obtained modelled replica can be exploited in all parts to build a 3D smart model and understand its state of conservation.

These are the reasons why Scan-to-BIM is considered the most suitable approach for HBIM, even if the methodology is relatively new and still requires a clear framework especially for quantitative and qualitative evaluations of the final model.

Objectives of the research

This research originated from three theoretical questions about HBIM methodology through a Scan-to-BIM approach:

1. How can a digital model match the AH requirements?
2. Is data capture based on MDCSs genuinely exhaustive and representative of the complex reality of an existing building?
3. How can manual modelling procedures be improved without resorting to complicated algorithms or experimental and resource-consuming techniques?

In order to provide their related answers, the illustrated research was carried out with the main objective of making the HBIM digitisation through a Scan-to-BIM approach a vehicle of documentation, information and communication which could support and enable a correct comprehension and the awareness on the AH assets, fostering improved conservation and restoration plans and empowering the collaboration among operators involved in their management.

During the development phase of the research, some attempts have been made to make the Scan-to-BIM workflow more resilient and compliant to the AH management requirements in different projects, overcoming the most recurrent limitations in the process and obtaining a faster and more reliable HBIM model.

This dynamic and customised workflow was aimed at:

- ✓ a more effective and less resource-consuming manual labour;
- ✓ the embodiment of the complexity of the real assets in all their geometric attributes and characteristics;
- ✓ the development of a brand-new library with architectural items typical of local historical Heritage;
- ✓ a systematic organization of the semantic heterogeneous contents into a useful tool for thematic exploitation of the model.

The *as-built* HBIM models thus created are not only capable of describing the actual state of the case studies but constitute at the same time a digital replica and an updated knowledge database of the real heritage buildings. At all times, these models must not be intended as the final products of a Scan-to-BIM application but as an informative tool for further analyses, providing all the necessary information for conservation plans and interventions on the artifacts.

Methodology

The operative methodology of this research has been tailored upon the purposes illustrated in the last paragraph, to validate an improved framework for optimising HBIM models which enable an interpretation of the AH buildings as correct and complete as possible. Indeed, albeit Scan-to-BIM could be considered nowadays a well-established framework, this research tried some experimental procedures aimed at empowering both the quantitative and qualitative aspects of the digitisation, especially affecting data acquisition and the manual modelling phases.

The data acquisition through MDCSs techniques and their post-processing are canonical routines which provide the most reliable outputs for the reality-based models; however, in the next chapters different capturing methodologies have been tested

either through their integration or their comparison in order to evaluate their effectiveness in detecting a sufficiently accurate initial information tailored to the scopes of both the surveys and the models.

The direct, manual approach with manual methods still represents the most used and valid method in modelling; despite this, to overcome its notorious limitations, it has been sided by some novelties, offering alternative workflows, tools and libraries whenever the standard ones provided by the BIM environment were not satisfactory for the CH management needs.

These testbeds were focused on:

- ✓ the digitisation of atypical architectural items through the NURBS modelling;
- ✓ the integration of heterogeneous, queryable data inside the models, enabling further investigations and thematic mapping;

Once the trustworthiness of this new dynamic framework has been benchmarked from a computational point of view, it could be serialised and implemented on a standard basis for providing more precise solutions to the most recurring issues in the generative parametrisation and the documentation of the historical evidence of the Architectural Heritage.

In order to validate the main purposes of development phase of this research, the improved framework illustrated in the last paragraph has been applied on four case studies. The first three cases, all belonging to the medieval AH in Sicily, have the same architectural, constructive and stylistic features. In order of presentation, they are the churches of San Giovanni dei Lebbrosi and San Giovanni degli Eremiti in Palermo, followed by the so-called Trinità di Delia in Castelvetro (Trapani, Western Sicily).

Their digitisation led to:

- ✓ the establishment of an adequate framework for a data acquisition campaign, capable of collecting and delivering more efficient information and their related outputs;
- ✓ the adoption of improved modelling procedures from point clouds for typical construction families (columns, walls, floors and roofs);

- ✓ the implementation of a small library of parametric and customisable elements related to a peculiar historic/architectural style;

The fourth case study is a cave Baroque church dug into an archaeological Punic settlement in Marsala (Western Sicily), named Santa Maria della Grotta. It offered the possibility:

- ✓ to document in an integral way a densely stratified area which hadn't been surveyed before;
- ✓ to test an experimental procedure for the thematic mapping of decay alterations affecting the real artifact;
- ✓ to create an expandable database collecting all the semantic information relevant to the decay monitoring and tailored on CH management purposes;

These buildings have been chosen because their digitisation could be relevant not only from a historical/architectural point of view but for all the technical and methodological aspects as well, as an actual testbed to benchmark the experimentations illustrated ahead against.

Their models thus obtained establish and offer a generalized and repeatable framework for other modellers in similar cases.

Structure of the research

The structure of the research which will be presented to follow is organised into separate chapters dedicated to different topics.

The first chapter presents the HBIM methodology applied to the Cultural Heritage from the point of view of academic research, with a focus on its derivation from BIM and all the related outcomes. The state-of-the-art will be then completed with a panoramic overview on the strengths and weaknesses of any HBIM digitisation, the different international and national regulatory standards and the framework adopted in Italy.

The second chapter regards the Scan-to-BIM approach and its typical workflow. Further considerations on how this method has been tailored and applied to the case studies in this dissertation have been added at the end, with a comprehensive overview focusing on the adopted strategies for the data acquisition and their subsequential processing, on the key issues encountered, and how these latter have been sorted.

The following four chapters are dedicated to Scan-to-BIM applied in detail respectively to the same number of case studies. After some brief historical notes, based on bibliographical and documental evidences, and an accurate analysis of the common typological and architectural features of these artifacts, their digitisation will be investigated first on their reality-based digital survey, aimed at the geometric-morphological acquisition of their current as-built conditions, and then in the subsequential data processing in order to obtain the three-dimensional point cloud outputs. Any possible further steps for easier computation purposes will be considered and examined.

The seventh chapter is entirely dedicated to the rendition of the digital models regarding the first three case studies (belonging to the Arab-Norman Architectural Heritage in Western Sicily) into a BIM environment, from a geometric point of view. The modelling phase, its procedures and potential will be investigated in depth according to a traditional direct approach, aimed at obtaining both the most geometrically accurate models and libraries of parametric objects related to a local architectural style of the past. The eighth chapter will introduce a novelty, applied to the fourth case study: it relies on testing a thematic mapping (such as decay phenomena) and its relative data management as semantic contents of the digital models, which will be thoroughly treated.

The results obtained in this research will be finally discussed in the dedicated paragraph.

1. Methodology

1.1 Introduction to Building Information Modelling

Building Information Modelling (BIM) (Van Nederveen and Tolman, 1992) is an integrated process which digitises a 3D model to plan, design, construct, and manage a building throughout its lifecycle. This model serves as both a visual representation and a data repository, containing all physical and functional details. Beyond geometry, it includes semantic metadata to enhance collaboration among professionals. Whilst definitions might vary, they all acknowledge that BIM fundamentally centralises information in a single database to improve cooperation in the construction process (Figure 1).

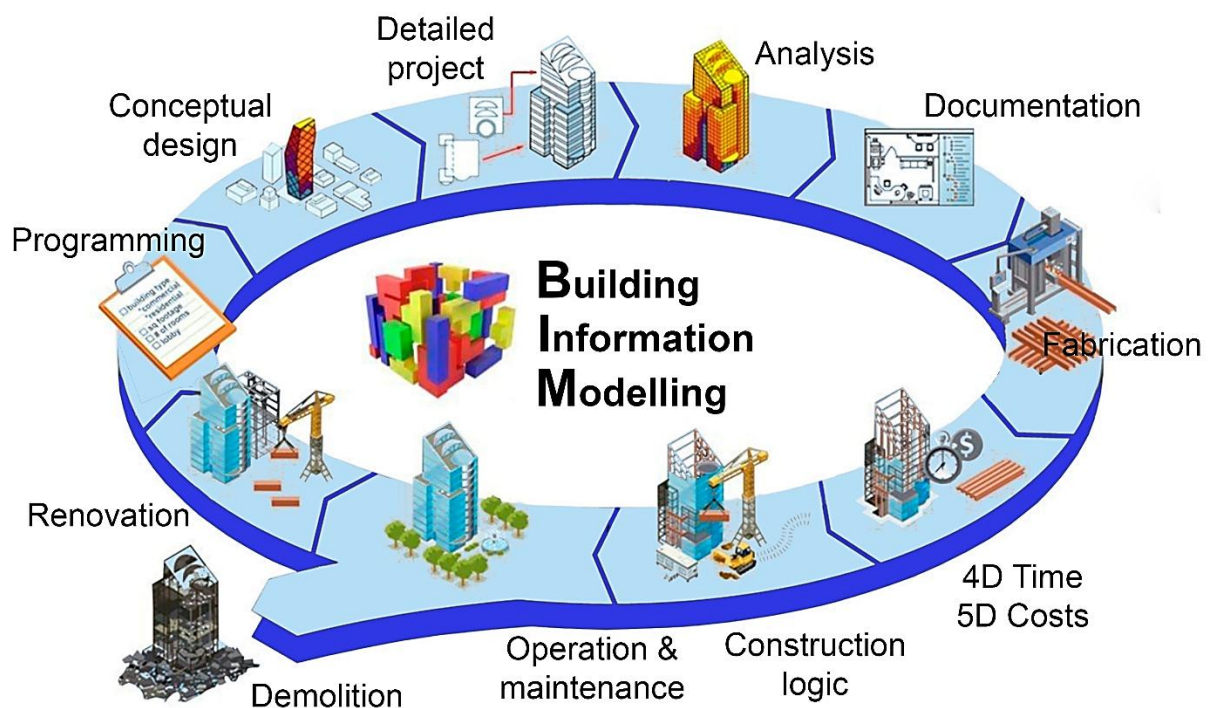


Figure 1. Life cycle of a building through BIM management.

1.1.1 Evolution of BIM

The rise of Computer Aided Design (CAD) in the 1970s led to debates on representing reality in design, inspiring a model-based approach which included both geometry and related data. In 1974, Charles Eastman from Carnegie-Mellon University introduced the concept of a "virtual model" for buildings through his Building Description System

(BDS) (Eastman et al., 1974); this computer-based database was aimed at addressing the limitations of 2D drawings by linking geometric and spatial data. BDS could automatically generate and update drawings, ensuring consistency and efficiency in the management of building documentation (Eastman et al., 1974). In 1975, he further developed his idea, describing how computerized modelling could use parametric objects (such as walls and windows) from libraries to build a 3D model. Each object contained detailed information on materials, suppliers, and specifications (Eastman et al., 1975).

Eastman's work laid the foundation for modern BIM. In 1984, Gábor Bojár developed for the architecture, engineering, and construction (AEC) sector the Radar CH software (later ArchiCAD) by his Graphisoft¹ company in Budapest, introducing "smart objects" which could be customised and updated in both 3D and 2D. In 1997, Leonid Raiz and Irwin Jungreis created Pro/Engineer, which evolved into Revit (from "*REVise Instantly*") by Autodesk in 2000. Revit revolutionized BIM by enabling parametric modelling without programming and introducing time-based simulations, solidifying its role as a leading tool in architecture, engineering, and construction.

1.1.2 BIM definitions

As BIM adoption grew, defining its terminology became essential. Since 2002, the meaning of the "M" in BIM has evolved from "Modelling" to also include "Model" (representing the 3D structure) and "Management" (focusing on information and process control). Whilst "Modelling" remains the most common term, there is no universally accepted definition.

Various organizations have provided key definitions:

- ✓ U.S. General Services Administration (GSA), 2007: A multi-faceted digital model used to document, simulate construction, and manage operations (General Services Administration, 2007).

¹ Founded in Budapest by Bojár himself in 1982 to provide software solutions for AEC industry, Graphisoft was acquired in 2007 by the German Group Nemetschek AG

- ✓ National Building Specification (NBS), 2007: A process for creating and managing information throughout a project's lifecycle using coordinated digital descriptions (NBS, 2011).
- ✓ National Institute of Building Science (NIBS), 2011: A digital representation of a facility's physical and functional characteristics, serving as a knowledge resource (NBIMS, 2011).
- ✓ ISO 16757-1:2015: A model containing information from all phases of a building's lifecycle (ISO 16757-1:2015).
- ✓ PAS 1192-5:2015: A structured set of electronic, object-oriented information for design, construction, and operation (BSI PAS 1192-5:2015).
- ✓ ISO 29481-1:2016: A shared digital representation of built objects (e.g., buildings, bridges, roads) for reliable decision-making (ISO 16757-1:2015).
- ✓ ISO 19650:2019: The use of a shared digital model to support design, construction, and operational processes (ISO 16757-1:2015).

These definitions highlight BIM's role in centralizing and managing building information throughout its lifecycle.

1.1.3 The BIM environment

BIM is more than just software or a 3D model; it serves as a shared database for managing a building's entire lifecycle, from construction to demolition. This database includes information about building components and their behaviour.

BIM models can be single (focused on one discipline) or federated (integrating multiple sub-models from different fields like architecture, structure, and systems). These models contain intelligent objects, called Building Object Models (BOMs), with parametric rules which allow automatic geometric adjustments, while maintaining relationships across three levels:

1. *Within-object relations*: Interactions between elements within the same object (e.g., reinforcement inside a column).
2. *Peer-object relations*: Adjustments in one object based on changes in another (e.g., a wall adjusting to a door).

3. *Hierarchical relations*: Global modifications that impact the entire model based on reference lines, axes, and planes.

BOMs are organized into families, characterised by model categories (structural and non-structural elements like walls, doors, and floors) and annotation categories (text, dimensions, notes). These categories are further divided into classes and subclasses, which define common attributes and allow user modifications through parameters. Families are characteristic tools of any BIM software, albeit they are more extensively used in Autodesk Revit ([Garagnani and Cinti Luciani, 2011](#)). Regardless the authoring software, there are three types of families: System families, Component (Loadable) families, and In-place families.

- ✓ System families are built into the software, cannot be created or removed, and follow a strict hierarchy.
- ✓ Component (Loadable) families are user-created from templates available in the software, stored separately as .rfa files, and can be reused in different projects. These offer full customization at all levels (even for the superclass and class), for parametric and freeform shapes.
- ✓ In-place families are custom elements created for a specific project and cannot be reused elsewhere.

Modifications within BIM models occur through Type parameters (affecting all instances of a type) and Instance parameters (applying to individual objects). This structured approach ensures flexibility and consistency in managing building components (Figures 2 and 3).

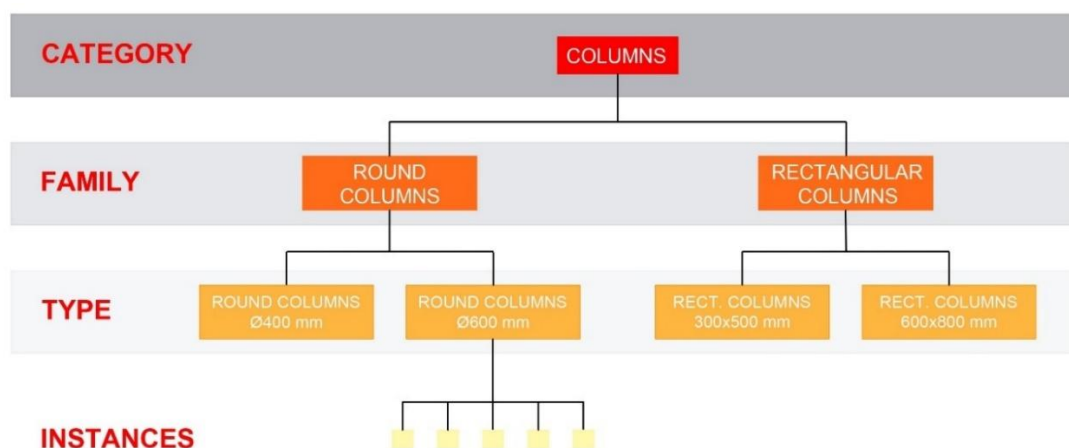


Figure 2. Further division of categories into families, types and instances.

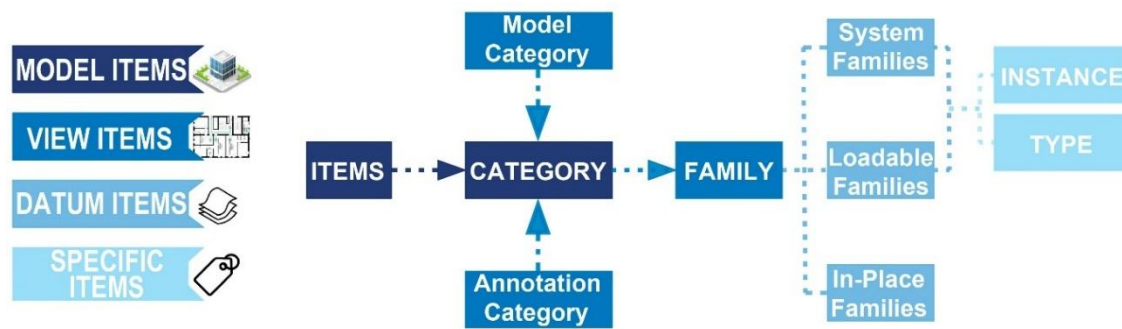


Figure 3. Structure of BOMs inside a BIM environment.

1.1.4 Levels of informational definition

BIM methodology enables construction professionals to create models suited to their expertise and project requirements. A key aspect is defining the Level of Development (LoD), which specifies the required dimensional and informational detail, differing from traditional drawings where detail depends on scale and project phase. Various international standards define levels of BIM model development, collectively known as LOx, which include:

- ✓ Model Progression Specification (MPS)
- ✓ Level of Development (LOD)
- ✓ Level of Detail (LOd)
- ✓ Level of Geometry (LOG)
- ✓ Level of Information (LOI)
- ✓ Level of Information Need (LOIN)

These classifications vary by country and standard, leading to different interpretations. Below are some key definitions from various sources:

AEC(UK) BIM Protocol (2012Akpinar): Based on Level of Detail (LOd), emphasizing geometric aspects only, divided in four categories from schematic to realistic grades (G0-G3) (AEC(UK), 2012);

PAS 1192-2:2013 (UK)²: Introduced Level of Definition (LoD), covering both graphical (LOG) and informational (LOI) components with a seven-grade scale (G1-G7).

² Publicly Available Specifications

NBS BIM Toolkit (2015): Built on PAS 1192-2, introducing an eight-level scale (0-7), with LOD levels from 2 to 5 and LOI levels from 2 to 6 (148). It is widely adopted internationally (Sattanino, 2018).

AIA (US) E202TM-2008: American Institute of Architects (AIA) defined LOD in five levels (LOD 100-500), from basic forms (LOD 100) to as-built models (LOD 500) (AIA, 2008). The 2022 update refined LOD as the minimum required description of model elements.

BIMForum (2011)³: Modified AIA's LODs, adding an intermediate LOD 350 and removing LOD 500 because it was more relevant to as-built models; it is more focusing on contractual use and distinguishing between geometric and informational aspects.

Each framework helps ensure information consistency and model accuracy throughout a project's lifecycle.

In December 2018, the ISO 19650-1:2018 standard redefined LOD as Level of Information Needed (LOIN), combining LOI and LOG. Unlike predefined LOD stages, LOIN is project-specific, allowing flexibility based on client needs and required detail levels.

1.1.5 The Italian reference standards

The Italian BIM reference standards, defined in the UNI 11337-4:2017 standard (UNI 11337, 2017), follows a similar approach to the U.S. system, defining Level of Development (LOD) into seven levels (A to G), ranging from basic symbolic representation (LOD A) to highly detailed and accurate models (LOD E) (Figure 4).

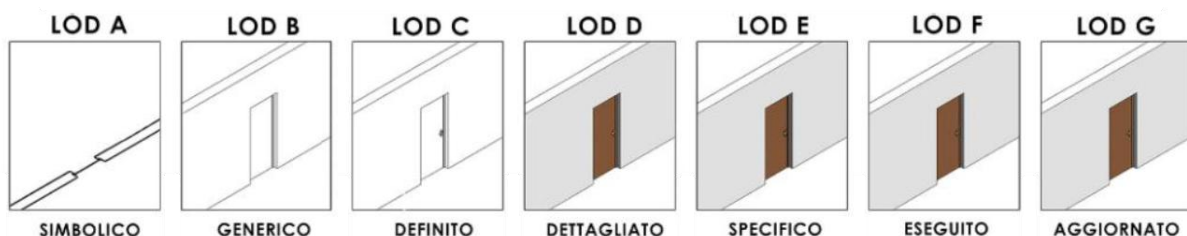


Figure 4. A sample of LOD classification according to UNI 11337.

³ American organization compliant to the British AEC(UK)

Each LOD is the sum of both geometric (LOG) and informational (LOI) attributes, which include assembly and maintenance data (AIA, 2008).

A key feature of UNI 11337 is its focus on historic building preservation and restoration, extending BIM's application beyond construction. To support this, it introduces two additional LOD levels (AIA, 2022):

- ✓ LOD F: As-built models based on precise surveys of existing conditions.
- ✓ LOD G: Includes maintenance and update information for heritage buildings (Figure 5).

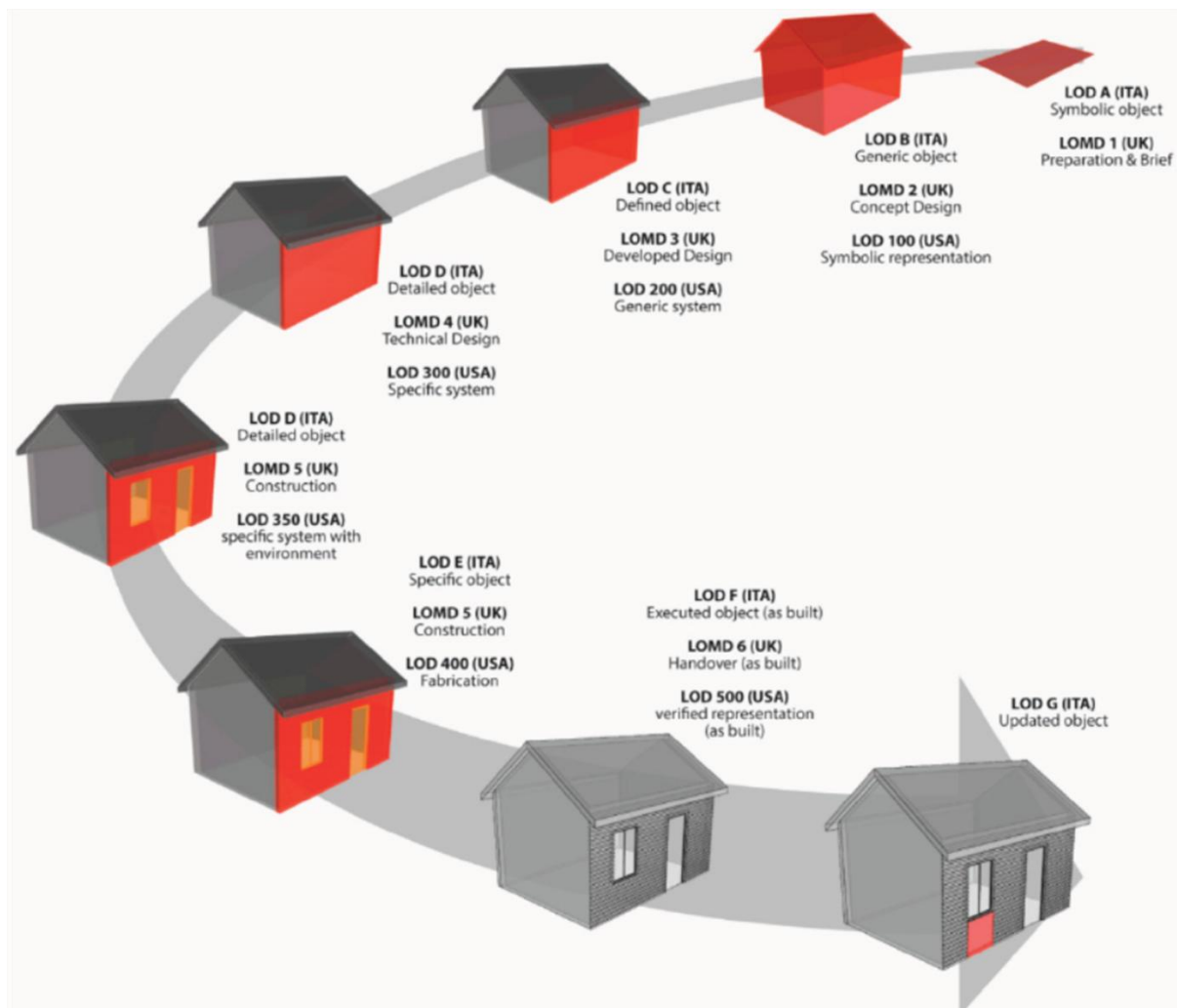


Figure 5. Comparison of LOD development in Italian, English and American standards (from Carnevali et al., 2019).

1.1.6 BIM maturity levels

The BIM Maturity Levels, introduced since PAS 1192:2013, were developed by Mark Bew and Marvyn Richards in 2008 to track BIM adoption in construction projects (Figure 6). These levels range from 0 to 3, based on collaboration and information exchange between project stakeholders:

- ✓ BIM Level 0: No collaboration; reliance on CAD and non-interoperable documents.
- ✓ BIM Level 1: Limited collaboration within a single organization, using a Common Data Environment (CDE) for contractors only.
- ✓ BIM Level 2: Full collaboration with 3D model exchange, creating a federated model.
- ✓ BIM Level 3: Full integration via a single shared online BIM model, supporting real-time collaboration and Building Lifecycle Management (BLM).

The ISO 19650-1:2019 standard updated this concept, replacing the original linear diagram with a matrix format to better illustrate the benefits of collaboration.

The UK pioneered BIM adoption, driven by government mandates since 2011. Italy follows a similar approach, with the UNI 11337-1:2017 standard defining BIM Maturity Levels on a five-grade scale (L0 to L4), based on model information content ([AIA, 2008](#)).

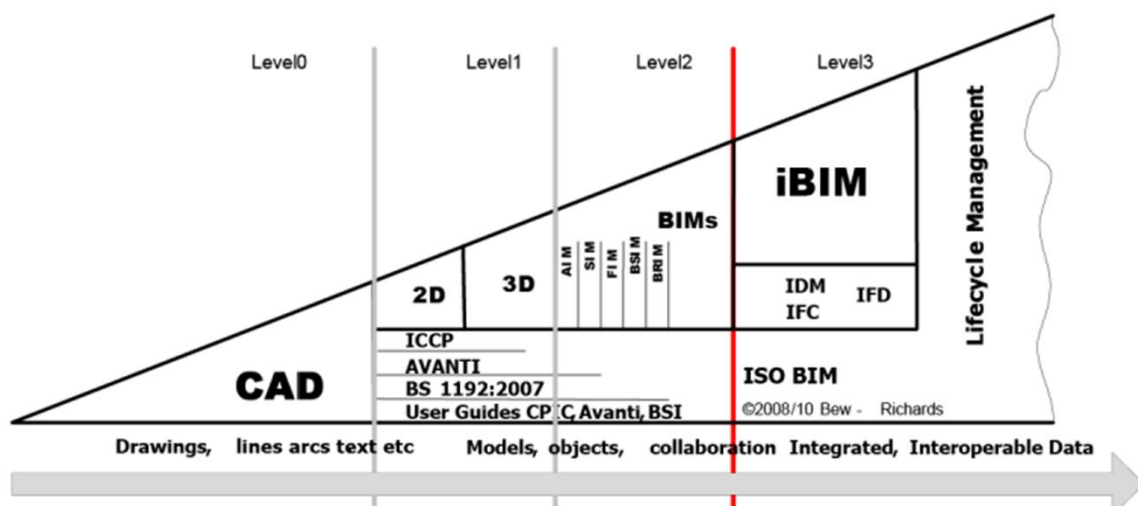


Figure 6. BIM levels on Bew-Richards' wedge in PAS 1192:2015.

1.1.7 Interoperability

Interoperability is a key feature of BIM, enabling interdisciplinary collaboration by integrating data from various disciplines into a shared platform. This allows professionals to work together efficiently, minimizing errors and ensuring consistency (Sacchi, 2016).

Work-sharing allows multiple users to collaborate on the same model simultaneously by dividing it into worksets based on parts, roles, or disciplines (Figure 7). This ensures that each task is assigned to the most qualified team member. The central (or federated) model is stored on a server or cloud, enabling real-time synchronization. Team members work on local copies and update the central model, ensuring consistency across the project and minimising errors or inconsistencies caused by miscommunication (Dalla Mora et al., 2014).

Work-sharing is categorized into:

- ✓ Closed BIM (Lonely BIM): Uses the same software, with the model saved in its native format.
- ✓ Open BIM: Uses different software, exporting models in open, neutral formats to ensure compatibility.

For Open BIM, models must be exported in formats which preserve component data for seamless sharing. Since the 1990s, buildingSMART International (bSI) (buildingSMART International) has regulated Open BIM through the IFC (Industry Foundation Classes) standard. Recognized as an ISO 16739:2013 standard, IFC ensures accurate export of model attributes in an interoperable format, based on the EXPRESS⁴ language and organized into four interconnected layers. IFC models a hierarchical structure, adding layers of detail to objects and their relationships.

Despite its advantages, IFC adoption remains limited due to:

- ✓ Information loss during export (software compatibility issues).
- ✓ Complexity in managing IFC files.

⁴ The EXPRESS language was developed in 1994 by Douglas Schenck and Peter Wilson for industrial production, and furtherly extended for the AEC sector. It employs two main types of representation: a lexical one where properties are defined into an ASCII, or a graphical one called EXPRESS-G.

These challenges hinder achieving global interoperability, which is necessary for BIM Level 3 Maturity (or Level 4 in Italy). However, IFC remains the preferred format for public tenders and large-scale projects requiring cross-platform integration.

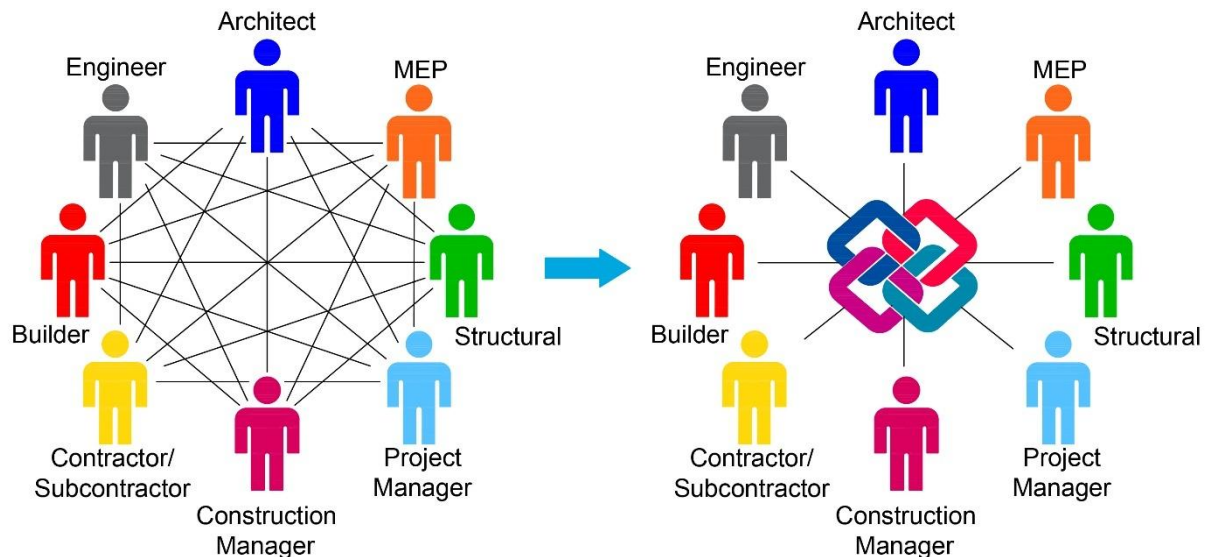


Figure 7. Advantages of an interoperable workflow.

1.1.8 Global BIM adoption: a comparative overview

The adoption of BIM in the construction industry is accelerating worldwide, improving efficiency, quality, and cost reduction. However, the pace of implementation varies across countries due to different policies, regulations, and industry readiness.

United States: BIM adoption in the U.S. is decentralized, with national organizations like the AIA defining LOD guidelines. However, since states and local governments have discretion in adopting BIM, implementation is uneven, with some regions more advanced than others. Despite this, BIM is gaining recognition for its ability to improve design, construction, and facility management.

United Kingdom: The UK government has taken a centralized and regulated approach to BIM. The PAS 1192-2:2013 introduced key guidelines and required contractual documents like:

- ✓ Employer's Information Requirements (EIR)
- ✓ BIM Execution Plan (BEP)

Since 2016, public projects must comply with BIM Level 2. The UK also developed the National BIM Library, offering standardized BIM objects across various software. The

“Digital Built Britain” strategy aims for Level 3 BIM, integrating BIM across the entire building lifecycle ([NBS, 2020](#)).

Italy: Italy's BIM adoption was driven by the New Public Procurement Code (D.Lgs. n. 50/2016) and the Ministerial Decree DM n. 560/2017 ("Baratono Decree"), which mandated progressive BIM adoption in public projects. Implementation follows a five-step process (2018-2025), based on contract value. However, due to challenges in the industry, DM n. 312/2021 introduced amendments to clarify procedures and merit classifications based on UNI 11337 standards. Italy's BIM implementation process remains one of the most unique and ambitious examples of national-level adoption globally.

While BIM adoption is growing globally, national policies and frameworks shape its development. Countries like the UK and Italy are at the forefront, setting structured implementation paths to ensure widespread use in the AEC sector.

1.2. The HBIM extension

Architectural Heritage (AH) management faces challenges in documenting historical buildings due to missing information, inefficient geometric representation, and unrecorded restorations. Traditional archival research and 2D documentation are often incomplete and time-consuming, leading to poorly planned interventions, resource loss, and higher maintenance costs.

As historical buildings require long-term maintenance, strategic and structured tools are essential ([Santagati et al., 2021](#)). Three-dimensional digitization, based on thorough knowledge of the buildings, offers an effective solution for planned maintenance and restoration.

Over the past 15 years, particularly in Europe, researchers have explored the potential of Heritage Building Information Modelling (HBIM), an extension of BIM tailored for historical structures. As a derivation of BIM, HBIM as well provides parametric models with geometric and semantic attributes ([Volk et al., 2014](#); [Allegra et al., 2020](#)), serving as a comprehensive database for documentation, analysis, and project development ([Rocha et al., 2020](#)).

The key benefit of HBIM is its ability to replicate both the physical structure and the embedded information within a collaborative digital environment. It fosters multidisciplinary cooperation, ensuring that decisions are interconnected and aligned with long-term master plans, preventing short-sighted choices. This integrated approach significantly enhances the management, conservation, and restoration of historical buildings ([Pocobelli et al., 2018](#)).

1.2.1 Definitions of HBIM and state of the art

HBIM was first introduced in 2007 at the 8th International Symposium on Virtual Reality, Archaeology, and Intelligent Cultural Heritage by Maurice Murphy, Eugene McGovern, and Sara Pavia from the Dublin Institute of Technology and Trinity College Dublin ([Murphy et al., 2007](#)). In 2009, they defined HBIM as “a new system for modelling historic structures by mapping parametric objects onto point cloud and image survey data” ([Murphy et al., 2009](#)). In 2012, M. Murphy proposed in his doctoral thesis an HBIM workflow to document Irish neoclassical architecture (1700–1830) through five case studies in Dublin’s Henrietta Street ([Murphy, 2012](#)).

This method combined Laser Scanning (LS) for data collection and extensive archival research to create a parametric library applicable to similar structures. During the following year, he further described this parametric modelling approach as a digital library of historical architectural elements, reinforcing HBIM’s reliance on parametric object libraries ([Dore and Murphy, 2012](#)) and digital survey techniques ([Dore and Murphy, 2013](#)).

Murphy’s HBIM definition has been widely acknowledged in research not just as a modelling tool but a proper framework ([Fai et al., 2011](#)), covering all workflow phases from data acquisition to the semantic enrichment of digital model ([Saygi and Remondino, 2013](#); [Volk et al., 2014](#); [Maiezze and Tata, 2021](#)). The application of BIM to AH has been validated through numerous studies showcasing successful digitisations of Heritage buildings ([Rocha et al., 2020](#)). Some researchers have focused on specific HBIM aspects, such as data collection, processing, modelling techniques, the role of HBIM in long-term AH management ([Historic England, 2017](#)), and the quality of these digitisations ([Pritchard et al., 2021](#)). However, other scholars highlighted current gaps and limitations in the process ([Penjor et al., 2024](#)).

A preliminary survey phase has been recognized as essential for obtaining comprehensive documentation, assessing a building's condition, and supporting maintenance ([Di Giulio et al., 2014](#)). Digital integrated surveys combining multiple methodologies are now the recommended practice ([Lovell et al., 2023](#); [Alshawabkeh and Baik, 2023](#); [Centarti et al., 2024](#); [Masciotta et al., 2023](#); [Lo Brutto et al., 2021](#)), though some studies focus on single techniques like static ([Buill et al., 2020](#); [Liu et al., 2023](#)) or mobile ([Sammartano and Spanò, 2018](#); [Sammartano et al., 2021](#)) laser scanning, terrestrial ([Nieto-Julián et al., 2024](#); [Lo Brutto and Dardanelli, 2017](#)) or aerial ([Pepe et al., 2022](#); [Martinez-Carricondo et al., 2021](#)) digital photogrammetry, or comparative reviews ([Mengiste et al., 2022](#)), even aimed at finding solutions to most common issues ([Scianna and La Guardia, 2019](#)).

Nowadays, the survey data processing is performed by dedicated software through a traditional semi-automated procedure, but this method becomes erratic whenever it comes to large-size sites or a huge number of scans are needed. For this reason, other researchers have investigated algorithms based on semantic point cloud segmentation ([Matrone et al., 2020](#)), with Machine Learning ([Shen et al., 2021](#); [Costantino et al., 2024](#)) or Deep Learning ([Pierdicca et al., 2020](#); [Moyano et al., 2021](#)) or both ([Cao et al., 2022](#)) frameworks for classification and labelling of recognised architectural items, but these methods are not part of this study.

Regarding the modelling phase, research has explored cost-effective methods for parametrizing historical architectural elements and developing reusable libraries of parametric components for similar building ([Dore and Murphy, 2013](#); [Sampaio et al., 2021](#); [Daniels and Georgopoulos, 2023](#); [Martinelli et al., 2022](#)). Manual methods are still the most used, but they have been proved to require greater time and resources ([Aricò and Lo Brutto, 2022](#)), and they could not provide the necessary accuracy for complex features. Alongside, alternative approaches have been studied to integrate meshes ([Moyano et al., 2022](#)) or polysurfaces into the BIM environment for accuracy purposes; whilst other scholars focused on novel semiautomated procedures offered by plugins for Visual Program Languages (VPL) such as Dynamo ([Roman et al., 2023](#)) Grasshopper ([Pepe et al., 2024](#)) or PointSense ([Wang et al., 2015](#)), programming scripts ([Andriasyan et al., 2020](#)) like Python (which are not part of this research), and their comparison to more traditional methods ([Angulo-Formos and Castellano-Román,](#)

2020). Whichever the method performed for obtaining the model, it must rely on a LOD adequate to the scope of the work; alongside with the already defined LODs (Jordan-Palomar et al., 2018), new categories have been proposed to take into account the peculiarities of each model and its digitisation (Maiezza and Tata, 2021; Santagati et al., 2018). Semantic contents of a HBIM model have been thoroughly investigated as well (Simeone et al., 2019; Bruno and Roncella, 2018), for supporting data interpretation (Adami et al., 2019) or for defining a consistent database to be exploited with standards promoted by AH management (Acierno et al., 2017; Cursi et al., 2022). Literature focused even on the several scopes of HBIM digitisations (Tucci et al., 2017), considered a fundamental tool mainly for structural analyses (Diz-Mellado et al., 2021), hypotheses of construction over time (Fazion et al., 2024), decay assessments (Donato et al., 2021) or other types of mapping such as stratigraphy (Brusaporci et al., 2018; Santoni et al., 2021), and the requirements a digital model must have to match for those purposes (Wang et al., 2019).

1.2.2 Similarities and Differences between BIM and HBIM

Being a derivation of BIM, HBIM shares some fundamental aspects, although applied to different contexts: indeed, HBIM as well relies on intelligent parametric models to represent buildings or infrastructures, enabling the management and analysis of architectural and structural information (Antonopoulou and Bryan, 2017).

These digital copies must be created in such a way which accurately represent the modelled items, facilitate information enrichment (i.e. adding material properties and construction techniques), and foster assessment and data interpretation. Furthermore, they should promote multidisciplinary among the various professionals, allow data sharing and interoperability and provide the possibility to perform simulations to support informed decision-making.

However, whilst BIM is about new constructions to manage their limited life cycle from design to an eventual decommission, HBIM is focused on the documentation, preservation, and restoration of existing assets of historical and architectural value, thus characterised by a potentially perpetual life cycle (Quattrini et al., 2017). From an ontological perspective, parametric objects in HBIM should address the "what," "why," and "how" of each modelled element (Biagini et al., 2016). Differently from the as-

designed BIM items, the as-built conditions of an artifact feature irregular shapes, handcrafted decorations, asymmetries and imperfections which cannot be easily represented.

To capture the as-is geometry of existing buildings and to enhance their digital reconstruction HBIM methodology increasingly relies on digital surveys, which is often the only way to get updated information on an historical asset. The data acquisition is often supported by archival research for increasing knowledge, understanding and awareness about the structures to be digitised.

BIM is based onto extensive libraries of standardised items, generally in-built and provided by authoring software; as explained more in detail in the next paragraph, HBIM deals with unique elements, and libraries dedicated to architectural styles of the past are lacking or missing.

Whilst BIM has been strictly regulated worldwide since the beginning (see paragraphs 1.1.4 and 1.1.5), for HBIM few guidelines inspired to the principles of AH management have been scarcely followed until only recently governments are dealing with proper legislations.

HBIM requires a broader work team than BIM, including historians, archaeologists and conservationists alongside professionals closely related to AEC sector.

1.2.3 Modelling of the irregular items and decays

The significant semantic and geometric heterogeneity of construction elements within existing AH makes them difficult to be accurately modelled in a BIM environment. These elements often have irregularities due to changes over time and past construction methods.

Many studies have focused on solutions for parametric and informational modelling of AH, with a special focus on translating survey data into HBIM and creating specific libraries. Some researchers, like Murphy et al., have created libraries based on architectural rules from historical texts, particularly from the Classic or Neoclassic ages ([Daniels and Georgopoulos, 2023](#); [Sakellaris et al., 2022](#)) and the Renaissance ([Murphy et al., 2015](#); [Apollonio et al., 2012](#)). However, this approach becomes almost

inadequate in reality-based modelling, which requires accuracy over idealized forms, as real elements often differ significantly.

Old construction methods, such as masonry or steam-bent timber, don't follow modern standards, creating geometric inaccuracies which require to be represented in the digital model. These inaccuracies can involve irregular geometry, such as out-of-plumb or tapered walls, deformed arches, variable dimensions of elements, and misaligned surfaces. These aspects differ from traditional BIM tools and need special solutions for accurate representation.

Fortunately, HBIM tools can address these issues. Nowadays, BIM environments provide strategies for the manual modelling of non-conventional geometries without recurring to in-built families and commands. Sometimes, custom families need to be created from scratch, which is a time-consuming process requiring advanced skills.

Adaptive parameters which allow geometrical alterations are a rather preferred approach; they can be applied to asymmetrical, irregular or deformed surfaces and volumes. They are particularly useful for mapping material decays (cracks, structural failures or damages) within the digital model, for restoration purposes.

Deformations or damages can be shown as parametric families containing information about the type of decay. BIM tools can also integrate the condition of a structure into a standard database.

Another approach is layered modelling, where changes over time or restoration plans are displayed on separate layers without affecting the general model, allowing a multitemporal view of the asset for better awareness and maintenance.

For highly ornamental structural elements (e.g., column capitals), some scholars suggest using mesh surfaces ([Tucci et al., 2019](#); [Castagnetti et al., 2017](#)). However, the Mesh-to-BIM approach lacks semantic and parametric data. Another method uses Non-Uniform Rational B-Splines (NURBS) from point clouds to create polysurfaces which can serve as the geometric base for parametrization in BIM ([Oreni et al., 2014](#); [Quattrini et al., 2015](#); [Fai and Rafeiro, 2014](#)). While this method is effective, it is time-consuming and requires external software, so interoperability is necessary.

To overcome this consumption of resources, many researchers are currently experimenting semi-automatic or automated algorithms, involving Machine Learning

(ML) or Deep Learning (DL) ([Gil et al., 2019](#)), not only for modelling complex items but for semantic enrichment as well ([Miky et al., 2024](#)).

1.2.4 HBIM international reference standards

The HBIM process should be traceable, reliable, and unambiguous, ensuring that metadata enhances asset interpretation and management. International reference systems serve as standardized frameworks for implementing HBIM worldwide and establishing common methodologies for its whole workflow, ensuring consistency and interoperability.

The first efforts to establish those standards were inspired by UNESCO's *Charter on the Conservation of Digital Heritage* (2003) and began formal codification in 2009 with the *London Charter*, later integrated into the *Principles of Seville* (2012). Although initially focused on archaeology and for restauration purposes only, these guidelines set ethical standards for digital visualization in AH, emphasizing intellectual and scientific transparency. Nowadays they widely are applied also for documentation purposes.

These principles were reinforced by the *Vancouver Declaration* (2015) and officially ratified at the ICOMOS General Assembly (2017). That same year, Historic England published *BIM for Heritage*, a guideline derived in part from ISO 19650, addressing interoperability, information exchange, and collaboration for historic buildings. This built upon prior work by Historic Scotland (2014) and aimed to bridge gaps in BIM's application to historical assets.

A formal structure for describing non-graphical attributes and mutual relationships between modelled items to be used for AH documentation was provided in 2006 by the Intercultural Centre of Documentation (CIDOC) within a Conceptual Reference Model (CRM) in ISO 21127, with a common semantic framework on which historical information can be mapped; whilst the Comité International de Photogrammétrie Architecturale (CIPA) and the International Centre for restauration of Built Heritage (ICCROM) set best practises for ensuring accuracy in digital surveys.

The European Union sought to integrate these various protocols into an interoperable platform based on open standard semantic web formats, supporting several initiatives

like INCEPTION and promoting standardization, accessibility, and interoperability (46). In Italy, the ISO guidelines aforementioned earlier have been acknowledged within the UNI 11337 standard.

1.2.5 HBIM LODs and Levels of Knowledge

Beyond the Levels of Information Definition (LOD) in BIM presented in paragraph 1.1.4, additional levels have been developed specifically for HBIM in AH.

HBIM models must comply with AIA standards, which define LOD 100–500, with an intermediate LOD 350 which introduces hierarchical relationships between model elements. LODs applied to HBIM can be summarised as follows:

LOD 100: Conceptual representation

LOD 200: Generic models and quantity estimation

LOD 300/350: Executive design

LOD 400: Construction design

LOD 500: As-built documentation

In literature, LODs sometimes can be intended as Levels of Knowledge (LOK) (Castellano-Román and Pinto-Puerto, 2019).

In Italy, the UNI 11337 standard defines seven LOD levels (A–G), combining Level of Geometry (LOG) + Level of Information (LOI) (see paragraph 1.1.5) (Italian Standardization Body, 2017). LOD F and G specifically address HBIM digitization based on digital surveys, supporting the management of historical assets. A sample of these levels has been reported by Brumana et al., 2018 (Brumana et al., 2018).

Recent literature has introduced additional thematic levels to refine the understanding and modelling of heritage buildings:

- ✓ Level of Reliability (LOR) evaluates the accuracy and objectivity of the modelled architectural elements (Bianchini and Nicastro, 2018).
- ✓ Level of Evolution (LOE) represents the construction phases of the building (Bianchini and Nicastro, 2018).

- ✓ Level of Accuracy (LOA) measures the geometric accuracy of the digital model compared to the point cloud data, often linked to graphic detail levels (Chiabrando et al., 2017).

These additional levels help define the HBIM modelling process based on expert knowledge, critical understanding, and intended use of the models (Radanovic et al., 2020). Although inspired by UNI 11337-4:2017, some researchers, such as Campi, Di Luggo, and Scandurra (Campi et al., 2017), have argued that HBIM accuracy is not necessarily tied to a specific operational standard, highlighting the need for flexible and case-specific methodologies.

1.2.6 Semantics and ontologies

In addition to geometric content, HBIM models require a set of information appropriate to the purposes for which they were created.

Specifically, this information must be structured to establish logical relationships between architectural elements, their organization and function within the model.

Ontologies are hierarchical structures which connect heterogeneous data (bibliographic or archival sources, images, surveys, or other types of documents) to HBIM models through a unique and easily interpretable representation. In this way, each element is identified by attributes assigned during the semantic enrichment phase (such as typology, materials, construction techniques, possible mappings, etc.), making it easier to search for and extract related information. There are vocabularies, such as the Getty Art & Architecture Thesaurus (AAT), which allow for the cataloguing of modelled elements and the assignment of a Cultural Heritage Object Code ID to each of them (Lopez et al., 2018).

At a larger scale, ontologies in HBIM enhance information accessibility and ensure more precise and interoperable documentation. To prevent misinterpretations, various standards and guidelines exist (though not a true regulatory framework) depending on the type of semantic attributes included in the model:

- ✓ As mentioned in section 1.2.5, the CIDOC-CRM standard is used to link historical data to the HBIM model; specific extensions are used for covering sectors such as archaeology;

- ✓ IFC Web Ontology Language (IfcOWL): a representation based on the IFC standard (see section 1.1.7), used to integrate construction and structural data into models;
- ✓ Custom ontologies tailored to represent unique details or non-standardizable data.

The management of this information usually takes place in databases external to the BIM environment, such as Protégé, which is based on the OWL language and offers customization possibilities, or platforms which visually represent semantic data, such as WebVOWL. Currently, BIM environments can only include heterogeneous semantic data (not included into standard databases) through integration with external plugins, such as OntoBIM, which support the IFC and CIDOC-CRM standards.

The most used open formats for representing, consulting, and exchanging semantic data are the Resource Description Framework (RDF) and the SPARQL Protocol and RDF Query Language (SPARQL), while Linked Open Data (LOD) are used to access digital archives.

2. The Scan-to-BIM approach

Creating digital replicas of AH buildings is challenging due to the lack of documentation from the original design and past modifications ([Allegra et al., 2020](#)). To achieve an accurate and detailed representation, the most advanced digital surveying technologies based on Massive Data Capture Systems (MDCSs), such as Terrestrial Laser Scanning (TLS) and/or aerial/terrestrial photogrammetry are employed.

This approach, known as Scan-to-BIM ([Brumana et al., 2020](#); [Andriasyan et al., 2020](#)), is widely recommended as it the most suitable to HBIM. However, despite its undisputable advantages, Scan-to-BIM is a relatively new methodology which still requires a clear framework for evaluating the final model's quantitative and qualitative aspects.

2.1 The Scan-to-BIM methodology

The Scan-to-BIM method aims to produce highly accurate digital models, following a structured and multidisciplinary workflow. Since 2015 ([Dore et al., 2015](#)), standardized guidelines and rules have been developed to outline decision-making processes and procedural steps, which generally include (Figure 8):

1. survey planning – Defining objectives, selecting technologies, and strategizing data acquisition.
2. data acquisition – Through MDCSs like TLS and photogrammetry technologies.
3. data collection and processing – Ensuring interoperability to prevent data loss during software transfers.
4. HBIM modelling – Creating parametric models using custom libraries of architectural elements tailored to the building's historical style.
5. semantic signification and data enrichment – Attaching contextual data, behaviours, and ontologies to modelled structures for better analysis and interpretation.

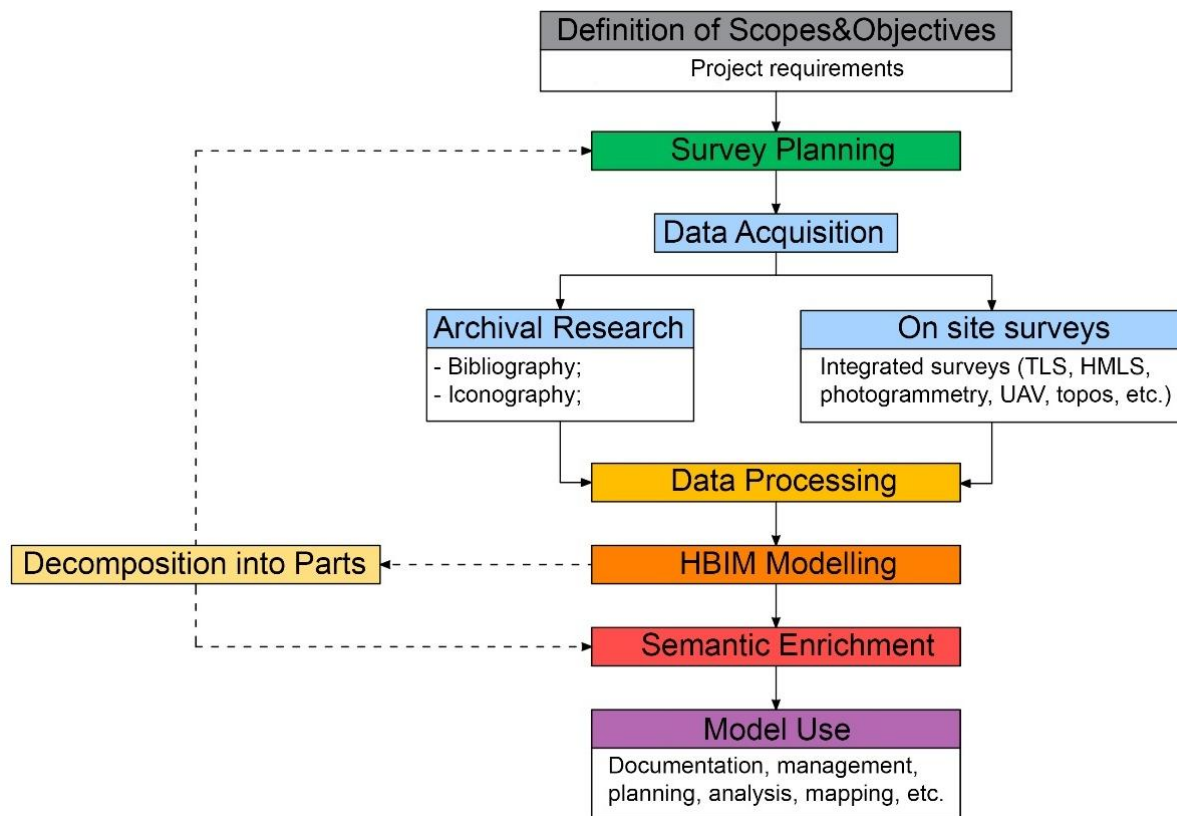


Figure 8. A typical Scan-to-BIM workflow.

Albeit Scan-to-BIM delivers unmatched geometric accuracy, the conversion of point clouds into parametric models remains a major bottleneck ([Chiabrando et al., 2017](#)). This is mainly due to BIM software limitations: originally designed for modern buildings with standardized elements, these tools struggle with irregular and complex historical shapes. Its semantic rigidity may not fully capture the complexity of heritage structures, requiring customized and more exhaustive modelling. Furthermore, unavoidable simplifications may occur, especially for deformed or non-standard components caused by traditional construction methods or structural failures, leading to a loss of details.

To avert this risk, the default semantics available on BIM must be replaced with other specific ones created ad-hoc, more exhaustive and comprehensive of the characteristics of the CH. Extreme expertise and awareness about the uniqueness of components to be implemented is thus requested obligatorily to operators ([Costantino et al., 2021](#)).

HBIM is inherently an abstraction and simplification of real-world heritage (Bruno, and Roncella, 2019). Excessive simplifications can reduce the model's reliability. To maximize fidelity in 3D reconstruction, professionals must develop adaptive strategies which balance accuracy and computational feasibility.

2.2 Massive Data Capture Systems

Over the past 20 years, advancements in Geomatics have introduced a wide range of data acquisition technologies tailored to meet the specific needs of different heritage artifacts. The selection of a surveying method depends on several factors, including the scope of investigations, dimensions of the site, complexity, desired accuracy, cost, time constraints, the optimisation of the process, etc (Pepe et al., 2022).

Given these variables, large-scale 3D digitisation requires versatile, reliable, and efficient solutions (Zlot et al., 2014). One of the AH requirements specifically points out how these methodologies must always be not invasive and not destructive (Moropoulou et al., 2013). Rather than competing, different survey techniques should be integrated to overcome individual limitations in accuracy and detail (Rinaudo and Scolamiero, 2021), ultimately leading to more coherent and refined input (Mateus et al., 2019; Buill et al., 2020; Ebolese et al., 2019) for an improved HBIM parametric modelling (Alshawabkeh and Baik, 2023).

The following sections will explore the primary surveying technologies, starting from the terrestrial laser scanning, and then going on with photogrammetry carried out with both terrestrial and aerial-based approach.

2.3 The Terrestrial Laser Scanning

In the terrestrial laser scanning the acquisition process, carried out automatically and regardless of the morphology of the object, produces a digital output called “point cloud”, which consists of a dataset of metric coordinates for points in space. These coordinates are calculated by measuring azimuth and zenith angles and the inclined distance between the object and the sensor, referred to the geometric centre of the instrument. Conceptually, these devices are like total stations used in topographic surveying, but with the ability to continuously acquire millions of points per second rather than individual points measured separately.

When laser scanners are equipped with a colour camera, RGB values are added to the geometric coordinates x,y,z, increasing acquisition times due to the need for image capture. Currently, various types of laser scanners are available on the market, each with specific characteristics regarding acquisition methods, precision⁵, accuracy⁶, resolution⁷, range and operational speed, which depend on the desired quality and resolution. Despite their differences, laser sensors can be classified into two main categories based on the measurement variables: Time of Flight (ToF) Laser Scanners, whenever they operate by emitting a short laser pulse, or Phase Shift Laser Scanners, if measurements are calculated from the shift between the emitted and received signals of a continuous modulated wave.

Compared to ToF devices, the latter ones provide higher accuracy (2-3 mm), faster acquisition speed and denser point clouds, but cover a limited range (~100 meters effective, up to 300 meters max)⁸.

A further classification of distance-measuring laser scanners pertains to the data acquisition method, which can be divided into two types: TLS can be performed either with instruments in fixed positions (static) or with instruments in motion (mobile).

2.3.1 Static Laser Scanning

This method is based on performing a scan at a time, reiterating the process until the whole surfaces of an artifact have been covered, moving the scanner in different fixed placements until the desired final point cloud resolution has been achieved without gaps and shadowing or grey areas (Wu et al., 2022).

The need to perform multiple scans arises from the fact that objects between the scanner and the target surface, create gaps and shadowing zones. Multiple scans on different positions help address this issue by ensuring full coverage of the area of interest. For this reason, it is crucial to carefully plan the scanning project before

⁵ The device's ability to repeatedly provide the same measurement under the same conditions.

⁶ Meant as how close the result of measuring a quantity is to the real value, in comparison with other measurements

⁷ The smallest geometric detail measurable by the device.

⁸ Conventional distance resolution of laser scanners is measured upon. The desired distance between points on a 10 m span is called "resolution" and it is a parameter of a scan.

proceeding with the survey. The plan should define, for each scan, the exact position of the instrument, the horizontal and vertical field of view, as well as the quality and resolution of the scans (Frias et al., 2022). This helps optimize the number of scans, their positions, and the time required for the acquisition process (Aricò et al., 2023a). Once these parameters are set, during each scan, the coordinates of the detected points are recorded. In the post-processing phase, the various scans are registered using either manual or automatic methods through rigid rotations and translations of adjacent point clouds. This cloud-to-cloud (C2C) registration allows for the creation of a global point cloud that integrates all the data collected during the survey.

The equipment used in this research - All the 3D TLS static documentation shown in this research (in chapters 2, 3, 4) has been obtained by the same phase shift-based laser scanner. The device chosen for the TLS acquisitions was a FARO Focus^{3D} S120 (Figure 9).



Figure 9. The FARO Focus^{3D} S120 during the operational survey.

This panoramic device, whose technical specifications provided by the manufacturer are reported in Table 1, comes equipped with built-in RGB camera sensor and dual-axis tilt levelling compensator, an altimeter and a magnetic compass.

Maximum Scan Rate	976,000 pts/sec
Ranging noise at 10m	0.6mm (at 90% reflectivity)
	1.2mm (at 10% reflectivity)
Ranging noise at 25m	0.95mm (at 90% reflectivity)
	2.2mm (at 10% reflectivity)
Ranging systematic error	±2mm
Ranging distance	From 0.6m up to 120m (indoor or outdoor)*
Horizontal Field of View (HFOV)	360°
Vertical Field of View (VFOV)	305°

* with an ambient light and a normal incidence to a 90% reflective surface

Table 1. Technical specifications of the FARO Focus^{3D} S120 laser scanner.

In order to fasten and optimise the operations on site, the FARO Focus^{3D} S120 scanner has some preset profiles (which can be adopted as they are or customised by request), based on the most important parameters which must be accurately valued during the survey planning phase: the scan resolution and the scan quality.

The scan resolution determinates the density of the points (and therefore their mutual distance) according to the distance of the scanning device from the surface to be detected. The closer the scanner to the surface, the shorter the distance between adjacent acquired points. Table 2 shows the average point distance measured in mm whenever the scanner is set at 10 m from the object.

The scan quality represents how many times a single measurement between the points to be determined and the centre of the device is repeated. It affects both the accuracy of the measurement itself and the acquisition duration in a direct proportion (the more the measurement is repeated, increased are its accuracy and the time needed for completing the scanning).

The most used settings are reported in Table 2 (as reported in the official manual provided by the manufacturer).

Scan Resolution Profiles	Scan Quality	Acquisition time* (full dome mode)	Points per Scan (full dome mode)	Point Distance (mm at 10 m)
1/1	3x	00:57:16	40,960	1.534
	4x	01:54:32		
1/2	3x	00:14:19	20,480	3.068
	4x	00:28:38		
1/4	3x	00:03:05	10,240	6.136
	4x	00:07:29		
1/5	3x	00:02:17	8,192	7.670
	4x	00:04:35		
1/8	3x	00:00:57	5,120	12.272
	4x	00:01:47		

* The time is calculated on a clear-cut acquisition with no extra-time for picture taken

Table 2. The most used default settings available on the FARO Focus^{3D} S120 laser scanner.

All the TLS surveys performed for this research have been preceded by a planning phase. This is considered a best practice before any data acquisition, to assess the artifact's condition, select the correct number of scans to be performed and their location and settings, and avoid issues during operations. Survey planning included a site inspection to familiarize with the case study and design an effective acquisition strategy.

2.3.2 Mobile Laser Scanning

Mobile Mapping Systems (MMSs) enable real-time, continuous data acquisition by tracking the scanner's trajectory within a scene ([Sammartano and Spanò, 2018](#); [Gollob et al., 2020](#)). Typically mounted on vehicles or worn as backpacks, these systems rely on Global Navigation Satellite System (GNSS) receivers and Inertial Measurement Units (IMUs) to determine position and distance, allowing for the digital reconstruction of environments. However, in confined spaces where GNSS signals are unavailable because of a weakness in the signal ([Del Perugia et al., 2019](#)), Handheld Mobile Laser Scanners (HMLSs) are preferred, which don't necessarily need a GNSS for acquisitions ([Bauwens et al., 2016](#)).

HMLSs utilize Simultaneous Localization and Mapping (SLAM) algorithms, which enable real-time mapping and self-localization by measuring laser beam return times to generate a 3D point cloud. Additional motion sensors track movement speed and orientation, continuously updating the scanned environment ([Alsadik and Karam,](#)

2021). Compared to TLS, HMLSs offer significant advantages in speed and efficiency, as the point's measurement itself takes less time to be calculated, and they allow for continuous scanning rather than requiring multiple static captures (Wu et al., 2022). This reduces data acquisition time and minimizes occlusion effects (Nikooohemat et al., 2017; Zlot et al., 2014).

Regardless their performance and accuracy are related to their technical specifications, whatever the device used, it always delivers an output in the form a point cloud containing metrical information where data are reported in their x,y,z coordinates and sometimes in their RGB values as acquired whenever a camera is integrated to these systems.

Furthermore, HMLS' more compact size and extreme portability is advantageous for the uninterrupted and more uniform coverage of scenes in few paths, above all for the detection of confined, narrow or occluded places (Akpinar, 2021; Xin et al., 2022; Ryding et al., 2015).

Walking paths for HMLS surveys should be always accurately planned before any operational phases, as pre-determined routes enable faster and more efficient acquisitions on-site. A key requirement is ensuring significant overlap between mutual paths to improve alignment accuracy. Paths should also be set at a certain distance from vertical surfaces to maintain a consistent laser beam inclination. Reference points must be accurately placed, as they help improve path alignment and ensure full area coverage. It is recommended that reference points be shared by multiple paths and that paths form a closed loop for improved accuracy of the final point cloud.

The SLAM algorithms, beyond enabling real-time calculations of the paths and acquisitions, enable the shape recognition of the captured elements on simple primitives such as horizontal and vertical planes and cylindrical items (Buratowski et al., 2022). This feature is helpful whenever the environment is characterised by either varied configurations such as dense vegetation (Cabo et al., 2018; Shao et al., 2020), uneven and multilevel landscapes, or scarce geometric references such as organic underground spaces (D'Agostino et al., 2022; Di Stefano et al., 2021).

These geometric primitives are used also for evaluating the propagation of positioning errors within the same SLAM algorithms (Del Duca and Machado, 2023). Despite these

pros, a notorious weakness of HMLS scanners is their minor accuracy, (usually around $\pm 10\text{mm}$, against the few millimetres of TLS devices), resulting in noisier point clouds.

Considering all the ins and outs about HMLSs, they still are an undisputably useful alternative of TLS in case of expeditious surveys on extensive areas whenever a centimetre level accuracy can be tolerated.

As different devices have been used during the operational survey of the case studies presented in this research (chapters 3 and 5), they will be introduced case by case in the dedicated chapters to follow.

2.4 The photogrammetric survey

Photogrammetry use passive optical measurement to analyse and reconstruct objects through a dataset of photographs taken from various positions. This cost-effective and efficient method relies on the principle that images are scaled-down central projections of objects. For accurate 3D reconstruction, each point of the object must be visible in at least two images.

A recommended preliminary step for any photogrammetric survey is an accurate planning phase, which must consider both the shape and size of the asset to be surveyed and its position in relation to the surrounding environment. A critical aspect of the planning is calculating the Ground Sampling Distance (GSD), which represents the actual area of the surface covered by a single pixel of the image; it depends on the camera-to-object distance, the focal length, and the pixel size of the camera sensor. Specifically, the GSD increases with a longer camera-to-object distance and decreases with a longer focal length.

The photogrammetric processing workflow typically includes Image Orientation, Dense Point Cloud production, Mesh Calculation, Texture Calculation, and Orthophoto Production (Dostal and Yamafune, 2018). This workflow is generally characterized by "Structure from Motion" (SfM) algorithms, typical of the field of Computer Vision, that enable an initial image orientation through the identification of key points in individual photos, calculating the approximate parameters of the images, and correlating recognizable points across multiple images, until their spatial coordinates are determined. At the end, a sparse 3D point cloud, enriched with colorimetric

information, is obtained. SfM simplifies the process by eliminating the need for exhaustive camera calibration data ([Martinez-Carricondo et al., 2021](#)).

The SfM process is integrated with a “bundle adjustment” process to recalculate the image orientation parameters. In this step several Ground Control Points (GCPs) whose coordinates are known from a topographic or GNSS survey are used. This further process provides the correct exterior orientation parameters of the camera.

After this step, a new point cloud, denser and metrically referenced, is finally achieved, to be used as it is or further processed through a polygonal procedure based on meshing algorithms, such as the Delaunay algorithm. The eventually resulting triangular surface allows for an additional stage of photorealistic representation: using texture mapping techniques, photographic textures extracted from the original images are projected onto the mesh model, creating a fully realistic 3D model. From this model, it is also possible to derive 2D orthophotos useful for describing specific areas.

This image-based survey methodology is particularly advantageous for the 3D reconstruction of Architectural Heritage assets due to its acquisition speed, low equipment costs, and wide range of applications.

Depending on the methods and the equipment used for capturing the initial set of images, photogrammetry could be roughly divided into terrestrial and aerial one.

2.4.1 The terrestrial photogrammetric survey

Terrestrial photogrammetry involves capturing images with ground-supported cameras, typically Digital Single Lens Reflex (DSLR) cameras, either handheld, tripod-mounted, or pole-mounted. This method includes two primary capture techniques: stereoscopic and convergent.

Stereoscopic captures maintain a parallel camera-to-object distance with the optical axis perpendicular to the surface. The planning of these captures is based on factors such as focal length and image overlap. Key calculated parameters include image scale, GSD, and forward and lateral overlap. When stereoscopic captures are impractical, convergent captures are used, where the camera follows a circular or semicircular path around the object with a consistent orientation toward a central point.

Photogrammetric image acquisition is often complemented by metric measurements, such as topographic surveys or direct object measurements. GCPs obtained from topographic surveys help scale and accurately orient the images during processing. Since different DSLR cameras were used in this research's terrestrial photogrammetric surveys, their specifications will be detailed in later chapters.

2.4.2 The aerial photogrammetric survey

For areas which are difficult or impossible to access using TLS or terrestrial photogrammetry, close-range aerial photogrammetry with Unmanned Aerial Vehicles (UAVs) is often integrated into the survey. This method has become widely used in BH documentation, offering versatility, high metric reliability, and reduced execution times ([Lo Brutto et al., 2017](#); [Pepe et al., 2022](#)).

UAVs provide operational flexibility, covering large areas quickly and capturing high-resolution data from multiple perspectives. They are commonly used to complement missing information from other surveys. When combined with terrestrial photogrammetry, UAVs utilize Multi View Stereo (MVS) algorithms to densify the point cloud generated by the Structure from Motion (SfM) approach ([Pepe and Costantino, 2021](#)). UAV surveys require minimal planning time and are typically conducted automatically via remote control applications, though manual operation is also possible.

Like terrestrial photogrammetry, UAV photogrammetry features two main capture techniques: convergent and stereoscopic. Convergent captures involve tilting the camera relative to the object, following a circular or elliptical trajectory. They can be further classified as parallel convergent (aligned with façade planes) or inclined convergent (angled captures). Stereoscopic captures maintain a constant camera-to-object distance with the optical axis perpendicular to the surface, particularly useful for surveying upper façades and flat roofs. In such cases, a nadiral optical axis (vertically downward) is used.

Key stereoscopic parameters include image scale, GSD, and forward and lateral overlap. Different drones were used for the three case studies in this research (Chapters 2, 4, and 5), and their specifications will be detailed in the respective chapters.

2.5 Challenges and Limitations in digital surveying: A Critical Overview

TLS, HMLS and both terrestrial and aerial photogrammetry have proved as essential methods for acquiring the as-built accurate geometric information and as-is conditions for AH whenever other types of documentation are lacking or missing. Despite their significant advantages, these technologies present specific challenges, limitations and drawbacks, which must be critically understood to ensure their effective application. This section provides an in-depth discussion of the technical, operational, and methodological issues inherent in these digital survey approaches. At the end of this analysis, an integrated survey diversely combining these techniques trying to balance the available resources and budget, the scope of work and the project's scale, the site's conditions and the desired accuracy of the final datasets will be discussed as the most appropriate strategy for the Scan-to-BIM digitisations presented in this defence.

2.5.1 The case studies

The acquisition projects were tailored to the specific characteristics of each site to be surveyed, with special attention paid to their morphological conditions, dimensions, and contextual settings.

These factors significantly influenced the choice of methodological combinations to be integrated and, consequently, the selection of the most appropriate tools. This choice, in turn, affected the potential accuracy of the point clouds obtainable from the data acquisition processes.

To clarify the operational phases, the case studies are presented here with a summary of the main challenges encountered and the techniques adopted to address them. These are:

1. San Giovanni degli Lebbrosi: A medieval church located on the outskirts of the city, surrounded by a small, flowerbed-lined garden on flat terrain. The building is modest in size and lacks adjacent tall structures. One of the longitudinal façades was partially obstructed by tall pine trees, which hindered visibility. A static TLS survey was conducted along the exterior perimeter and through an unobstructed interior path. To accurately capture the bell tower and avoid the distortions inherent to laser

scanning at height, a UAV survey was also performed, which included the church's roofs. However, the presence of the trees prevented a perfectly circular flight path. The objective of these surveys was the development of a HBIM digital model.

2. The complex of San Giovanni degli Eremiti: Situated in the historic centre of Palermo, where UAV flights are restricted by regulation, this methodology was excluded from the outset. The site features architectural and archaeological stratifications from various centuries, situated on uneven terrain and characterized by dense vegetation. Given its considerable extension and complex topography, a HMLS (Handheld Mobile Laser Scanning) survey was chosen to document the complex as a whole, with the sole purpose of studying the ground conditions in relation to the foundations of the various structures. Specifically, the church and the so-called "Islamic Hall", both located on flat ground and relatively small in scale, were also surveyed using static TLS. This latter survey was used to create an HBIM digital model of the two main buildings.
3. Santissima Trinità di Delia: A medieval church contemporaneous with the other two, located in open countryside, isolated and surrounded by sparse vegetation on flat terrain. A high enclosing wall and dense shrubs on one side partially obstructed the acquisition of the adjacent façade. Due to the extremely compact size of the site, a static TLS survey was carried out alongside both terrestrial and aerial photogrammetric surveys. Like the case of San Giovanni dei Lebbrosi, the flight paths could not follow a perfectly circular trajectory but were optimized as best as possible. This survey was also aimed at producing a HBIM model.
4. The complex of Santa Maria della Grotta: This millenary complex is located on the outskirts of Marsala and features architectural and archaeological stratifications ranging from the Punic era to the 18th century. It is distributed across multiple levels with a height difference of over nine meters, connected by a staircase carved into the bedrock. The extensive site includes dense vegetation on the upper level and remnants of Roman quarries on the lower level, where a partially rock-cut Baroque church and medieval hypogea are located. Given the site's vastness and complexity, a full HMLS survey was undertaken to ensure operational efficiency despite the significant - particularly altimetric- obstacles.

This survey had a dual purpose: on the one hand, to produce a mesh model for web-based visualization; and, for the Baroque church, the development of a HBIM model. To complete portions otherwise inaccessible to the HMLS, such as the upper areas and roof of the church, a UAV flight was conducted, whilst a terrestrial photogrammetric survey was used to produce high-resolution textured orthophotos of the internal and external longitudinal walls of the church, aimed at mapping surface deterioration.

2.5.2 TLS with static devices: accuracy versus practical constraints

Static TLS delivered dense point clouds with millimetric accuracy, making it particularly suitable for HBIM digitisations. Nevertheless, the method entailed significant operational constraints.

Due to operational constraints, the method - being static and capable of capturing only one scan at a time from a fixed position- required repeated application. The laser scanner had to be repositioned multiple times to cover the entire area and to achieve the target resolution of the final point cloud ([Wu et al., 2022](#)). It required a careful planning of scan positions to minimize occlusions and ensure full spatial coverage, with different settings for each acquisition, which had to be forecast before the proper operational phase; plus the minimal operational time required for data acquisition, combined with downtime needed to relocate the device between successive positions. This method is usually discouraged for extensive environments, because of a longer time of acquisition and large, burdensome datasets which were computationally demanding to process. Moreover, the accuracy of static LS resulted highly sensitive to environmental factors, especially to dense vegetation which affected complete coverage of the assets and the readability of the point clouds. This has been experienced in San Giovanni dei Lebbrosi and some buildings in the complex of San Giovanni degli Eremiti, where some walls have shown altered colours due to the shadowing effects from near tall trees, and removal of noise brought by climbing plants caused gaps in the cluster.

2.5.3 HMLS: improved mobility at the cost of accuracy

HMLS systems, based on SLAM algorithms, drastically reduce fieldwork time and simplify access to environments characterised by a wide extension, uneven terrains, dense vegetation or eventual occlusions ([Aricò et al., 2023a](#)). They are even more compact and portable ([Sammartano and Spanò, 2018](#)), with no downtime for carrying the device.

However, the advantages of mobility come with notable limitations which should be addressed prior to acquisitions. The SLAM-based positioning system is inherently prone to drift, particularly during long, unlooped trajectories, whilst the accuracy of the resulting point cloud is therefore lower than the static TLS, typically ranging around 1 cm. Furthermore, the point density by HMLS relies on walking speed of the operators which should be kept constant and free from obstacles, and results anyway lower and less homogeneous, affecting the ability to capture fine details. These inconveniences may not be acceptable for all applications.

Given the peculiar environmental conditions in the complexes of San Giovanni degli Eremiti and Santa Maria della Grotta, and the scope of work of the related digitisations (respectively a study on the morphology of terrain and a HBIM model), an accuracy of 1 cm was tolerated. To improve the application of HMLS, stable and close trajectories have been designed, preventing loops and planning generous overlaps between paths which would have helped the algorithm to shape the scans in real time.

2.5.4 Photogrammetry: cost-effective versatility and visual quality

Photogrammetry, whether terrestrial or aerial, is widely appreciated for its ability to combine geometric reconstruction with high-resolution texture mapping and is a cost-effective solution.

In this dissertation it has been applied mainly for the coverage of all those parts which could not be surveyed with other methodologies: the roofing systems of San Giovanni dei Lebbrosi, Santissima Trinità di Delia, and Santa Maria della Grotta. In the latter case, it has been fundamental even for obtaining the textured orthophotos of the long walls of the building (from external and internal façades).

It hasn't been applied to San Giovanni degli Eremiti because of flight restriction on the historical town, and this is currently one of the issues linked to UAV flights.

About aerial photogrammetry, the other constraints to be aware of are the wind sensitivity, the limited autonomy of the device, and the expertise of the operator in case of manual flight (this happened in Santa Maria della Grotta). The generation of accurate 3D models from UAV images also demands rigorous planning in terms of image overlap, flight altitude, and ground control. Errors in any of these aspects can lead to geometric distortions, poor model resolution, or misalignments when integrating data with ground-based surveys.

Terrestrial photogrammetry is highly dependent on environmental and operational factors as well. It requires sufficient surface texture to identify matching points across images, whilst variations in lighting, shadows, and overexposure can lead to inconsistencies in texture or affect the quality of the reconstructed geometry.

Both types of photogrammetry needed to be carefully planned to prevent insufficient coverage of the asset and had to be performed at specific hours of the day (half of the morning until noon or first time in the afternoon) to ensure uniform lighting: sometimes the surveys had to be stopped for risk of overexposure and resumed later with better conditions.

2.5.5 Challenges and implications of method integration

One of the main challenges in digital surveying lied in the integration of data acquired from different sources. Combining TLS and photogrammetric data yielded highly comprehensive models, but it also introduced problems of alignment, consistency, and scale, as explained in the following section dedicated to data processing in this chapter.

Another important issue regarded the translation of raw survey data into semantically meaningful models. Whilst laser scanning and photogrammetry produced geometrically accurate meshes or point clouds, they didn't inherently include information about material properties, construction techniques, or historical phases. This limited their direct integration into HBIM environments, which relied on parametric objects enriched with semantic attributes. Developing reliable methods to convert

geometric data into usable, structured, and informative digital twins remains a key area of research.

Digital survey technologies undoubtedly were fundamental in the documentation and analysis of architectural and archaeological features of the case studies. However, their application had to be accompanied by a critical understanding of their limitations. Static TLS offered unmatched accuracy but was time-intensive and logistically demanding. HMLS provided mobility and speed but sacrificed geometric precision and consistency. Photogrammetry delivered information which hadn't been collected with other devices but was constrained by environmental conditions. Only through a structured integration of these techniques - supported by robust planning phase and workflows and clear scope of works - the full digital surveying can provide the most suitable information.

2.6 Challenges and Limitations in data processing: A Critical Overview

The objective of the data processing was to generate highly accurate, reliable, and up-to-date information regarding the selected case studies from the raw data acquired on site. To achieve this, hybrid and comprehensive point clouds were produced, with the specific intent of serving as a foundation for subsequent parametric modelling workflows within BIM environment.

To obtain consistent and coherent point clouds, raw data collected during the survey campaigns had to be systematically processed and structured. This involved two principal operations: registration and optimization.

2.6.1 Registration of the acquired data

Registration can be conducted either manually or through automated algorithms; in the present work, the latter approach was adopted to enhance efficiency and ensure consistent results. The registration process typically relies on aligning the relative positions and orientations of the various scans, beginning with an approximate alignment and subsequently refining it within a common coordinate system (Cheng et al., 2018).

The specific registration workflow may vary depending on the acquisition technology and devices used. In this research, consistent software tools were utilized across all surveyed datasets, according to whether the data were acquired via TLS (either static and mobile) or photogrammetric methods.

Static TLS data workflow - Datasets from static TLS were processed using Autodesk ReCap. To reduce computational effort, scans from each case study were divided into two distinct groups: one for external areas and one for internal spaces. These scans were imported into the software in the chronological order in which they were acquired during the fieldwork.

The registration process consisted of two main phases. The first phase involved coarse registration, which estimated correspondences between adjacent scans based on identifiable features. This phase enabled the preliminary alignment of the datasets. The second phase involved fine registration, aimed at improving geometric accuracy. This was achieved through the Iterative Closest Point (ICP) algorithm, the most widely adopted method for aligning 3D point clouds. The ICP algorithm iteratively minimized the distance between corresponding points in overlapping areas of different scans, and in this context, it enabled an alignment accuracy in the range of a few millimetres, with an average point spacing of about 3.5 mm (having the same point been surveyed in many scans, with overabundant measurements).

Despite its effectiveness, the ICP algorithm has shown limitations, particularly in transitional areas between interior and exterior environments (such as passageways in the churches of San Giovanni dei Lebbrosi and Santissima Trinità di Delia) and in the tallest parts of the façades (i.e. the bell tower in San Giovanni dei Lebbrosi, probably due to the inclination of the laser beam), where the alignment proved unstable and unreliable leading to eventual misalignments.

To address these criticalities, two specific strategies were implemented. To sort the first inconvenient, redundant scans were deliberately included in both internal and external datasets. These overlapping scans increased the number of shared features across different zones, improving the registration process in problematic areas and ensuring better integration of the complete models. At the end of the process, once ensured the correct alignment of the scans with no discrepancies or misalignments through a

thorough double check, redundant data have been cut off and the acquisitions merged in a wholesome cluster.

For the second concern, manual intervention was used to select at least three pairs of clearly recognizable and corresponding points between adjacent scans, thereby assisting the software in establishing reliable connections under supervision of the operator.

HMLS data workflow - The data obtained from the HMLS surveys were processed differently depending on the case studies, although always through automated procedures by the manufacturer of the laser scanners used. In the case of the Church of San Giovanni degli Eremiti, the data were processed in real time during acquisition by the proprietary software installed on the operator's personal device, which was also employed to visualize the six different scanning paths. The three scans acquired along as many paths at Santa Maria della Grotta were instead post-processed in the laboratory by Microgeo's own technicians, who provided the final point cloud cluster, albeit not fully optimized.

Both point clouds exhibited lower accuracy compared to those obtained via static TLS surveys: in the first case, accuracy was below 1 cm, whilst in the second it was approximately 6 mm. Resulting point spacing was about an average of 5 mm, being this value a function of the operator's speed during the acquisition.

The two datasets were subsequently optimized by the author using the same techniques applied to the static TLS data, as described in detail later.

Photogrammetric data workflow - Like static TLS data processing, photogrammetric point cloud registration involved both coarse and fine stages, though it employed different algorithms. In this study, all the photogrammetric information - whether acquired terrestrially or aerially - was processed using an automated workflow in Agisoft Metashape, through a preliminary image orientation via a Structure from Motion (SfM) algorithm, and a subsequent bundle adjustment for further refinement and improvement of the dataset accuracy.

Given that photogrammetry is a passive data acquisition method, it depends on ground references to ensure metric reliability and minimize scaling errors ([Rashdi et al., 2022](#)). For this reason, the coordinates of few Ground Control Points (GCPs), acquired

beforehand via topographic methods during on-site data collections, were integrated into the process. This step led to the computation of both the mean re-projection error and the RMSE on the GCPs. The average reprojection error was calculated of about ± 1 px in San Giovanni dei Lebbrosi, ± 2 px in Santissima Trinità di Delia, and ± 1 px in Santa Maria della Grotta. Their RMSEs were estimated respectively of ± 2 mm, ± 1.1 cm and ± 1.4 cm. The relatively higher RMSE observed in the last photogrammetric survey can be attributed to limiting environmental conditions such as a dense vegetation cover and the terrain complexity which may have introduced uncertainty errors in matching images.

Subsequently, the images of each project underwent dense stereo matching MVS algorithms, ultimately leading to the generation of high-resolution dense point clouds, whose average spacing was about 6 mm.

Because of the intrinsic method to generate a point cloud, photogrammetric models have been proved less accurate and dense than laser scanning datasets (both static and HMLS). However, given the scope of the work, these key issues have been considered acceptable, as explained in further detail in the next paragraphs.

2.6.2 Optimization of the registered data

These consistent clusters thus obtained had to be further optimised prior to being correctly imported into the BIM environment: essential operations such as the segmentation, subsampling, alignment of different datasets, retention of the consistent data, discard of the unnecessary information, the overall fusion and eventual roto-translation were performed at the end of the registration to refine the final point clouds, in order for them to match the desired precision and quality standards, and enhance the interpretability of the generated models.

Segmentation - A significant challenge inherent in the Scan-to-BIM methodology lies in the huge volume of data contained within TLS clusters, which can range from millions to billions of points and presents considerable computational demands. MDCSs indiscriminately capture vast quantities of points, including those corresponding to extraneous or redundant elements - such as vegetation, furniture, or human presence - without the capacity for discerning critical geometric features. This indiscriminate data acquisition results in significantly larger file sizes and a more

resource-intensive post-processing phase, further exacerbated by the limited storage and computational capabilities of standard workstations. The initial stage in the data filtering process involves the outlier removal with the segmentation of irrelevant information (commonly referred to as “noise”) which contaminates clusters. In this research, segmentation was conducted manually using the “Segment” and “Cross Section” tools available in Cloud Compare, and was primarily applied to the following categories:

1. Peripheral external areas surrounding the case study sites, generated through extensive scanning procedures (e.g., buildings, gardens, streets);
2. Artifacts associated with liturgical furnishings, including benches, statues, and ornamental tombs;
3. Human presence on-site, such as operators or visitors;
4. Vegetation - particularly in the cases of San Giovanni degli Eremiti and Santa Maria della Grotta - as well as any visible electrical wiring or utilities.

Automated filtering procedures were also experimented with in specific sections of the San Giovanni degli Eremiti complex, employing Cloud Compare algorithms designed to identify and segment “off-ground” anomalies, for another purpose rather than HBIM modelling. However, these attempts proved ineffective (refer to paragraph 4.5).

This initial filtering phase contributed to an effective reduction in file sizes. Quantitative results of this process are presented in Table 3 at the end of the paragraph, alongside data reflecting subsequent subsampling operations.

Subsampling - To ensure a more efficient workflow, it was necessary to subsample the data to reduce the density of the TLS point clouds by increasing the spacing between adjacent points. In this dissertation, the voxel-based subsampling algorithm available from the Cloud Compare tools has been employed. This method increased point spacing based on a predefined average grid step along the X, Y, and Z axes (as opposed to alternative approaches which apply a uniform percentage reduction). The reduction in file size was necessitated by the current limitations of the BIM environment, which is unable to efficiently manage point clouds exceeding a certain size threshold. Consequently, it was essential to ensure that the total number of points in each cloud remained below 100 million to allow for proper import and visualization.

However, this technique indiscriminately applied the same grid step to all the points in a cloud, without the capability to preserve critical features, thereby leading to a loss of local detail. The subsampling has been overlaid to all the external and internal clusters coming from static survey with a desired homogeneous, consistent final spacing of about 7/8 mm. This expedient reduced the initial accuracy discrepancies between the different datasets to be fused (being the internal ones denser and with closer points), levelling the resulting accuracy of the TLS clusters closer to that of the photogrammetric point clouds, which haven't been subsampled. This process offered a valuable perspective on the challenge posed by that issue on subsequential data fusion.

In the overall point cloud from HMLS acquisition in Santa Maria della Grotta, the same final point spacing of 7/8 mm was set as well. The HMLS point cloud of San Giovanni degli Eremiti, containing just the information related to the ground level once other redundant data about vegetation and building has been stripped off, has been subsampled as well with the same settings in order to reduce consistently that point cloud, which had to be further turned into a mesh model, for computational limitations in Cloud Compare. The reduction values, expressed both in absolute quantities and percentages, are presented in Table 3 at the end of the paragraph. It must be noted that this step didn't involve the photogrammetric point clouds, given their relatively small sizes. This table doesn't report the values encountered in HMLS point cloud subsampling of San Giovanni degli Eremiti because it hasn't been used for HBIM digitisation.

Case Study	Cluster	Initial Density (≈ million points)	After segmentation (≈ million points)	% segm.	After Subsampling (≈ million points)	% subsam.
San Giovanni dei Lebbrosi	TLS External	145	82.5	56.9	23.6	71
	TLS Internal	186	149	20.9	68.5	54
San Giovanni degli Eremiti	TLS External	456	114	75	46	60
	TLS Internal	216	183	15.3	25.8	86
Santissima Trinità di Delia	TLS External	85	53	37.9	29	44.5
	TLS Internal	196	110	56	36	67
Santa Maria della Grotta	HMLS whole	356	193	54.2	80	58.9

Table 3. Reported values for segmentation and subsampling filtering operations in the TLS acquisitions.

Fusion of the overall point cloud - At this stage of each project, the various datasets acquired through different techniques were prepared for integration, ensuring that the resulting point cloud was both continuous, without any gaps and free of redundant areas. All subsequent processing steps were carried out using Cloud Compare.

Initially, the point cloud clusters were aligned with a C2C procedure. The TLS data served as the reference, whilst the other photogrammetric datasets were aligned to them manually through at least four pairs of corresponding points. This preliminary alignment was then refined using automatic registration, yielding a more precise roto-translation matrix and the corresponding RMSE value.

After the alignment, the parts missing in the reference acquisitions were retained from the other clusters: i.e., the roof tops have been cut off from their respective photogrammetric datasets without any subsampling. The remaining data (considered redundant when compared to the higher-precision TLS scans) were excluded and discarded.

In San Giovanni degli Eremiti, all the ground surfaces from the HMLS point cloud have been kept in a similar way, turned into 3D meshes and then aligned and merged to the static point cloud of the church and the Islamic Hall, to obtain a wholesome model for studying the morphological conditions of the sites.

Finally, the reference point clouds and the other stripped relevant elements were fused together into a single, coherent dataset for each project; regardless having been subsampled, TLS (static and HMLS) clusters remained always more accurate than unsubsampled photogrammetric ones, even if subsampling made them closer in value. Anyway, the photogrammetric point clouds granted to cover the gaps left in the other acquisitions with details which were completely missing, so albeit the fusion has been made with little different accuracy values in the datasets, these discrepancies fell under the tolerances of the scopes of work.

Once fused all the parts together, the resulting point clouds were then conveniently roto-translated into an arbitrary coordinate system optimized for subsequent integration into the BIM environment.

Export - The final phase involved converting the data into suitable formats to ensure smooth integration with BIM platforms. Given that Autodesk Revit was selected as the

primary environment for parametric modelling, the processed point clouds - initially refined in Cloud Compare and saved in the exchange format .e57 - needed to be imported into Autodesk ReCap. This intermediary step was necessary to convert the data into Autodesk's proprietary format, enabling the final export as .rcp files.

3. The church of San Giovanni dei Lebbrosi in Palermo

This church is the first estate built in an Arab-Norman style in Sicily, even before the establishment of the French conquerors in the island. It introduced brand new architectural features merging the late European Romanesque and the Islamic constructive traditions; considering these novelties, it became a stylistic fore type not only for the following religious buildings in northern-western Sicily, but for other coeval assets.

Since this building had never been surveyed before through modern methodologies, its digitisation was aimed above all at providing the most complete information and at delivering a high-detailed digital replica with an up-to-date database. This latter tool could be used to share and foster the awareness on this asset after having been filed for entering the UNESCO World Heritage list.

3.1 - Historical background

The church of San Giovanni dei Lebbrosi likely dates to 1071 when the Normans ranks, led by Robert and Roger I of Altavilla, besieged Palermo to end Arab rule. It was first built as a temporary structure near the ruins of a Saracen castle named “Yahya” (John in Arabic) ([Bellafiore, 1990](#)). After the Normans conquered the island in 1072, king Roger I turned it into a permanent church as a vow for his victory. By 1085, it was fully built and is considered the first Arab-Norman structure in Sicily, showing early architectural elements but lacking the refinements of later buildings ([Valenti, 1921](#)).

In 1155, king Roger II ordered a hospital next to the church to house leprosy patients from St. Leonard’s church, keeping them away from the old town to prevent disease spread. In 1219, emperor Frederick II handed control of the church and hospital to the Teutonic Knights, who managed them until 1495, when the hospital was moved back to the city due to a plague outbreak.

During the 17th and 18th centuries, the church underwent Baroque modifications. The bell tower was altered, and a sacristy was added, partially blocking the porch. The façade was stuccoed, and decorative elements were introduced for uniformity. Inside,

the floor was raised, partially burying the pillars, and the walls were covered in stucco. Wooden ceilings were replaced with masonry vaults (a barrel one with lunettes on the main nave, cross ones on the lateral aisles), weakening the structure and blocking the side windows (Genovese, 2010) (Figure 10).



Figure 10. The church before the reinstatement in 1921 (from Genovese, 2010).

Between 1920 and 1934, architect Francesco Valenti led a major restoration to address structural issues and restore the church's original look. The masonry vaults were removed, the damaged upper walls were repaired, and the blocked windows were reopened. New wooden coffered ceilings replaced the vaults, whilst the floor was lowered to its original level. The walls were stripped of stucco to assess their condition. A new altar replaced the old one, and the small columns dividing the three apses were reconstructed after being lost in previous restorations (Figure 11).

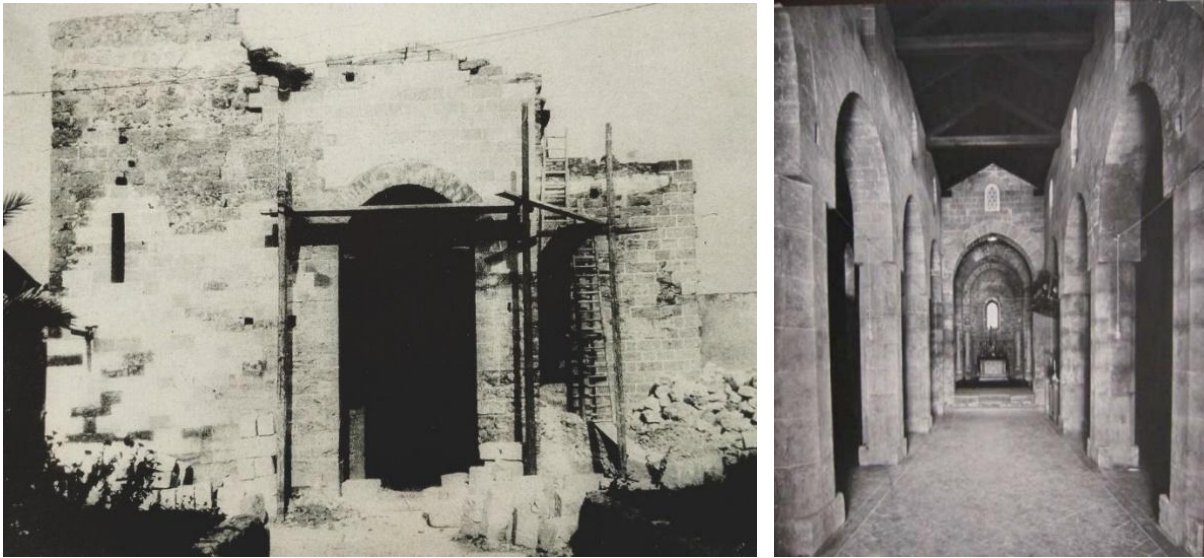


Figure 11. The church reinstated by Valenti in 1934 (from Bellafigliore, 1990).

3.2 - Architectural description

San Giovanni dei Lebbrosi stands in the southern suburbs of Palermo, surrounded by a green garden with remnants of the Saracen castle of Yahya (Bellafigliore, 1990). The main façade (west side) features a large round arch at the southern corner, leading to a small porch with a pointed cross vault and the main entrance. Above it, Valenti's bell tower rises with elegant arched windows and a dome inspired by the original one above the presbytery.

The side walls (north and south) are plain, with five pointed arched windows on each side, decorated with recessed mouldings and stuccoed grills (musharabyas) based on Islamic designs. The northern side has a stepped outline due to the higher presbytery and stairwell sections, whilst the southern side ends with the presbytery. Additional arched doors lead into the lateral naves. Stairwell is characterised by the presence of slits cut in the walls.

At the rear, the three apses appear as simple curved walls with windows and masharabyas. The presbytery, apses, and stairwell have flat, pinkish mortar-covered roofs, whilst the naves have traditional pitched tile roofs. The domes, though now red, were originally whitish, following North African Fatimid influences (Figure 12).



Figure 12. The exteriors of San Giovanni dei Lebbrosi.

The church has a hybrid Norman plan, combining a basilica-style nave with a three-apsed transept which does not extend beyond the outer walls. A vaulted porch serves as a transition space before entering the church (Figure 13).

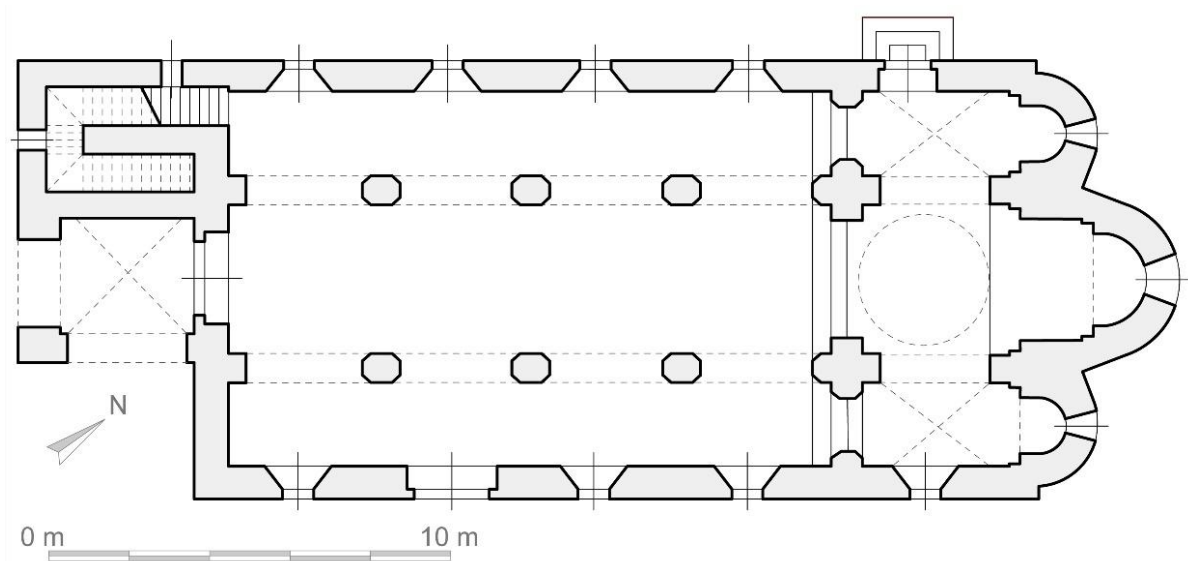


Figure 13. The plan of San Giovanni dei Lebbrosi (from Aricò et al., 2023)..

Inside, three pillars with chamfered rectangular sections support round arches, dividing the nave from the aisles. The transept, raised slightly above the main floor, is separated from the basilica by cruciform pillars and pointed arches, with the central arch being the tallest. The presbytery is further divided into three sections: the central chancel, covered by a hemispherical dome supported by recessed point arched squinches at the four corners, the diaconicon on the left and the prothesis on the right, both covered by cross vaults. These are the only parts of the original Arab-Norman roofing system

which were spared by both the Baroque restoration and the reinstatement by Valenti. The three apses have interior rounded contours and are separated by columns with Arabic-inscribed capitals. The middle apse has a distinctive composite exterior contour, making this church the only Arab-Norman building in Sicily with this feature.

Following Valenti's vision of Norman architecture, the church remains simple and unadorned, with exposed limestone walls made of small, regular blocks (Genovese, 2010). Replacements were carefully matched to the original materials. The wooden ceilings, replacing Baroque vaults, use modular trusses and coffered panels repurposed from Cuba Castle (Genovese, 2010). The floor is modern, with terracotta herringbone tiles (Figure 14).



Figure 14. The interiors of San Giovanni dei Lebbrosi.

3.3 - Data acquisition

Data acquisition for San Giovanni dei Lebbrosi required the combination of TLS and aerial photogrammetry methods, to collect all the available geometric information in the most complete way.

3.3.1 The TLS Survey

To design an effective strategy, the TLS survey was preceded by an on-site inspection to evaluate the site's condition, choose appropriate technologies, and prevent operational issues. During the inspection three main concerns were spotted:

1. The presence of tall trees that limit the visibility of the south facade.
2. Interior objects (benches, statues) leading to redundant data and gaps in the final point cloud.

3. Peculiar areas needing extra care during the acquisitions, such as the taller bell tower and the transition between the garden, the porch and the entrance of the church.

The TLS survey was then performed with some precautions to sort these potential nuisances. I.e., external scans were performed first starting early in the morning from the southern façade to reduce the shadow impact on the acquisitions; whilst furniture would have caused unavoidable gaps, however without compromising the understanding of contours, so redundant data were deemed acceptable. To ensure complete surface coverage without errors, misalignments and gaps, a structured scan sequence was followed: starting outside, continuing inside, and ending in the bell tower stairwell. This sequence was taken into account with a double care at performing more scans in the passageways and in the critical areas for an improved alignment. Scans have been divided into two blocks for the external and internal environments, with generous portions of overlapping areas. Both the external and internal scan resolution aimed for an average 7 mm to 10 m resolution to achieve a point spacing of 6-10 mm in the final point cloud. For this purpose, 17 acquisitions were performed outdoor: 5 around the apses, 8 on the long sides, 3 on the main façade and one close to the arch of the porch (Figure 15).



Figure 15. The Faro Focus 3D 120S during the survey operations on site.

The most part of them had reduced 150° Horizontal FOV (HFOV) and a 125° Vertical FOV (VFOV) towards the fronts only, disregarding the garden to prevent unnecessary

data capture. In this group, the scans on the long walls had an average 3.5 m distance from surf aces except for the two scans on the main façade which were set to a 15.5 m and 13.3 m, with a reduced 60° HFOV and a slightly increased 135° VFOV, to account for the bell tower's height and avoid an excessive beam inclination. The scan in front of the round arch of the main façade was thought in a full-dome setting (360° HFOV, 305° VFOV) to ensure an adequate overlapping area with the internal group of acquisitions.

Indoor, 19 scans were performed, all with full-dome settings to ensure comprehensive coverage and aid registration accuracy: 2 in the porch, 9 in the naves at the centre of each span, 3 in the transept and then 4 in the stairwell and storage. The latter ones had a lower resolution of 12 mm at 10 m due to the confined spaces to be acquired. Another scan, with a reduced 150° HFOV towards the entrance, was added to enhance overlap between the interior and exterior datasets. As a result, 36 scans were carried out (Figure 16), whose detailed final settings are listed in Table 3.

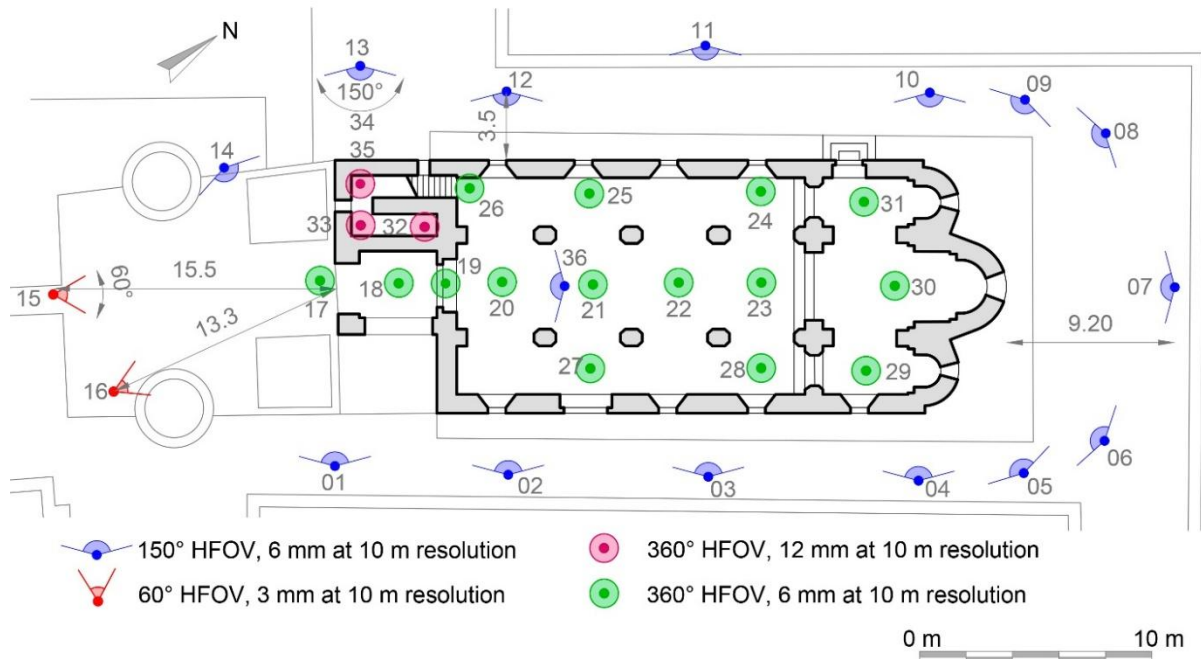


Figure 16. The TLS acquisition scheme in San Giovanni dei Lebbrosi.

Number	Resolution Profile	Quality	Point Distance (mm at 10 m)	HFOV (°)	VFOV (°)	Time per Scan*
01-14	1/4	3x	6.136	150	125	00:04:35
15-16	1/2	3x	3.068	60	135	00:23:15
17-31	1/4	3x	6.136	360	305	00:08:05
32-35	1/8	3x	12.272	360	305	00:03:24
36	1/4	3x	6.136	150	305	00:06:12
* Acquisition time includes also taking pictures						04:13:00

Table 4. The scan settings for the data acquisition at San Giovanni dei Lebbrosi' church..

3.3.2 The UAV photogrammetric survey

The UAV image acquisition at San Giovanni dei Lebbrosi was focused on its exterior parts in order to integrate the missing bits from the TLS survey and performed by a multi-rotor ultra-lightweight DJI Mavic Mini drone, characterized by a weight of 249 g and a maximum flight duration of 30'; this device comes with a 1/2.3" 6.3 mm x 4.7 mm CMOS sensor of 12 MP resolution which produces images of 4000 pixels x 3000 pixels.

The acquisition was planned to be performed in an automated way via the Dronelink app, controlled remotely via a mobile device (Figure 17).

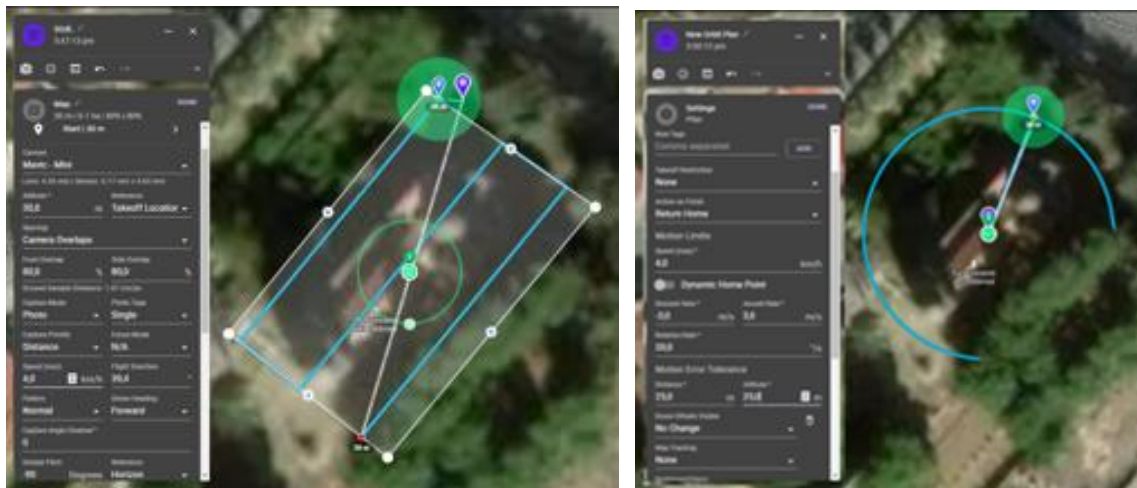


Figure 17. The acquisition plan for two UAV flights.

Different image configurations were adopted for this purpose:

- ✓ a nadir acquisition;
- ✓ two 270° arc of circular paths with different camera tilting angles;
- ✓ two frontal-view flights parallel to the northern and southern façades;
- ✓ a circular capture around the bell tower;

The nadir flight acquired the roofing system of the church, its terraces, the domes and the bell tower from top at a 30 m altitude, delivering 38 images. The two 270° circular flights were performed at 25 m altitude and 20 m radius, with camera tilt angles of 30° and 45°, delivering 48 images.

These focused on the upper parts of three façades, as tall trees along the southern façade prevented a full circular path which was thus reduced. The unobstructed portions of the southern façade were captured via frontal-view parallel flights at 7 m distance and 9 m altitude, resulting in 12 images. The same method was applied to the northern façade, yielding 25 images. Finally, the bell tower was captured in 50 images using a circular flight at 15 m altitude and 9 m radius. Overall, the UAV survey collected a total of 173 images.

3.3.3 The Topographic survey

The topographic survey was aimed at obtaining the coordinates of the GCPs to be used for the processing of the photogrammetric data and was carried out by measuring a 4-vertex closed traverse around the church. Each vertex was positioned near the central span of each wall and permanently fixed into the ground to ensure constant mutual visibility, even in areas with dense vegetation; mini-prisms were used for the backward and forward measurements. The coordinates of these vertexes were then measured with a Leica 1105 total station (Figure 18) within a local reference system, with the origin at the first vertex and the X, Y axes aligned with the building walls. The coordinates of the traverse were calculated with a Root Mean Square Error (RMSE) of ± 4 mm for planimetric coordinates and ± 1 mm for height.



Figure 18. The Leica TPS 1105 during the survey at San Giovanni dei Lebbrosi.

Additionally, the coordinates of 8 GCPs, evenly distributed along the northern façade and located at prominent features like ashlar's corners, were measured and used for UAV data processing.

3.4 - Data processing

3.4.1 TLS survey data

The TLS scans were processed in two separate groups - external and internal scans - to reduce computational effort. The external scans (1 to 17) were imported into Autodesk ReCap in acquisition order, allowing the ICP algorithm to automatically align them due to their overlapping features. After completing the perimeter path, three additional scans (two on the porch and one in the main nave) were added to facilitate future registration with the internal scans.

At the end of this ICP processing, the group of 20 aligned scans was thoroughly checked to prevent accidental misalignments and then merged into a unified point cloud of approximately 145 million points, averaging a 3 mm point spacing. After manually filtering out redundant data (such as vegetation and environmental elements), the cloud was reduced to 82.5 million points. It was then resampled to achieve a uniform 6 mm point spacing, resulting in a final external point cloud of about 23.6 million points (Figure 19).



Figure 19. The point cloud of the external scans after the filtering and resampling.

The same workflow was applied to the internal scans. All 15 interior scans, along with the overlapping porch and main nave scans, were imported separately. The scans were ordered to follow the church's layout: starting from the main nave, then the presbytery, left and right aisles, and ending with the stairwell leading to the bell tower. Thanks to full-dome settings, the internal scans captured the church's interior without gaps. After verification and merging, the initial internal point cloud reached about 186 million points (2.2 mm spacing). It was then filtered to remove furniture and decorative elements, and resampled to match the external cloud's spacing, resulting in a cloud of 68.5 million points (Figure 20).



Figure 20. The cluster of the internal scans after the filtering and the resampling.

The two external and internal cluster have been aligned together thanks to their generous overlapping parts related to the porch and the main entrance areas which were in common; after checking their correct mutual alignment, redundant data related to those parts were deleted from the external cluster only and the two groups were merged. Finally, a comprehensive point cloud of approximately 66 million points was obtained. The entire church was uniformly captured, except for the roof, which was not accessible by TLS (Figure 21).

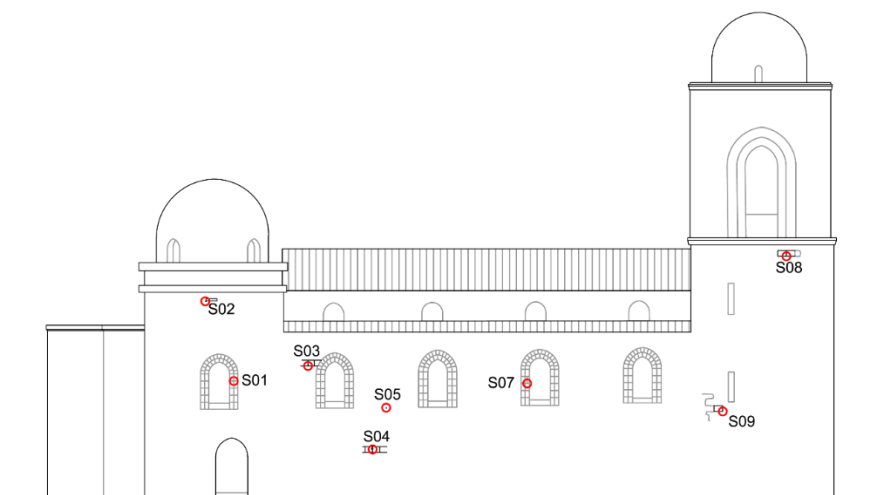


Figure 21. Isometric section view of the overall final TLS point cloud.

3.4.2 Photogrammetric survey data

The UAV photogrammetric data were processed through Agisoft Metashape, following the typical workflow. After importing all 173 images, the SfM algorithm performed an initial automated image orientation.

The 8 GCPs, previously measured during the topographic survey, were then imported to refine this orientation through a bundle adjustment procedure. This step recalculated the exterior orientation parameters of the images and assessed the precision of the dataset, leading to a mean re-projection error to less than two pixels, whilst a RMSE on the GCPs of ± 2 mm (Figure 22).



Markers	X (m)	Y (m)	Z (m)	Precision (m)	Error (m)	Projections
✓ S1	31.373226	15.797982	4.904262	0.005000	0.002161	25
✓ S2	32.110670	16.048454	7.280780	0.005000	0.003428	65
✓ S5	25.557131	14.227786	4.079861	0.005000	0.001115	15
✓ S6	20.995999	12.867762	4.791865	0.005000	0.002235	59
✓ S7	20.975845	12.868429	4.775204	0.005000	0.001913	26
✓ S8	11.601826	10.279380	6.428204	0.005000	0.001623	12
✓ T1	39.105715	12.942099	4.217083	0.005000	0.001600	26
✓ T4	38.030885	9.224853	1.799866	0.005000	0.001759	7
Total Error					0.002080	
Control points						

Figure 22. The RMSE obtained for the 8 GCPs measured with topographic survey.

At the end of the process, a sparse point cloud of tie points was generated (Figure 23).



Figure 23. The tie points obtained from the SfM algorithm.

The images were then reprocessed using dense stereo matching. This process applied MVS algorithms to calculate depth maps from overlapping image pairs (Figure 24).

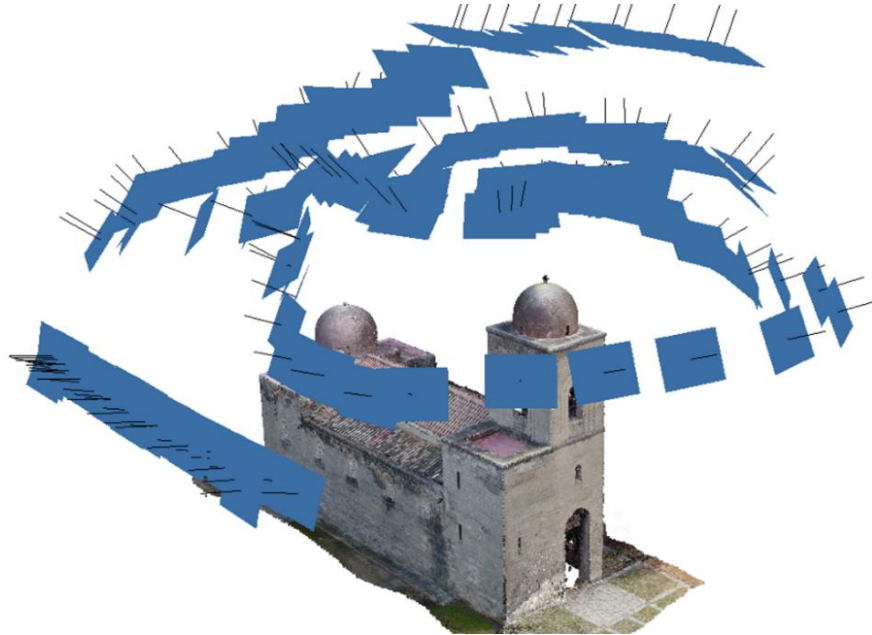


Figure 24. The dense point cloud with the orientation of UAV frames.

The MVS algorithm enabled the creation of a high-quality dense point cloud containing around 10 million points; the roofing system was successfully captured, complementing the TLS data (Figure 25).



Figure 25. The dense photogrammetric point cloud.

3.4.3 - The overall point cloud

At this stage, the TLS and UAV point clouds were ready to be integrated, ensuring the final dataset had no redundant areas or gaps. The registration was performed manually in CloudCompare software by identifying at least four common points. The TLS point cloud, having higher accuracy, was used as the reference, with the UAV data aligned accordingly.

This initial alignment was further refined through automatic registration, providing a more accurate roto-translation matrix and the RMSE value of the process. The resulting merged point cloud included both the full interiors and exteriors captured by TLS and the roofing and upper exterior parts captured by UAV. Redundant UAV data on the façades were manually removed, preserving only the missing roof elements, resulting in a combined dataset of about 79 million points (Figure 26).

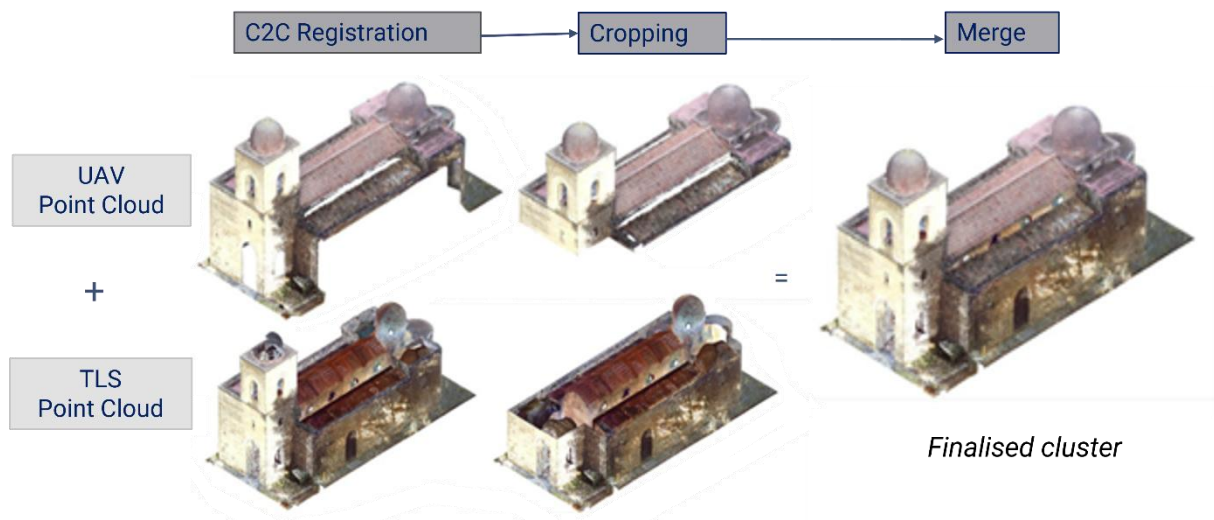


Figure 26. The process for obtaining the overall cloud.

Finally, to facilitate the subsequent HBIM modelling phase, the overall point cloud was reoriented to align the western façade with the X-axis and the northern façade with the Y-axis, setting the origin at the bell tower's corner.

4. The complex of San Giovanni degli Eremiti in Palermo

San Giovanni degli Eremiti is a monastic complex located near the old town walls of Palermo, between the churches of San Mercurio and San Giorgio in Kemonia, bordered by Via dei Benedettini. The area features notable slopes from a depression where the Kemonia stream once flowed, alongside natural caves. The site includes layers of buildings from the 6th to the 19th centuries. Its current form results from a restoration by Giuseppe Patricolo starting in 1877, which restored the original core and demolished later additions. The remaining structures include the church, the "Islamic Hall", the cloister, the "Abbot's house," and the upper walkway (Figure 27). Some ruins of the 16th century monastery are still visible in the hanging garden and of a system of vaults of the same age in the upper garden between the Islamic Hall and the surrounding wall.

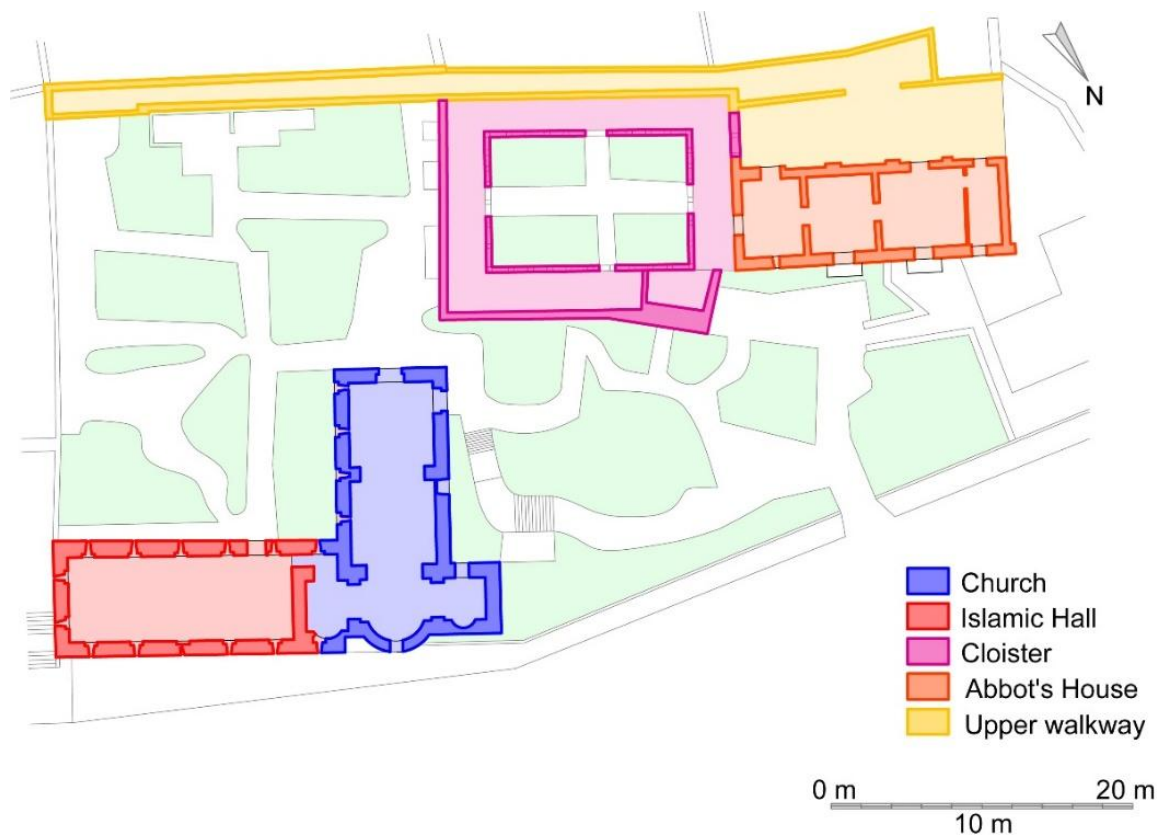


Figure 27. Plan of the remaining buildings of the complex.

4.1 - Historical background

The Benedictine monastic complex of San Giovanni degli Eremiti was built by King Roger II between 1132 and 1148 near the Royal Palace, on the banks of the Kemonia stream, in an area with pre-existing structures.

On the same site, a previous monastery founded in 581 by Pope Gregory the Great was destroyed by the Saracens in 842. Nearby stood one of Palermo's nine city gates, the *bàb-al-abnà* ("gate of the buildings" in Arabic), and a section of the city walls, still partially visible today. Roger II designated the site as a burial place for his court dignitaries in 1148, enriching the church with a dormitory, refectory, chapter house, and abbot's residence. Following Benedictine self-sufficiency rules, a mill and shops were added in 1166. The monastery was fortified in 1325 during the Angevin siege. By 1464, it was in decline and repopulated with monks from San Martino delle Scale.

Over the centuries, various modifications altered the original Arab-Norman structure. In 1593, King Charles V transformed the Islamic Hall into a church dedicated to the Virgin Mary. Further expansions, including a chapel dedicated to St. John the Evangelist in 1606, modified the church layout ([Torregrossa, 2013](#)).

By 1739, Antonino Mongitore described its enlarged structure, additional naves, and vaulted ceilings. In that description, the monastery and the refectory are also mentioned for the first time, built immediately behind the N-W corner of the church (completely covering the apses) along today's Via dei Benedettini and in the area corresponding to the current hanging garden, connecting the religious building to the Abbot's house, enlarged in 1834 ([Mongitore, 1739](#)).

The monastery fell into disrepair and was taken over by the state in 1865. Restoration efforts began in 1876 under Giuseppe Patricolo, who reconstructed the central apse, strengthened the bell tower, and restored architectural elements. A significant discovery during this process was a well-preserved plaster masharabya, serving as a model for similar reconstructions ([Bellafiore, 1990](#)).

During the demolition of the chapels of San Giovanni and the Virgin, Giuseppe Patricolo discovered structural anomalies in the Norman church, including misaligned walls and detached sections. Scraping off plaster revealed remnants of five cross vaults and column stubs, leading Patricolo to hypothesize that the space had once

been the prayer hall (*haram*) of a small mosque, originally at a 1.70 m lower floor level. He also suggested that the hall was originally longer, with evidence indicating modifications to accommodate the Norman church's diaconicon.

Further findings suggested that the church's southeast façade incorporated elements of the mosque's courtyard (*sahn*) extending with a row of five bays until the wall of the adjacent San Giorgio in Kemonia, which was repurposed for Norman construction (Patricolo, 1883) (Figure 28).



Figure 28. The church during the restoration campaign, before and after the decommissioning of the chapel of San Giovanni Evangelista (from Tomaselli, 2023).

Excavations in the citrus grove in front of the Islamic Hall uncovered burials near the adjacent church of San Giorgio and beneath the hall itself.

After decommissioning the monastery (whose the Abbot's house only was spared), Patricolo restored the domes of the church, initially white in the Fatimid tradition, but misinterpreted reddish traces in the plaster as their original color, leading to the now-iconic red hue, which influenced later restorations of Arab-Norman churches.

In 1882, he resumed work on the cloister, which had begun in 1875 under Saverio Cavallari. Due to poor preservation, many columns were heavily renovated or replaced using various materials. After Patricolo's death, the restoration was completed by Carlo Rao and Francesco Valenti in 1920 (Figure 29).

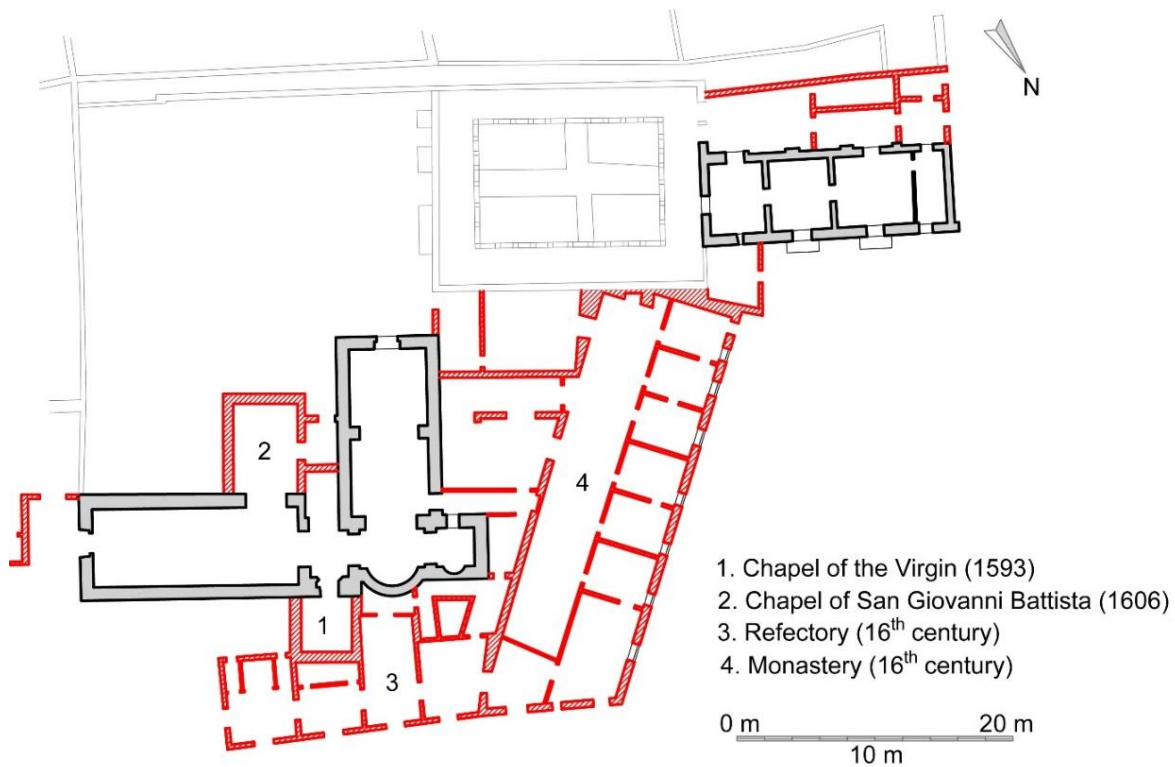


Figure 29. Plan of the complex of San Giovanni degli Eremiti before the restoration by Patricolo in 1877. In red the decommissioned buildings.

4.2 - Architectural description

4.2.1 The church

The church features a composition of simple, almost cubic modular volumes, topped by five domes of varying sizes. Its structure is characterized by a regular, compact stereometry, built with small, squared sandstone ashlar laid on thin mortar layers without plaster. Only the domes are plastered externally, while their internal construction remains exposed.

The façades have undergone significant alterations, visible in the slightly different squared ashlar used during Patricolo's restorations. The northern façade on Via dei Benedettini Bianchi and the western façade were almost entirely rebuilt after demolishing adjacent structures and reinforcing the damaged walls (Tomaselli, 2023). The western façade's secondary entrance was reduced in size and reshaped with a pointed profile to match the original main entrance, which remained unchanged (Figure 30). At the corner between these two façades, the bulk of the massive bell tower protrudes, surmounted by a dome and lightened on the highest floor by a cubic gallery,

opened on the sides by four pointed arches framed by recessed mouldings; on the two lower levels, on each side, there are two openings of decreasing height, pointed arches without recesses (Figure 31).

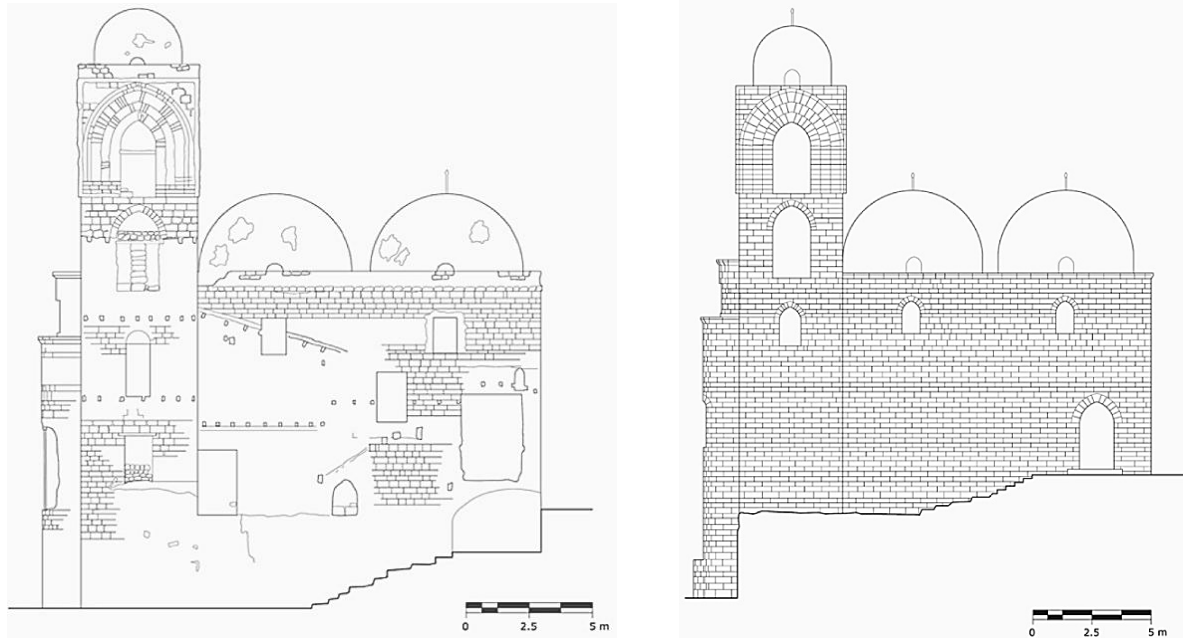


Figure 30. The western façade of San Giovanni degli Eremiti before and after Patricolo's restoration (from Tomaselli, 2023).



Figure 31. The northern façade of San Giovanni degli Eremiti.

The southwest elevation features significantly larger ashlar blocks down to the keystone of the entrance arch, whilst the pointed profile of the window above the main entrance was restored. The southeast façade includes five blind arches, each enclosing a pointed window with slits, as well as the remnants of four cross vaults exposed by Patricolo after demolishing the chapel of San Giovanni. At the end of this façade stands the volume of the Islamic Hall.

The church follows a Latin cross plan with a single nave, a protruding transept, and three apses, though only the central apse is visible externally. Each section is covered by domes. The nave consists of two cubic spans, separated by a large, pointed arch. A similar arch divides the nave from the presbytery, which is smaller and square in plan. Two smaller arches separate the presbytery from the transept arms, where the *prothesis* and *diaconicon* are located.

At the back of the presbytery, the semi-cylindrical central apse - entirely rebuilt by Patricolo - features a pointed window. Recent archaeological research in this area uncovered a pre-existing cemetery from the Arab period. A dedicated walkway, built to provide access to the Islamic Hall while preserving the excavation, allows visitors to view the presbytery's foundations (Figure 32).



Figure 32. Interior view of the church.

The bell tower is attached to the arm of the prothesis and has a square plan, featuring a small apse within the wall thickness, covered by a cross vault. The structural

anomalies of the diaconicon are emphasized by a large arch connecting its current rectangular plan to the square base supporting the dome. A narrow corridor in the opposite wall links the diaconicon to the Islamic Hall. These irregularities indicate that the diaconicon underwent significant alterations during the construction of the 16th-century chapels.

The two large hemispherical domes covering the nave, raised on piers, are identical and remain the largest surviving Norman domes, each with an internal diameter of 5.40 m. They are illuminated by four small, pointed arch windows aligned with the bays and are connected to the walls and arches through a system of triangular pendentives with slanting trumpets.

The church's roofing system includes three additional domes, replicating the same geometric and formal structure on a smaller scale. These cover the diaconicon, the bell tower, and the presbytery. The diaconicon's dome is at the same height as the two larger ones, while the presbytery's dome is elevated on a lantern.

4.2.2 The Islamic Hall

The diaconicon of the church gives access to a rectangular hall which nowadays appears covered by three large cross vaults, whose volumetric configuration dates to the 16th century. Upon closer inspection the traces of the pre-existing structure in which Patricolo recognized a small mosque and which have been deliberately left exposed, appear at about 4.50 m from the floor (Figure 33).



Figure 33. Interior view of the Islamic Hall.

Under each of the three vaults is a pointed window with a thin slit splayed on the inside, except for the central span of the northern wall, where the window has been blocked to accommodate a fresco in poor condition. This fresco, dating back to the 13th century, depicts the Madonna on a throne inside a niche, likely holding Baby Jesus (only one foot is visible), with St. John on her left, blessing, and St. Hermes on her right.

On the same wall, remnants of the apse basin from the previous *mirhab* can be seen emerging from the current floor level, confirming that the mosque was originally situated at a lower level. Other traces of writing on the lower parts of the long walls suggest that this area and its caves were once used for burials. The entrance door to the current garden once provided access to the demolished chapel of San Giovanni. It is still adorned with 16th-century decorative stucco elements, including two pilasters on high plinths and a moulded architrave with volutes (Figure 34).

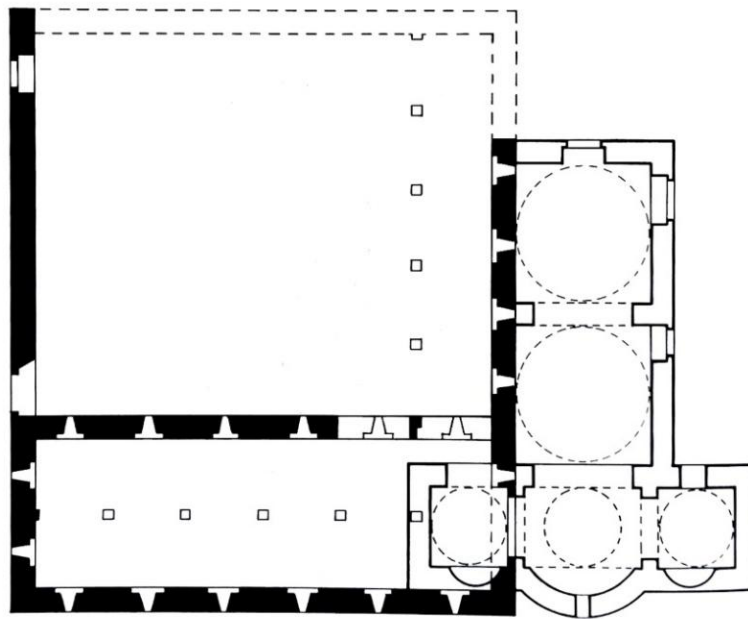


Figure 34. The plan of the church. In black, the Islamic Hall (from Bellafore, 1990).

4.2.3 The garden

The space between the Islamic Hall, the church, and the cloister was once a citrus grove planted by the Benedictines, later uprooted by Patricolo, and is now a simple ornamental garden. It is bordered to the south by city walls and to the east by a wall separating it from the San Giorgio in Kemonia monastery. Along these walls, there are

remnants of at least four cross vaults, believed to date to the 16th century when the Islamic Hall was transformed into a church.

Recent restoration uncovered a drainage pipe embedded in the perimeter wall, which slopes toward San Mercurio Alley, connecting to a canalization system. The boundary wall, accessible via an upper walkway, shows the height difference, revealing its ancient structure.

4.2.4 The cloister

The cloister has a rectangular layout with open walkways surrounding a garden. Off-centre from its main axes, there is a sheltered well. The walkways feature eight pointed arches on the short sides and twelve on the long sides, supported by twin columns on a continuous tuff base. The columns have Corinthian capitals with acanthus leaves and geometric motifs. At the corners, the columns form tetrastyle groups. Differences in the arrangement of the ashlar suggest two construction phases, likely from different building sites.

The southern corridor is bordered by the old town wall, slightly angled with the cloister. At one end, there's a shrine with pilasters and a semi-spherical basin with a stuccoed shell, featuring a Madonna and Child fresco. The western wall aligns with the church façade but doesn't touch it. The cloister is accessed through four entrances on this wall. On the opposite walls, remnants of the demolished monastery rooms, especially in the northwest corner, are visible, including an older well. The northern wall separates the cloister from a hanging garden, located on a slope about 5 meters high, connecting the upper floor to the current entrance in Via dei Benedettini Bianchi. The west corridor is attached to the Abbot's house on the upper floor.

4.2.5 The abbot's house

The building, known as the "Abbot's house" or, since 1877, the "caretaker's residence", consists of two levels, with the upper floor at the same height as the cloister. The lower floor is a large rectangular room divided into three areas by two cross vaults and a larger barrel vault with stone lunettes, supported by sturdy transverse partitions. These vaults likely date back to the 16th century. The easternmost area, once connected to the monastery, ends in a small tunnel leading to a cave at the northeast corner of the upper cloister, where a fountain was located.

The upper floor mirrors the lower in terms of layout, with three passage rooms covered by decorated and frescoed reed vaults. Access is via the western corridor of the cloister, and two balconies overlook the north elevation. This wall once housed some convent rooms that utilized the significant height difference between levels, now part of the hanging garden. The masonry throughout the building shows significant alterations, with parts made from coarse tuff ashlar.

4.3 - Data acquisition

San Giovanni degli Eremiti, located in the historic centre of Palermo, is in a legally restricted area for UAV flights. The complex is situated in a complicated logistical situation, featuring a multi-level space with dense vegetation, archaeological remains, and scattered buildings. These conditions made photogrammetry difficult, prompting the use of TLS and HMLS techniques.

TLS was used to capture the church and Islamic Hall only for HBIM digitisation purposes, whilst HMLS was chosen to survey the entire site, providing comprehensive documentation of the complex, even in areas not covered by TLS.

4.3.1 The TLS survey

For future computational convenience, the TLS acquisition in San Giovanni degli Eremiti as well forecast two group of scans for the outdoor and the indoor environments; however, in comparison to San Giovanni dei Lebbrosi, the operational approach was reversed. In this case, it was more efficient to begin data capture indoors, as it was quicker, whilst scanning the external perimeter was slowed by the sloped terrain and dense vegetation.

During the preliminary inspection, several issues were identified which could affect data acquisition. One problem was capturing the upper parts of the church, hall, and bell tower with TLS alone, as aerial photogrammetry was legally prohibited. To address this, additional scans were planned on taller nearby buildings to cover all detectable surfaces. This required careful examination of the surrounding area to find suitable positions for the scanner without obstructions.

Another issue was the dense vegetation, particularly shrubs and vines on the main fronts, which could result in inconsistent data which would be hard to separate from

the relevant information. Additionally, a tall cypress tree in the northern corner of the central garden would block the detection of surfaces behind it, especially parts of the domes (Figure 35).



Figure 35. Obstructions on site which would affect the TSL acquisition.

Both the internal and the external acquisitions were aimed at achieving an average point spacing of 7 mm in the final internal point cloud.

The first group was made up of 14 scans: the first 8 were performed at the centre of each span inside the church and the Islamic Hall, and on the passageways between the different environments with a full-dome mode and a resolution of 6 mm at 10 m. For accuracy purposes, 2 additional scans were then carried out along the archaeological trench dug across the presbytery, with the same settings; whilst another 4 acquisitions were taken at each corner of the Islamic Hall, with a resolution of 12 mm at 10 m.

Outdoor, the acquisition started from the 18 acquisitions closer to the two buildings, performed across the garden, the main street and the backyard of the Islamic Hall with an average distance of 4.5 from the external walls. Among them, the three on the thresholds of the buildings have been performed with full-dome settings and a resolution of 6 mm at 10 m for an improved alignment to the internal scans, whilst the rest was set to a 150° HFOV, a 135° VFOV and a resolution of 6 mm at 10 m. The

farther scans (ranging from around 25 m to 40 m) needed an increased resolution and a longer time, and for this reason were performed last.

Five acquisitions have been carried out on the upper walkway and on the building facing the complex on the other side of the main street, with a 150° HFOV, a 125° VFOV, and an increased resolution of 3 mm at 10 m given a maximum distance of about 30 m (Figure 36).

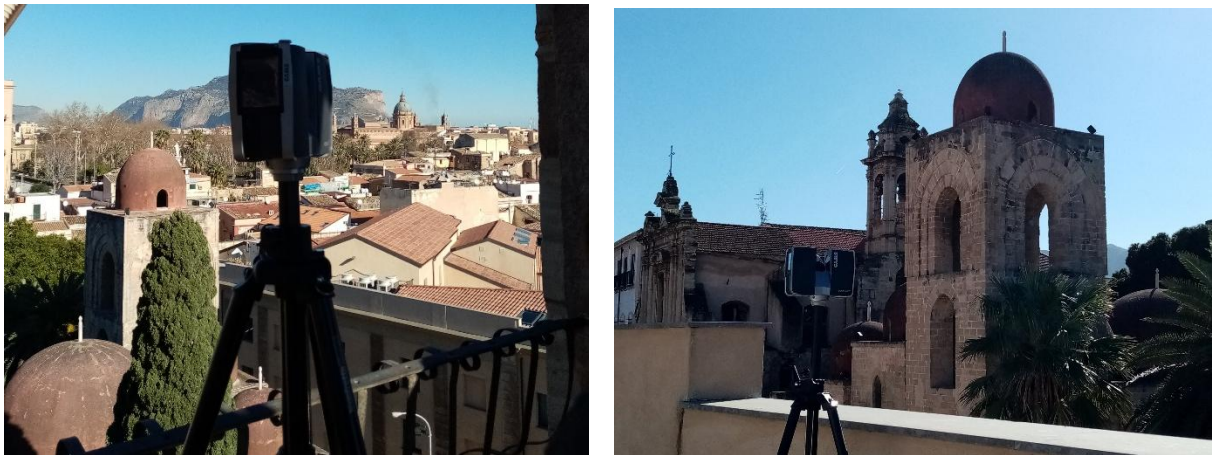


Figure 36. The TLS acquisitions performed from taller neighbouring buildings.

Similar arrangements have been made for the farthest two scans, to be carried out from the bell tower of the adjacent church of San Giuseppe Cafasso; keeping the same HFOV and VFOV of the previous group, just the resolution was way increased to 1.5 mm to 10 m (the maximum possible for the scanner capabilities), because the scanning positions were forecast almost 40 m away from the domes to be detected.

An additional scan, performed in the courtyard of San Giuseppe Cafasso for covering the parts in the background of the cypress; it was set at about X m, with a 60° HFOV and 135° VFOV and a resolution of 3 mm at 10 m. The TLS survey delivered a total of 40 scans, 14 indoor and 26 outdoor (Figure 37).

The final settings for all the scans are reported in Table 4.

The church of San Giovanni degli Eremiti in Palermo

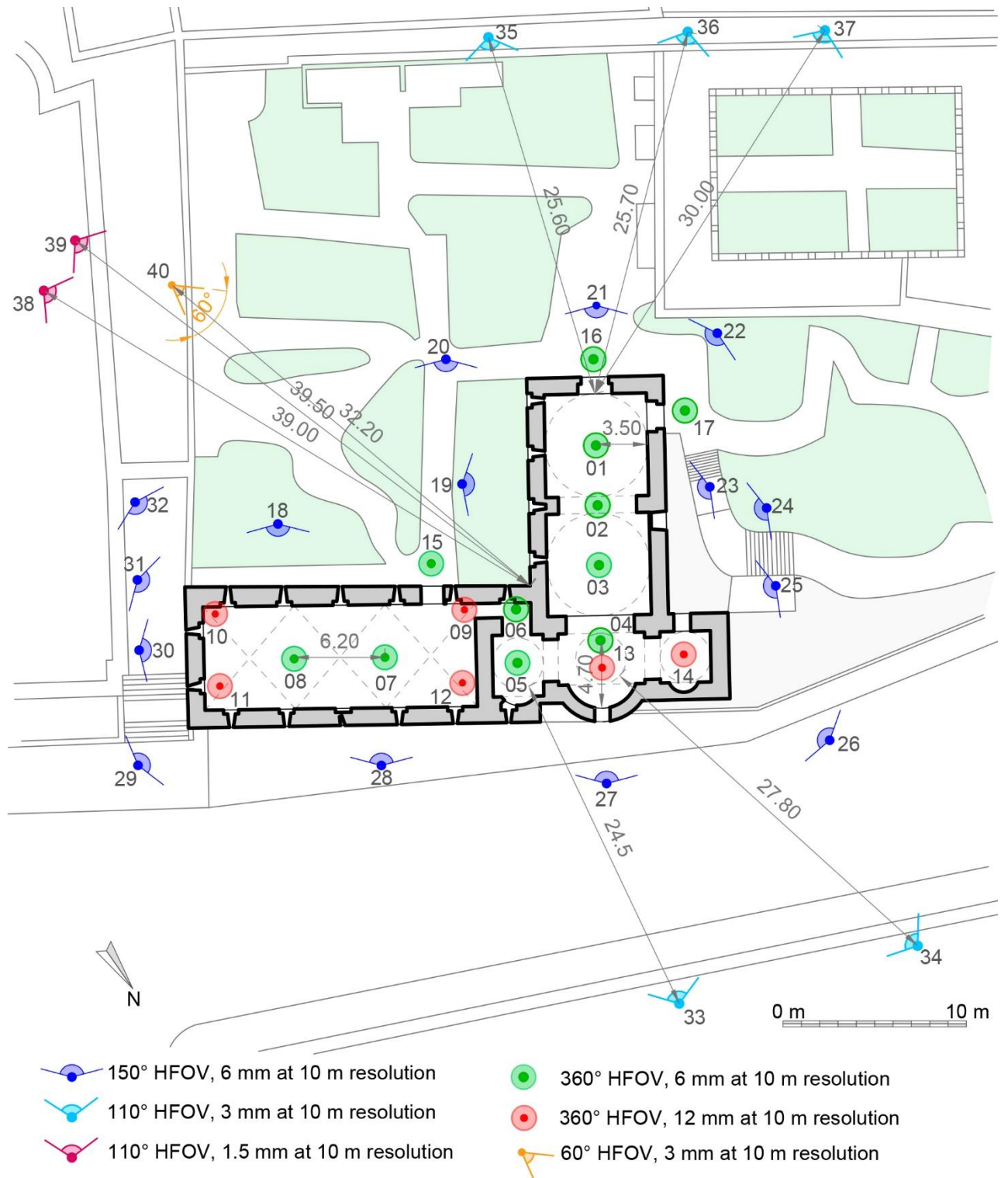


Figure 37. The scan positions for the data acquisition at San Giovanni degli Eremiti's church. The additional scans are reported in red.

Number	Resolution Profile	Quality	Resolution at 10 m (mm)	HFOV (°)	VFOV (°)	Time per Scan*
01-08, 15-17	1/4	3x	6.136	360	305	00:08:05
09-14	1/8	3x	12.272	360	305	00:03:24
18-32	1/4	3x	6.136	150	125	00:04:35
33-37	1/2	3x	3.068	110	125	00:10:50
38-39	1/1	3x	1.534	110	125	00:22:15
40	1/2	3x	3.068	60	135	00:13:45
						05:04:02

* Acquisition time includes also taking pictures

Table 5. The scan settings for the data acquisition at San Giovanni degli Eremiti's church.

4.3.2 The HMLS survey

After the static laser scanner survey a HMLS survey was carried out for the San Giovanni degli Eremiti complex planning six walking paths: (Figures 38 and 39):

- The first path covered the church, Islamic Hall, and central garden.
- The second path included the lower garden and external access street.
- The third path circled the lower and central gardens.
- The fourth path covered parts of the church, central garden, and cloister.
- The fifth path covered the Abbot's house, cloister, and parts of the lower garden.
- The sixth path went around the Abbot's house, upper walkway, cloister, and upper garden.

Furthermore, two reference points were also planned to start and finish the several paths; the first reference point was inside the church, at the center of the second span, the second was inside the second room of the Abbot's house.

The first four paths started and ended at reference point 1, whilst the last two ended at reference point 2. The archaeological trench inside the church was excluded from the survey due to safety concerns.

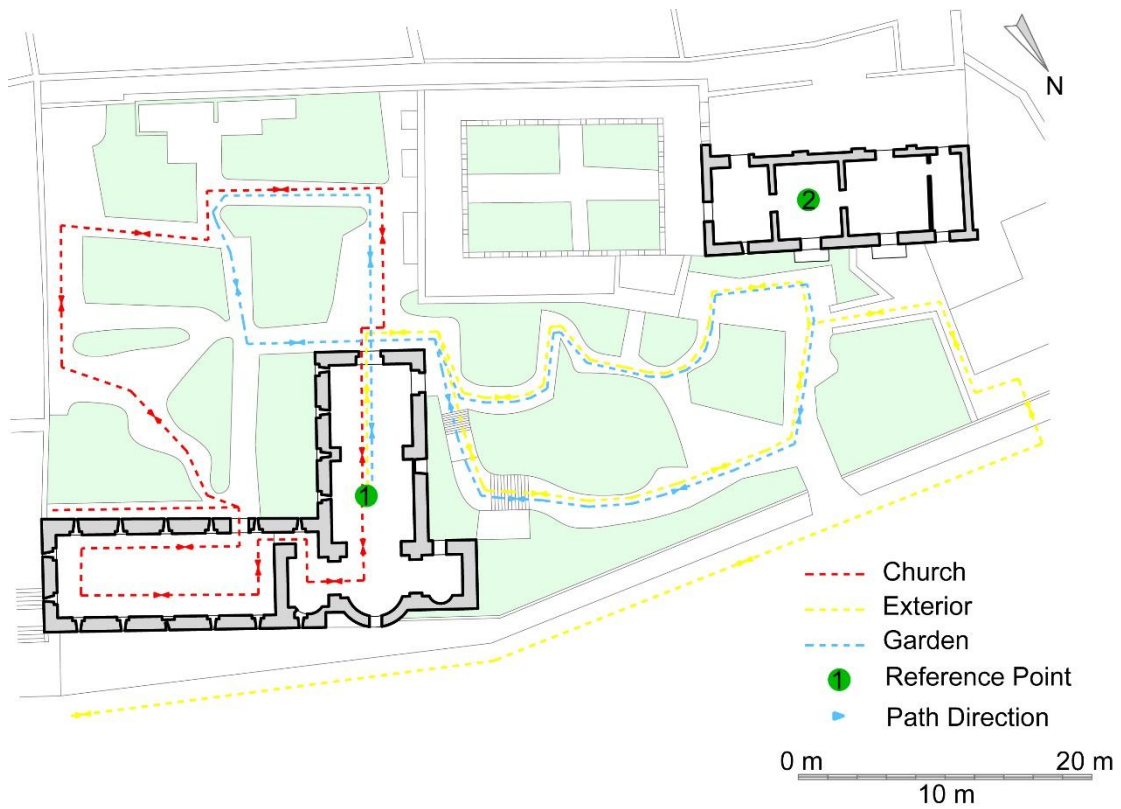


Figure 38. Three paths for the HMLS acquisition at St. John of the Hermits.

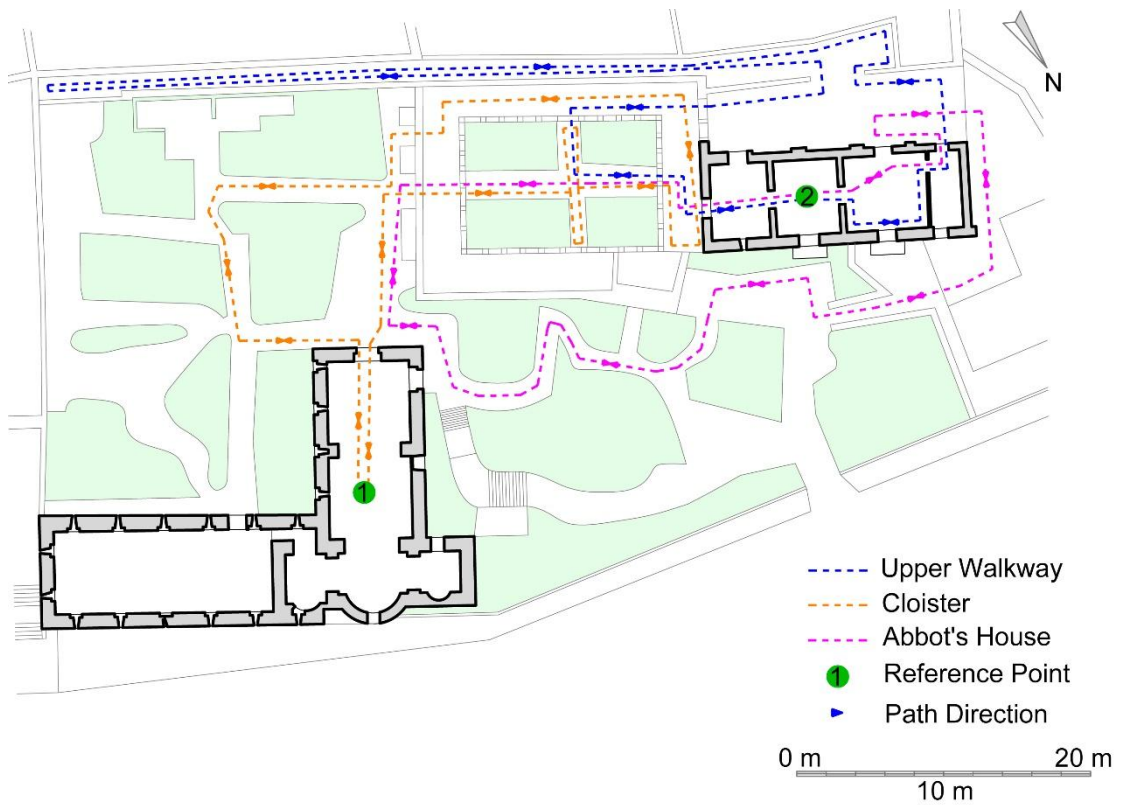


Figure 39. Another three paths for the HMLS acquisition at St. John of the Hermits.

The HMLS survey at St. John of the Hermits' complex was carried out according to the acquisition scheme outlined earlier, using a Stonex XH 120 laser scanner (Figure 40). The technical specifications of the device, provided in a data sheet by the manufacturer, are reported in Table 5.

Equipped with SLAM technology, the device produces high-precision point clouds processed in real-time. However, the device used lacked an RGB sensor and was unable to generate coloured point clouds.



Figure 40. The Stonex XH 120 device and during the data acquisition.

Maximum Scan Rate	655,360 pts/sec
High Resolution RGB Camera	Not available
Relative accuracy *	±10 mm
Vertical Angular sampling	±0.01°
Horizontal Angular sampling	±0.01°
Ranging distance	From 0.5m up to 120m
Horizontal Field of View (HFOV)	360°
Vertical Field of View (VFOV)	360°

Table 6. Technical specifications of the Stonex XH 120 laser scanner from official data sheet by the manufacturer.

According to the acquisition scheme, the six walking paths across the site were sufficient to capture both the architectural features and the natural landscape in a consistent and detailed full-scale manner.

Each path, starting and ending at the previously mentioned reference points, was repeated in both directions and overlapped for a significant portion, particularly around different flower beds in the garden. This overlap allowed the Stonex Cube-Slam software to automatically correct the point clouds, processing the acquisition in real-time and displaying the results on a tablet (Figure 41).

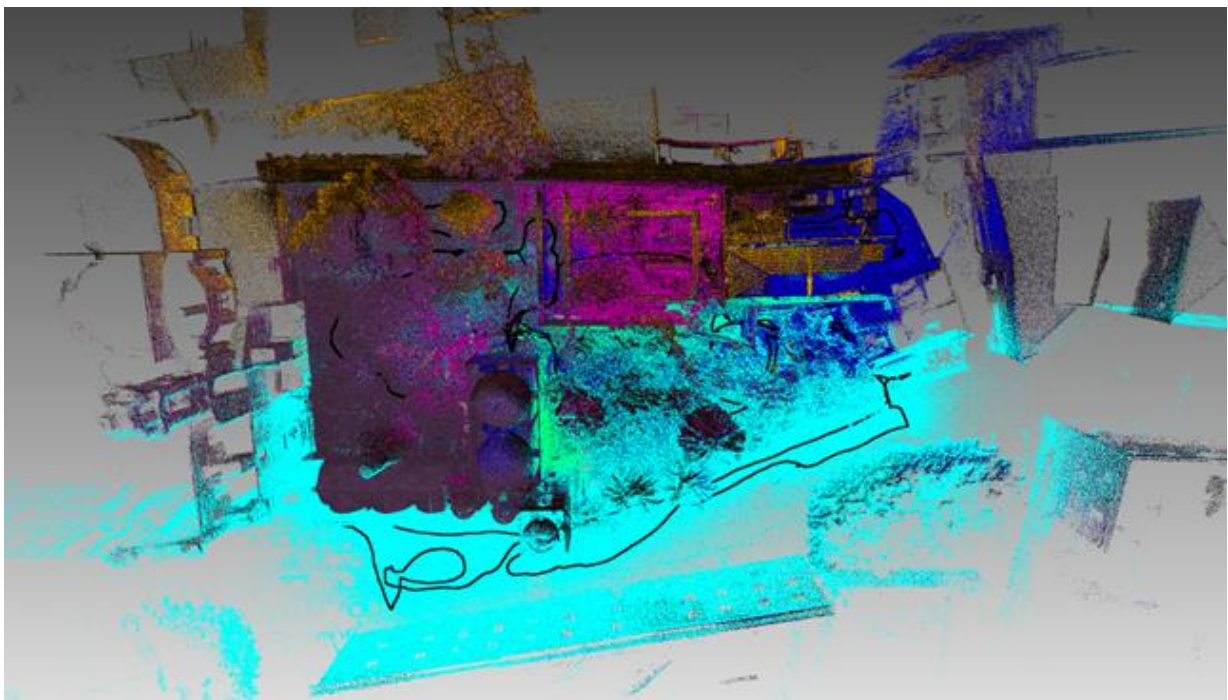


Figure 41. The HMLS point cloud displayed in real time during the acquisition (from Aricò et al., 2023).

4.4 - Data processing

4.4.1 TLS survey data

The TLS data processing was automated using Autodesk ReCap software and splitting the acquisitions into two groups to simplify the computational process. The first group consisted of 17 scans, including the 12 internal acquisitions, along with additional scans from the archaeological trench and three positioned on the thresholds. These threshold scans were added to improve alignment between the mutual groups,

following a procedure similar to the one used for San Giovanni dei Lebbrosi (see page 42).

The full-dome settings, along with the sequence and similarity of these scans, which had substantial overlap, allowed the ICP algorithm to automatically align them correctly, including the parts inside the trench, without gaps. After aligning the internal scans, they were reviewed for misalignments and then merged into a unified point cloud of approximately 216 million points, with an average point spacing of 2 mm.

The filtering process removed only a small amount of data, as the environment was naturally poor of noise, with minimal elements like sprinklers, lamps on the walls, and scaffolding leading to the trench, which did not cause any gaps in the captured surfaces. The archaeological excavation was captured comprehensively. The point cloud was then resampled to ensure an even distribution with a point spacing of 6 mm, reducing the final count to 25.8 million points (Figure 42).



Figure 42. The cluster of the internal scans after the filtering and the resampling.

The process was repeated for the second group, which included all 26 outdoor scans and the first two internal ones (to ensure good overlap with the previous set). These scans were imported into ReCap following the same sequence in which they were

performed, starting with the perimeter acquisitions and ending with the scans positioned on the upper walkway and neighbouring buildings.

Despite the large amount of data from the last eight scans, which were aimed at capturing the roofing system in high resolution, the resulting point cloud had significant gaps in the extrados of two domes, caused by the aforementioned presence of the cypressus. After the initial alignment, the acquisitions were double-checked to prevent any misalignments between adjacent scans. They were then merged into a single point cloud of 456 million points, with an average point spacing of 3.2 mm.

This point cloud was further processed to remove inconsistencies caused by the surrounding buildings and dense vegetation, which caused shadowing effects on the acquired surfaces. Manual segmentation was used to address these issues. Finally, the cluster was subsampled using the same settings as the previous one, reducing the point cloud to 46 million points (Figure 43).



Figure 43. The cluster of the external scans after the filtering and the resampling.

The 3 scans performed on the thresholds of the church and the Islamic Hall and the first two internal acquisitions in the span of the church provided a generous overlapping

area between the two clusters, so they have been registered together within the ReCap software without errors. At this step, the internal acquisitions were manually segmented from the second group of external acquisitions and the threshold scans deleted from the first bunch, and the two cluster were merged for a total of 82 million points. Except for the aforementioned gaps in the corner between the two buildings (which however could still suggest the actual outline of the interested elements), the final point cloud was uniformly detected in all its parts (Figure 44).



Figure 44. Isometric section view of the overall final TLS point cloud.

4.4.2 HMLS survey data

Once obtained, the final HMLS point cloud was used to model the ground surface of the complex, accounting for its heterogeneous configuration developed over centuries. It also allowed for comparing automatic and manual filtering methods to remove inconsistent data captured by the scanner and evaluating its accuracy against the TLS point cloud.

Although the HMLS processor handled data in real-time, an additional optimization step was necessary to refine the results. First, the six point clouds from the acquisition campaign were aligned using their ground reference markers. These point clouds were then converted to the .e57 format, and the alignment was further refined with the Iterative Closest Point (ICP) algorithm, using Stonex Reconstructor software. For site

documentation and research purposes, the raw data followed an appropriate processing workflow. The point clouds were processed with CloudCompare, where they were merged into a single dataset containing approximately 512 million points, occupying about 15 GB of storage. However, due to the absence of an RGB sensor in the HMLS device, the resulting dataset was monochromatic, making it more difficult to identify redundant or erroneous data within the point cloud, which contained terrain, surrounding environment, built structures, and vegetation (Figure 45).

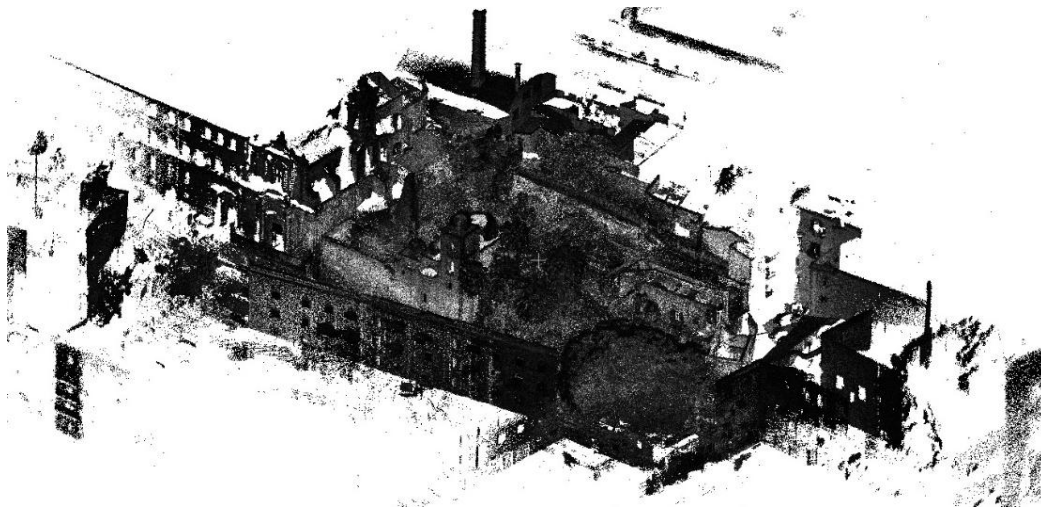


Figure 45. The HMLS point cloud before optimisation.

The raw data from the HMLS point cloud was initially segmented to remove irrelevant information from neighbouring structures and dense vegetation, reducing the cluster to 257 million points. To accurately define the ground shape, further optimization was needed, stripping buildings such as the church, Islamic Hall, Abbot's House, and cloister, which were easily distinguishable and manually segmented.

Removing vegetation proved more difficult due to the dense greenery, leading to the testing of two automatic processes: the *Automatic Ground Classification* (AGC) algorithm in Autodesk ReCap and the *Cloth Simulation Filter* (CSF) in Cloud Compare ([Zhang et al., 2016](#)). Despite removing built structures, the dataset remained too large for efficient processing, so the algorithms were tested on smaller terrain samples. Two areas were chosen for evaluation (Figure 46): Area1, a terraced garden with uneven terrain and dense vegetation (58 million points), and Area2, a flatter area with less vegetation facing the Islamic Hall (54 million points) ([Aricò et al., 2023a](#)).

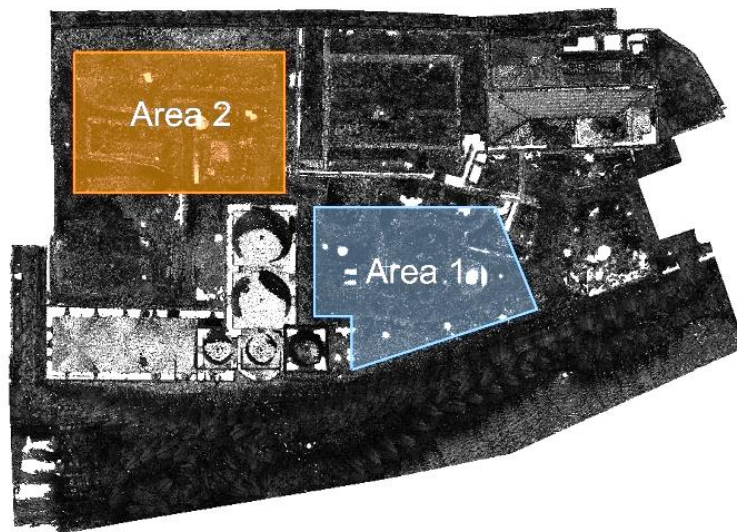


Figure 46. The two sample areas used for testing the algorithms.

4.5 Automatic Point Cloud Filtering

The latest version of Autodesk ReCap 2024 introduced the AGC tool for automatically classifying ground points, allowing separation of "ground" and "off-ground" points with four quality settings: less detail, more detail, optimum, and custom. Custom settings were used for precise control, removing high vegetation before final filtering. Tree trunks became more distinguishable, and the parameters for "ground details" and "processing window size" were set to 0.10 m and 0.5 m, respectively.

The AGC algorithm performed better on flat terrain: in Area1 (steep slopes), tree trunks remained, while in Area2 (mostly flat), it worked more effectively (Figure 47). After filtering, Area1 had around 10 million points (83.4% reduction), and Area2 had about 13 million points (74.6% reduction).

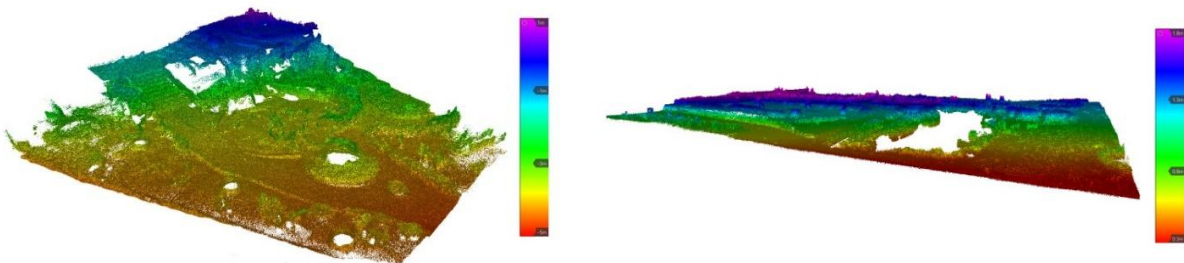


Figure 47. Application of the AGC algorithm on both areas (from Aricò et al., 2023).

The CSF algorithm in Cloud Compare simulates a cloth dropping over the terrain to differentiate between ground and off-ground points, requiring only a few parameters.

When tested with a "steep slope" setting and adjusting parameters like "Cloth resolution" and "Classification threshold," both areas saw a point reduction of about 66%. Albeit CSF effectively removed tree trunks, it also created more holes in the point cloud. Both algorithms had limitations: AGC was better suited for flat surfaces, while CSF caused gaps in the cloud (Figure 48).

As the illustrated automatic methods have proven to be limited and not fully effective for highly vegetated and complex datasets such the one in San Giovanni degli Eremiti, at last manual filtering was employed to recreate the ground surface more accurately, for information purposes.

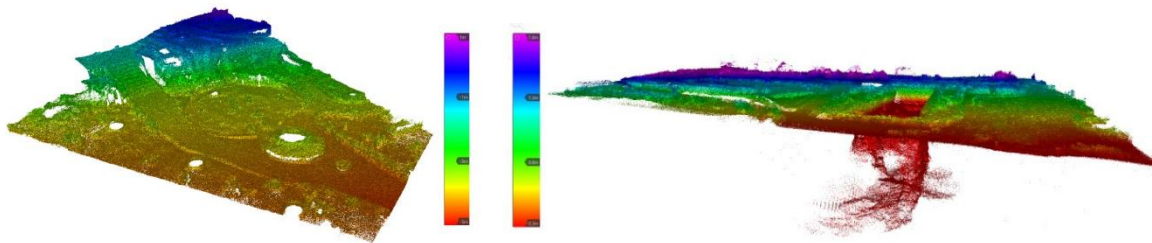


Figure 48. Areas after the application of the CSF algorithm (from Aricò et al., 2023).

4.6 Ground Surface Reconstruction with manual methods

Given the constraints of the automated methods, the 6 point clouds from the HMLS survey were processed individually to prevent errors. After stripping the vegetation, they were merged and subsampled in Cloud Compare using a 8 mm minimum point spacing. To recreate the ground morphology, the point clouds were converted into mesh surfaces using the Poisson Surface Reconstruction plugin, with the best results achieved at an "octree depth" of 11, ensuring minimal holes, reduced noise, and uniform point distribution.

After meshing, the segmented building point clouds were realigned with the ground surface mesh. The HMLS dataset was then aligned with the TLS survey data in Cloud Compare by manually matching key features, such as the church and Islamic Hall, followed by further refinement using the ICP algorithm. Ultimately, the built environment of the church and Islamic Hall in the HMLS point cloud was replaced with the more reliable corresponding parts from the TLS point cloud (Figure 49).

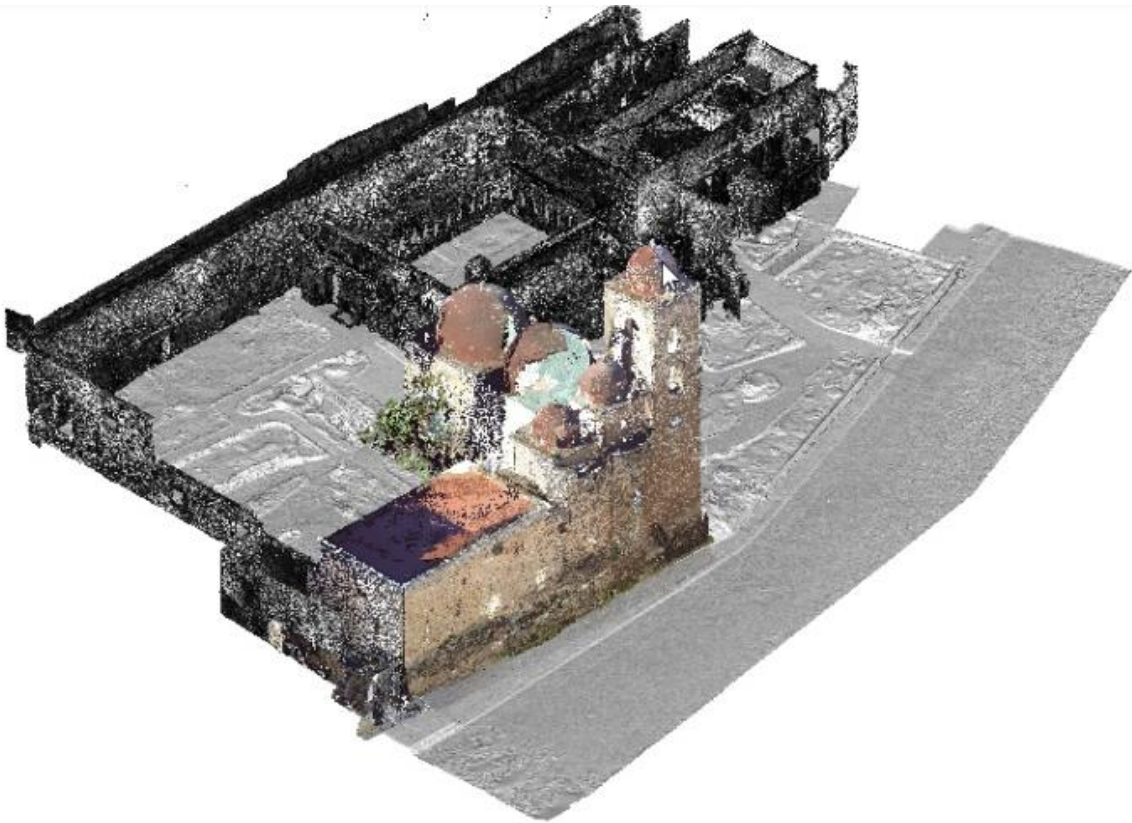


Figure 49. The ground surface reconstruction. In light grey, the mesh of the terrain.
In black, the HMLS cluster. In RGB colour, the TLS cluster.

5. The church of Santissima Trinità in Castelvetro

The third case study, the Church of Santissima Trinità di Delia or Cuba di Delia in Castelvetro (Trapani), was selected for its combination of Arab-Norman typological features with unique innovations which make it different from the other previous two coeval buildings. Its most distinctive aspect is its stereometry, as it follows a central scheme based on a simple square for both the plan and elevations, resulting in an almost perfect cube. This design reflects the influence of Greek Orthodox churches in Sicily since the 7th century (the so-called “Cube”), later embraced by Arabic culture for their geometric abstraction. Additionally, this church stands out as one of the few Arab-Norman structures built outside Palermo, providing a valuable comparison with more renowned examples.

5.1 - Historical background

The church of Santissima Trinità was built in the ancient fief of Delia, now part of Castelvetro's countryside in northwestern Sicily. While its exact construction date is unknown, stylistic similarities to 12th-century Sicilian churches (San Niccolò la Regale in Mazara del Vallo, 1124; Santa Maria dell’Ammiraglio in Palermo, 1143; San Giovanni degli Eremiti in Palermo, 1142-1148) suggest it was built around 1140 (Di Stefano, 1979).

The first recorded mention of the church dates to 1392, when its administration was entrusted to the prior of Delia, including responsibility for maintenance. Major and arbitrary renovations occurred in 1527 and 1742: the former reinforced the vaults and added battlements on top of the roof, giving the church a fortress-like appearance, whilst the latter assessed earthquake damage, leading to structural reinforcements and modifications, such as the main access, which was moved to the central apse, contrary to its current appearance (Volpe, 2007).

Following the abolition of religious orders in Sicily in 1862, the church became private property and was acquired by the Saporito Ricca family in 1866 (Calabrese Liotta and

Nicolosi, 1998). In 1880, architect Giuseppe Patricolo was commissioned to build a family mausoleum beneath the church, marking the end of its religious function. His subsequent restoration sought to recover the church's original appearance by removing Baroque additions, reopening sealed windows and doors, dismantling battlements, repairing the spurious entrance and restoring pointed arches.

After this restoration, Patricolo carried out the first survey of the entire building, whose drawings have been published in his book (Figures 50 and 51) (Patricolo, 1880). Since Patricolo's intervention, only minor maintenance work has been carried out on the building.

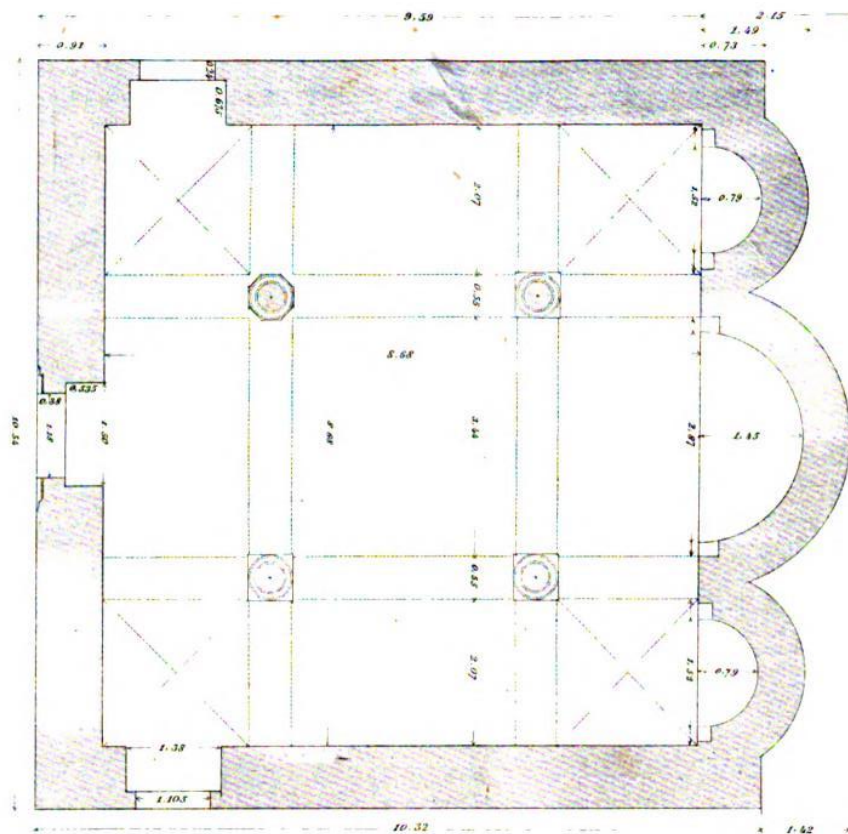


Figure 50. The plan of the church after its restoration in 1880 (from Patricolo, 1880).

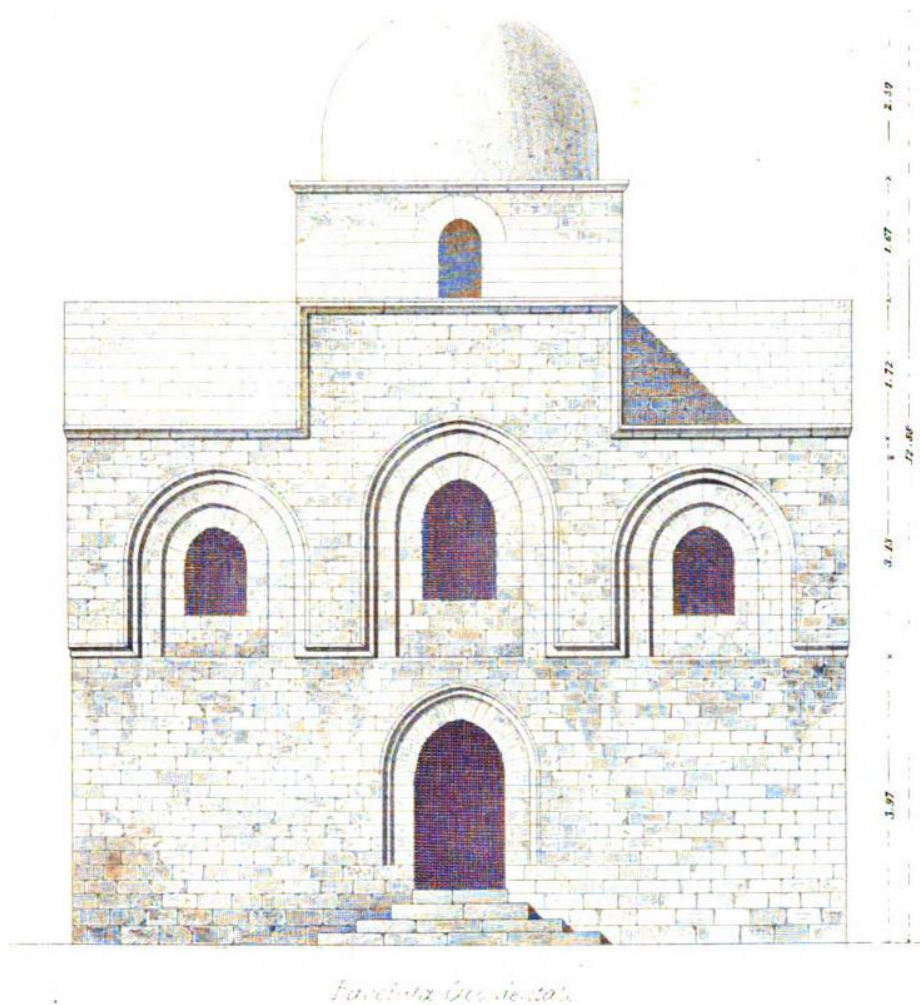


Figure 51. The western façade after the restoration (from Patricolo, 1880).

5.2 - Architectural description

The term "Cuba," of uncertain etymology (the most accredited hypotheses trace the word back to the Arabic equivalents *qubbah* = *dome*, *kabah* = *cube* or to the Latin *cupa* = *barrel*), refers to a type of religious building in Sicily dating back to the 7th century. These structures typically have a square central layout, thick walls, small openings, at least one eastern-facing apse, and a dome. The Santissima Trinità di Delia follows this model with Arab-Norman influences. It has a nearly square plan (about 10 m per side) with three pronounced eastern apses and a total height of nearly 13 m at the dome's extrados.

Externally, the façades reflect the interior structure, divided into two height sections. The lower part is flat, while the upper features mouldings framing three pointed arches windows per façade. The roof is structured into different-levelled terraces, highlighting

the Greek cross layout, with a taller central square lantern supporting the dome. Patricolo added a plaster layer for waterproofing, composed by lime mortar, quarry sand and brick dust. The façades, made of exposed limestone tuff, showcase the construction technique as a decorative element. The pointed arch windows feature recessed mouldings, whilst the masharabyas were modern additions by Patricolo, inspired by San Giovanni degli Eremiti in Palermo (Figure 52).



Figure 52. The church seen from its southern-western corner.

The church has three entrances, one central and two on the sides, reflecting Greek Orthodox traditions of gender-segregated access. Inside, the space is divided into nine bays around four reused red granite and cipollino marble columns with composite capitals. These columns support pointed arches defining the Greek cross arms, covered by barrel vaults, whilst the corner bays have cross vaults (Figure 53). The latter ones are peculiar because of their keystone raised by about 20 cm from the one of the perimetral arches. The central dome, set on pendentives transitioning into slanting trumpets like those already seen in the previous examples, is blind.

At the entrance doors and their windows above, the thickness of the wall is reduced so that the latter are framed by an archivolt. The apses have a curved structure, with the central one larger and separated by slender embedded columns. The original floor has been replaced with modern terracotta bricks.



Figure 53. The interior space of the church from its central span.

5.3 - Data acquisition

The data acquisition for Santissima Trinità di Delia was planned and conducted using an integrated survey combining TLS and both terrestrial and aerial photogrammetry to capture the most comprehensive and efficient dataset. TLS was employed for the entire interior and all four elevations, whilst terrestrial photogrammetry focused solely on the external façades. Since these methods could not accurately capture the roofing system, aerial photogrammetry was used to document the terraces, dome, and upper sections of the façades. This ensured a complete and detailed point cloud after data processing. Additionally, a topographic survey was conducted to acquire GCPs coordinates for photogrammetric processing.

5.3.1 The TLS survey

The data acquisition for Santissima Trinità was preceded by an on-site inspection to assess potential challenges and determine the best options for the operational phase. The major concerns to be considered in the planning were:

- the proximity of the church to a perimeter wall of a "baglio" (farm) built during some restoration works and located 6 m away from the northern façade, which was a spatial constraint for acquisitions in this area;
- dense vegetation such as trees and tall bushes across one corner of the building;
- tombs along the church's internal perimeter, which caused unavoidable gaps in the data capture;
- difficulties in the transitions between interior and exterior scans due to the limited space of the doors.

Scans were performed with a resolution settings aimed for a final point cloud with point spacing between 5mm and 10mm. To facilitate the acquisition, they have been divided into two blocks for exterior and interior datasets. The first group was performed first, and included two frontal scans on each side, plus one scan at each corner to link them together (Figure 54).



Figure 54. The Faro Focus 3D 120S during the survey operations on site.

Acquisitions on the corners were set at about 2 m from the walls with a higher resolution (6 mm at 10 m) because they served as a reference for the frontal ones, thus achieving a <2 mm point spacing to ensure a better connectivity. Another scan with the same settings was performed on a lateral entrance (the other one was closed) to improve the alignment between the external and the internal blocks. The other 8 external scans were positioned 3 m from the church, following a square perimeter with

rounded corners, with a resolution of 7 mm at 10 m. In order to prevent redundant data, the HFOV and VFOV of all the external acquisition was reduced to 140° towards the detectable surfaces only. The internal group forecast nine full-dome scans at the centre of each bay of the church, with a resolution of 7 mm at 10 m; plus, two additional scans which were necessary to detect the central apse, with a decreased resolution of 12 mm to 10 m given the confined space. At the end, the TLS survey delivered 24 scans, 13 outdoor and 11 indoor, with an acquisition time of about two hours excluding downtime (Figure 55).

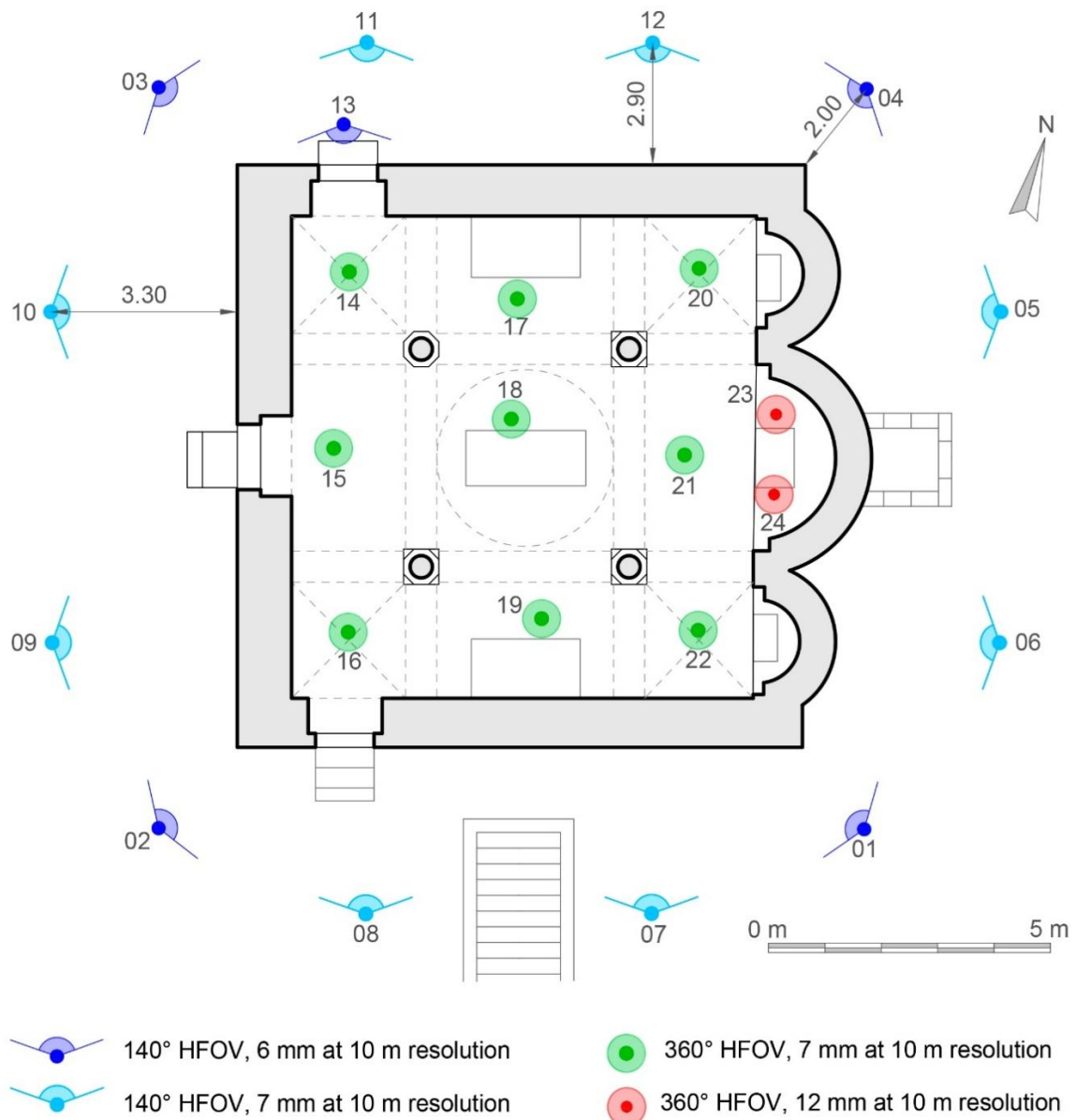


Figure 55. The scan positions for the TLS data collection at Santissima Trinità's church.

The specific scan settings used for the data acquisition are reported in detail in Table 6.

Number	Resolution Profile	Quality	Resolution at 10 m	HFOV (°)	VFOV (°)	Acquisition Time*
01-04, 13	1/4	3x	6.136	140	140	00:04:35
05-12	1/5	3x	7.670	140	140	00:03:17
15-22	1/5	3x	7.670	360	305	00:04:47
23-24	1/8	3x	12.272	360	305	00:03:24
* Acquisition time includes also taking pictures						01:49:37

Table 7. The actual scan settings for the TLS data acquisition at Holy Trinity's church.

5.3.2 The terrestrial photogrammetric survey

The terrestrial photogrammetric survey of Santissima Trinità regarded exclusively the exterior surfaces of the church. The preliminary on-site inspection highlighted some spatial constraints in correspondence of the northern façade and the presence of some tall bushes which prevented convergent shooting to be performed on a full circular perimeter, reducing thus the path to an approximate 270° arc.

Conducted around noon to ensure uniform lighting, the survey began at the northeastern corner. A Nikon D80 DSLR camera with a 23.6 x 15.8 mm sensor, a 6.07 µm pixel pitch, and a 10 MP resolution was used. The shooting strategy involved single strips per front, capturing the entire height of the church with the camera rotated at 90° in portrait position. In this way, eastern, southern, and part of the western façades were captured with an average camera-to-object distance from the wall of about 5 m (it was forcedly reduced at N-E corner because of the aforementioned bushes), whilst the step between adjacent shooting positions was about 1.5 m ensuring a 70% forward overlap.

Corners, being critical for linking adjacent façades, were captured with an average distance of 2.5 m from the relevant surfaces whilst base between shooting positions was reduced to less than 1-meter distance. To ensure more consistent coverage, the corner's surfaces were captured in three separate strips: the first with the camera tilted downward, the second positioned horizontally, and the third tilted upward. The northern façade required stereoscopic shooting with a nearly parallel alignment at about 3 m distance. The capturing of this façade was divided into two strips, with the camera repeatedly tilted downward and upward at each position to fully cover the surface.

Special attention was given to maintaining significant overlap to ensure accurate reconstruction. According to the camera specifications and this latter setting, a GSD of about 0.9 mm/pixel was obtained for the images at the corners, while a GSD of about 1.7 mm/pixel was obtained for all the other pictures taken on the fronts (Table 7).

Nikon D80 camera settings:		Minimum Ground Sampling Distance [GSDmin]
Focal length [c] [mm]	18	GSDmin= $D_{min} \times D_{pix}/c = 0.9 \text{ mm/pixel}$
Sensor length [mm]	23.6	
Sensor height [mm]	15.8	Maximum Ground Sampling Distance [GSDmax]
Pixel dimension [Dpix] [μm]	6.05	GSDmax= $D_{max} \times D_{pix}/c = 1.7 \text{ mm/pixel}$
Minimum Distance [Dmin] [mm]	2800	
Maximum Distance [Dmax] [mm]	5000	

Table 8. The calculation of minimum and maximum GSD.

By the end of the survey, a total of 114 images had been acquired (Figure 56).

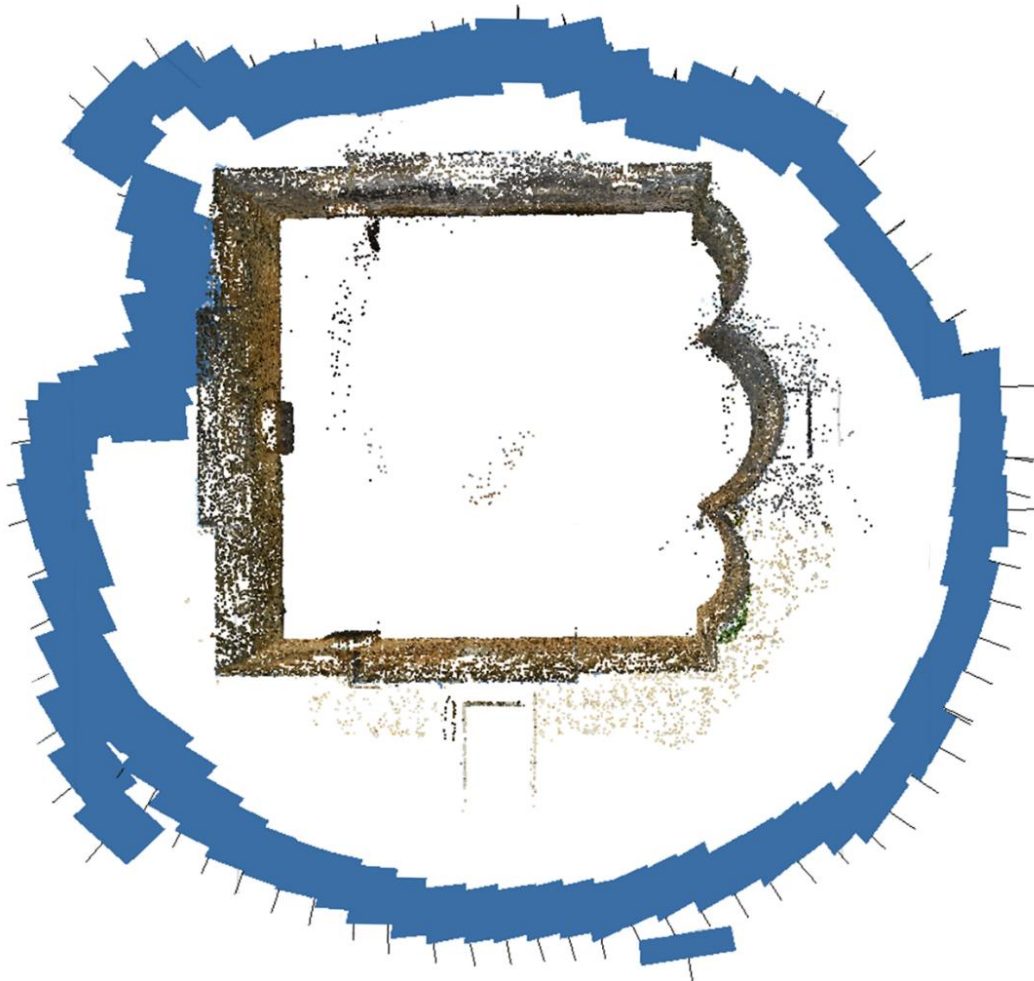


Figure 56. The terrestrial photogrammetric acquisitions.

5.3.3 The UAV photogrammetric survey

The aerial photogrammetric survey was conducted to complement the TLS and terrestrial photogrammetry acquisitions, particularly for capturing the upper parts of the building. A DJI Phantom 2 drone was used, featuring a 1 kg weight, a maximum flight autonomy of 25 minutes, and a 14 Mpx camera sensor. The survey was carried out through multiple flights, including:

- ✓ A nadiral capture, focusing on the roof and dome.
- ✓ Two circular paths, with the camera tilted at 30° and 45° angles from the horizon.
- ✓ A parallel flight along three façades (north, west, and east), with the northern façade omitted.

For the nadiral capture, 38 images were taken at an altitude of 9.6 m from the upper terrace and 18 m from the ground. The circular flights were conducted at a 15 m altitude, with a 15 m radius from the church's centre and a 6 m distance from its façades, capturing a total of 38 images. The parallel flight along the façades resulted in:

- ✓ 5 pictures of the north façade, taken at a 6 m distance and a 7 m altitude.
- ✓ 12 pictures of the west façade, taken at the same height with a 4 m camera-to-object distance.
- ✓ 18 pictures of the east façade, which required more acquisitions due to the curved apses, taken from an 8 m perimeter.

By the end of the survey, a total of 243 images was collected (Figure 57).

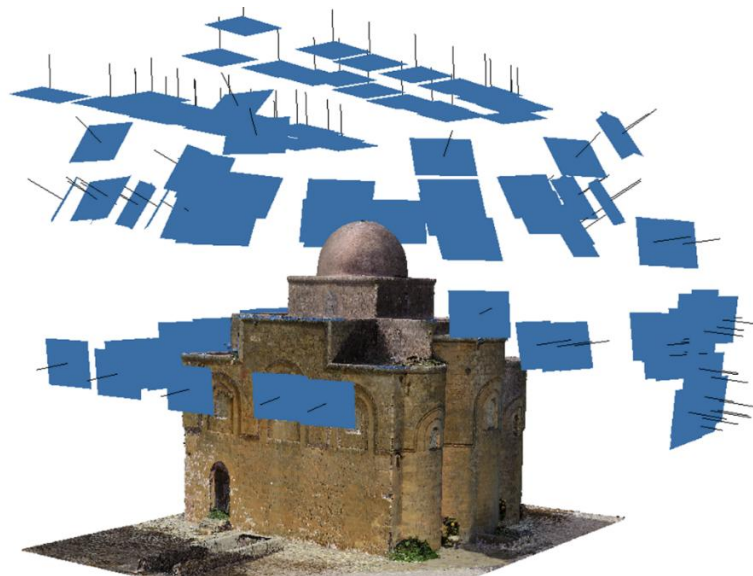


Figure 57. The scheme for the UAV flights at Santissima Trinità.

5.3.4 The topographic survey

The topographic survey at Santissima Trinità was focused on obtaining the coordinates of the GCPs necessary for processing the photogrammetric data. Due to the limited space on the northern front, which made it difficult to measure accurately, the survey was carried out on the other façades only.

To overcome the space limitations, an open traverse consisting of three vertices was established, roughly aligned with the axes of the primary façades. As in the case of San Giovanni dei Lebbrosi, the used equipment was a Leica TPS 1105 total station. The GCPs were strategically placed in easily identifiable spots distributed across the façades, 6 points on the southern wall, 4 points on the apses, and 6 points on the main elevation (Figure 58). After measuring the traverse, the coordinates of the 16 GCPs were calculated, which were then used for photogrammetric data processing.

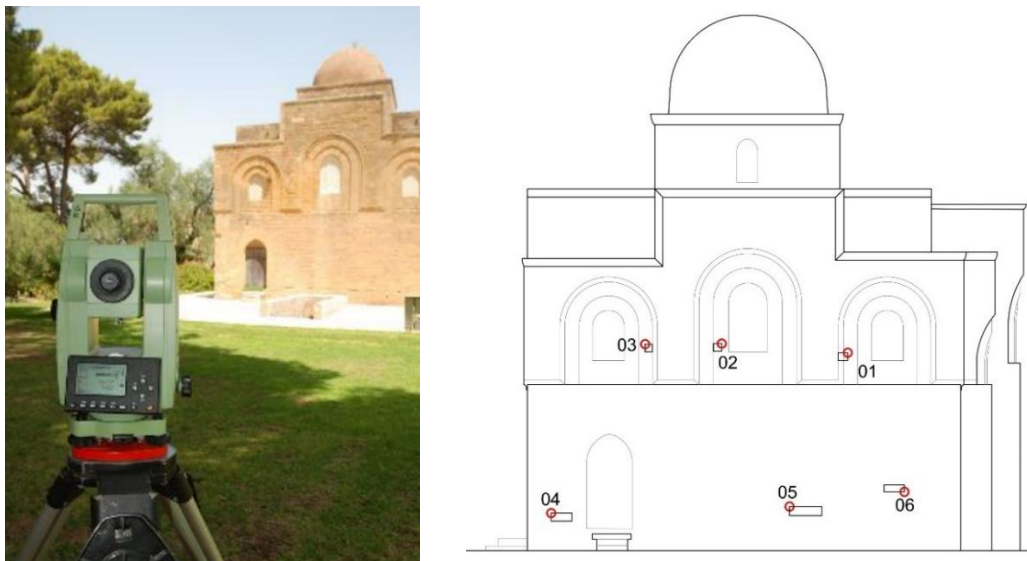


Figure 58. The Leica TPS 1105 at Santissima Trinità and the scheme for GCPs at southern façade.

5.4 – Data processing

5.4.1 TLS survey data

The TLS data processing was performed within Autodesk ReCap software, structured into two separate blocks of the external and internal. The goal was to ensure accurate alignment and merging of all scans to create a unified point cloud.

External scans were processed first. They were imported according to each façade of the church, starting from the angular scan followed by the others sharing the same side and vertex; this approach ensured that each front was aligned correctly, with the ICP algorithm being used for automatic alignment. This process continued until all external scans were linked, forming a coherent block. When the scans from the southern-eastern corner were added, the automatic registration procedure failed due to insufficient overlap between those scans. To resolve this issue, manual registration was performed using three homologous points across the three scans.

After successfully aligning the 13 scans, the point cloud was checked for discrepancies and misalignments. Once confirmed, the scans were merged, resulting in a cloud containing around 85 million points, with an average point distance of 3.5 mm. The point cloud was then filtered to remove redundant data, such as sparse vegetation, and resampled to achieve a more uniform distribution, maintaining about 7 mm between adjacent points, resulting in a total of 29 million points (Figure 59).



Figure 59. The point cloud of the external scans after the filtering and resampling.

The internal scans were imported in the order they were taken, starting with the ones near the entrances. Given their full-dome settings, abundant overlapping data allowed the automatic registration process to proceed smoothly without issues. After checking

and merging the scans, the resulting point cloud contained around 196 million points, with an average distance of 2.5 mm between points. The cloud was then filtered to remove unnecessary data (such as tombs in the central bay and around the walls) and resampled to match the same point distance as the external cloud. The final internal point cloud was finally reduced to 36 million points (Figure 60).



Figure 60. The cluster of the internal scans after the filtering and the resampling.

The merging of the external and internal point clouds proved to be problematic, as seen for the church of San Giovanni dei Lebbrosi. To solve the failure of ReCap to automatically register the two clusters, an additional connecting block was created with four scans carried out near the north entrance (outdoor and indoor), which had sufficient overlapping data with both the previous groups.

More in detail, the two outdoor scans, in common with external block, made the additional block to be aligned (with a double care at not merging yet) to the outdoor group; similarly, the other two internal scans of the additional block helped to make it aligned to the previous internal block of scans. Once these four acquisitions have been added to both blocks, internal and external point clouds were aligned manually in

CloudCompare software using at least three homologous points from the overlapping area. This process was refined after a final check for potential misalignments.

The connecting block was then deleted to avoid redundancy and the two point clouds were merged, resulting in a unified cluster of about 65 million points, albeit still lacking data on the roofing system and the extrados of the dome (Figure 61).



Figure 61. The overall final TLS point cloud.

5.4.2 Photogrammetric survey data

The photogrammetric data were processed through a typical workflow within Agisoft Metashape. After importing all the images into a single chunk, the software calculated an initial automated image orientation through SfM algorithm.

At this step, the coordinates of the 16 GCPs, obtained from the topographic survey, were imported into the software and the initial orientation was further refined and optimized using a bundle adjustment procedure; at the end, the mean re-projection

error was about 2 pixels, and the XYZ RMSE in object space for the GCPs was about ± 1 cm (Figure 62).

Marcatori	X (m)	Y (m)	Z (m)	Precisione (m)	Errore (m)	Proiezioni
✓ 1	98.153000	123.135000	104.634000	0.005000	0.009430	11
✓ 2	95.151000	123.117000	105.011000	0.005000	0.001387	25
✓ 3	93.391000	123.005000	105.013000	0.005000	0.015870	10
✓ 4	91.079000	122.969000	100.947000	0.005000	0.014306	6
✓ 5	96.765000	123.110000	101.112000	0.005000	0.010204	12
✓ 6	99.498000	123.179000	101.471000	0.005000	0.007130	7
✓ 7	101.449000	124.795000	104.037000	0.005000	0.010111	27
✓ 8	102.086000	128.140000	104.173000	0.005000	0.013758	21
✓ 9	101.408000	131.687000	106.385000	0.005000	0.014737	26
✓ 10	101.879000	127.525000	101.358000	0.005000	0.008039	7
✓ 11	100.958000	130.742000	101.508000	0.005000	0.005589	10
✓ 12	90.301000	131.504000	103.769000	0.005000	0.015386	6
✓ 13	90.421000	128.991000	102.169000	0.005000	0.011651	7
✓ 14	90.458000	125.178000	102.382000	0.005000	0.008657	11
✓ 15	90.445000	125.262000	103.861000	0.005000	0.015211	7
✓ 16	90.409000	126.952000	102.016000	0.005000	0.007635	12
Errore Totale Punti di contr...					0.011303	

Figure 62. The residuals and XYZ RMSE of the GCPs.

A sparse point cloud of tie points was obtained (Figure 63).

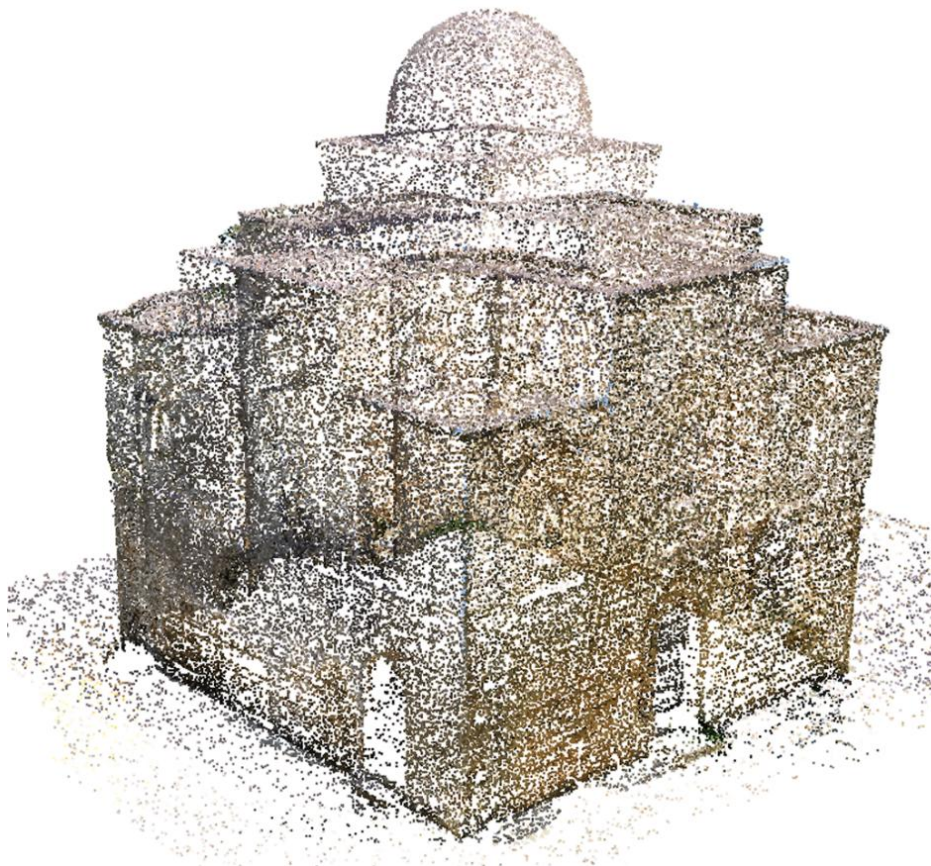


Figure 63. The sparse photogrammetric point cloud.

The further processing through high-quality settings with MVS algorithm was used to calculate the dense point cloud; a point cloud with over 50 million points, including the roof data which were missing from the TLS acquisition, was obtained (Figure 64).



Figure 64. The dense photogrammetric point cloud.

5.4.3 - The overall point cloud

At this point, the two point clouds from the TLS and the photogrammetric surveys were integrated in order to have neither redundant areas nor gaps in the final cluster, to be used for the parametric modelling of the church.

This integration has been carried out with a manual process within the Cloud Compare software, through the identification of at least 4 common points on both clouds and the imposition that TLS cloud should have acted as a reference for the photogrammetric one to be aligned on.

This alignment has been further improved with an automatic registration. The resulting point cloud contained a huge amount of redundant data, corresponding to the main fronts of the church, which have been detected in all the surveys. Since the TLS cloud was considered more accurate, these redundant parts were stripped from the photogrammetric cloud at the edges of the facade, taking care to retain the part relating to the roof only. At last, the complete TLS cloud and the retained parts of the photogrammetric one were merged into an overall point cloud counting about 78 million of points (Figure 65).

Finally, the overall point cloud was rotated arbitrarily so that the facades were parallel to the X and Y directions used in the BIM software into which the point cloud would later be imported.

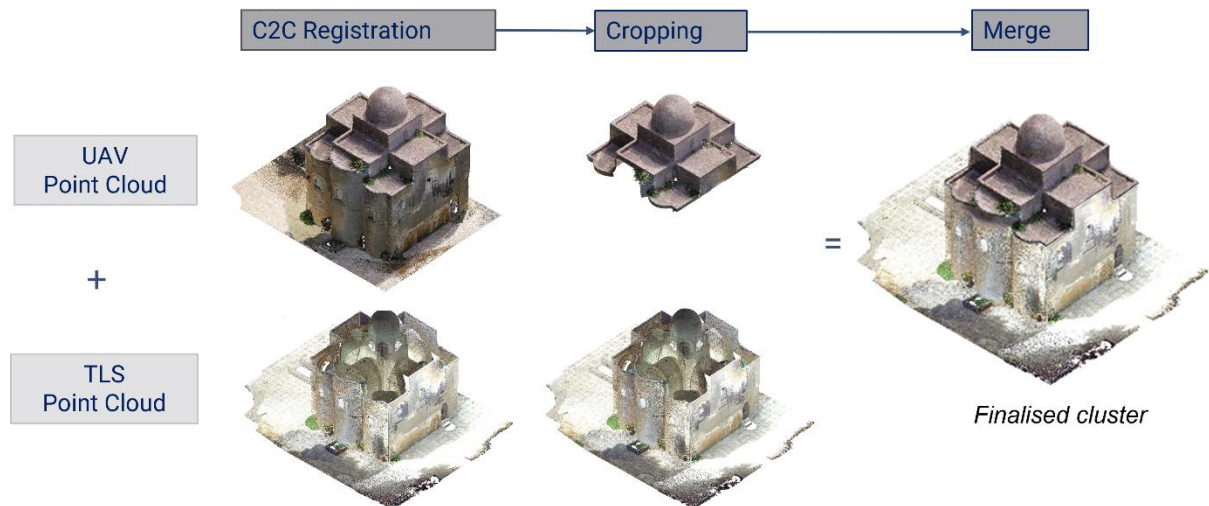


Figure 65. The process for obtaining the overall point cloud.

6. The church of Santa Maria della Grotta in Marsala

Santa Maria della Grotta is a monastic complex in the suburbs of Marsala (western Sicily), notable for its unique site morphology and layers of archaeological remains dating from the 4th century B.C. Phoenician colonization to the Medieval period. The area includes underground chambers originally used for burials and worship, later modified in the 17th century with the construction of a church partially dug into sandstone. Today, the complex comprises the central church (A) and three hypogea - one to the north (B) and two to the south (C, D). Access was formerly through a lower churchyard (E) connected by stairs (F) to an upper Punic necropolis (G) with visible burials (Figure 66).

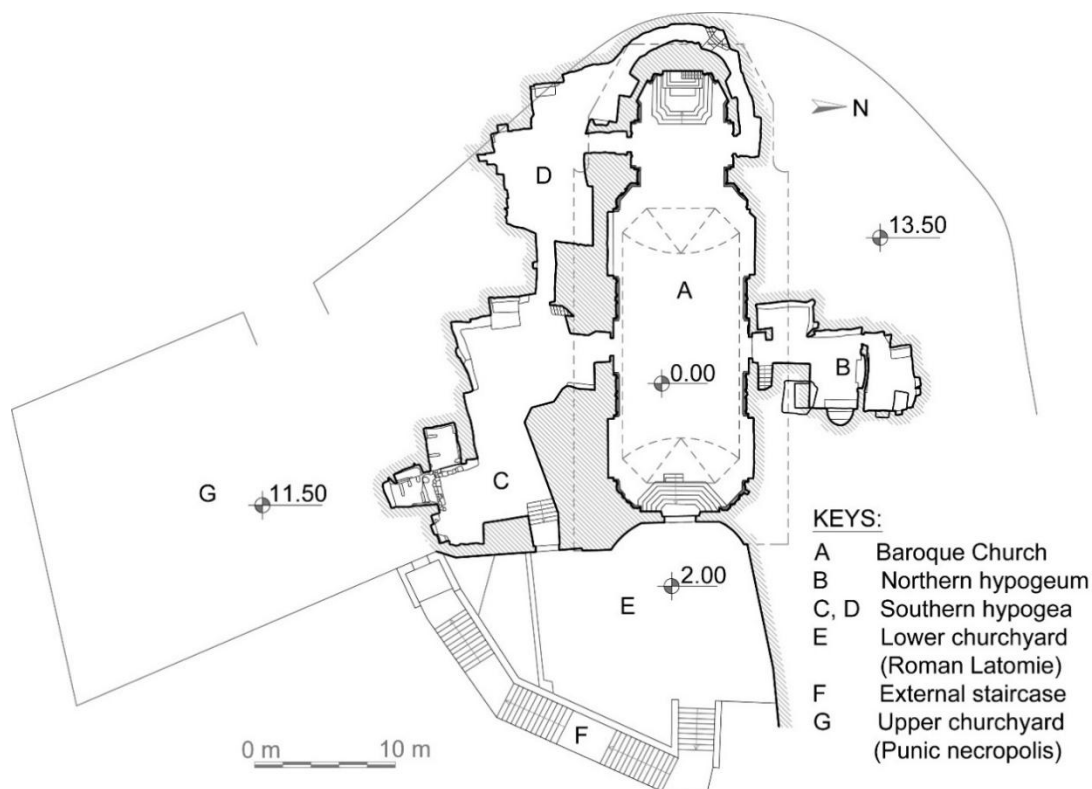


Figure 66. Plan of the complex of Santa Maria della Grotta at level 1.20 m..

Currently, the site is closed to the public due to deterioration and lack of maintenance, making access difficult. Additionally, it had never been studied using modern geomatics methods capable of producing detailed 3D data of its unique structure. Whilst the

overall goal was to acquire complete 3D information of the complex, this chapter focuses specifically on the digitization of the church for the creation of an HBIM model.

6.1 - Historical background

The Church of Santa Maria della Grotta is part of a wider thousand-year-old 4,400 m² archaeological complex in Marsala, Italy, containing remains from the Punic, Roman, and Medieval periods. Located within the Phoenician necropolis of Capo Boeo (4th century B.C.), the church is partly carved into rock. Fully uncovered in 1888, the site revealed vertical-shaft burial pits, some later adapted as skylights for the underlying hypogea. In the 3rd century A.D., during Roman rule, the settlement of Lilybaeum (the ancient name of Marsala) became a thriving colony, and the area was converted into a sandstone quarry (latomie), later serving as catacombs for Paleo-Christian and Jewish communities by the 5th century. In 1097, under the orders of King Roger I, a Greek Orthodox monastic community established a coenobitic abbey within the former catacombs, dedicating it to the Virgin Mary. A fortified tower, later transformed into a bell tower, marked the entrance ([Caruso, 1995](#)). By the 15th century, the church changed hands multiple times, first managed by the Diocese of Palermo and later by the Jesuits, who commissioned Giovan Biagio Amico (1712–1715) to redesign it in a late Baroque style (Figure 67).



Figure 67. Aerial view of the site.

Despite continued use, the church deteriorated, and a 1968 earthquake caused partial collapse, including the bell tower. Now under the Archaeological Park of Lilibeo-Marsala, it remains closed to the public due to insufficient restoration and maintenance.

6.2 - Architectural description

The current church, approximately 31 meters long and 10 meters wide, is built over a Punic necropolis and caves, expanding upon its medieval foundation. Access is via a four-ramp sandstone staircase (carved in 1072) from the upper churchyard, which altered the original bell tower's function; this staircase leads to a lower open space 9 meters below within the former quarries (latomie).

The plain entrance façade features only a central circular rose window, with exposed sandstone visible where plaster has detached. A balustrade crowns the building, and the flat roof reveals the shape of a boat-vaulted ceiling beneath. Over the presbytery, a green-tiled hemispherical dome - added posthumously by Mario Pisano - sits supported by sandstone ribs. This dome and the roofing system are the only visible parts of the church at ground level (Figures 68,69,70).



Figure 68. The main façade of the church.



Figure 69. The southern façade of the church from the upper churchyard.



Figure 70. The northern façade of the church from the access street.

The interior, situated 2 meters below the lower churchyard, is reached via polygonal steps. It comprises a single nave, square presbytery, and polygonal apse with minimal decorative elements. Excavations in the current floor revealed a medieval terracotta pavement and traces of Jewish burials. Sandstone walls, leaning on carved surfaces and coated in white plaster, feature four recessed arched chapels, two symmetrical balconies on decorated brackets, and Tuscan pilasters framing the arches beneath a continuous cornice.

The apse, narrower and slightly elevated, houses a simple marble and alabaster altar and a niche flanked by composite columns. Six openings provide access to interconnected underground chambers. The false ceilings, made of cane straw and plaster, include a boat vault in the nave, a barrel vault with lunettes in the presbytery (lit by an octagonal lantern), and a five-rayed dome in the apse. Interior deterioration

is evident, with humidity and poor maintenance causing visible damage, particularly where sandstone contacts the walls (Figure 71).



Figure 71. The interiors of the church: the counter façade and the aisle.

The pre-existing Paleo-Christian hypogea north and south of the Baroque church were repeatedly modified between the 13th and 15th centuries by the Basilian monastic community (Tisserye, 1995). The northern hypogaeum likely served as a funerary chapel, featuring an iconostasis and an arcosolium later used as an ossuary. Originally two stories, its upper dormitory level was partially removed during Baroque renovations. The larger southern hypogaeum functioned as a refectory, evidenced by food remnants in former burial arcosolia. A connecting hypogaeum links it to both the southern hypogaeum and the presbytery via corridors. All three hypogea include altars, perimeter seating, and Orthodox Christian frescoes (12th- 17th century), depicting Basilian Saints, the Martyrdom of St. Stephen, and Madonnas with Child or St. John. Whilst some frescoes remain well-preserved, others suffer from humidity and Baroque-era damage (Figure 72).



Figure 72. Details of the hypogaeum environments with traces of Medieval frescoes.

6.3 - Data acquisition

The digitisation of Santa Maria della Grotta's church involved a detailed workflow divided into two main phases: documenting the as-built conditions through a point cloud and four orthophotos for the creation of thematic decay mapping (further discussed in Chapter 7). Figure 73 outlines the data acquisition and processing phase, whilst the modelling phase is covered in Chapter 7.

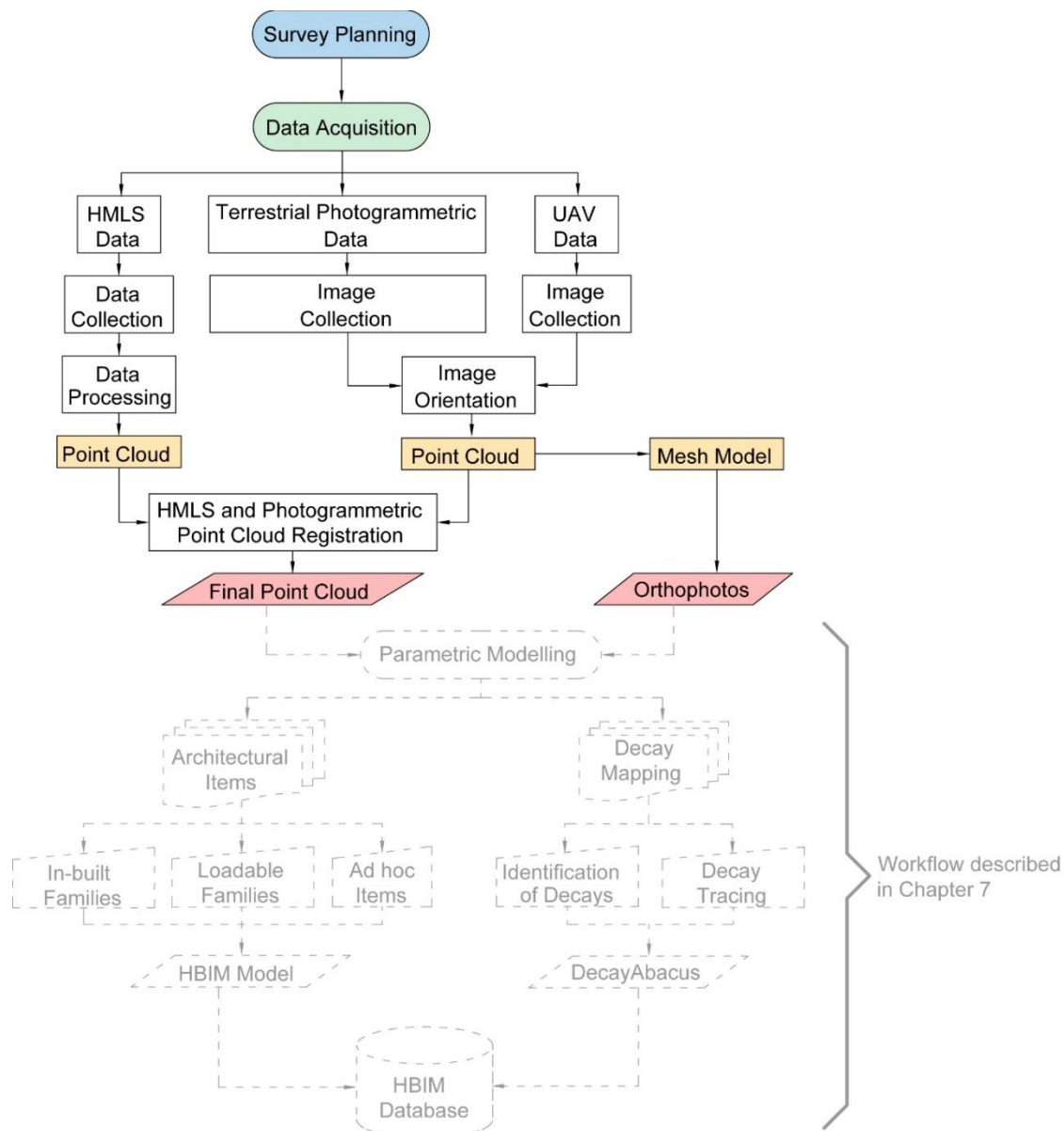


Figure 73. The workflow leading to the outputs for the 3D digital model of the church. In grey, the steps applying to the HBIM modelling phase reported in Chapter 7.

Given the complexity and irregularity of the grottoes, careful survey strategies and coordination were essential. As the site had never previously been surveyed using digital methods, the data collected served both for research and for purposes beyond the HBIM model (Aricò et al., 2023b). A preliminary onsite inspection was conducted to identify critical issues and determine the most suitable techniques. The survey combined HMLS methods with both terrestrial and aerial photogrammetry, ensuring detailed 3D documentation of the church, the surrounding environment, and the hypogea.

6.3.1 The HMLS survey

The unique morphology of the Santa Maria della Grotta complex, with extensive outdoor flat areas, dense vegetation, and challenging indoor spaces, made the use of a static LS impractical. Instead, a HMLS method was chosen for its efficiency, cost-effectiveness, and ability to capture the complex organic surfaces, connecting both internal and external parts seamlessly.

The survey was carried out with a ZEB Horizon, manufactured by GeoSlam (Figure 74), whose technical specifications are reported in Table 8.



Figure 74. The GeoSLAM ZEB Horizon device held by the operator during the survey.

Maximum Scan Rate	300,000 pts/sec
High Resolution RGB Camera	Zeb Vision sensor available *
Relative accuracy *	±6 mm **
Vertical Angular Resolution	±2°
Horizontal Angular Resolution	±0.2°
Ranging distance	From 0.5m up to 100m
Horizontal Field of View (HFOV)	360°
Vertical Field of View (VFOV)	270°

* Purchased separately

** When processing data in GeoSLAM Connect V2

Table 9. Technical specifications of the GeoSLAM ZEB Horizon laser scanner from the manufacturer.

This scanner, using SLAM technology, provides high-precision point clouds processed in real-time. It also features a RGB sensor for colorised point clouds and can be connected to smartphones or tablets via Wi-Fi, allowing real-time path visualization.

After an onsite inspection, three convenient scanning trajectories were designed, to be performed in both directions:

1. From the staircase across the lower churchyard, the central nave up to the apse, and southern hypogeum, returning to the nave centre (Figure 75).
2. Starting at the external premises, crossing the nave, northern and southern hypogea, through the annular passage, and into the apse (Figure 75).
3. Crossing the external premises only, including the lower and upper churchyard (Figure 76).

Seven reference points were established along these paths, permanently marked with stable nails to ensure accuracy:

- ✓ Point 1: On the third ramp of the staircase to the lower churchyard (start and end of all routes).
- ✓ Point 2: On the first ramp of the staircase.
- ✓ Point 3: On the lower churchyard, 2 meters from the main entrance.
- ✓ Point 4: At the centre of the church's long axis.
- ✓ Point 5: At the centre of the apse.
- ✓ Point 6: Under the skylight of the S-W hypogeum.
- ✓ Point 7: In the second room of the northern hypogeum.



Figure 75. In light blue, the first planned path of the HMLS survey. In orange the second one.

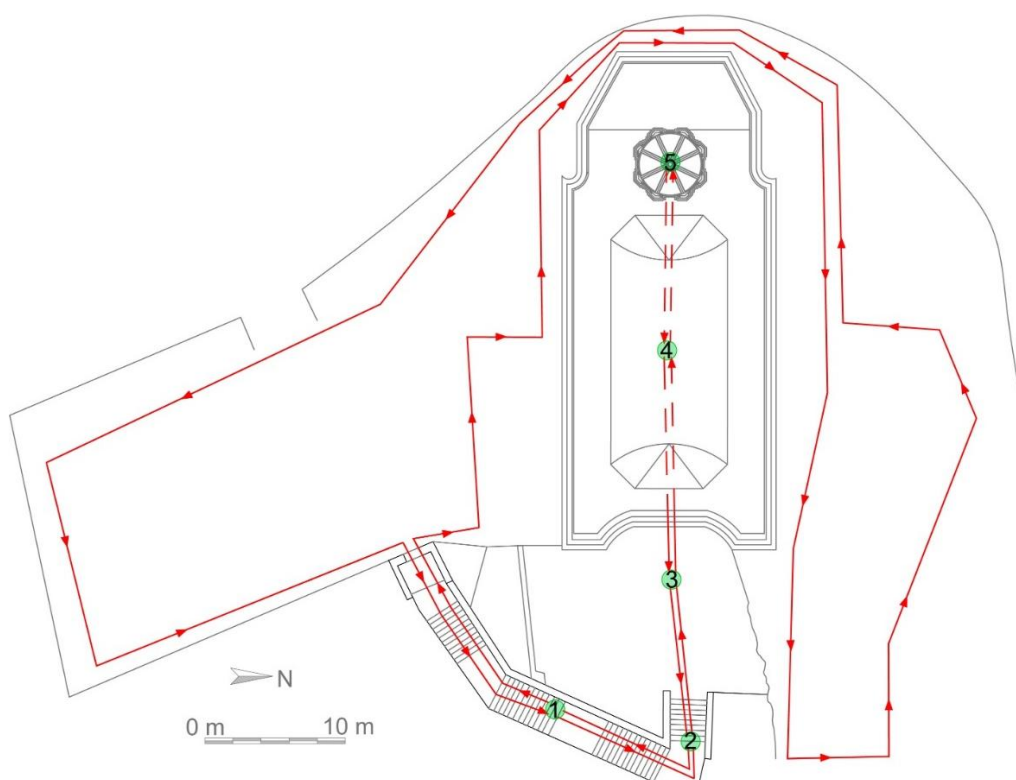


Figure 76. The third planned route for the HMLS survey on the exterior environments.

Once the survey paths were confirmed clear of obstacles, the survey began. The ZEB Horizon was connected to the Data Logger and smartphone via Wi-Fi, ensuring the correct position of the reference system's origin by holding it static for 10 seconds. The operator then followed the predefined paths in both directions.

On the walks the SLAM algorithm provided three different point clouds displayed in real time on the operator's smartphone.

6.3.2 The terrestrial photogrammetric survey

The terrestrial photogrammetric acquisition regarded the interior of the church only. As spotted during the onsite inspection, the interior environment, although open, presented reduced lighting that could prevent a good radiometric quality of the images.

A mirrorless Sony $\alpha 6000$ camera, with a CMOS 23.5 x 15.6 mm sensor, a 3.91 μm pixel pitch and a resolution of 24 Mpx was used for this survey. All the interior façades have been captured in just two strips with the camera rotated at 90° in portrait position to increase the coverage in vertical direction; pictures have been taken from a height of about 1.5 m from the ground, with a focal length of 16 mm.

The operational phase was organised according to four macro-areas: the long walls of the aisle and apse, the cross walls, and the roof. The camera settings were established based on the different surface geometry of these parts. Shooting positions were signed on the floor for an improved accuracy before the operational phase.

Aisle long walls: The camera-to-object distance was set to 9.2 m, with a 2 m base between shooting positions, resulting in 78% forward overlap, 60% lateral overlap, and a GSD of 2.2 mm/pixel (Figure 77).

Apse long walls: Due to the smaller size of the apse, the camera-to-object distance was reduced to 6.1 m, with a 1.2 m base between shooting, achieving 83% forward overlap, 60% lateral overlap, and a GSD of 1.47 mm/pixel (Figure 77).

Cross walls: Given the shorter length of the cross walls, the camera-to-object distance was reduced to 7 m, maintaining a 2 m base between shootings. This provided 70% forward overlap, 60% lateral overlap, and a GSD of 1.69 mm/pixel (Figure 78).

Roof: The roofing system of the central aisle was surveyed with a strip of horizontal "landscape" images spanning 15.10 m, with a 2.90 m step. This resulted in 80% forward overlap and a GSD of 3.36 mm/pixel (Figure 79).

The specifications for these settings are summarized in Table 9.

	Camera-to-object distance (m)	Base (m)	Forward Overlap (%)	Lateral Overlap (%)	GSD (mm/pixel)
Long Walls	9.2	2.0	78	60	2.23
Apse Walls	6.1	1.2	83	60	1.47
Cross Walls	7.0	2.0	70	60	1.69
Roof	15.10	2.9	80	n/a	3.36

Table 10. The setting of the terrestrial photogrammetric survey per areas..

The survey delivered a total of 92 images, whose 68 were from the long walls (in the nave and in the apse), 12 for the cross walls and another 12 for the roofing parts.

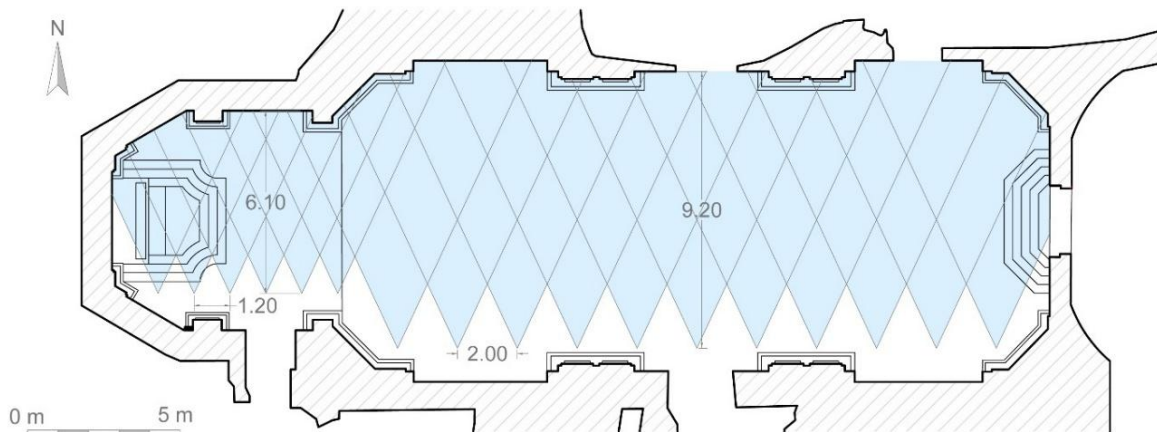


Figure 77. The image acquisition scheme for the long walls of the aisle and the apse.

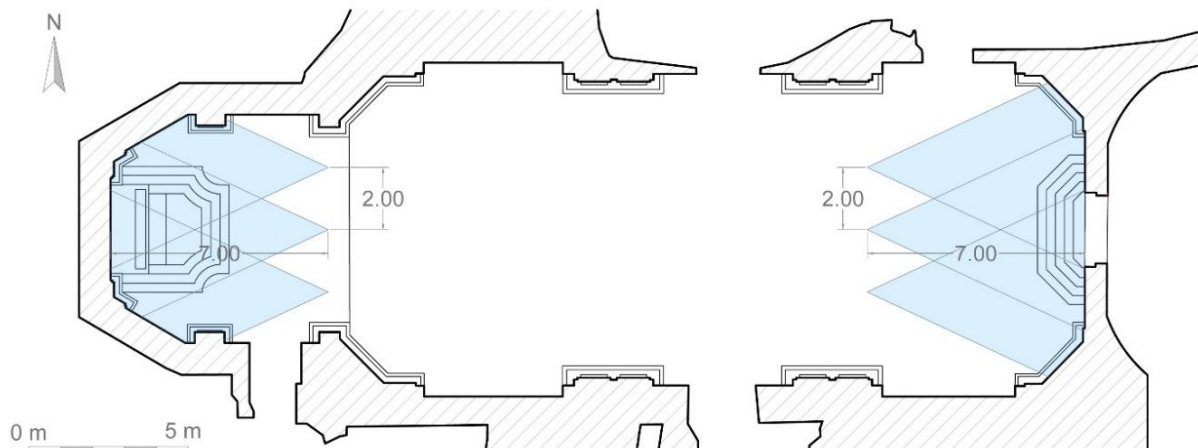


Figure 78. The image acquisition scheme for the cross walls of the aisle and the apse.

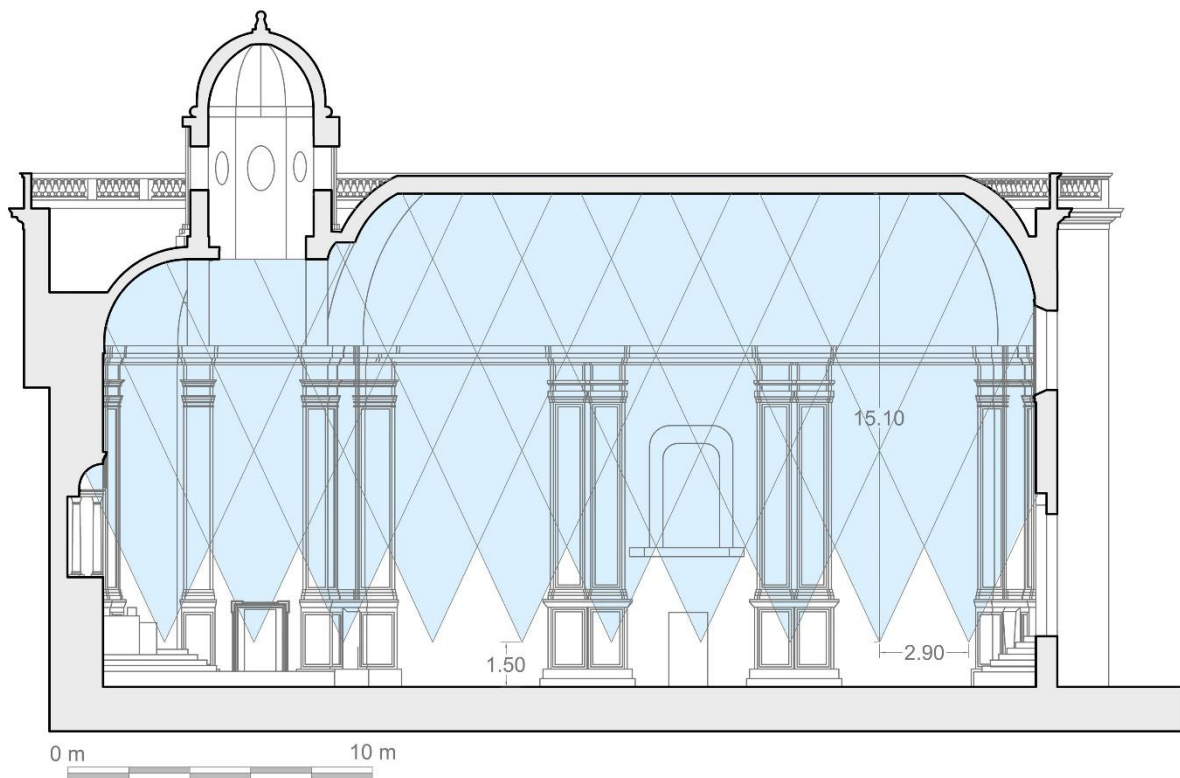


Figure 79. The image acquisition scheme for the roof seen through a long section.

6.3.3 The UAV photogrammetric survey

As seen in the previous paragraphs, the inaccessibility of the external roofing system of the church, isolated by the upper churchyard and logistically impractical to the HMLS survey operator, would have caused a gap during the data acquisition of those parts. To overcome this issue, an UAV flight was performed, which not only provided the missing information but also contributed to the integration with the other two techniques delivering a complete documentation of the complex into an extensive area of the surrounding premises.

A Parrot Anafi drone, characterised by a 250 gr. weight, a maximum flight autonomy of 25', and a 21 Mpx 4K HDR camera sensor, performed in a preplanned automatic way different flights on the exteriors of the complex, configured as follows:

- ✓ a nadiral capture: the drone flew at an altitude of approximately 16 m from the roof and 20 m from the upper churchyard.

- ✓ an elliptical path: with axes measuring 50 m and 40 m, aligned with the roof's center, the drone flew 20 m above the roof, with the camera tilted at a 30° angle from the horizon.
- ✓ two frontal acquisitions of the capturable fronts; flights were taken parallel to the main and southern façades at varying heights, with distances of 15 m and 10 m from the walls.

These external datasets provided a total of 224 images.

In order to obtain a metrically correct model after the photogrammetric acquisition, during the survey the coordinates of 16 GCPs (uniformly sparse on the upper churchyard in proximity of notable corners of the burial chambers) have been measured through a total station as a reference for the subsequent processing.

Another UAV flight was also performed inside the church, to capture images of the top surfaces hidden by protruding elements (such as the continue cornice) or scarcely visible from the ground, which would have caused gaps of data.

This flight was conducted in a manual mode to acquire the internal surfaces at different heights and tilting angles of the camera, with a double care of keeping the device well away from the walls.

This dataset delivered a total of 181 images; because of the low light inside the church these latter had to be adjusted to be used during the data processing.

6.4 - Data processing

6.4.1 HMLS survey data

The three point clouds from the HMLS survey were processed using the authoring software provided by Microgeo. The first point cloud contained approximately 93 million points, the second had over 159 million points, and the third contained 107 million points (Figure 80).

During this stage, the point clouds were aligned and overlaid on each other, then registered to create a single unified cluster. The result was a total of 358 million points, delivered in a .laz format.



Figure 80. The 3 different raw datasets from the HMLS survey provided by MicroGeo.

The obtained point cloud cluster was then processed in CloudCompare, where it was segmented to remove unnecessary data, such as the exterior parts and the hypogea, which were not relevant for the HBIM digitization. This segmentation was carried out manually using the “cross-sections” tool, dividing the cluster into smaller portions to facilitate identifying and removing the unwanted points without accidentally deleting any useful information.

Following this, the point cloud was resampled to maintain a mutual minimum distance of 8 mm between contiguous points, which reduced the total number of points to approximately 80 million (Aricò et al., 2024) (Figure 81).

As expected, the resulting point cloud showed a significant gap corresponding to the roofing system, which could not be surveyed using the HMLS methodology. To resolve this issue, data from the photogrammetric survey were integrated.



Figure 81. The HMLS point cloud at the end of the postprocessing phase.

6.4.2 Photogrammetric survey data

The photogrammetric data were processed within Agisoft Metashape into separate projects, aimed at two different purposes: extracting the information related to the roofing system of the church to be integrated into the HMLS cluster, and obtaining the orthophotos of the exterior and interior façades of the long walls.

For the point cloud of the roof, the 224 UAV images have been imported into the software and used to calculate an initial automated image orientation through SfM algorithm.

The coordinates of 16 GCPs measured on site with a total station were used for the bundle adjustment procedure, obtaining a mean re-projection error of about 1 pixel whilst a XYZ RMSE in object space for the GCPs of about ± 1.4 cm.

At the end of this step, a sparse point cloud of 40 million tie points was delivered (Figure 82).

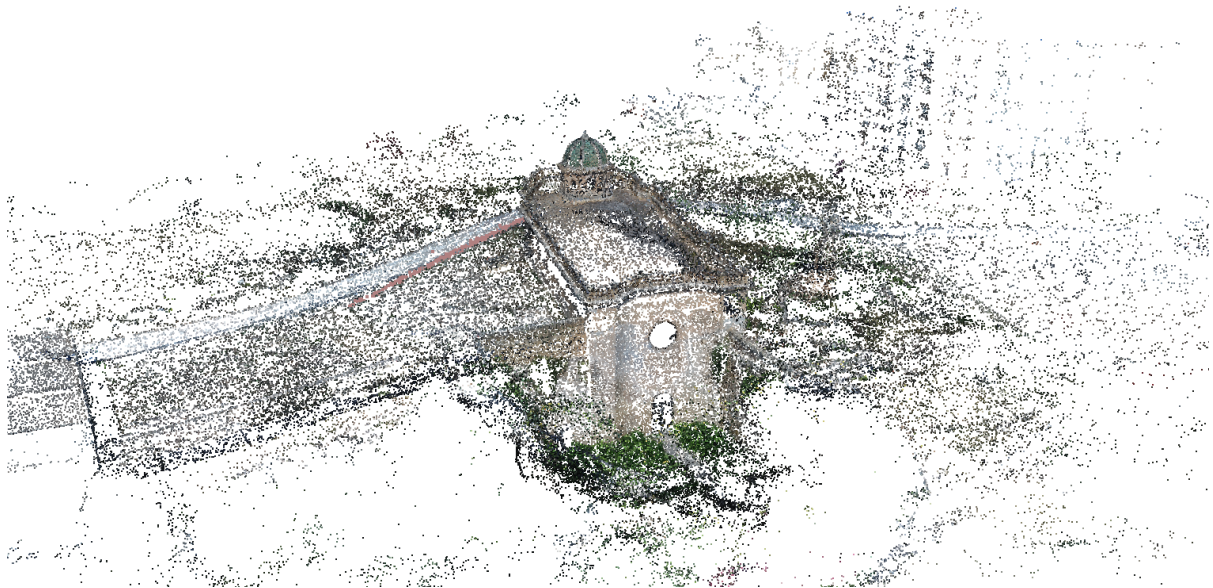


Figure 82. The sparse point cloud from the alignment of the 224 UAV captures.

The images were then further processed through high-quality settings with MVS algorithm (Figure 83). The external point cloud, counting more than 137 million points, was used to crop and retain the roofing system to be merged to the HMLS point cloud (Figure 84).

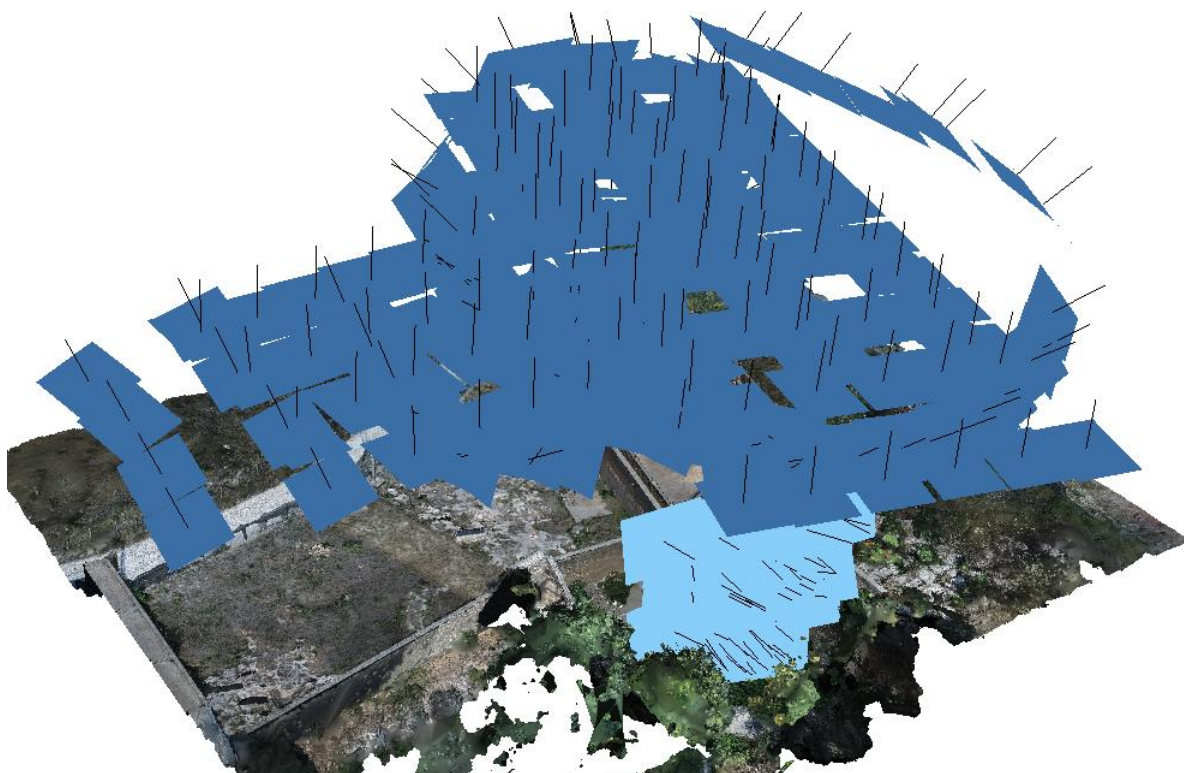


Figure 83. The 224 pictures dataset for the external UAV photogrammetric survey.



Figure 84. The dense point cloud from the external UAV survey..

6.4.3 The overall point cloud and the orthophotos of long façades

The final photogrammetric point cloud of the external parts was then aligned to the HMLS cluster (imposed to be a reference) by a C2C registration process into CloudCompare through four equivalent point pairs. To further refine the alignment, an automated process was applied, taking advantage of the redundancy of information between the two outputs. Then, the photogrammetric data underwent a manual segmentation process using the interactive tools available in CloudCompare. The goal was to retain only the roof, dome, and parapet while discarding any overlapping parts that were already represented in the HMLS cluster.

After this segmentation, the retained segment, which included only the relevant parts of the photogrammetric data, consisted of 815 thousand points. These were then merged with the HMLS dataset, resulting in a final point cloud of 81 million points (Figure 85).

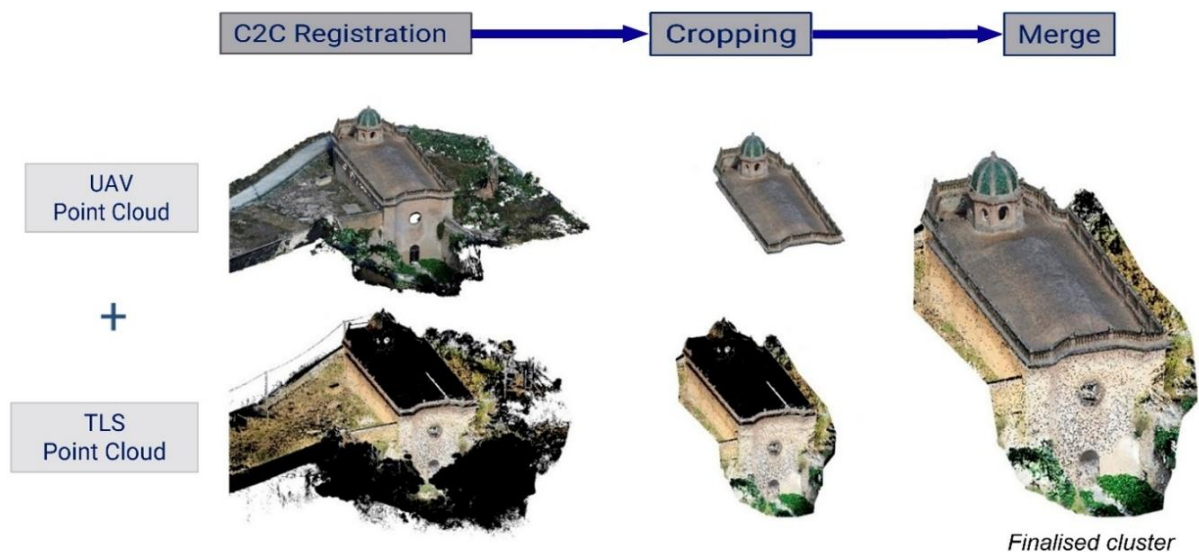


Figure 85. The process for obtaining the overall cloud.

As the overall point cloud was set into an arbitrary reference system, to make it more suitable for an easier further HBIM digitisation, it was rotated in such a way to align its main façade on a X axis, its southern façade on the Y axis and the included corner at the origin of this system.

The photogrammetric project used for obtaining the overall church was further processed to obtain the orthophotos of the external walls of the church. Once generated the two external orthophotos, they have been exported into a .tiff format (Figures 86 and 87).



Figure 86. The orthophoto of the external southern façade.



Figure 87. The orthophoto of the external northern façade.

To create orthophotos of the church's internal walls, images from both terrestrial and aerial photogrammetric surveys were used. Before applying the SfM algorithm, a selection and editing of the best frames were made to enhance brightness, saturation, hue, and reduce contrast. After this, 75 UAV and 48 terrestrial images were imported into Metashape. A similar process as for the external photogrammetric point cloud was followed. The SfM algorithm generated a sparse point cloud, and bundle adjustment refined it using some GCPs, measured with a total station, to estimate the external orientation parameters of the images. A high-quality dense point cloud was produced using the MVS algorithm and aligned with the overall cluster using some pairs of common points. (Figure 88).

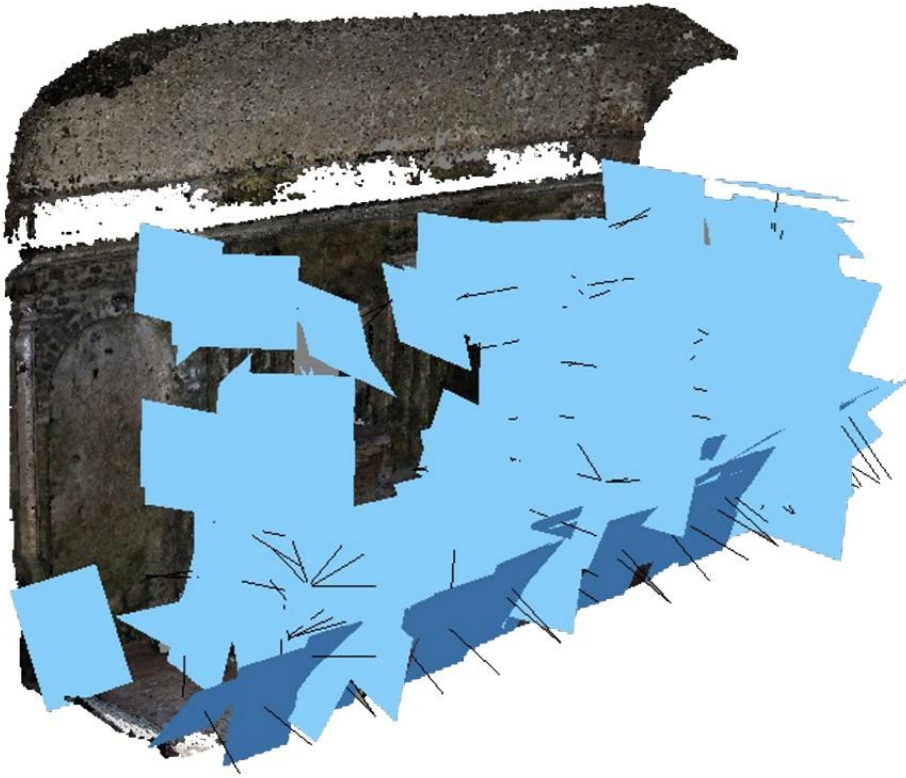


Figure 88. The 181 pictures dataset for the internal UAV photogrammetric survey. Finally, orthophotos of both internal long walls of the church were created and exported in .tiff format (Figures 89 and 90).



Figure 89. The orthophoto of the internal southern façade.



Figure 90. The orthophoto of the internal northern façade.

7. The HBIM modelling: from a parametric approach to the creation of a typological library

Once obtained the datasets from the digital surveys and subsequent processing to be used as the most reliable basis for the parametric modelling phase, the HBIM digitisation of the case studies in this research was aimed at turning the geometric information contained in the point clouds into recognizable structural items, capable of describing the whole architectural systems and the features of single elements in their as-built conditions, dimensions and functions.

An effective digital replica from a point cloud information should provide an adequate representation of the real historical assets including their peculiarities, and a reproduction of their logical structures as consistent as possible ([Adami et al., 2019](#)).

The digital reconstruction of the case studies followed this principle. Each building was analysed and decomposed through a top-down investigation, from an overall to an elementary level, in order to understand the role of each item in its broader context, how they have been built and connected to other parts in terms of hierarchies and spatial relationships. The parametric modelling was performed in a BIM environment using Autodesk Revit. This software was chosen because it efficiently handles point clouds and has an intuitive interface. It is also a powerful database which can catalogue all 2D and 3D elements along with necessary semantic information for modelling.

Although the process took more time, the modelling followed a “direct method”, segmenting the point cloud into horizontal and vertical 2D planes to clarify the buildings' structure and spatial organization. Automated or semi-automated methods were not used, as they are still under development, require extensive training, and need powerful computers ([Donato et al., 2021](#); [Aricò et al., 2023c](#)).

The architectural elements were modelled with a parametric approach, starting with structural elements already included into the software's built-in libraries. More complex items related to the Arab-Norman architectural style were modelled from scratch using

Revit templates and made fully parametrizable. Items which couldn't be parametrized were modelled individually from case to case as in-place and are not reusable.

These digitisations led to a two-fold result. On one side, they delivered complete and accurate 3D parametric models of three Sicilian medieval churches in a BIM environment. Furthermore, given the stylistic similarities of these buildings, this chapter explored the possibility of creating a brand-new library of typological parametric families, based on the Arab-Norman constructive tradition, to be implemented into the digital models of the case studies and which could be reused in future similar projects.

7.1 The creation of a typological library: a methodological approach

The research methodology presented in this chapter is structured into four stages (Figure 91), beginning with the identification of a key issue: a gap in the knowledge and in the application of the potentialities offered by BIM tools to AH assets.

As previously discussed on page 15, BIM's parametric libraries were primarily developed for standardised, contemporary construction and tailored to prefabricated elements. Maurice Murphy's 2012 proposal to adapt digital libraries specifically for AH -using point clouds and stylistic rules architectural essays- marked a significant step forward ([Murphy, 2012](#)). Nevertheless, existing HBIM libraries still remain narrow in scope, often focusing mainly on classical or Renaissance European architecture ([Murphy, 2012](#); [Apollonio et al., 2012](#); [Kontoudaki and Georgopoulos, 2022](#); [Sakellaris et al., 2022](#); [Daniels and Georgopoulos, 2023](#)) and struggling to represent irregular geometries.

Relatively to the models shown in this chapter, the research tried to partially address this gap through an extensive literature review and selected case studies on Islamic and Middle Eastern architecture, offering valuable insights into Arab structural systems and decorative elements ([Khalid et al., 2024](#); [Benli et al., 2024](#); [Zeitouni et Asslan, 2025](#)).

The second stage defined the project's main objective: to produce digital models which support knowledge dissemination and raise awareness of Arab-Norman heritage,

particularly relevant after the inclusion of one of these case studies in the UNESCO World Heritage List in 2015 and another's nomination.

STUDY METHODOLOGY:

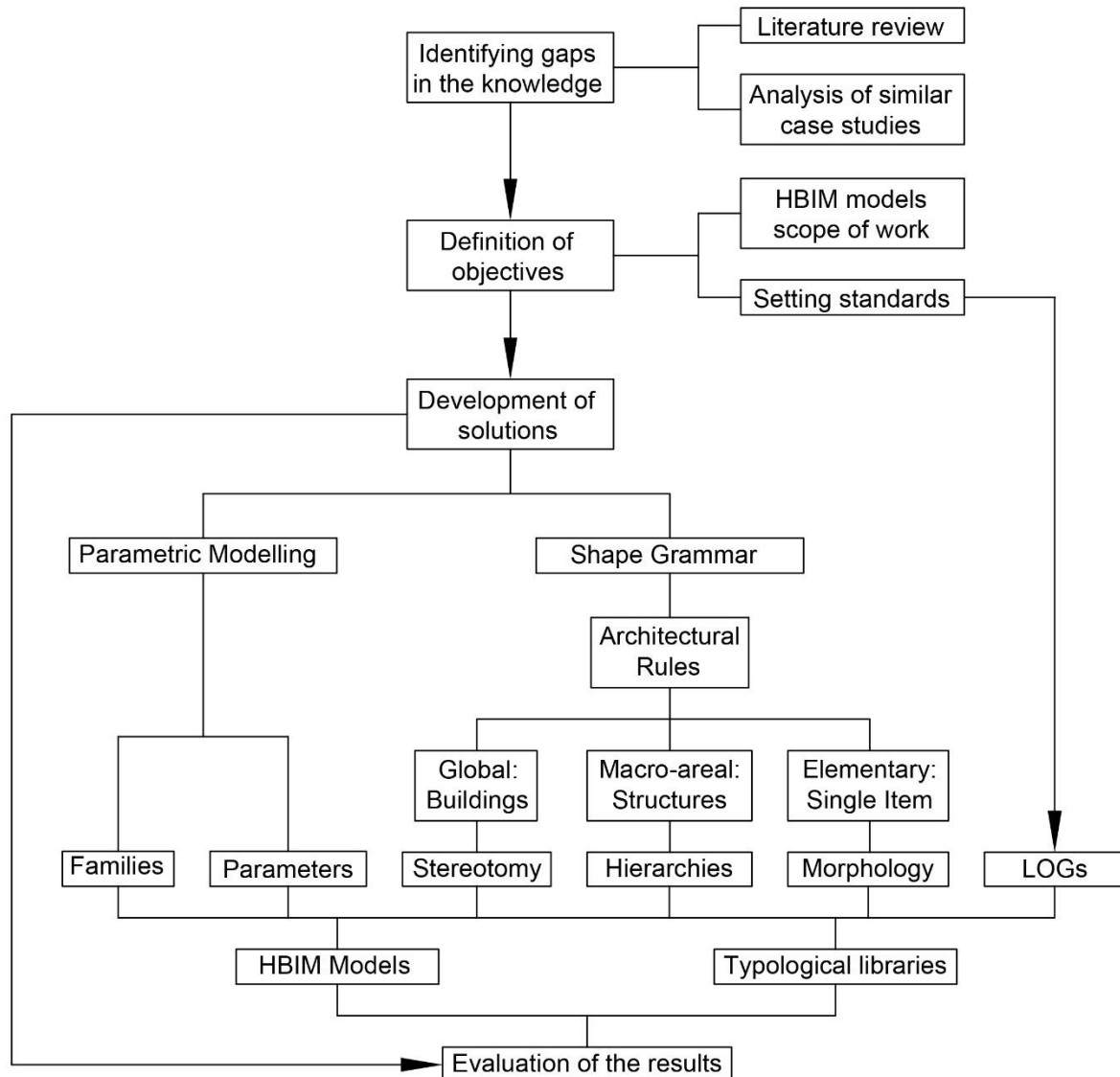


Figure 91. The methodological workflow leading to the HBIM models of this dissertation and the creation of new parametric families.

The models were developed with a purely geometric focus, aiming to replicate the as-built architectural, structural, and decorative features of the real buildings as faithfully as possible for visualization, 3D documentation, and graphic analysis purposes. Whilst the models incorporate basic semantic data (e.g., materials, construction phases from standard software databases), further semantic enrichment was intentionally omitted

due to the complexity of standardising heterogeneous historical elements and this study's emphasis on formal representation.

The modelled elements were developed with a Level of Geometry (LOG) appropriate to the corresponding LOD whenever a semantic content had been attributed, with the aim of balancing representational fidelity and modelling efficiency.

In particular, three different LOGs have been chosen, according to AIA standards:

- ✓ **LOG 300:** Generic elements from standard libraries (e.g., walls, floors, ceilings)
- ✓ **LOG 350:** Custom loadable families for typical Arab-Norman features (e.g., domes, windows, vaults)
- ✓ **LOG 400:** Detailed elements modelled in place or as families (e.g., trumpet or spherical pendentives, musharabyas)

The proposed solution was developed according to a modelling strategy based on Shape Grammar, which relies on creating libraries of parametric objects based on architectural principles, through computer algorithms (which are not included in this dissertation) and encoded rule sets derived from historical manuscripts.

The case studies have been investigated through quantitative and qualitative analyses aimed at defying the spatial and organizational relationships occurring between the different objects, according to three different approaches:

- global: this was applied to the buildings on their whole, to establish geometrical and mathematical rules (such as reference plans, symmetries, max/min. values, mutual proportions) involving the placement and the composition of the architectural items into a measurable space;
- macro-areal: for understanding the hierarchical structure, the arrangement and the behaviour of spatial classes (naves, spans, supports, etc.) connected by topological relationships;
- elementary: regarding single items in a unit (columns, walls, arches, etc.), affecting the morphology of their primary and secondary components;

Shape Grammar has then been subsequently tailored to the tools made available by BIM software, where the modelling withstood the formal scheme of the families defined

by parameters, typical geometric properties which can be modified by the user through digit.

Parameters have been used to enable rapid, flexible, and efficient adjustments to properties while preserving their formal and relational structure. Primary components of an object were based on instance properties, whilst secondary components relied on type properties. The attributes in common to a family type have been encoded into shared parameters.

Leveraging the Family feature in BIM reduced the need for multiple models differing only by parameter values. At the end of the process, inspired by the in-built families already provided by the software, and beside the final HBIM models of the case studies, brand-new families of architectural items belonging to the medieval Arab-Norman Heritage in Sicily have been obtained; their operative method will be discussed in further detail in the next paragraphs, whilst an evaluation of the primary results and other consideration on the followed methodology will be provided at the end of this chapter.

7.2 Preliminary operations and best practises

For each case study, a new architectural project was filed in Revit, and the corresponding point cloud from the data processing was imported through the "Insert" panel. In this step, it was important to choose the "import from origin to internal origin" option to ensure proper alignment and consistency between the point clouds and the project's reference system. After importing, the point cloud was locked to avoid accidental movement during modelling and used as a "scaffold" for building the model upon ([Martinelli et al., 2022](#)).

The first task was to identify the construction planes of the actual buildings, such as the levels of floors, roofs, arch springers, and main axes, based on the point cloud (Figure 92). After setting the main sections through the dedicated command in the "View" panel, reference grids and levels were created from the "Architecture" ribbon. These helped with the spatial placement of construction elements and provided geometric constraints for structural modelling.



Figure 92. Setting of the main levels on the point cloud: long section of San Giovanni dei Lebbrosi.

7.3 The modelling of parametric objects: system families

After these initial settings, the architectural elements were modelled following a top-down approach, starting with the simpler and progressing to the more complex ones. The modelling began with the parametric objects, which were already provided by default in the software. Their families were edited using a *family > family type > instance* structure to create customized objects which correspond to the real structures, and these were integrated into the Revit relational database. Examples of these parametric objects include floors, walls, ceilings, and roofs.

Floors – The modelling began with the internal floors of the buildings. Vertical sections through the point clouds revealed that no floor had continuous structural alignment (e.g., the presbytery areas were raised, and at San Giovanni degli Eremiti, several levels were present throughout the building). To accurately represent their slopes, an appropriate strategy was devised. Initially, floor portions were modelled as horizontal using the “floor” system family.

Their outlines were traced based on the perimeter from the point cloud at the levels corresponding to their finished surface. Since only the upper decking was known, and there was no information on the thickness or layers of the floor, a conventional variable thickness was applied to match the external ground planes. A top layer of 3 cm, representing terracotta tiles on a 2 cm bed, was assumed.

Next, specific points in the point cloud, like corners, pillar bases, or level changes, were identified. Their elevation was measured by calculating the height difference between these points and the horizontal reference plane of the floor. These points were then placed on the corresponding elements in the model using the “add point” command, with their elevation adjusted using the “edit sub-element” command. This allowed the floors to be divided into smaller triangular elements which reflected the profiles defined by the slopes (Figure 93).

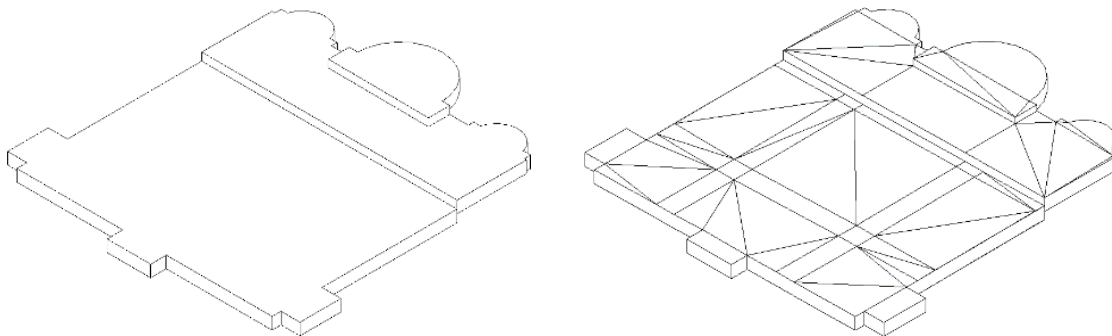


Figure 93. Example of floor in Santissima Trinità di Delia: the horizontal portion and the sloped element after the “edit sub-element” command.

Walls – The walls in the digital models were classified into two categories: straight and curved. Straight walls were the majority, whilst curved walls were used for the apses. Regardless of their type, walls were modelled according to the point cloud outlines in plans and sections, respecting their base and top levels as constraints, along with their thickness.

A singularity was found in Santissima Trinità di Delia, where the perimetral walls had two different widths, being the upper part an average 14 cm thicker than the lower, with an overhang profile outward. In this case, an intermediate level was traced in correspondence of the changing dimensions, then the lower and the upper walls have been treated as separate units.

Throughout the modelling process, the “Connect” option was kept active to join walls together, ensuring a consistent perimeter. Due to historical construction techniques, some walls were not perfectly orthogonal, but this was addressed by turning off the snap option for more precise tracing. Fortunately, the point clouds did not reveal significant tapering, and the walls displayed consistent thicknesses.

In all three case studies, the walls were bare, with no visible plaster finish due to their last restoration campaigns. Consequently, they were assigned a uniform sandstone material throughout their structure (Figure 94).

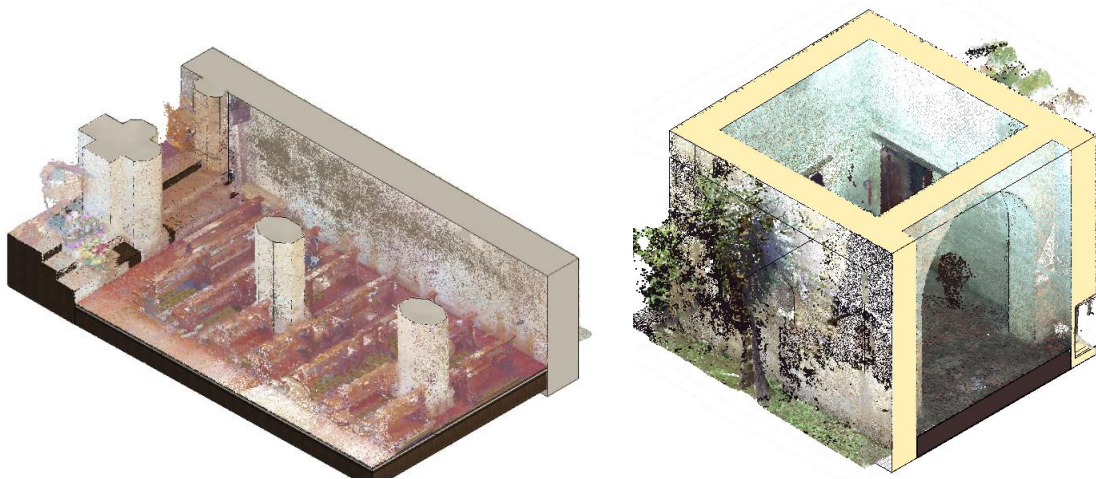


Figure 94. Model construction after the application of walls and floors.

Pitched Roofs – The central and side aisles of San Giovanni dei Lebbrosi are covered by pitched roofs, with double and single slopes, respectively. These roofs were not original but built in 1934 during restoration work by Patricolo, who reused timber from the Cuba Castle in Palermo (see page 33).

The roofs consist of eight repeating modular elements along their length: four perimeter beams with a rectangular cross-section of 20x25 cm, and four rafters with a rectangular cross-section of 10x25 cm, spaced 30 cm apart in the longitudinal direction. These frames are supported in pair by three simple triangular trusses along the aisle, resting at both ends on the counter-facade and presbytery arch. The frames support a wooden board made of six boards, each 25 cm wide and 5 cm thick, running along the slope. Above the frame, the finish of Sicilian roof tiles is placed and bedded in mortar. The frames are contained within the thickness of the perimeter masonry, along with the board of the side aisles, while the slopes of the central aisle extend beyond the external walls.

To model these elements, a nested family was used, consisting of two system families: one for the ceiling (the lower wooden frames) and the other for the roof (the board and tiles). The ceiling was modelled by first defining the inclined slope plane based on the point cloud. The "Beam System" command in the "Structure" panel was used to trace

the contour of the edge beams. These beams were then created by selecting the section type and entering dimensions in the properties panel, followed by drawing the small rafters according to their dimensions and spacing. After creating a single frame, it was copied seven times in the longitudinal direction and mirrored to form the double slope of the central aisle (Figure 95).



Figure 95. The double-pitch wooden ceiling in San Giovanni dei Lebbrosi and the modelled frames in pair without the boarding system.

The roof was modelled using the “Roof by Surface” command in the “Architecture” panel. The perimeter was drawn, and the required slope and number of slopes were assigned. The roof was then given a stratigraphy, consisting of a 5 cm thick board, mortar bedding, and a layer of tiles.

Flat Roofs – Flat roofs are typical in Arab-Norman architecture, characterized by their projecting footprints over the walls and minimal slopes. In the three case studies, flat roofs are distributed discontinuously across the main spaces, at varying levels:

- In San Giovanni dei Lebbrosi, these roofs cover the central bay of the presbytery, the diaconicon, the prothesis, the apses, and the bell tower.
- In San Giovanni degli Eremiti, they cover the two bays of the aisle, the presbytery area, the bell tower, and the Arab hall. In the Arab hall, the roof does not project but is surrounded by attic walls.
- In Santissima Trinità di Delia, they cover the raised central bay and, at a lower level, the lateral spaces.

The shapes of these roofs were drawn on the plan views of the point clouds, at the elevations corresponding to their extrados, using the "roof from perimeter" command

to trace their outline. These surfaces were assigned a thickness equal to the one measured in the sections, with a 5 cm external finishing layer made of exposed plaster or terracotta tiles (only in the Arab hall). Since the internal stratigraphy could not be extrapolated from the point cloud, the remaining thickness was assumed to consist of a conventional material, such as a mortar conglomerate. The roofs were then cut at the domes' locations using a round void extrusion with a diameter matching the overlying structures. Finally, external cornices, whose profile was extracted from the point cloud, were extruded along the contours and added to the main elements (Figure 96).

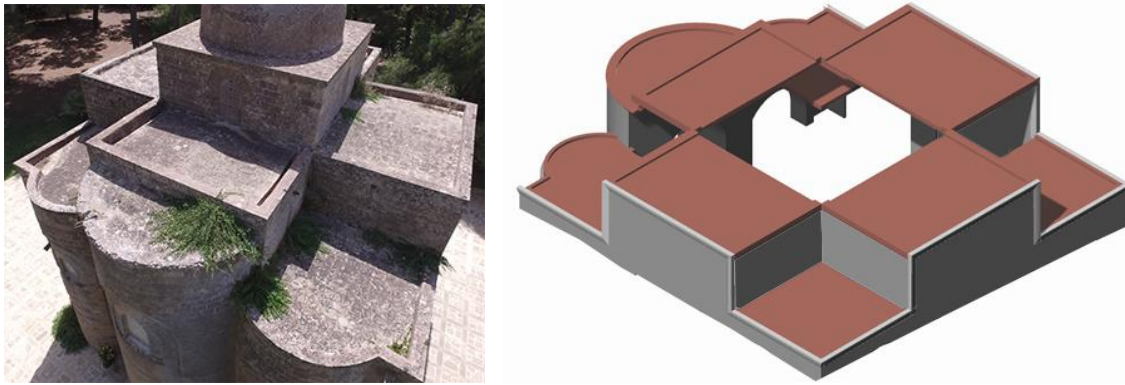


Figure 96. Example of flat roof in Santissima Trinità di Delia and its model.

7.4 The parametrisation of not in-built objects: loadable families

Several architectural items which were not possible to be modelled through the in-built families have been shaped from scratch, through pre-formed templates. This was a time consuming, long process, but it enabled the possibility of having the items parametrised; meaning that the items can be easily adapted in their geometrical features whenever a similar case occurs, and this enabled the implementation of these objects in loadable families within the three case studies.

Pillars and Columns - At San Giovanni dei Lebbrosi, six irregular octagonal pillars on a rectangular base and capital were not part of the software's standard system families. To model them, a new reusable parametric family was created, using the "Generic Metric Pillar" template; the pillar's geometry was drawn on the reference plane based on point cloud measurements.

Four type parameters controlled the shape: width, depth, and chamfer width and depth. Another 3 parameters adjusted the pillar's elevation for alignment with the upper arches: height of pedestal, shaft and capital. A similar method was used for the two cruciform pillars separating the naves from the presbyterial zone. After importing these families into the project, their proportions were adjusted by dragging handle symbols to match the point cloud. Materials were then assigned and in order to match the sloped floor, the "Attach Top/Base" command was thicked (Figure 97).

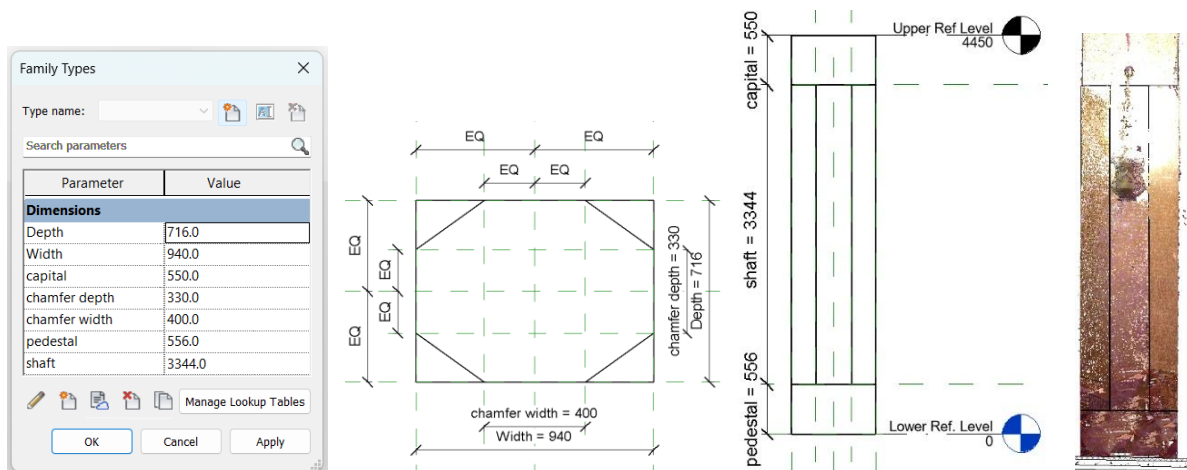


Figure 97. The parametric pillars in San Giovanni dei Lebbrosi and the correspondence with the point cloud.

In Santissima Trinità di Delia, four columns at the corners of the central span support the upper arches. These columns, likely reused from Roman structures, vary in design but share common elements. A nested family was created, using a point cloud of the best-preserved column as a reference. The structure included a stylobate, base, shaft, capital, and abacus. These elements were made parametric to adapt to the other columns, especially the abacus, which had the task of levelling the springer of the arches, since the columns had varying heights.

The "Generic Metric Pillar" template was used again. The stylobate was a simple square-based prism, whilst the base featured toruses and a scotia. The smooth, unfluted shaft was modelled with a 360° solid revolution. Due to limited detail in the point cloud, a standard Corinthian capital was chosen, scaled, and placed on the shaft. The abacus was a rectangular prism with adjustable height. After modelling, level constraints were added, and the family was imported into the project. Materials were

assigned: marble for the stylobate, base, and shaft, and sandstone for the abacus (Figure 98).

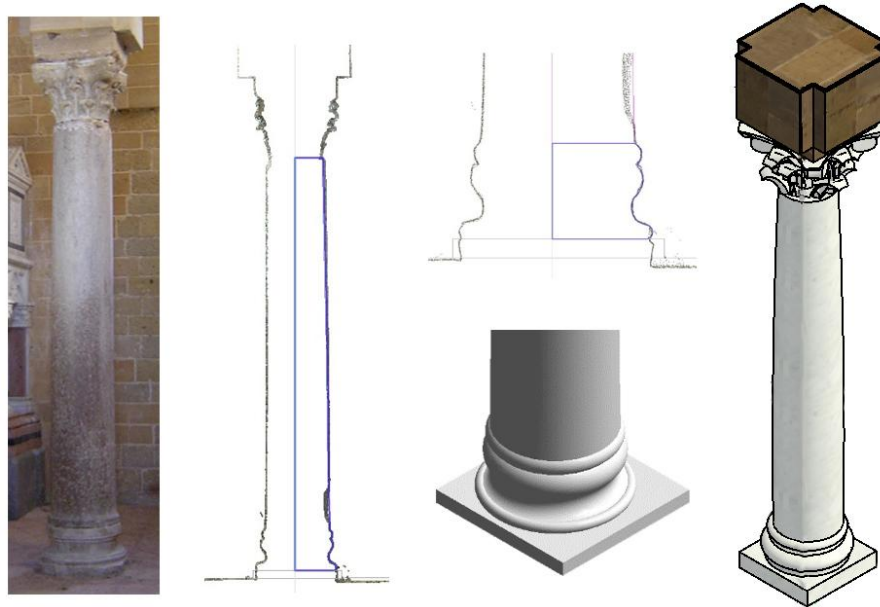


Figure 98. The real column taken as a sample and the development of its model.

Openings and windows - The openings in the three case studies fall into four types:

1. Simple arched openings - Basic, unembellished, going through the entire wall thickness. This type is also the base for all other more elaborated windows.
2. Framed arched openings - Like the first type but with continuous mouldings along the vertical sides. Found on both straight and curved walls.
3. Chamfered sill openings - The vertical section is longer on the inner side of the wall and shorter on the outer.
4. Chamfered sill openings with moulded frames - Like the third type but with external decorative mouldings (Figure 99).



Figure 99. Different typologies of windows in the case studies.

Framed openings on curved walls cannot be parametrized and are treated as in-place elements in the following paragraph.

Simple arched openings are the most common. A specific family was created using the "Metric Window" template. A pointed arch profile was drawn on a vertical plan with adjustable width, sill height, and length parameters. The profile was extruded as a hollow solid, adaptable to different wall thicknesses (Figure 100).

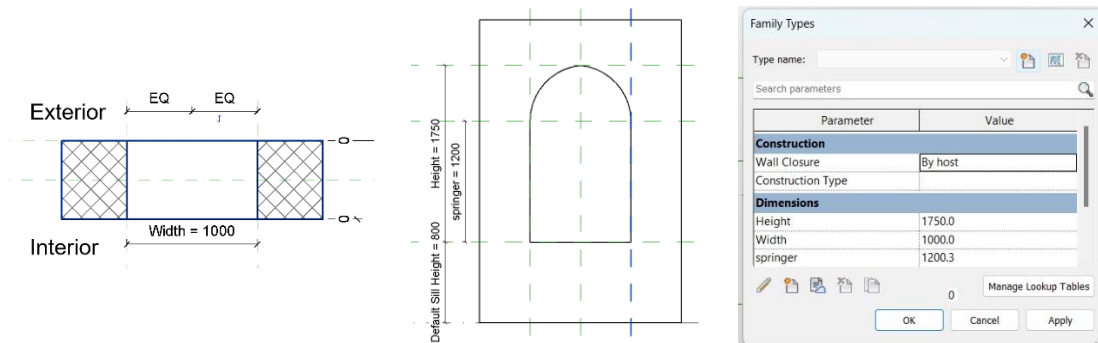


Figure 100. Definition of a generic parametric hollow opening family..

This type was used for all the doors, the arches and the windows on the tambours in the case studies, and all windows of San Giovanni degli Eremiti. It also appears as the generator shape of the barrel vaults in Santissima Trinità di Delia and San Giovanni dei Lebbrosi (Figure 101).

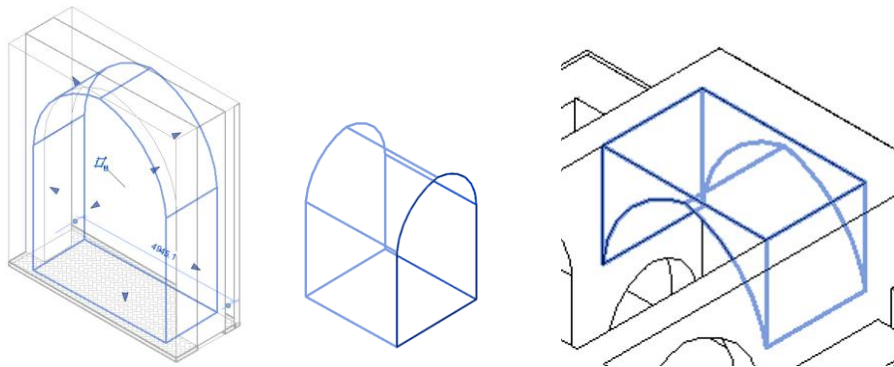


Figure 101. The parametric hollow opening used for arches, windows and barrel vaults.

Framed arched openings on straight walls were created by adding mouldings to the simple arched opening. These mouldings always extend along the window's vertical edges and top but not below the sill. A standard profile was drawn making all the dimensions adjustable; then, a "Void sweep" command was used to extrude the profile along the vertical path and to subtract the mouldings from the wall thickness (Figure 102).

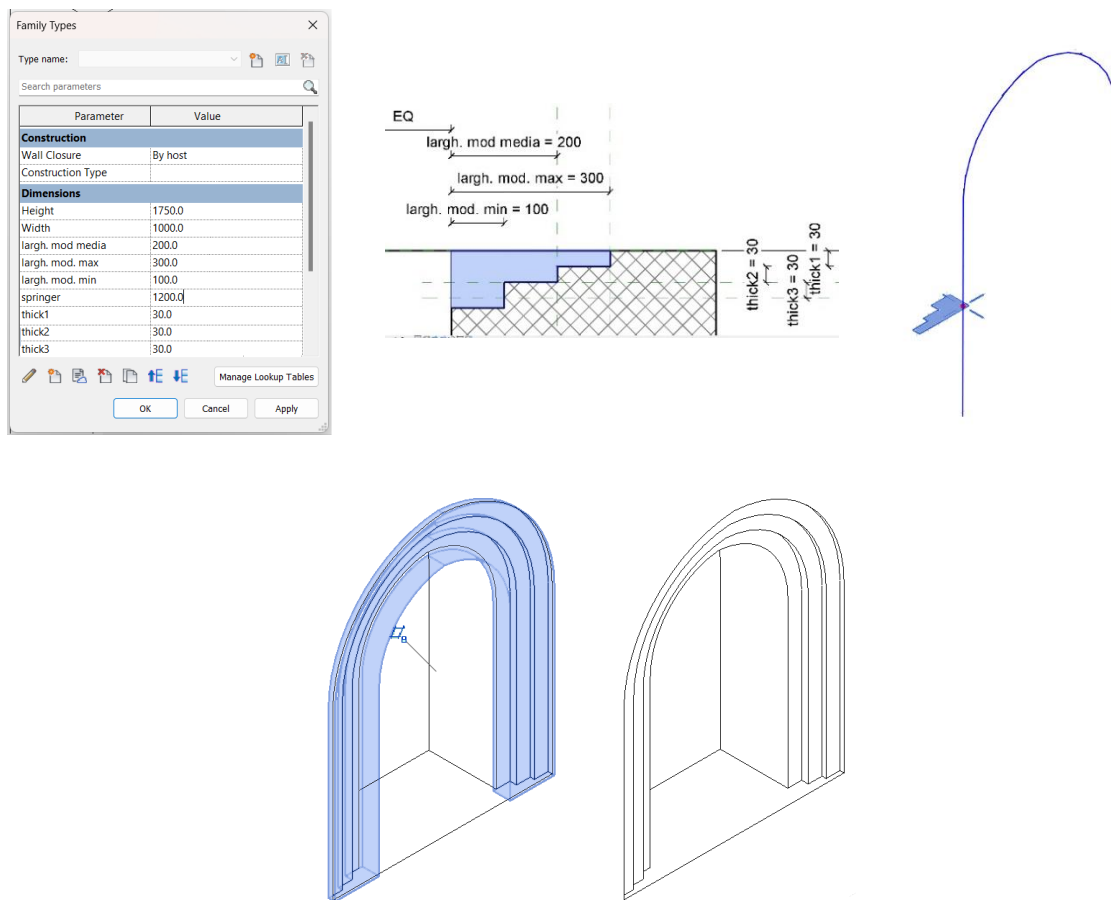


Figure 102. The process for obtaining a parametric framed arched opening family.

Chamfered sill openings are found in San Giovanni dei Lebbrosi only, in the side aisles and upper central nave. The inward-facing chamfer makes the windows longer inside. Moulded frames appear only in the side aisles, while upper openings have a plain profile.

To model these, a reference was placed near the middle of the wall, since sills are partially flat. The lowest chamfer point was marked on the inner façade, and the highest point on the outer façade. The simple arched opening was then extruded from the central reference plane outward. The inward-facing chamfer was modelled using the "Blend" command, with the outer profile shorter than the inner one. The final step was adding the external moulding using the same procedure as before. This window type has been made fully parametric (Figure 103).

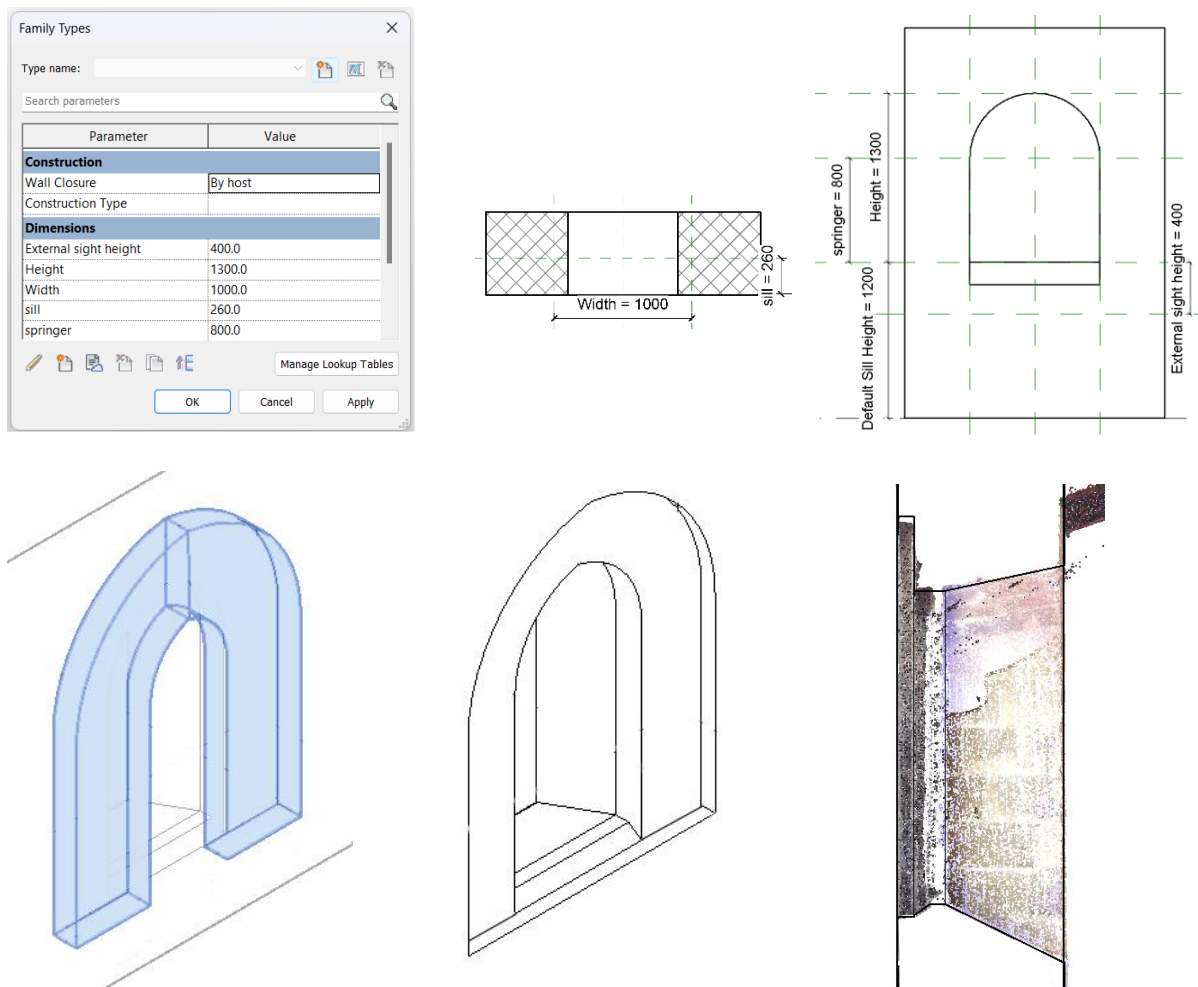


Figure 103. The parametric chamfered window with mouldings in San Giovanni dei Lebbrosi and its correspondence to the point cloud (in section).

Cross- vaults - Parametric modelling allowed for the creation of adaptable cross-vault mass models based on point cloud data. These models represent the intrados of the vaults.

Using the "Adaptive Metric Generic Model" template, a horizontal work plane was set at the vault springer level, where a square was drawn to match real dimensions. To account for the small pedestals supporting the vaults, four square sections were cut from the corners. The vertices of this Greek cross were made adaptive, with a "length" parameter assigned to each side.

On the vertical planes, lateral arches were drawn with midpoint segments representing their rise. An "arch rise" parameter controlled this height, and the upper end was made adaptive. The arches were traced with slightly lowered profiles passing through three points: the base perimeter corners and the arch key.

On the horizontal work plane, the geometric centre of the vault was identified using diagonals through the pedestal corners. From this centre, another vertical segment, equal in height to the lateral arches, represented the vault keystone, controlled by a "vault rise" parameter. Diagonal arches were added to complete the framework for the vault webbing.

To model the webbing, the central keystone was connected to the arch keystones, and the "Create Form" command was used to generate a half-webbing, which was then mirrored to complete the structure. This process defined the intrados with eight half-webbings (Figure 104).

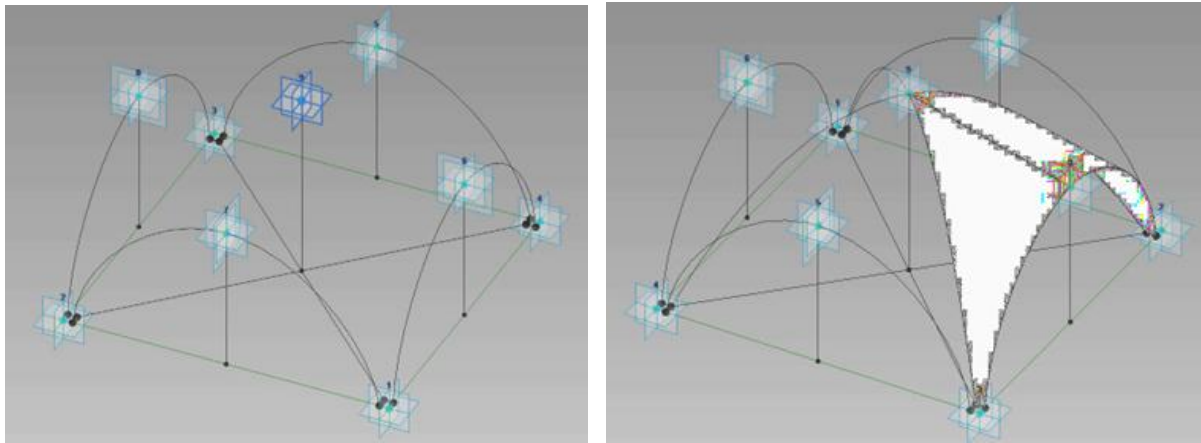


Figure 104. Generating a parametric cross vault from the "Adaptive Metric Generic Model" template.

The model was then imported into the case study project and duplicated as needed: three vaults in San Giovanni dei Lebbrosi (above the entrance pronaos, diaconicon, and prosthesis) and five in San Giovanni degli Eremiti (above the diaconicon, prosthesis, and the three vaults of the Islamic Hall).

Parameters were adjusted to match real dimensions based on the point cloud. An exception was found in the cross vaults of Santissima Trinità di Delia, where the central keystone was raised by 28 cm compared to the arch keystones, and the vault's generating line was slightly inclined rather than horizontal. Adjusting the "vault rise" parameter corrected this, ensuring an accurate match with the as-built conditions (Figure 105).

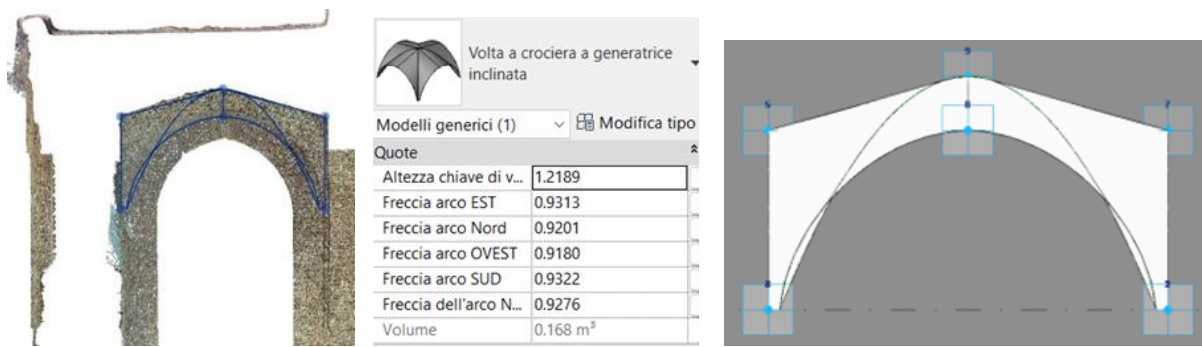


Figure 105. The risen cross vault type found in Santissima Trinità di Delia.

Finally, the vaults were created using the "Roof by Surface" command in the "Massing & Site" panel. Since survey data provided only the intrados, a nominal thickness of 40 cm was assigned, with sandstone as the structural material. In the Arab Hall of San Giovanni degli Eremiti, a 3 cm plaster finish was added on the inner side according to the actual appearance of the structures.

Trumpet-shaped pendentives - They are a constant feature in Arab-Norman architecture; with the spherical ones, they form the connecting elements between the square-shaped lantern and the overlying circular-plan dome (Figure 106).

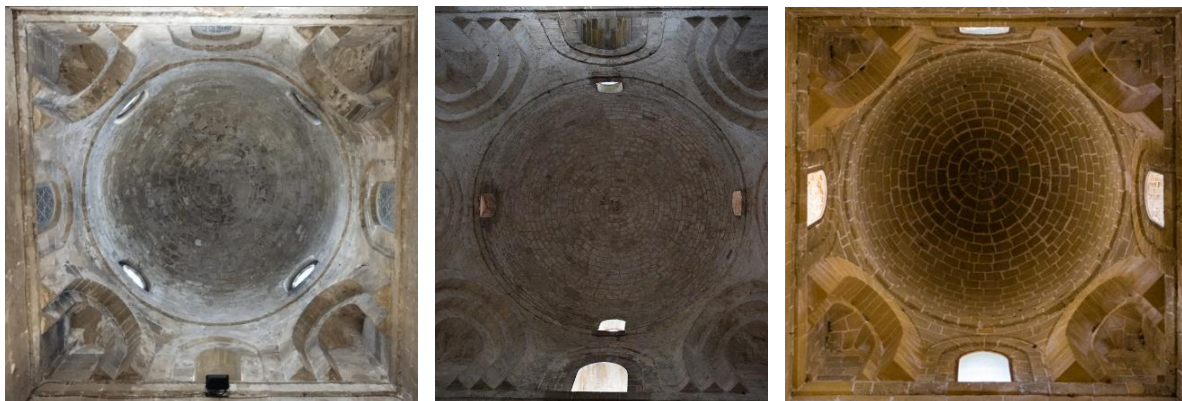


Figure 106. Pendentives supporting the domes in San Giovanni dei Lebbrosi, San Giovanni degli Eremiti and Santissima Trinità di Delia.

These pendentives are made with single, double or triple rings projecting from the lantern's frame, characterized by a sequence of profiles inclined at a 45° angle to the main masonry, surrounding a half-cross vault put at the corners of the lantern itself (Figure 107).



Figure 107. Examples of trumpet-shaped pendentives with single, double or triple ring inside the churches of San Giovanni degli Eremiti, Santissima Trinità di Delia and San Giovanni dei Lebbrosi.

To model these elements, a particular strategy was used, with the nesting of two different families: the system family for a ribbed vaulted ceiling (appropriately modified) and the one created specifically for the trumpet-shaped pendentives.

The half-gothic cross vaults make up the inner part of the pendentives and the connection between the recessive rings and the angles formed by the lantern. For this reason, they were modelled as parametric cross vaults cut at one of the diagonal arches, copying the corresponding template and eliminating the two superfluous spurs. Additionally, between the two remaining spurs, a square profile was derived corresponding to the angular pediment typical of these elements. Despite the modification, this semi-cross vault remained parametric, and the diagonal profile obtained by the 45° cut became the extrusion profile for the actual pendentive profiles (Figure 108).

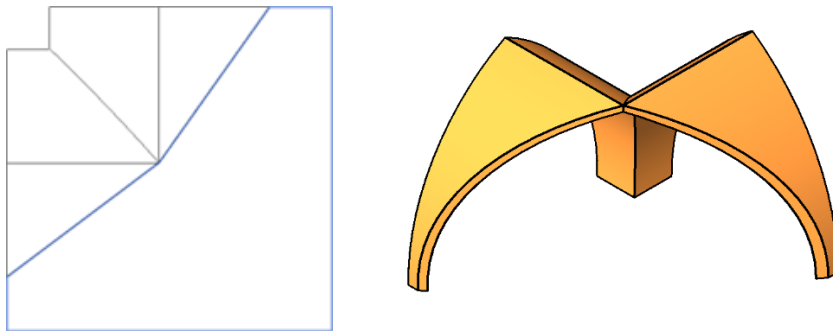


Figure 108. The half cross vault used for shaping the trumpet-shaped pendentives.

The trumpet-shaped pendentives were obtained from the "Generic Metric Profile" template, where the diagonal profile of the previous semi-cross vault was copied on the vertical plane, made parametric through adjustable width, springer, and height. On the horizontal plane, the profile of the mouldings was drawn as a sequence of one, two or three isosceles right triangles (the one shown here features a triple ring, but the

process is the same and a sample for each category has been created), with adjustable sides and thickness.

The trumpet-shaped pendentives were then created by using a "solid sweep" command for these triangles along the path given by the arch profile. Once the model was obtained, it was assigned a material of sandstone (Figure 109). The connection is then completed by spherical pendentives, but as these elements are not parametric, they will be described in the next section.

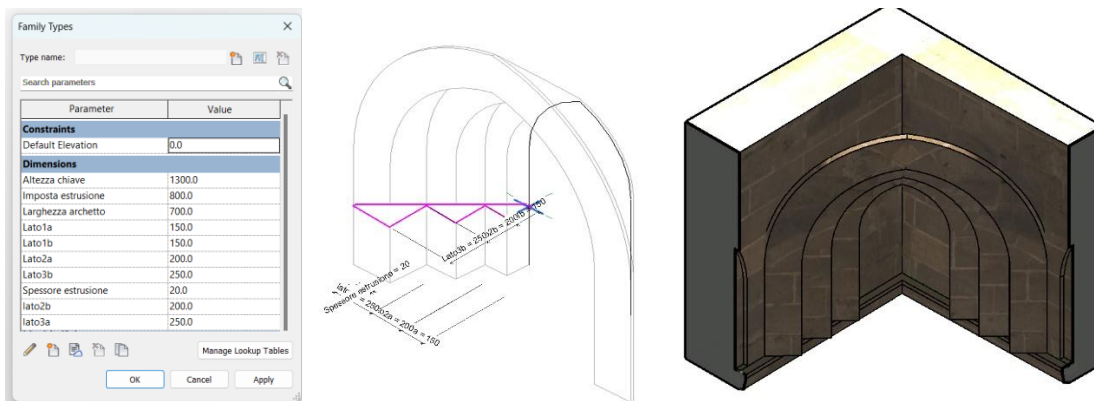


Figure 109. Generation of trumpet-shaped pendentives from sweeping a parametric profile.

Domes - For domes raised on tambours (Figures 110), a generic metric template was used, modelled as a parametric mass created by a 360° revolution of an adaptive profile around the central Z-axis.



Figure 110. The two domes in San Giovanni dei Lebbrosi, the five in San Giovanni dei Lebbrosi and the one in Santissima Trinità di Delia

Within this template, a vertical work plane was set, and the profile was defined with four segments (three straight and one curved). Each segment was assigned adjustable parameters: the base radius, the tambour height, the keystone height at the intrados, the vaulting radius. This mass was then imported into different project files, duplicated, and placed at the domes' springer levels. The surface model was adjusted based on point cloud measurements. Using the "Wall by Mass" command, a parametric wall was

shaped along the intrados. Since the exact wall stratigraphy was unknown, the detected thickness was assigned as 5 cm of reddish plaster externally and the remaining width in sandstone (Figure 111).

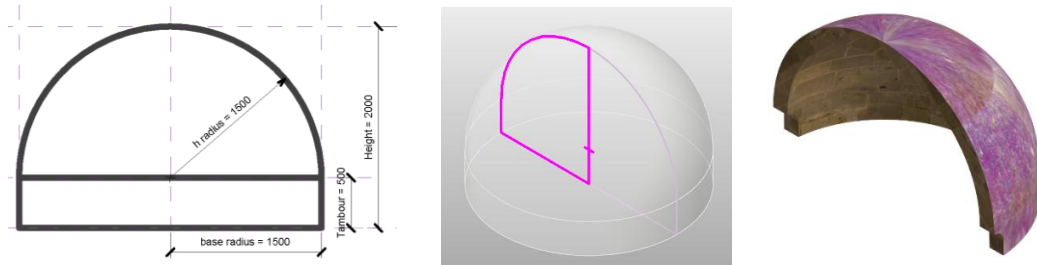


Figure 111. The development of a parametric dome from mass definition to the modelled item.

This method was used to model 7 out of 8 domes. Indeed, the presbytery dome in San Giovanni dei Lebbrosi was found to be non-concentric based on point cloud sections. Due to its uniqueness, it was modelled as an in-place item, not reusable in other projects, in this way:

- The springer level was set, and a vertical plane aligned with the Z-axis was created.
- The actual cross-section was drawn, excluding a 5 cm external plaster layer.
- The profile was revolved 360° to form a solid sandstone mass. A separate plaster layer was created as an offset profile and added on top (since in-place masses do not support stratigraphy). The non-concentric void was modelled as a revolved void mass and subtracted from the solid mass to match the as-built structure (Figure 112).

All domes except the one in Santissima Trinità di Delia have arched windows on their tambours, modelled as explained earlier in this paragraph.

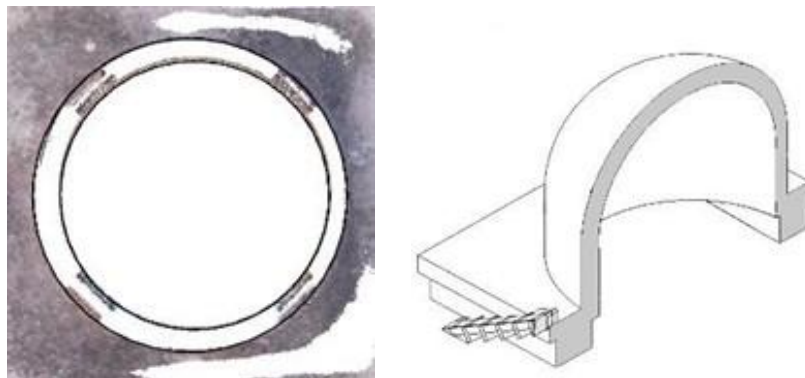


Figure 112. The not concentric presbytery dome in San Giovanni dei Lebbrosi and its model.

7.5 Other examples of in-place objects

Although system families and ad hoc parameterization effectively replicated most Arab-Norman architectural elements, some unique shapes remain which cannot be modelled using the parametric tools and techniques described so far.

These include spherical pendentives, apse basins, curved apse windows and mashrabiyas. Modelled as in-place elements, they have two drawbacks: they are exclusive to a specific project, which prevents any possibility of creating adaptable families and being reused; furthermore, while being geometrically accurate, they do not contain any additional semantic data. It is possible to assign them only one material, but not the potential stratigraphy which that element is composed of.

Spherical Pendentives - Unlike trumpet-shaped pendentives, spherical ones cannot be parameterized in Revit due to their double-curved, triangular shape. To model them, the relevant portions of the point cloud were manually segmented in Cloud Compare and exported as .ply files into Rhinoceros, being careful to set meters as the unit of measurement.

After identifying the three edge lines and vertices of a pendentive, the external perimeter was drawn with the "curve" command. Edge curves were then created to generate the double-curved surface using "create surface from edge curves." This element was replicated seven times to form the connection with the circular-plan domes above. The pendentives were exported as .dwg files, imported as masses into Revit, and placed correctly. Using the "Roof by surface" command from the "Massing & Site" panel, the digital model was finalized, assigning a 1 cm thickness with exposed sandstone (Figure 113).

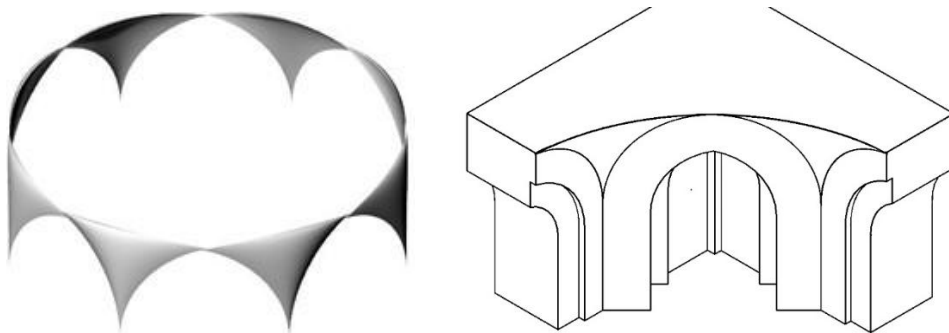


Figure 113. The triangular pendentives completing the chamfered square corner of tambours.

Apse basins - Like spherical pendentives, apse basins are double-curved surfaces which are difficult to manage in Revit. They form the upper half-domes of the central and lateral apses and are characterized by a semicircular plan with a pointed-arch vertical section.

Whilst the apses were modelled as curved walls (or partially curved, as in San Giovanni dei Lebbrosi) with a straight vertical development from the exterior ground level up to the springers of the basins, the wall family could not be used for the basins themselves. Instead, an unconventional but effective strategy was adopted: representing them as solid, single-layer ceilings in sandstone, from which the hollow basin was then subtracted.

These ceilings were created with a thickness matching the height difference between the overhanging flat roof level and the springer level. Their perimeter was derived from a horizontal view of the point cloud at the keystone level of each basin. The hollow portion was modelled as a local component, obtained through a void sweep. The main profile followed the generator curve of the pointed arch from a cross-section, whilst the path corresponded to the wall's curvature.

This void mass was then used to cut the ceiling, ensuring that the remaining portion formed a continuous masonry structure, accurately reflecting the real elements (Figure 114).

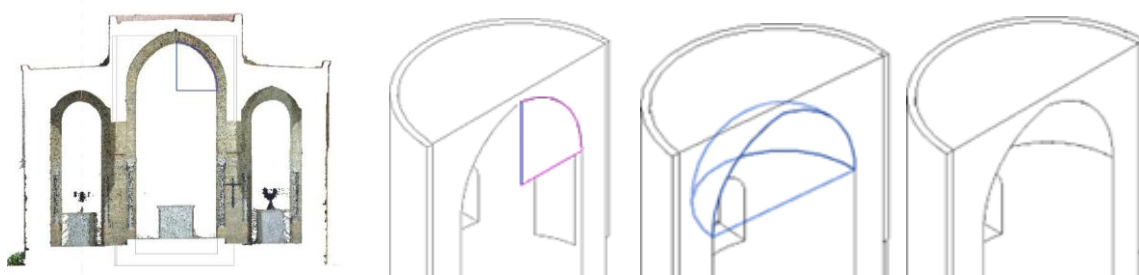


Figure 114. The basins as swept voids subtracted to the solid ceilings of the apses..

Mashrabiyas - The churches of San Giovanni degli Lebbrosi and Santissima Trinità in Delia feature windows decorated with mashrabiya - geometric-patterned grills made of painted plaster or wood, inspired by Arab designs. These were added in the 20th century during restorations by Valenti and Patricolo, following the discovery of an original example in San Giovanni degli Eremiti . Despite being later additions, they emphasize the stylistic character of the buildings (Figure 115).



Figure 115. Samples of mashrabiya in San Giovanni dei Lebbrosi and in Santissima Trinità.

Mashrabiya fall into two categories: straight-profile and curved (for apse windows). Though similar, their components are not easily replicable, making them non-parametric. Given their variety, they were modelled as loadable elements rather than in-place components, forming a library which reflects their diverse compositions, albeit not reusable.

In Revit, their representation started with a generic metric profile, creating a solid extrusion from the edge curves of each window. Photos of each window were imported, scaled to the correct dimensions, and used to trace the perimeter of the decorative patterns. These were then subtracted from the solid using void extrusions. The finalized models were saved and loaded into their respective positions within the project files (Figure 116).



Figure 116. Creation of a mashrabiya from a pattern definition and extrusion.

Curve windows - In the previous section, it has been discussed how windows with recessive mouldings were modelled on straight walls. The same windows are

displayed on curved walls as well, such as in the apses of San Giovanni dei Lebbrosi and Santissima Trinità, but a similar approach can't be followed (Figure 117).



Figure 117. Curve windows on the apses of San Giovanni dei Lebbrosi and Santissima Trinità.

Unfortunately, on the latter elements, moulding cannot be shaped using a simple void sweep along a vertical profile because it would create a double-curved surface. Instead, the thickness of the window archivolts was measured from the point clouds at a horizontal section passing through their springer levels. The curved apse wall was then modelled as a solid with its full thickness up to the window's sill. From this level to the intrados of the flat roof, the remaining upper section was modelled, excluding the thickness of the recessive archivolts.

A hollow extrusion, matching the inner outline of the pointed windows, was then used to create openings, just as with straight walls. The recesses were formed by adding another curved wall, as thick as the first archivolt, and cutting it with a larger window-shaped extrusion. The same method was applied to create the outermost layer with the final archivolt. After shaping the recesses, the two thin walls were merged with the main wall to restore the original thickness (Figure 118). In Santissima Trinità di Delia, this process also considered the protruding profile of the upper masonry.

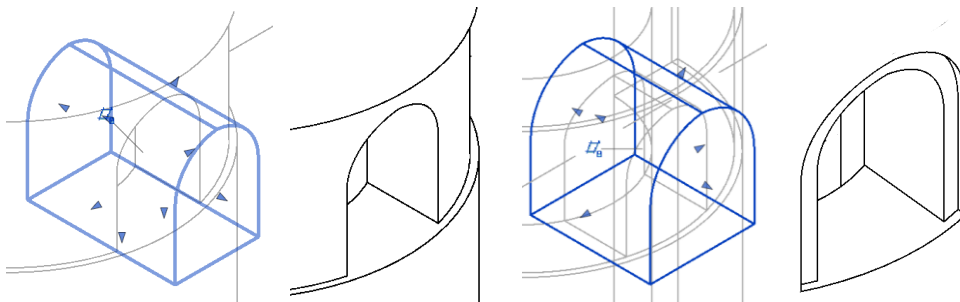


Figure 118. The process for obtaining curved walls with mouldings.

7.6 Critical remarks on developing a new typological library

This chapter illustrated the whole HBIM process for obtaining the detailed digital models of the three churches (Figures 119, 120, 121) and examined the potential to develop a typological library of digital elements from the Arab-Norman AH, demonstrating the effectiveness of the proposed parametric modelling methodology. The elements were analysed based on their geometric, morphological, and hierarchical characteristics, using parameters and constraints to structure their representation.

Despite minor differences in size and decorative richness, a coherent architectural style was identified, reflecting the stylistic evolution of that peculiar architecture in Sicily due to structural, functional, and symbolic factors.

The representation was structured across three different Levels of Geometry (LOGs), aligned with the digital models' intended purpose - primarily for dissemination and promoting awareness among conservation professionals. This integrated strategy resulted in a catalogue of typical structural components - such as pillars, vaults, windows, domes, and supports - which remains open to future updates and expansions.

Thanks to the adaptability of parametric modelling, this approach can be extended to similar, yet undigitized, buildings. Library components can be transferred across projects, edited and modified to meet specific needs, supporting a more versatile modelling process.

This digital archive establishes a foundation for further development, offering a consistent and replicable workflow which partially addresses the lack of standardized methods, often leading to inconsistencies in modelling historic architecture. A prospective advancement involves enriching these elements semantically, as they currently focus solely on geometric attributes. Additional historical data can be incorporated to support broader heritage management objectives.

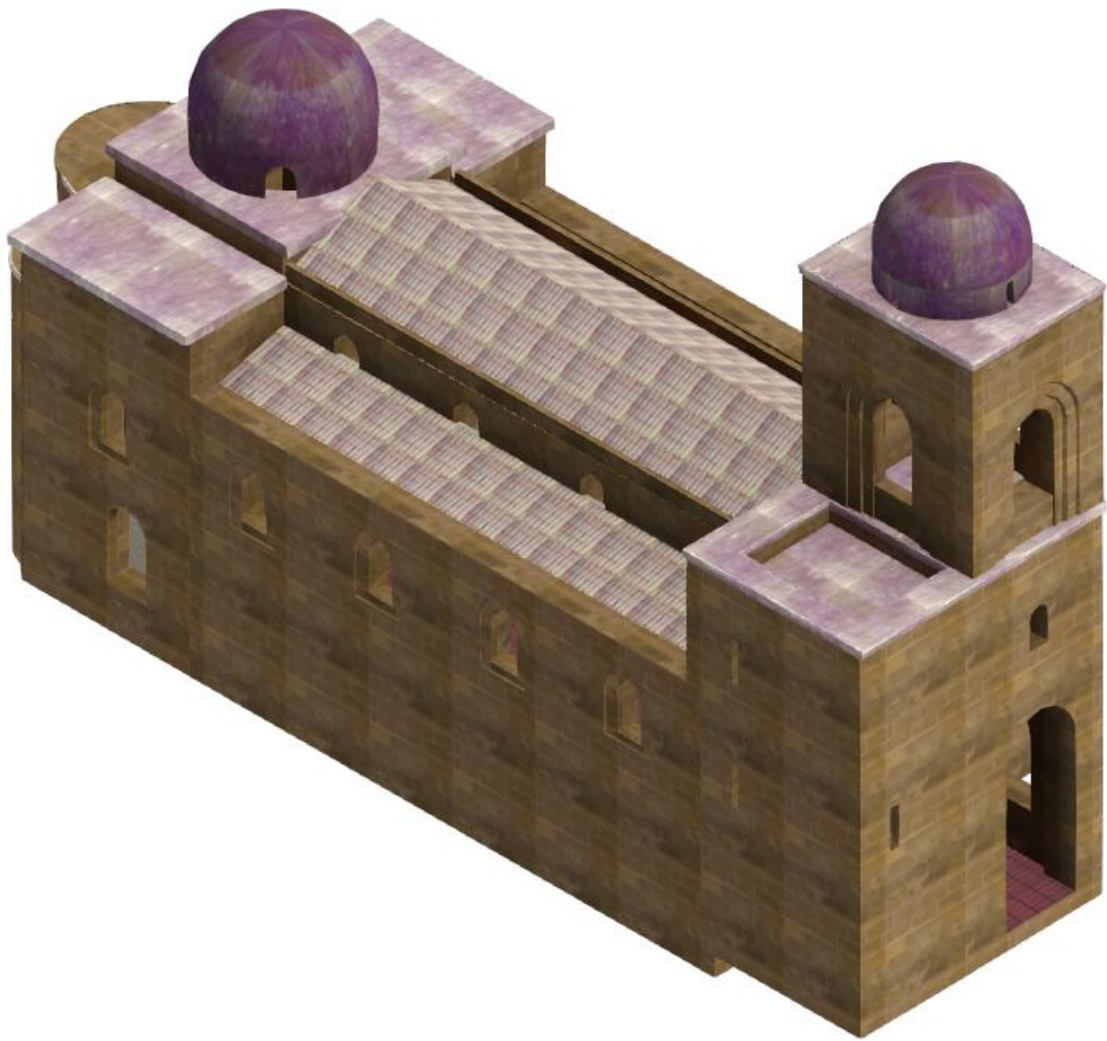


Figure 119. The final model of San Giovanni dei Lebbrosi.

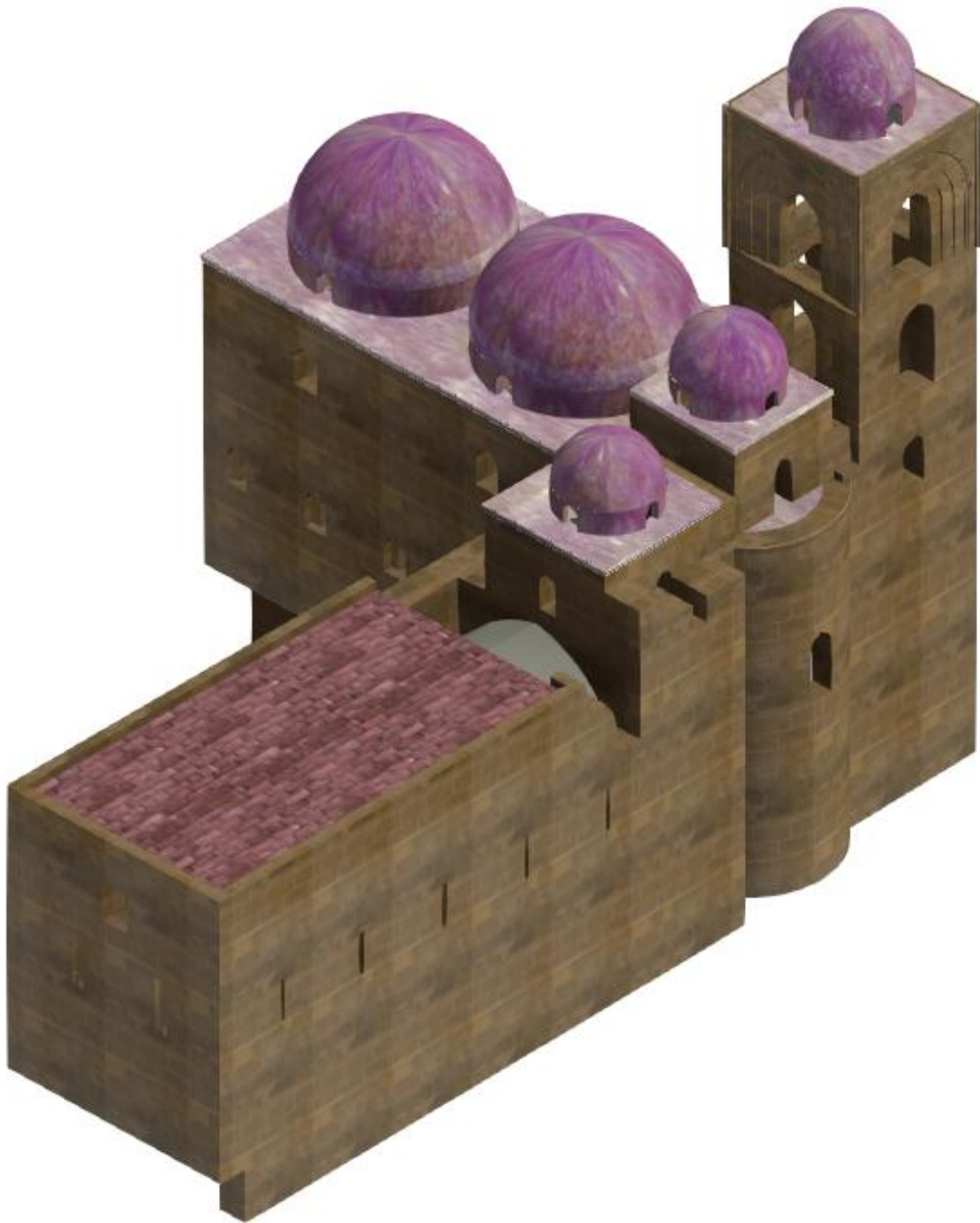


Figure 120. The final model of San Giovanni degli Eremiti.



Figure 121. The final model of Santissima Trinità di Delia.

8. The HBIM Modelling for a thematic mapping

Based on the comprehensive data collection and processing outlined in chapter 5, the HBIM digitization of Santa Maria della Grotta's church serves two primary objectives:

- ✓ developing a parametric model and creating parametric families to accurately represent the as-built structure of the building;
- ✓ enhancing the default BIM database with semantic data linked to thematic decay mapping, applied to the primary planar surfaces of the model.

The followed workflow, resulting from the data acquisition and processing as explained in Chapter 5, is reported in Figure 122.

The digital model was created using a direct and manual approach, following the top-down methodology described in the previous chapter. This involved first shaping the customized in-built family components, followed by addressing the remaining non-parametric architectural features.

The default BIM database was tailored to store and manage specific information related to the church's preventive conservation. This database always remains queryable and updatable, providing a practical tool for stakeholders involved in the restoration of Architectural Heritage, and supports the planning of future interventions.

Since standard BIM tools lack families which effectively represent the deterioration of historical structures, researchers have attempted to address this limitation with custom solutions. However, these efforts have often been restricted to small sections of artifacts and rely on 2D graphical representations which lack an integrated retrievable database (as detailed in Paragraph 7.4).

The aim of this experimentation was to establish a robust framework for decay mapping and other conservation themes using a fully 3D approach inside the BIM environment. This involved creating specific parametric families to represent various types of degradation, which were organized into a quantitative and qualitative abacus within the default database. The ICOMOS (International Council on Monuments and Sites) glossary was adopted as a standard reference for identifying stone material decay.

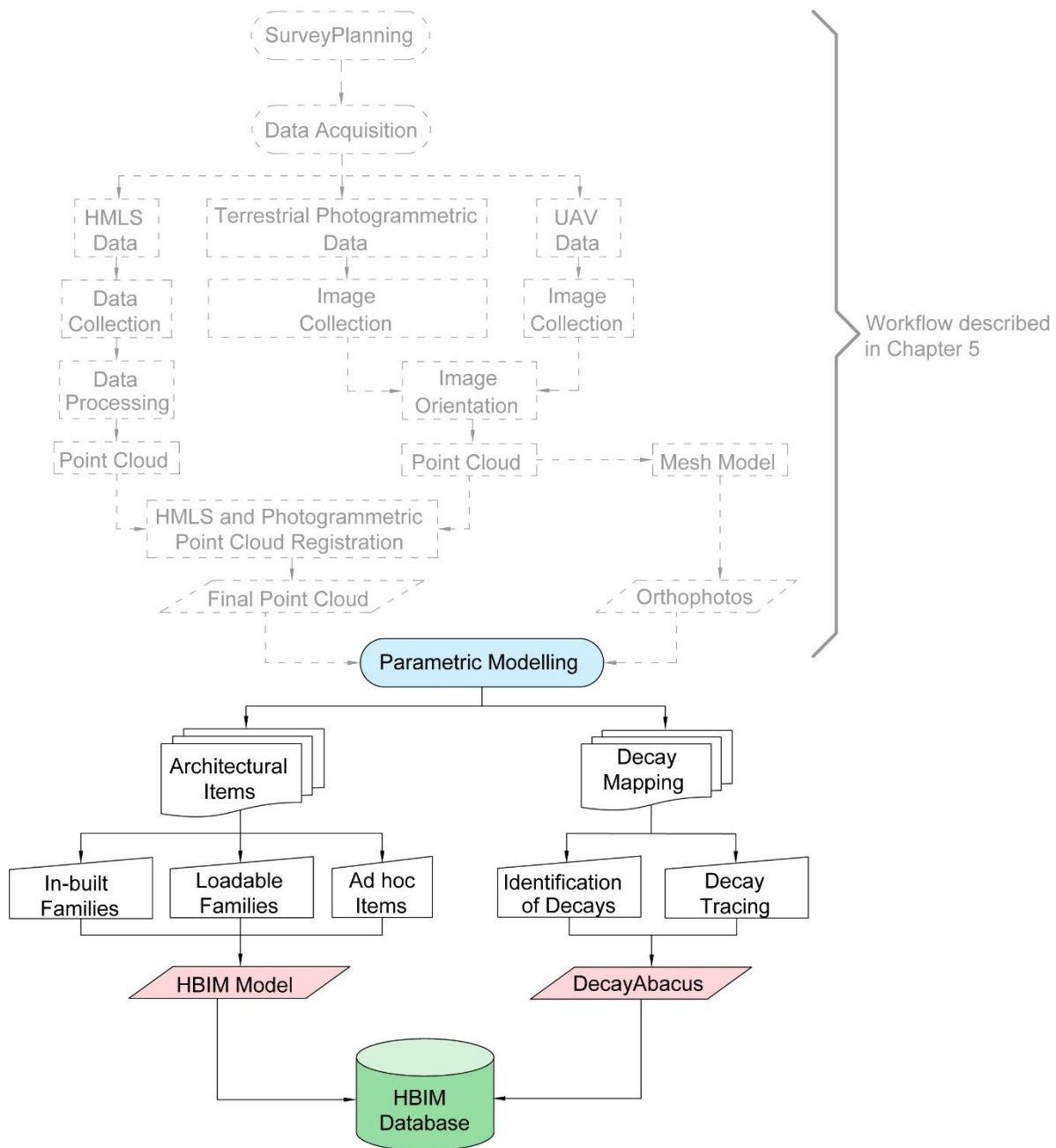


Figure 122. The workflow to the 3D digital model of the church and expansion of its database. In grey, the steps applying to the data acquisition and processing reported in Chapter 5.

Moreover, the decay mapping was applied simultaneously to both the interior and exterior faces of the church's main walls. This dual mapping allowed for a direct comparison of degradation phenomena between internal and external surfaces. By the extensions of the mapped contours, the analysis facilitated an immediate understanding of how different environmental conditions influenced decay, offering a comprehensive view of deterioration across the model.

8.1 The modelling of parametric objects

As explained in Chapter 6, also the creation of the HBIM model of Santa Maria della Grotta was divided into several phases, adopting a direct approach and manual procedures. The point cloud, obtained from integrated surveys, was first imported into Revit software, locked in its position, and used as a geometric reference for subsequent modelling operations (Quattrini et al., 2017). From the sections traced along the building's main axes, the most significant reference levels and grids were identified; the system of views created in this way decomposed the structures and enabled the identification of all the architectural typologies, with a considerable simplification of the modelling.

The reference planes, corresponding to the internal and external floors, the spring of the vault, the intrados of the dome, and the axes of the main walls, and enabled the correct placement of the parametric elements in space, serving as proper constraints. At the end of these preliminary steps, the point cloud was divided into 27 levels, 13 sections and a 3x6 grid (Figure 123).

The analysis of the segmented point cloud suggested once again the adoption of a top-down strategy, which was based on the hierarchical relationships between the parts according to their constructive phases and logic.

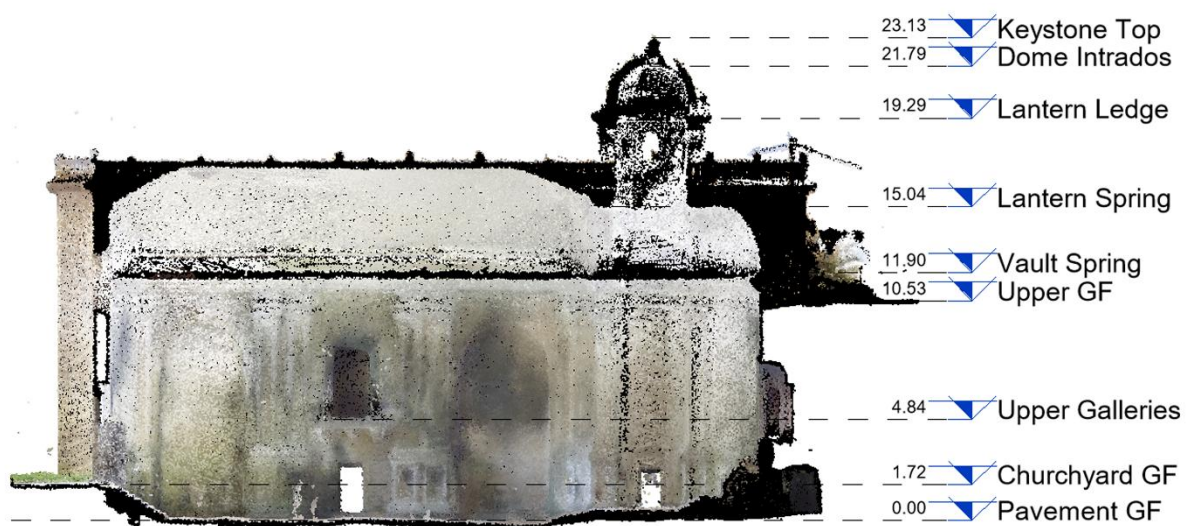


Figure 123. Some of the main reference plans as per the imported point cloud.

The architectural elements to be modelled were divided into two categories: those which could be replicated with minor variations and those requiring a tailored and

unique approach. For many elements in the first category, system families were utilized, allowing adjustments to their in-built geometric parameters or type and instance properties to meet the needs. Built-in families were used to digitize the walls, the floors, the balconies of the upper galleries, the flat parts of the roof in the main aisle and the apse, respecting their geometric characteristics and structural constraints.

A horizontal section of the point cloud at 1.20 meters revealed the presence of double-shelled vertical walls resting on the carved rock base, which were not visible during on-site survey operations. These walls were modelled through the software's built-in families, according to their actual profile and respective thickness (70 cm for each shell with a 40 cm cavity between), following the path outlined by the point cloud. A sandstone material without texture was applied to these walls.

The discontinuous floors of the main nave and the presbytery area were modelled following the perimeters suggested by the point cloud. Due to the absence of a finishing layer, the corresponding floor was represented as a 30 cm thick granular layer resembling gravel (Figure 124). The steps leading to the altar in the presbytery area were paved with a 3 cm layer of marble. The two balconies of the galleries were assumed to consist of a single 25 cm sandstone slab.

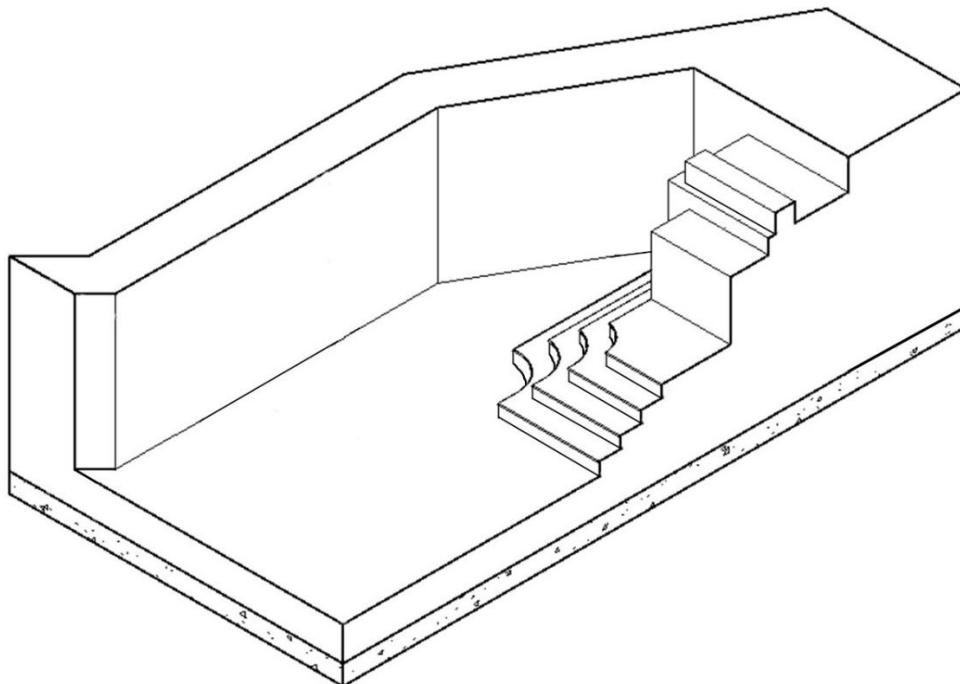


Figure 124. Model construction after the application of primary system families.

The flat parts of the roof in the main nave (central boat vault excluded) and, at a lower level, around the apse were treated as a 35 cm slab, a thickness identified from the point cloud. The upper finishing, as detected from the UAV flights, consisted of terracotta flooring tiles, whilst the lower layer at the intrados was made of a whitish plaster. Since the intermediate plies were unknown, they were supposed with uniform timber structures; these materials have been added to the stratigraphy of the architectural items (Figure 125).

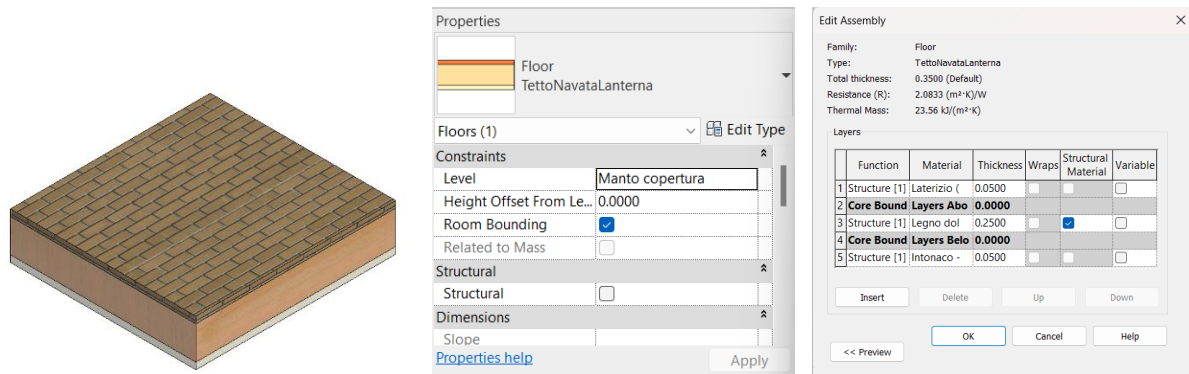


Figure 125. Flat roof modelling: assigning layers and materials.

8.2 The modelling of non-parametric objects

The in-built families enabled the initial stages of the modelling process but were insufficient to capture the architectural complexity of certain elements of the church. For this case study, loadable families were utilized to represent other distinctive architectural features.

These loadable families were custom-built from scratch using appropriate templates available in Revit's family database. Once created and loaded into the file, the geometric parameters were tailored to be altered and to align with the specific requirements of the project and the church's features. This process, although time-consuming, led to the creation of different families of parametric objects which could be reused in future projects for similar buildings.

In particular, the upper fascia running on top of the whole perimeter of the church and the pillars have been modelled on the point cloud used as a main reference, but according to the modules defined by Giovan Biagio Amico, the architect of the building himself, in his essay "L'architetto pratico" (Amico, 1726). In that book, written in 1726,

the author gives his personal interpretation of classical orders together with other practical instructions for architects and masons. This important testimony, discovered during archival research, supported a deeper understanding of the architectural elements which make up the church and enabled the correct modelling of its components.

The Fascia- The fascia is a simplified version of Vignola's composite order according to Amico's interpretation: it is composed by an upper frame, a frieze and a lower lintel in touch with the capital of the pillars below. In this fascia, some modules are repeated whilst corbels and dentils are missing: as-designed dimensions in the essay are not always matched due to the construction methods of the past (Figure 126).



Figure 126. The fascia on Amico's essay (from Amico, 1726).

It was created using a "Wall extrusion profile" template. Its actual profile was traced based on a sample cross-section extracted from the point cloud and then extruded on its path (Figure 127).

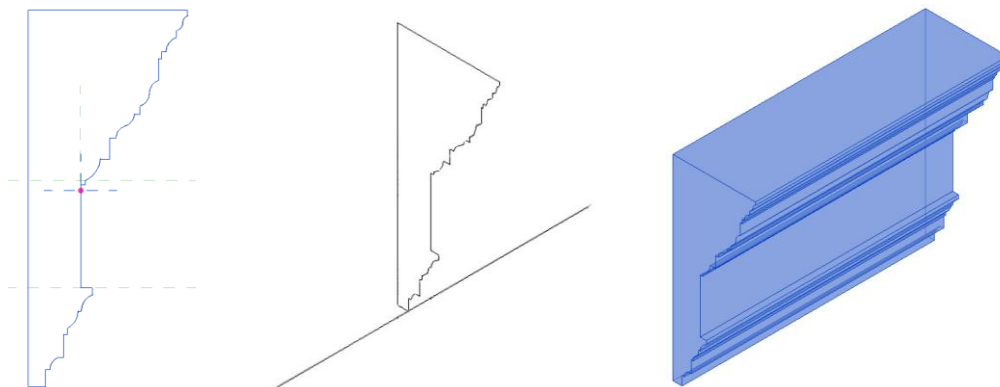


Figure 127. The modelling phases for shaping the fascia on top of the perimetral walls.

The pillars - The internal façades feature giant-order pilasters in three variations: single, double, and corner types. According to Amico's interpretation, the pedestals match Vignola's Corinthian order (despite the base of the shaft doesn't fully adhere to this model), whilst the capitals are treated as a simple Tuscan order, given the complexity of the composite upper fascia, as mentioned above (Figure 128).



Figure 128. The pedestal on Amico's essay (from Amico, 1726).

The modelling process for all three types followed a consistent approach. The "Metric architectural pillar profile" template provided by the software was chosen for this purpose, because architectural pillars are ideal to shape items which could be partially integrated or embedded into wall system families (like in this case study), whilst the "Metric structural pillar profile" template leads to columns which are always considered by the software as self-referred elements.

For illustrative purposes, the double pillars serve as an example of the modelling process. Once the different profiles were extracted directly from the point cloud and measured to ensure accurate proportions, the measurements were used to set geometric parameters such as the length and width of the base outline, the main horizontal levels and the overall height. Whilst the horizontal parameters served as the path for the subsequent Boolean operations shaping mouldings and recessed profiles, the height was created as an instance parameter, enabling the same pilaster to be

adapted. When linked to other instance parameters, changes in height automatically ruled the proportions of all modelled parts. All the geometric features used for these families are instance-based and tied to the column's height, ensuring consistent scaling and flexibility according to the project's needs.

This parametric family was conceived as a nest of other families, including the bases, shafts, and capitals into a single loadable category. Considering the three different components, the lower fascia of the pedestals was modelled first, using a basic "Sweep" operation in the "Create" panel, following their base outlines (Figure 129).

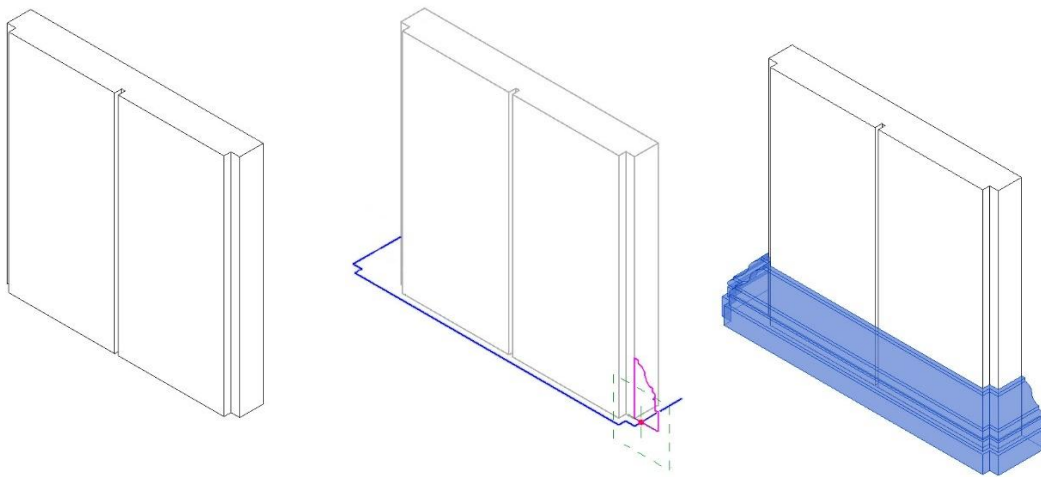


Figure 129. Sweeping of the lower mouldings of pedestals.

The upper decorative moulding was added via another swept extrusion (Figure 130).

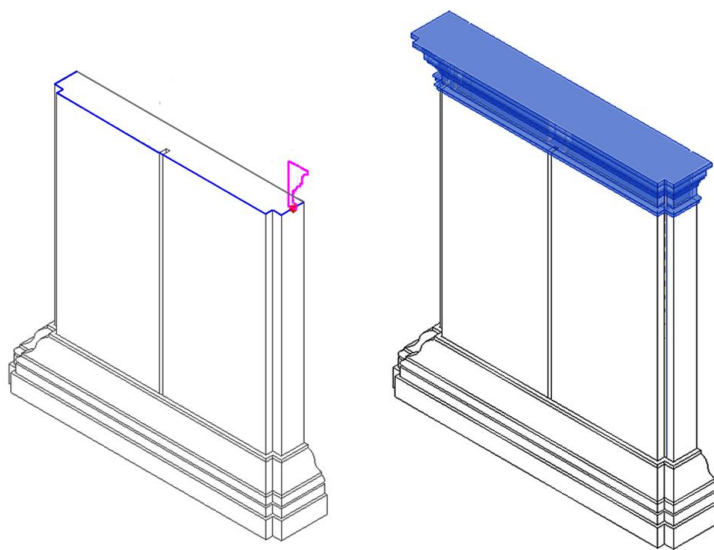


Figure 130. Sweeping of the upper mouldings of pedestals.

The shafts were modelled through simple extrusions matching their actual length, and the capitals were crafted similarly to the upper fascia. The recesses in the shaft of the pillars and the pedestals have been obtained as a void subtracted from the solid extrusion (Figure 131).

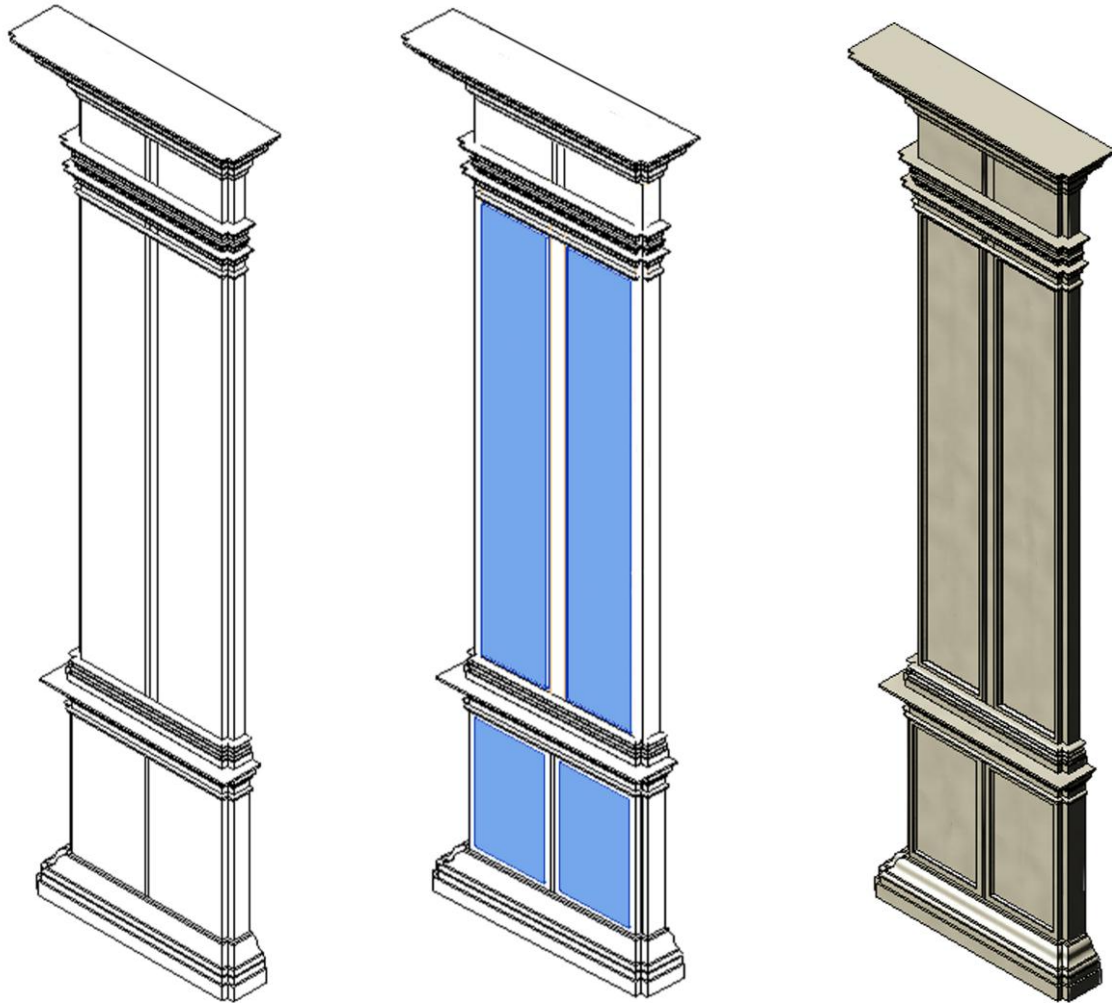


Figure 131. The double pillars at the end of the modelling.

The rose window - The rose window consisted of two concentric circles with different diameters, the larger one positioned on the counter façade. The window was modelled by subtracting a cylindrical void extrusion from the interested wall. After creating the void cylinder, the inner face was splayed to a wider diameter. The annular moulding surrounding the window was then modelled as a profile derived from the point cloud and added to the inner circumference as a 360° solid revolution (Figure 132).

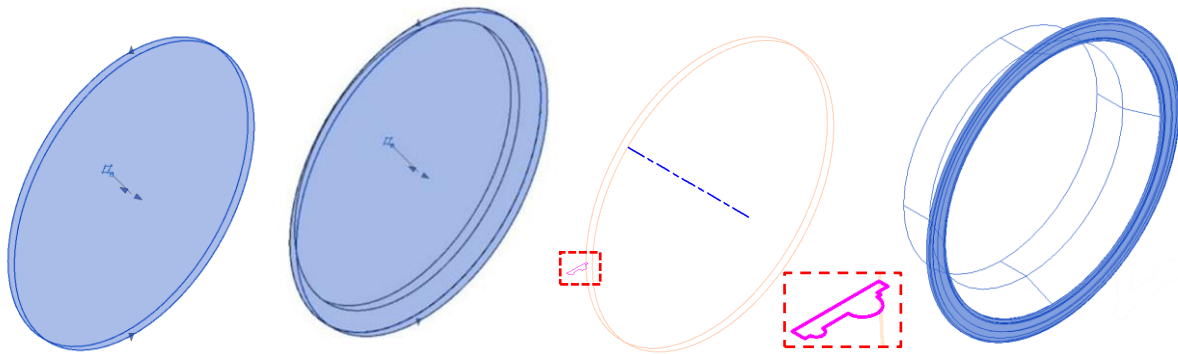


Figure 132. The rose window in the main façade and its mouldings.

The parapet - The parapet atop the roof was modelled using two external families: the upright components and the profiled stringers. The upright elements were created with the software’s “General Model” template, while the stringers were based on the “Profile” template. After defining a single upright with parameters such as center-to-center spacing, number, offset from the central axis, and height, the stringers were applied around the entire perimeter of the building (Figure 133).

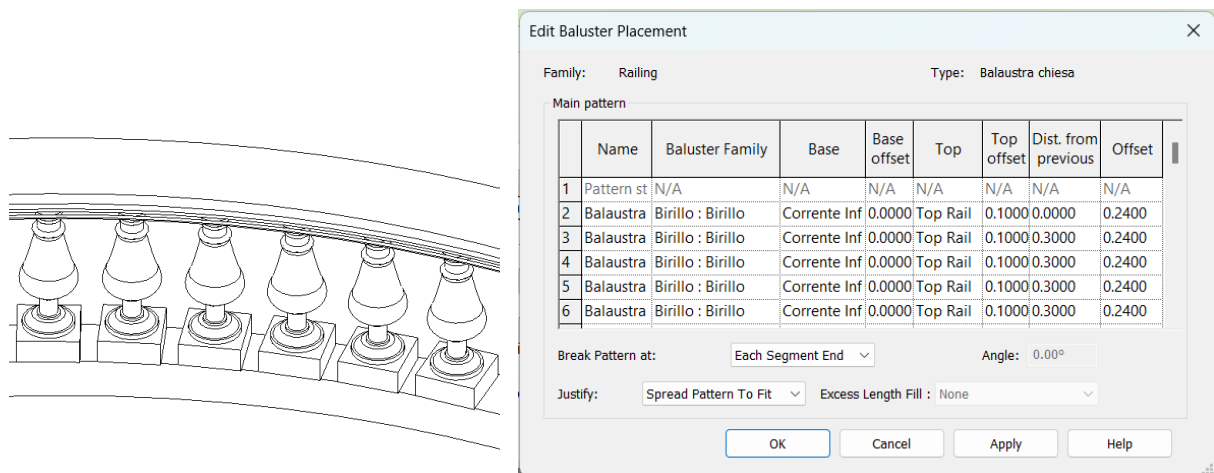


Figure 133. The parapet and its settings.

8.3 Other examples of in-place objects

In this digital model, in-place families were applied to all the architectural elements unique to the church, which would not have been reusable for similar buildings. For example, the four recessed chapels in the main nave and the doors were modelled as void extrusions based on their actual contours, applied along the respective wall thicknesses, and subtracted from the long walls (Figure 134). For the doors, this

process was repeated to account for their distinct profiles on the interior and exterior faces.

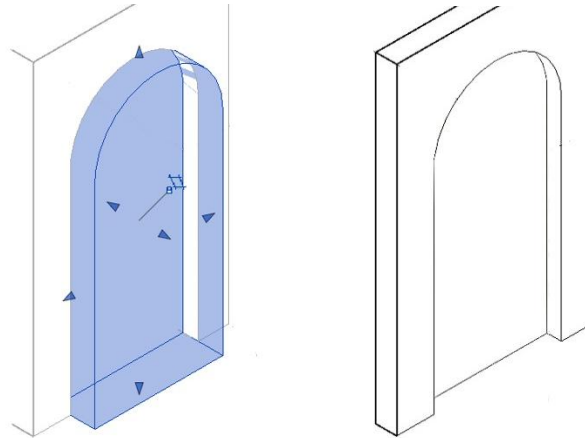


Figure 134. The recessed chapels of long walls obtained as void extrusions.

A different approach was taken for modelling the false ceilings above the various spaces within the church. These were treated as parametric masses created using Boolean operations. The mass for the boat vault was generated by extruding half of the arched profile along the octagonal path formed by the main walls of the nave and their chamfered 45° angles. Near the lantern, the perimeter of the mass was trimmed by the arch leading to the presbytery.

The barrel vault over the presbytery was modelled as an extrusion of the arched profile along the path defined by the long walls between the arches separating the presbytery from the nave and the cap dome. This vaulted mass was then intersected with an octagonal void extrusion corresponding to the overhead lantern (Figure 135).

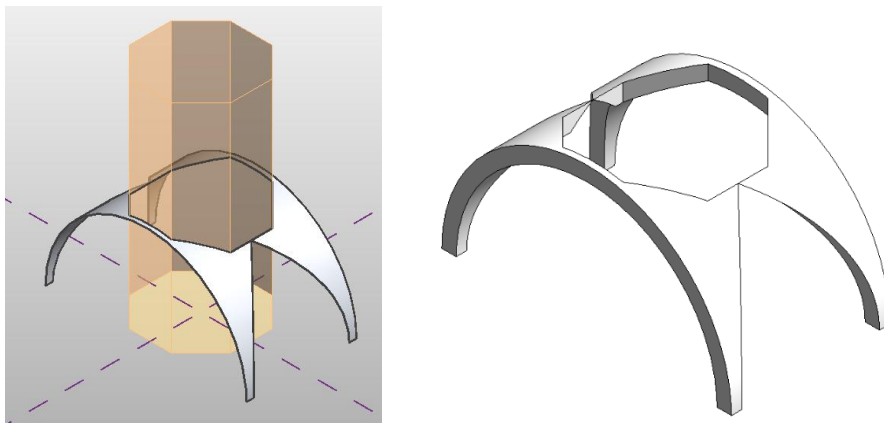


Figure 135. The barrel vault over the presbytery.

The cap dome, consisting of three spindles, was created by extruding its arched profile along the polygonal path defined by the apse walls (Figure 136).

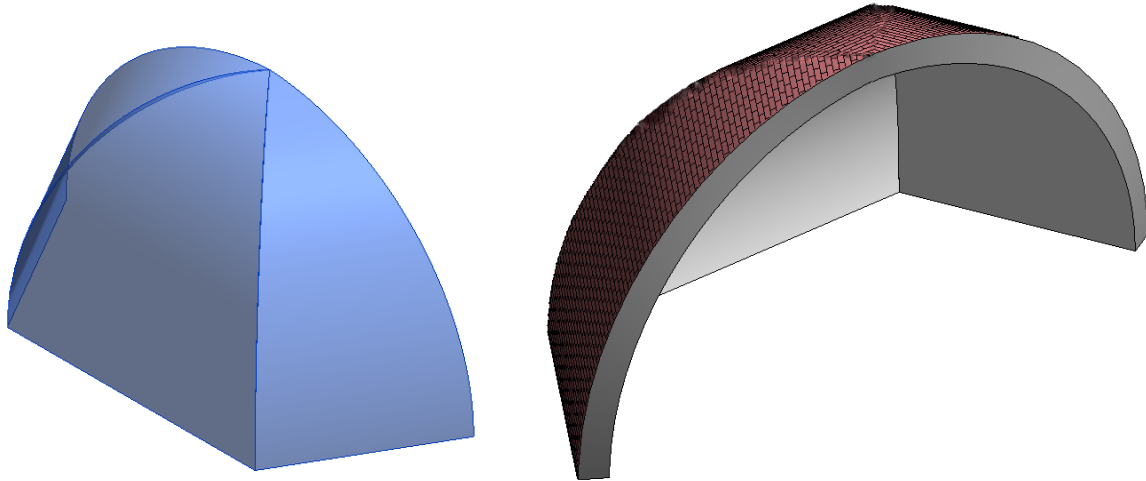


Figure 136. The cap dome above the apse.

After generating these masses, the same type of roof used for the flat sections of the sheltering was applied using Revit's "Roof from Mass" tool (Figure 137).

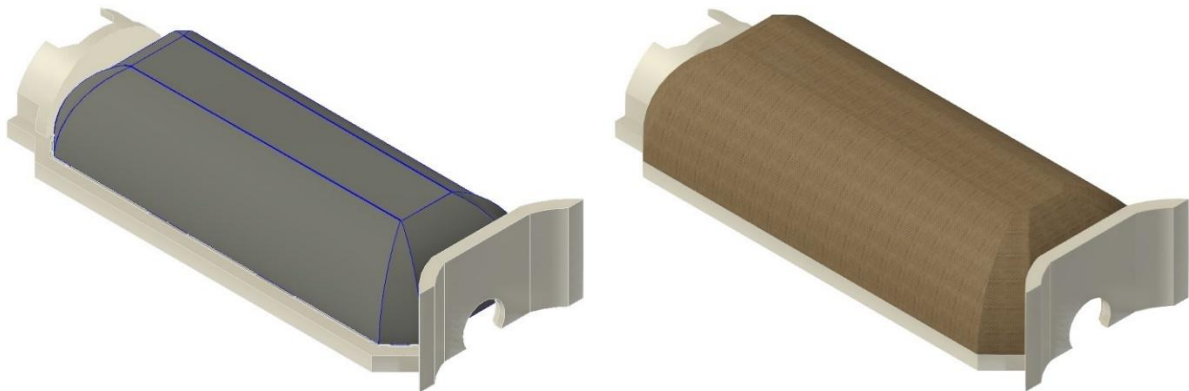


Figure 137. The boat vault false ceiling modelled as "Roof from mass".

A similar method was used for the main dome as well, modelled as an extrusion of its profile along the closed octagonal path formed by the lantern's perimeter walls. The roof mass was customised to represent the internal plaster layer and the emerald-green tile finish on its exterior surface.

These iterative steps facilitated the creation of a detailed, as-built parametric digital representation of the church, highlighting its architectural style (Figure 138). This 3D

model served as a foundation for incorporating data about degradation phenomena, as discussed in the following sections.

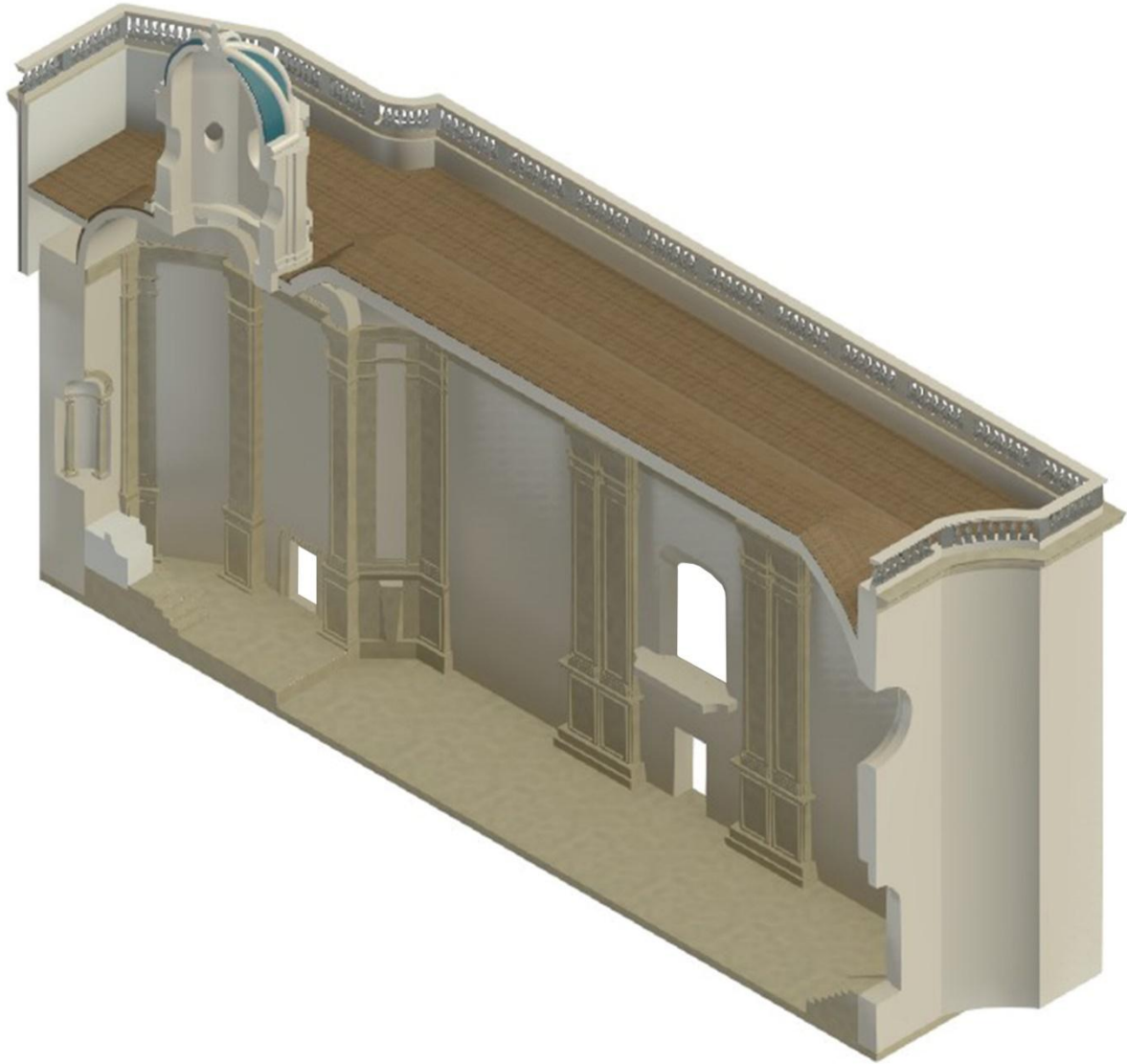


Figure 138. An isometric longitudinal section of the final model.

8.4 Materials and construction phase application

After creating the general model, items were assigned specific structural or finishing materials based on a visual inspection on-site. For built-in families, materials were applied during the geometric modelling phase by altering a dedicated property key, selecting from the available database or creating a custom material when necessary. For loadable families, it was not possible to define a single material from the template,

so one was assigned after the family had been loaded into the project, varying depending on the case.

In the model of the church, these materials were applied using specific RGB values and textures to match the real-world characteristics of the asset. Information about the local sandstone used for the overall structure and other stones for decorative elements were added with great care, trying to match their actual appearance.

Among the property keys which can be modified, the construction phase is customisable to provide details about the different stages of the asset's construction, from the foundation to potential demolitions and refurbishments over the centuries. In HBIM projects, this timeline management of construction phases helps gaining a deeper understanding of the asset, cataloguing the phases it has undergone and any alterations made.

Since the case study refers to an 18th century construction which has not undergone any refurbishments since then, the database was updated with specific keys forecasting future surveys and interventions. Additionally, the database was expanded with another thematic mapping, as detailed in the following sections.

8.5 The current state of the art of decay mapping in HBIM

A significant challenge in preserving AH lies in the lack or loss of detailed information about the asset in question - how it was originally built and its restoration history. This gap becomes particularly problematic when planning future maintenance or intervention strategies.

Traditional archival research and 2D documentation methods for existing structures have proven both labor-intensive and incomplete, because of their inconsistency in framing discontinuous and insufficiently documented previous maintenance campaigns; whilst effective management of BH requires updated and structured tools to thoroughly understand historical assets and ensure their sustainability over time (Santagati et al., 2021).

Beyond standard 2D graphical representations, thematic mappings can also be integrated into HBIM systems as proper 3D entities (He et al., 2017). Indeed, numerous researchers have explored ways to embed this type of semantic data into the database

of digital models resulting from Scan-to-BIM processes, with varying methods and outcomes, including VPL language ([Guida et al., 2021](#)).

One commonly used technique involves tracing decay contours using filled patterns ([Chiabrando et al., 2017](#)), though this method lacks data on intervention quantities and costs. A similar approach utilizes thin-layered filled regions on affected surfaces, enabling the addition of semantic metadata ([Croce et al., 2019](#)). This information can even further detail the material's conservation state, describe specific interventions ([Ferro et al., 2023](#)), or highlight structural issues and prioritize areas requiring attention ([Saricaoglu and Saygi, 2022](#)).

More advanced techniques involve adaptive, contoured patterns linked to different types of decay. For instance, one approach utilized identification codes, although it did not facilitate data extraction ([Malinverni et al., 2019](#)). Alternatively, this methodology has been applied to individual masonry ashlar for greater precision ([Del Pozzo et al., 2022](#)), or a single architectural element ([Nieto-Julián et al., 2024](#)).

Some researchers have also integrated orthophotos into models, allowing for direct tracing of decay areas ([Lanzara et al., 2021](#)). These areas are subsequently analysed in a separate database outside the BIM environment used for modelling ([Banfi et al., 2022](#)).

8.6 Decay and alteration phenomena identification in Santa Maria della Grotta

Today, conservation plans for AH largely rely on thematic mappings which document various types of decay phenomena, such as crack patterns and structural failures, as well as strategies to address or prevent them. These graphical outputs enhance the basic geometric representation of the asset by incorporating detailed information about its condition, often derived from visual inspections, non-destructive diagnostic tests conducted on-site, or laboratory analyses of sampled materials.

These evaluations have become increasingly significant to the scientific community and governmental authorities, establishing themselves as standard practices in AH management. They also serve as predictive tools to determine the urgency of interventions. To provide consistency and common standards, such practices are now

regulated by national and international guidelines, including those outlined in the ICOMOS glossary (ICOMOS, 2008; Cameron, 2015).

As described in Chapter 5, Santa Maria della Grotta's church has been carved into a sandstone bank, extending to a height of approximately 9 meters, whilst the built part of the perimeter walls rise above the ground level for only about 2 meters. Due to its location and construction, the church's restricted airflow and unique microclimate have contributed to the development of deterioration caused by humidity, both from surface seepage and condensation.

The underground environment of the church shows significant conservation challenges. These include excessive moisture and widespread biological colonization on the interior surfaces. Inside, there are signs of biological growth, blistering, crumbling, crust formations, material loss, and fragmentation. The external surfaces exhibit similar issues, compounded by visibly moist areas.

Regarding this research, they have been defined in alphabetical order according to the ICOMOS glossary as:

“Biological colonization - Colonization of the stone by plants and micro-organisms such as bacteria, cyanobacteria, algae, fungi and lichen (symbioses of the latter three). Biological colonization also includes influences by other organisms such as animals nesting on and in stone”.

Within the church, the interior surfaces exhibit a range of issues related to biological colonization, from a thin and uneven patina to heavy encrustations which primarily damage the plaster layer on the walls. On the exterior, vegetation has taken root, likely sprouting in cracks where windborne seeds have settled (Figure 139a).

“Blistering - Separated, air-filled, raised hemispherical elevations on the face of stone resulting from the detachment of an outer stone layer. This detachment is not related to the stone structure”.

This degradation is primarily caused by capillary water rise, exposure to atmospheric conditions, and inadequate maintenance over time. It predominantly affects the sections of the interior walls below the fascia and large areas of the exterior plaster (Figure 139b).

“Crumbling - Detachment of aggregates of grains from the substrate. These aggregates are generally limited in size (less than 2 cm). This size depends on the nature of the stone and its environment”.

This decay was observed inside the building, particularly affecting the wall sections already experiencing blistering. It is caused by biological organisms which thrive in the moisture, infiltrating the stone's pores and leading to its erosion. The same type of degradation was seen on the external parapet, exacerbated by the alternating effects of wind and rain, along with capillary water rise (Figure 139c).



Figure 139. a) Biological colonization affecting the pillars; b) blistering of the plaster layer; c) Crumbling of the internal sandstone layers.

“Crust - Generally coherent accumulation of materials on the surface. A crust may include exogenic deposits in combination with materials derived from the stone. A crust is frequently dark coloured (black crust) but light colours can also be found. Crusts may have a homogeneous thickness, and thus replicate the stone surface, or have irregular thickness and disturb the reading of the stone surface details”.

This alteration has been spotted across extensive areas of the whole building, and it is a consequence of biological colonization (Figure 140a).

“Missing part - Empty space, obviously located in the place of some formerly existing stone part. Protruding and particularly exposed parts of sculptures (nose, fingers...) are typical locations for material loss resulting in missing parts”.

These losses are due to decohesion of the materials, mainly spotted on the indoor surfaces (Figure 140b).

“Fragmentation - The complete or partial breaking up of a stone, into portions of variable dimensions that are irregular in form, thickness and volume”.

This phenomenon interested the internal surfaces of the apse walls; it is linked to the presence of moisture and the dissolution of salts in the water, along with the effects of freeze-thaw cycles. Daily temperature fluctuations can lead to thermal stress within the stone material, causing further deterioration (Figure 140c).

“Moist area - Darkening (lower hue) of a surface due to dampness. The denomination is preferred to moist spot, moist zone or visible damp area”.

These areas were recognisable as dark spots on the outdoor surfaces close to the downpipes, due to the incorrect disposal of rainwater (Figure 140d).

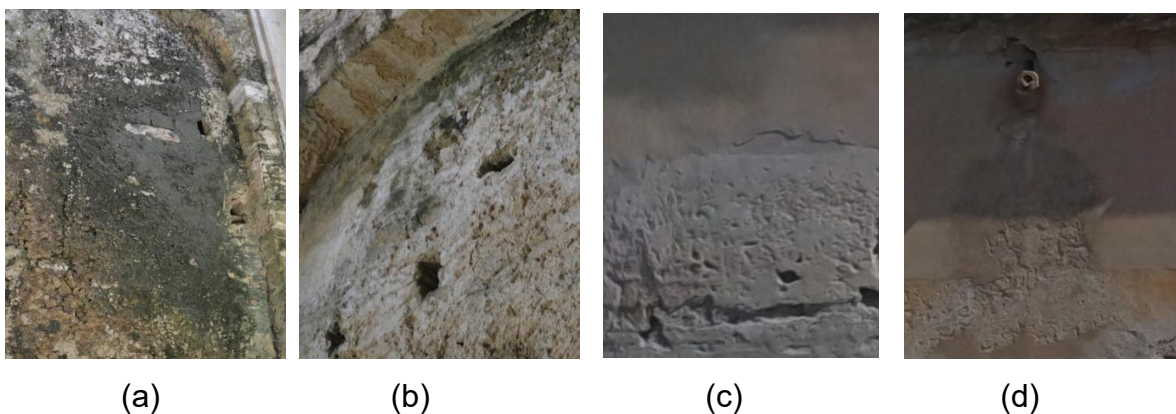


Figure 140. a) Crust on the recessed chapels of the interiors; b) missing parts on the main walls; c) fragmentation in the external walls; d) moist areas below the rainpipe outside.

8.7 Decay mapping in HBIM: the semantic enrichment of the digital model

The potential of HBIM models for AH preservation was explored in the previous paragraphs. The digitization of this case study was aimed at representing in a BIM environment the decay phenomena affecting Santa Maria della Grotta's church on the digital model. Specifically, it was created to reflect the actual conditions of the building and to store detailed information about the various types of degradation observed on-site and their corresponding treatments, hosted as semantic contents within the database provided by the software.

After obtaining the HBIM model and importing four high-resolution orthophotos of the long walls (as detailed in Section 5.4.3) into Revit, scaled and aligned with the corresponding surfaces, the creation of the thematic map began with the development of parametric objects to represent the related decay phenomena.

The aim was to create queryable objects which would move beyond simple graphic representations, serving as true data repositories. A "Generic Model" family type was chosen, as it was best suited to hold all necessary information on decay types, extent, and affected materials. This family template enabled the creation of 3D adaptive objects starting from a reference surface, such as a wall. In this case, the orthophotos served as direct references, with decay contours traced onto to match their actual forms (Figure 141).



Figure 141. Tracing of decays onto the orthophotos.

The 2D outlines defined in this manner were then extruded with a thin conventional thickness to create a film-like layer adhering to the surface of the digital walls. This process resulted in a comprehensive parametric map of the decay state of the church's perimeter walls, including both the internal and external faces (Figures 142, 143).

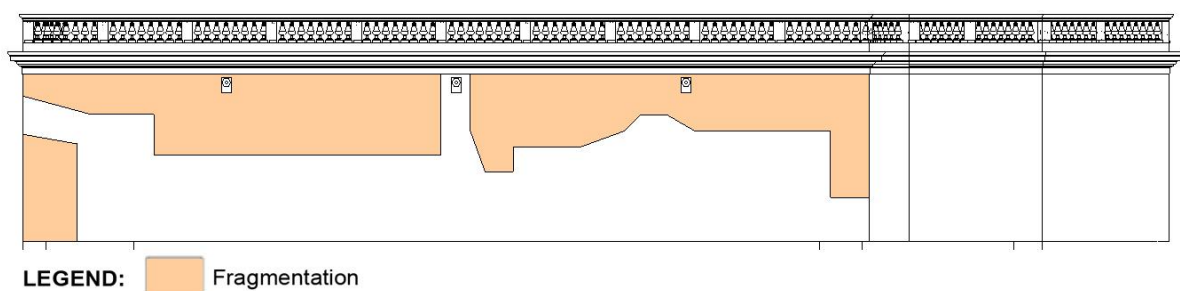


Figure 142. Decay map traced on the northern exterior façade of the church.

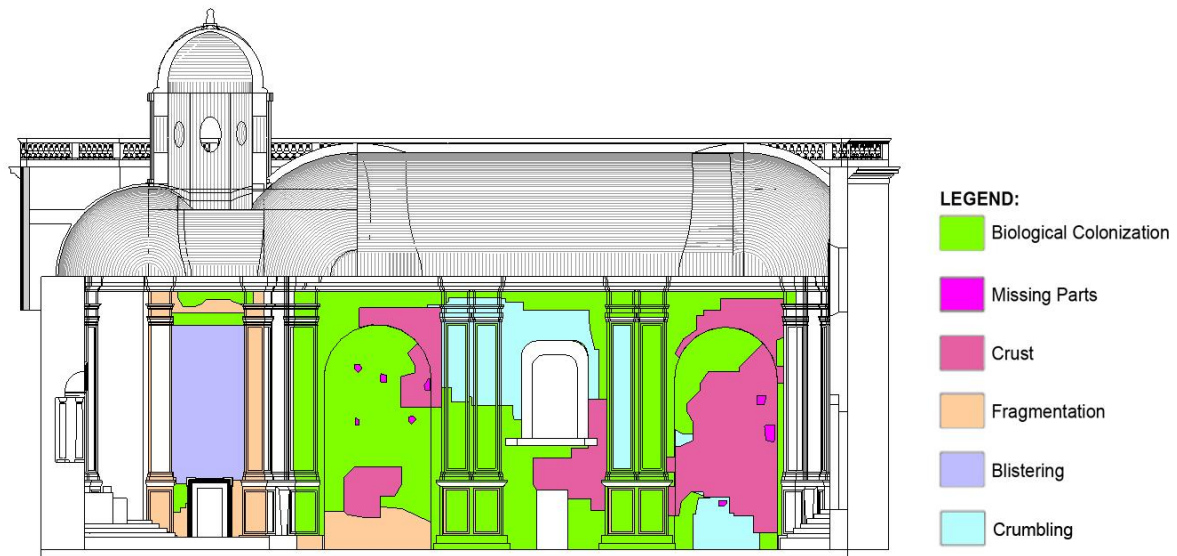


Figure 143. Decay map traced on the northern interior façade of the church.

The application of a 60% default transparency to these newly created objects enabled a clearer visual comparison of the degradation phenomena affecting both sides of the structure (Figure 144).



Figure 144. Isometric view with the decay maps on both sides of the long walls.

This geometric representation was further enriched with semantic data based on the ICOMOS glossary, where each decay was assigned a specific colour and pattern for easy visual identification and classification. Each decay shape was accompanied by a description of the alteration, its location, extent, and a reference image. This led to the development of an abacus of decay, a thematic catalogue within the HBIM model database, offering a complete analysis of the decay phenomena (Figure 145).

Abacus of Decays			
A	B	C	D
Type of Decay	Description	Surface	Area
Biological colonization	Colonization of the stone by plants and micro-organisms such as bacteria, cyanobacteria, algae, fungi and lichen	Internal left wall	15.90 m ²
Biological colonization	Colonization of the stone by plants and micro-organisms such as bacteria, cyanobacteria, algae, fungi and lichen	Internal right wall	219.60 m ²
Blistering	Separated, air-filled, raised hemispherical elevations on the face of stone resulting from the detachment of an outer stone la	Internal left wall	18.50 m ²
Blistering	Separated, air-filled, raised hemispherical elevations on the face of stone resulting from the detachment of an outer stone la	Internal right wall	19.40 m ²
Crumbling	Detachment of aggregates of grains from the substrate	Internal left wall	47.00 m ²
Crumbling	Detachment of aggregates of grains from the substrate	External left wall	10.90 m ²
Crumbling	Detachment of aggregates of grains from the substrate	Internal right wall	40.70 m ²
Crust	Coherent accumulation of materials on the surface	Internal left wall	46.30 m ²
Crust	Coherent accumulation of materials on the surface	Internal right wall	48.40 m ²
Fragmentation	Complete or partial breaking up of a stone, into portions of variable dimensions that are irregular in form, thickness and volu	Internal left wall	230.90 m ²
Fragmentation	Complete or partial breaking up of a stone, into portions of variable dimensions that are irregular in form, thickness and volu	External left wall	80.00 m ²
Fragmentation	Complete or partial breaking up of a stone, into portions of variable dimensions that are irregular in form, thickness and volu	Internal right wall	248.00 m ²
Fragmentation	Complete or partial breaking up of a stone, into portions of variable dimensions that are irregular in form, thickness and volu	External right wall	61.30 m ²
Missing parts	Empty spaces, obviously located in the place of some formerly existing stone part	Internal left wall	2.70 m ²
Missing parts	Empty spaces, obviously located in the place of some formerly existing stone part	Internal right wall	0.09 m ²
Moist area	Darkening (lower hue) of a surface due to dampness	External left wall	5.00 m ²
Plant	Vegetal living being, having, when complete, root, stem and leaves	External left wall	1.80 m ²

Figure 145. The abacus of Decays from the HBIM model of Santa Maria della Grotta.

The catalogue is a valuable tool, retrievable and updatable for future in-depth studies and more comprehensive analysis. It can also be expanded with additional categories and details, such as required actions, procedural steps, materials to use, costs, and timelines for interventions (Nieto-Julián et al., 2024). Moreover, it can be enhanced with images, technical sheets, or tutorials on advanced intervention techniques (Brumana et al., 2018).

Such catalogues can serve as a reference framework for preliminary restoration plans, acting as a predictive tool to estimate the financial and operational resources needed for the maintenance of BH.

By following a highly efficient process, both in terms of time and accuracy, which is repeatable and applicable to various contexts, the approach used to model Santa Maria della Grotta's church enabled the creation of a digital replica closely resembling the real building, while also offering a new tool which can aid in the preservation of BH and raise awareness of its significance.

Discussions and Conclusions

HBIM processes are established as a powerful tool for the preservation, restoration, and enhancement of Architectural Heritage. The HBIM models act as integrated digital archives, storing semantic and geometric data; they can be explored, exploited, updated and revised at all times, and enable further queries, analysis, and simulations, supporting informed decision-making processes.

Interoperable and open-source platforms allow data from diverse software to be stored within one environment and shared among professionals and stakeholders, fostering awareness and promoting collaborative and team-oriented methods of work.

Given the notorious lack of information affecting the historical existing buildings, nowadays HBIM relies on a Scan-to-BIM approach to address this issue through the methodical use of modern Geomatics techniques.

The main objective of this research was to validate the Scan-to-BIM approach as an effective method for the documentation, representation and communication of AH, to support and to be integrated into HBIM methodology.

For this purpose, the Scan-to-BIM approach was tested on three magnificent built examples of the Arab-Norman Heritage and on a Baroque church in western Sicily, trying to establish and implement an efficient and replicable workflow for the geometric and semantic reconstruction of historical assets, and assessing the advantages, limitations, and criticalities of the application of this approach for modelling existing buildings.

The work has been structured to endorse the assumption that in-depth knowledge about the buildings should have been compulsory to develop more effective HBIM models aimed at sharing improved awareness on those assets.

Prior to starting any operational phase of the workflow, it was essential to deepen the understanding of the historical and architectural context of the case studies through archival and bibliographic research. These investigations initially allowed for an analysis on their evolution over the centuries, as well as the identification of any interventions aimed at restoring original conditions. Subsequently, they contributed to

understanding the specific characteristics of each architectural element -especially from a technological-structural, constructional, and material perspective- with the goal of reflecting and conveying these aspects throughout the modelling process; in particular, they aided the aggregation and hierarchy of the various parts within the models establishing their mutual relationships.

From a purely geometric standpoint, the accurate and detailed documentation of the sites in their actual condition was achieved through the integration of diverse survey techniques, in an effort to overcome the limitations of each method and to produce datasets which are as complete, homogeneous, and consistent with the aims of the Scan-to-BIM process as possible, not only for conservation purposes.

From a methodological perspective, all surveys in this research were conducted using two main techniques: terrestrial laser scanning (both static and mobile) and photogrammetry (both terrestrial and aerial, when possible). Additionally, topographic surveying was marginally employed to acquire specific control points, which supported data processing and improved overall accuracy.

All the collected data, coming from the investigation process and the surveys, served as a reliable basis for replicating geometrical information during the modelling phase, albeit they needed to be optimized and interpreted prior to being uploaded into parametric models.

During the subsequential development of the HBIM digitisations for the case studies, a crucial phase was the decomposition of the architecture into its structural and formal components, followed by the reconstruction carried out exclusively through manual processes.

The parametric reconstruction process highlighted the effectiveness of the survey techniques, but also the challenges of modelling elements which inevitably had to take into account the rigidity of the tools offered by the BIM platform. In fact, the in-built system families and predefined libraries within BIM software typically include only parametric objects suitable for newly constructed buildings and -except in rare cases- do not account for elements characteristic of historical architecture. Whilst these system families were essential in the early stages of the process and in the modelling of primary elements such as floors, walls, and ceilings, the main challenge was to

define modelling strategies capable of representing the unique features of Arab-Norman and Baroque architecture.

Thanks to the editor function and the available templates, through manual drafting and Boolean operations, it was possible to parameterize most of the typical elements of those architectural styles: the main dimensions of the most recurring profiles were made customizable, and the resulting model was saved as a downloadable family, to be imported into future projects and altered as needed. This approach enabled the creation of reusable families, such as windows, vaults, domes, etc.

However, a residual portion of architectural elements was created as local families, and thus usable only within a specific project, prioritizing model accuracy at the expense of parametrization.

Although based on shared modelling processes, the HBIM digitisations in this research pursued different objectives, which justify their varying degrees of geometric and semantic contents, as well as their levels of development.

In particular, the models related to the first three case studies -given their stylistic and chronological homogeneity- were suitable for creating and implementing a brand new library of Arab-Norman architectural types (arches, windows with molded frames, trumpet squinches, domes), contributing to greater awareness of the structural aspects and specific features of the three churches, in line with the principles of AH documentation. The rigor of archival research ensured critical elaboration processes throughout their modelling.

Semantic contents in the form of a thematic mapping for degradation have been added to the fourth case study only. The digital replica of Santa Maria della Grotta demonstrated how the Scan-to-BIM process can be a valuable tool for analysing the building's current state of preservation and for conducting investigations as an essential foundation for conservation efforts and scheduled maintenance. Within that model, detailed analysis was carried out on the various forms of decay affecting the church, through mapping conducted on both faces of the main walls. This first experiment overcame the usual bidimensional representation of one side of the wall at a time, to be redone from scratch whenever updated: in this case, the extension of affected surfaces can be altered on demand and stored and enables both a

multitemporal visualisation through a frame of time, and the contemporary inspection of different faces of the same element.

The default database provided by the BIM environment has been expanded and enriched with abacuses reporting extensions, causes, descriptions and locations on ad-hoc sheets, and can be further expanded in the future, for example by integrating restoration techniques, costs or other specificities related to AH management.

After these considerations, the Scan-to-BIM approach applied to the case studies in this research demonstrated significant advantages in documenting the actual conditions of the architectural artifacts and in creating parametric models which serve as digital replicas.

The digital surveys, conducted for the first time ever on the artifacts studied, contributed significantly to their comprehensive and thorough documentation. The resulting datasets, beyond their potential use as a base for HBIM modelling, represent a valuable outcome on their own.

Furthermore, the research has proven how integrated, multi-source surveys combining mobile and aerial and terrestrial photogrammetry, can effectively support the development of accurate 3D digital reconstruction of monumental architectures especially whenever made of organic parts as in the fourth case study.

The parameterization of irregular geometries through manual methods, although directly related to the purposes for which the models were created, has been overcome thanks to the analysis of the most recurring shapes and their redesign and led to two libraries of objects related to the Arab-Norman and Baroque styles, completely new in their kind. In fact, available libraries of historical objects were usually limited to those associated with the classical and neoclassical orders of architecture. This represents another result achieved through this research.

The latter HBIM model, instead, enabled further consideration on the retrieval of information from professionals with different backgrounds, and how this information could have improved collaborative work and multidisciplinary.

Despite increasingly efficient management, some issues remain unresolved: whilst this research has proposed several strategies to address the lack of complete geometric

and architectural documentation and the challenges of modelling historic buildings, often characterized by complex forms, there are still critical concerns. These include the limited interoperability between data shared on the hosting platform when originating from different software, and the absence of a common vocabulary and clear guidelines, which continue to hinder the broader adoption of the Scan-to-BIM approach.

The digital models produced as part of this doctoral research do not resolve all the challenges, but they have proven to be valuable tools for the meaningful enhancement and management of real-world artifacts, in an effort to achieve the most comprehensive understanding possible.

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References

- Acierno, M., Cursi, S., Simeone, D., Fiorani, D., 2017. Architectural heritage knowledge modelling: An ontology-based framework for conservation process. *J. Cult. Herit.*, 24, 124–133. <https://doi.org/10.1016/j.culher.2016.09.010>
- Adami, A., Fregonese, L., Rosignoli O., Scala, B., Taffurelli, L., Treccani, D., 2019. Geometric Survey Data and Historical Sources Interpretation for HBIM Process: the Case of Mantua Cathedral Façade. *ISPRS Archives*, XLII-2/W11, 29–35. <https://doi.org/10.5194/isprs-archives-XLII-2-W11-29-2019>
- AEC(UK), 2012. *AEC (UK) BIM Protocol - v2.0. Implementing UK BIM Standards for the Architectural, Engineering and Construction industry*. <https://aecuk.files.wordpress.com/2012/09/aecukbimprotocol-v2-0.pdf>
- Akpınar, B., 2021. Performance of Different SLAM Algorithms for Indoor and Outdoor Mapping Applications. *Applied System Innovations*, 4, 101, 1-11. <https://doi.org/10.3390/asi4040101>
- AIA, 2008. *E202TM-2008, Building Information Modelling Protocol Exhibit*. <https://www.aiacontracts.org/contract-doc-pages/64526-e-series-exhibits>
- AIA, 2022. *Guide and Instructions to the AIA Digital Practice Documents*. https://zdassets.aiacontracts.org/ctrzdweb02/zdpdfs/digital-practice_guide
- Allegra, V., Di Paola, F., Lo Brutto, M., Vinci, C., 2020. Scan-to-BIM for the management of Heritage Building: the case study of the Castle of Maredolce (Palermo, Italy). *ISPRS Archives*, 43-B2-2020, 1355–1362. <https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-1355-2020>
- Alsadik, B., Karam, S., 2021. Simultaneous localization and mapping (SLAM): An overview. *Surveying and Geospatial Engineering Journal*, 1(2), 1-12. <https://doi.org/10.38094/jastt204117>
- Alshawabkeh, Y., Baik, A., 2023. Integration of photogrammetry and laser scanning for enhancing scan-to-HBIM modelling of Al Ula heritage site. *Heritage Science*, 11(147), 1-18. <https://doi.org/10.1186/s40494-023-00997-2>
- Amico, G.B., 1726. *L'architetto pratico*. Anstatic reprint, Dario Flaccovio Editore, Palermo, 1997
- Andriasyan, M., Moyano, J., Nieto-Julián, J.E., Antón, D. (2020.) From Point Cloud Data to Building Information Modelling: An Automatic Parametric Workflow for Heritage. *Remote Sens* 12, 1094. <https://doi.org/10.3390/rs12071094>
- Angulo-Formos, R., Castellano-Román, M., 2020. HBIM as support of preventive conservation actions in Heritage Architecture. Experience of the Renaissance quadrant façade of the Cathedral of Seville. *App. Sci.*, 10, 2428. <https://doi.org/10.3390/app10072428>
- Antonopoulou, S., Bryan, P., 2017. *BIM for Heritage: Developing a Historic Building Information Model*. Publisher: Historic England, Swindon, England, 2017

- Apollonio, F. I., Gaiani, M., Zheng, S., 2012. BIM-Based Modeling and Data Enrichment of Classical Architectural Buildings, *SCIRES*, 2(2), pp. 41-62. <https://dx.doi.org/10.2423/i22394303v2n2p41>
- Aricò, M., Lo Brutto, M., 2022. From Scan-to-BIM to Heritage Building Information Modelling for an ancient Arab-Norman church. *ISPRS International Archives*, XLIII-B2-2022, 761–768. <https://doi.org/10.5194/isprs-archives-XLIII-B2-2022-761-2022>
- Aricò, M., La Guardia, M., Lo Brutto, M., Rappa, E. M., Vinci, C., 2023a. Mobile Mapping for Cultural Heritage: the survey of the complex of St. John of the Hermits in Palermo (Italy). *ISPRS Archives*, XLVIII-1/W1-2023, 2023, 25-32. <https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-25-2023>
- Aricò, M., La Guardia, M., Lo Brutto, M., 2023b. Web exploration of Cultural Heritage with limited accessibility: First experimentation for archaeological sites. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, 48, 111–117. <https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-111-2023>
- Aricò, M., Lo Brutto, M., Maltese, A., 2023c. A Scan-to-BIM approach for the management of two Arab-Norman churches in Palermo (Italy). *Heritage*, 6, 20142-1644. <https://doi.org/10.3390/heritage6020087>
- Aricò, M., Ferro, C., La Guardia, M., Lo Brutto, M., Taranto, G., Ventimiglia, G. M., 2024. Scan-to-BIM Process and Architectural Conservation: Towards an Effective Tool for the Thematic Mapping of Decay and Alteration Phenomena. *Heritage*, 7(11), 6257-6281. <https://doi.org/10.3390/heritage7110294>
- Banfi, F., Brumana, R., Landi, A.G., Previtali, M., Roncoroni, F., Stanga, C., 2022. Building archaeology informative modelling turned into 3D volume stratigraphy and extended reality time-lapse communication. *Virtual Archaeology Review*, 13(26), 1–21. <https://doi.org/10.4995/var.2022.15313>
- Bauwens, S., Bartholomeus, H., Calters, K., Lejeune, P., 2016. Forest Inventory with Terrestrial LiDAR: A Comparison of Static and Hand-Held Mobile Laser Scanning. *Forests*, 7(6), 127. <https://doi.org/10.3390/f7060127>
- Bellafiore, G., 1990. L'architettura in Sicilia nell'età islamica e normanna (827-1194). Arnoldo Lombardi Editore, Milano, 1990
- Benli Yıldız, N., Kalpaklı, Z., Özkaraca, N., 2024. Creation of Historical Building Information Modelling (HBIM) Library, A Case Study of Registered House (No:56), Akçakoca. *Duzce University Journal of Science and Technology*, 12(2), 901-914. <https://doi.org/10.29130/dubited.1241508>
- Biagini, C., Capone, P., Donato, V., Facchini, N., 2016. Towards the BIM implementation for historical building restoration sites. *Automation in Construction*, 71, 74-86. <https://doi.org/10.1016/j.autcon.2016.03.003>
- Bianchini, C., Nicastro, S. 2018. The definition of the Level of Reliability: a contribution to the transparency of Heritage-BIM processes. *3D Modelling & BIM*
- Brumana, R., Della Torre, S., Previtali, M., et al., 2018. Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): surveying, preservation, site intervention -the Basilica di Collemaggio (L'Aquila). *Appl. Geomat.* 10, 545–567. <https://doi.org/10.1007/s12518-018-0233-3>

- Brumana, R., Oreni, D., Barazzetti, L., Cuca, B., Previtali, M., Banfi, F., 2020. Survey and Scan to BIM Model for the Knowledge of Built Heritage and the Management of Conservation Activities. In *Digital Transformation of the Design, Construction and Management Processes of the Built Environment*, Daniotti B., Gianinetto M., Della Torre S., Eds.; Publisher: Springer, Cham, 391-400. https://doi.org/10.1007/978-3-030-33570-0_35
- Bruno, N., Roncella, R. A., 2018. Restoration oriented HBIM system for Cultural Heritage documentation: The case study of Parma cathedral. *International Archives of Photogrammetry, Remote Sensing and Spatial and Information Sciences*, XLII-2, 171-178, <https://doi.org/10.5194/isprs-archives-XLII-2-171-2018>
- Bruno, N., Roncella, R., 2019. HBIM for Conservation: A new proposal for Information Modelling. *Remote Sens.*, 15, 1751. <https://doi.org/10.3390/rs11151751>
- Brusaporci, S., Maiezza, P., Tata, A., 2018. A Framework for Architectural Heritage HBIM Semantization and Development. *ISPRS Ann.*, XLII-2, 179–184. <https://doi.org/10.5194/isprs-archives-XLII-2-179-2018>
- Brusaporci, S., Ruggeri, G., Maiezza, P., Tata, A., Trizio, I., Giannangeli, A., 2018. AHBIM per l'analisi stratigrafica dell'architettura storica, *Restauro Archeologico*, 26(1), 112–131. <https://doi.org/10.13128/RA-23463>
- BSI PAS 1192-5:2015: Specification for security-minded building information modelling, digital built environments and smart asset management. Published online at <https://knowledge.bsigroup.com>
- buildingSMART International. *Industry Foundation Classes (IFC)*. <https://www.buildingsmart.org/standards/bsi-standards/industry-foundationclasses/>
- Buill, F., Amparo Núñez-Andrés, M., Costa-Jover, A., Moreno, D., Puche, J.M., Macias, J., 2020. Terrestrial Laser Scanner for the formal assessment of a Roman-Medieval structure - The cloister of the cathedral of Tarragona (Spain). *Geosciences*, 10, 427. <https://doi.org/10.3390/geosciences10110427>
- Buratowski, T., Garus, J., Giergiel, M., Kudriashov, A., 2022. Real-Time 3D Mapping in Isolated Industrial Terrain with Use of Mobile Robotic Vehicle. *Electronics*, 11, 2086. <https://doi.org/10.3390/electronics11132086>
- Cabo, C., Del Pozo, S., Rodríguez-Gonzálvez, P., Ordóñez, C., González-Aguilera, D., 2018. Comparing terrestrial laser scanning (TLS) and wearable laser scanning (WLS) for individual tree modeling at plot level. *Remote Sens.*, 10(4), 540. <https://doi.org/10.3390/rs10040540>
- Calabrese Liotta A., Nicolosi E., 1998. La Trinità di Delia. Castelvetro, 1998
- Cameron, C., 2015. UNESCO and Cultural Heritage. In: *A Companion to Heritage Studies*, eds W. Logan, M.N. Craith and U. Kockel. <https://unesdoc.unesco.org>
- Campi, M., Di Luggo, A., Scandurra, S., 2017. 3D modelling for the knowledge of architectural heritage and virtual reconstruction of its historical memory. *ISPRS Archives*, XLII, 2, W3, 133. <https://doi.org/10.5194/isprs-archives-XLII-2-W3-133-2017>
- Cao, Y., Teruggi, S., Fassi, F., Scaioni, M., 2022. A Comprehensive Understanding of Machine Learning and Deep Learning Methods for 3D Architectural Cultural Heritage

- Point Cloud Semantic Segmentation. In: Borgogno-Mondino, E., Zamperlin, P. (eds) *Geomatics for Green and Digital Transition*. ASITA 2022. Communications in Computer and Information Science, vol 1651. Springer, Cham. https://doi.org/10.1007/978-3-031-17439-1_24
- Carnevali, L., Lanfranchi, F., Russo, M., 2019. Built Information Modeling for the 3D Reconstruction of Modern Railway Stations. *Heritage*, 2(3), 2298-2310. <https://doi.org/10.3390/heritage2030141>
- Caruso, E. L'abbazia basiliana di Santa Maria della Grotta. In: *Archeologia e architettura*, Ediprint, Italy, 1995, pp. 239-245.
- Castagnetti, C., Dubbini, M., Ricci, P. C., Rivola, R., Giannini, M., & Capra, A., 2017. Critical issues and key points from the survey to the creation of the historical building information model: the case of Santo Stefano Basilica. *ISPRS Archives*, 42 (5/W1), pp. 467-474. <https://doi.org/10.5194/isprs-archives-XLII-5-W1-467-2017>
- Castellano-Román, M., Pinto-Puerto, F., 2019. Dimensions and Levels of Knowledge in Heritage Building Information Modelling, HBIM: The model of the Charterhouse of Jerez (Cádiz, Spain). *Digital Applications in Archaeology and Cultural Heritage*, 14. <https://doi.org/10.1016/j.daach.2019.e00110>
- Centarti, L., Ferreyra, C., Guida, C.G., Limongiello, M., Messina, B., 2024. Documentation and management of complex 3D morphologies through digital technology. *Acta IMEKO* **2024**, 13, 2, 1-7. <https://doi.org/10.21014/actaimeko.v13i2.1845>
- Cheng, L., Chen, S., Liu, X., Xu, H., Wu, Y., Li, M., Chen, Y., 2018. Registration of Laser Scanning Point Clouds: A Review. *Sensors*, 18, 1641. <https://doi.org/10.3390/s18051641>
- Chiabrando, F., Lo Turco, M., Rinaudo, F., 2017. Modelling the decay in a HBIM starting from 3D point clouds. A followed approach for Cultural Heritage knowledge. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 42- 2/W5, 605-612. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-605-2017>
- Chiabrando, F., Lo Turco, M., Santagati, C., 2017. Digital invasions: From point clouds to historical building object modelling (h-BOM) of a Unesco WHL site'. *ISPRS Archives*, 2, W3, 171. <https://doi.org/10.5194/isprs-archives-XLII-2-W3-171-2017>
- Construction-Building Information Modelling, 2021, available at <https://interoperable-europe.ec.europa.eu/>
- Costantino, D., Pepe, M., Restuccia, A., 2021. Scan-to-HBIM for conservation and preservation of Cultural Heritage building: the case study of San Nicola in Montedoro church (Italy). *Applied Geomatics*, Published online: 28 January 2021. <https://doi.org/10.1007/s12518-021-00359-2>
- Costantino, D., Alfio, V.S., Pepe, M., Scaringi, M., 2024. Point Cloud classification using Machine Learning algorithms: Application in Cultural Heritage Environment. 11th AIT Conference, Bari, Italy
- Croce, V., Caroti, G., Piemonte, A., Bevilacqua, M.G., 2019. Geomatics for Cultural Heritage conservation: integrated survey and 3D modelling. *IMEKO TC-4 International Conference on Metrology for Archaeology and Cultural Heritage*, 217-276.

- Croce, V., Caroti, G., Piemonte, A., 2021. Propagation of semantic information between orthophoto and 3D replica: a H-BIM system for the north transept of Pisa Cathedral. *Geomatics, Natural Hazards and Risk*, 12(1), 2225–2252. <https://doi.org/10.1080/19475705.2021.1960432>
- Cursi, S., Martinelli, L., Paraciani, N., Calcerano, F., Gigliarelli, E., 2022. Linking external knowledge to Heritage BIM. *Autom. Constr.*, 141, 104444. <https://doi.org/10.1016/j.autcon.2022.104444>
- D'Agostino, G., Figuera, M.; Russo, G., Galizia, M., Militello, P.M., 2022. Integrated 3D survey for the documentation and visualisation of a rock-cut underground built heritage. *ISPRS Archives*, 46, 167–174. <https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-167-2022>
- Dalla Mora, T., Peron, F., Cappelletti, F., Romagnoni, P., Ruggeri, P., 2014. *Una panoramica sul building information modelling (BIM)*. Milano, AiCARR, 2014
- Daniels, L., Georgopoulos, A., 2023. Doric temple HBIM library for Cultural Heritage management. *ISPRS Archives*, X-M-1, 55-62. <https://doi.org/10.5194/isprs-annals-X-M-1-2023-55-2023>
- Del Duca, G., Machado, C., 2023. Assessing the Quality of the Leica BLK2GO Mobile Laser Scanner versus the Focus 3D S120 Static Terrestrial Laser Scanner for a Preliminary Study of Garden Digital Surveying. *Heritage*, 6, 1007-1027. <https://doi.org/10.3390/heritage6020057>
- Del Perugia, B., Giannetti, F., Chirici, G., Travaglini, D., 2019. Influence of Scan Density on the Estimation of Single-Tree Attributes by Hand-Held Mobile Laser Scanning. *Forests*, 10, 1-13. <https://doi.org/10.3390/f10030277>
- Del Pozzo, D., Treccani, D., Appolonia, L., Adami, A., Scala, B., 2022. HBIM and thematic mapping: preliminary results. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 46-2/W1-2022, 199-206. <https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-199-2022>
- Di Giulio, R., Balzani, M., Ferrari, F., 2014. Digital morphometric survey for documentation, conservation and restoration works: the MUDI project. In: Ioannides, M., Magnenat-Thalmann, N., Fink, E., Žarnić, R., Yen, A-Y., Quak, E.: Digital heritage. Progress in cultural heritage: documentation, preservation, and protection: 5th international conference, EuroMed 2014, Limassol, Cyprus, November 3–8, 2014. Proceedings. Cham: Springer International Publishing; 2014. p. 617–24 (Lecture Notes in Computer Science; vol. 8740). <http://link.springer.com/10.1007/978-3-319-13695-0>
- Di Stefano, F., Torresani, A., Farella, E.M, Pierdicca, R., Menna, F., Remondino, F., 2021. 3D Surveying of Underground Built Heritage: Opportunities and Challenges of Mobile Technologies. *Sustainability*, 13(23):13289. <https://doi.org/10.3390/su132313289>
- Di Stefano, G., 1979. La chiesa della Trinità di Delia. In *Monumenti della Sicilia Normanna*, Krönig, W., Palermo, 1979, pp. 59
- Diz-Mellado, E., Mascort-Albea, E.J., Romero-Hernández, R., Galán-Marín, C., Rivera-Gómez, C., Ruiz-Jaramillo, J., Jaramillo-Morilla, A., 2021. Non-destructive testing and Finite Element Method integrated procedure for heritage diagnosis: The

- Seville Cathedral case study. *Journal of Building Engineering*, 37, 102134. <https://doi.org/10.1016/j.jobbe.2020.102134>
- Donato, A., Randazzo, L., Ricca, M., Rovella, N., Collina, M., Ruggieri, N., Dodaro, F., Costanzo, A., Alberghina, M.F., Schiavone, S., 2021. Decay Assessment of Stone-Built Cultural Heritage: The Case Study of the Cosenza Cathedral Façade (South Calabria, Italy). *Remote Sensing*, 13(19), 3925. <https://doi.org/10.3390/rs13193925>
- Dore, C., Murphy, M., 2012. Integration of Historic Building Information Modelling (HBIM) and 3D GIS for Recording and Managing Cultural Heritage Sites. *18th International Conference on Virtual Systems and Multimedia*, Milan, Italy, 2012, pp. 369-376. <https://doi.org/10.1109/VSM2012.6365947>
- Dore C, Murphy M., 2013. Semi-automatic modelling of building façades with shape grammars using historic Building Information Modelling. *ISPRS Archives*, Volume XL-5/W1, 57-64. <https://doi.org/10.5194/isprsarchives-XL-5-W1-57-2013>
- Dore, C., Murphy, M., McCarthy, S., Brechin, F., Casidy, C., Dirix, E., 2015. Structural Simulations and Conservation Analysis - Historic Building Information Model (HBIM). *ISPRS International Archives*, Volume XL-5/W4, 351-357, <https://doi.org/10.5194/isprsarchives-XL-5-W4-351-2015>
- Dostal, C., Yamafune, K., 2018. Photogrammetric texture mapping: a method for increasing the fidelity of 3D models of cultural heritage materials. *J Archaeol Sci Reports*, 18, 430–6. <https://doi.org/10.1016/j.jasrep.2018.01.024>
- Eastman, C. M., Fisher, D., Lafue, G., Lividini, J., Stoker, D., & Yessios, C., 1974. An Outline of the Building Description System. *Research Report, 50*, Institute of Physical Planning, Carnegie-Mellon University, Pittsburgh (USA)
- Eastman, C. M., 1975. The Use of Computers Instead of Drawings in Building Design, *AIA Journal*, 63(3), 46-50.
- Eastman, C. M., Teicholz, P., Sacks, R. Liston K., 2008. *BIM Handbook. A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers, and Contractors*. Hoboken (NJ, USA): John Wiley & Sons, 13.
- Ebolese, D., Lo Brutto, M., Dardanelli, G., 2019. The integrated 3D survey for underground archaeological environment., 42, 311–317. <https://doi.org/10.5194/isprs-archives-XLII-2-W9-311-2019>
- Fai, S., Graham, K., Duckworth, T., Wood, N., Attar, R., 2011. Building Information Modelling and Heritage Documentation. Proceedings of the 23rd International Symposium, International Scientific Committee for Documentation of Cultural Heritage (CIPA), Prague, Czech Republic, 12-16.
- Fai, S., Rafeiro, J., 2014. Establishing an Appropriate Level of Detail (LoD) for a Building Information Model (BIM) – West Block, Parliament Hill, Ottawa, Canada. *ISPRS Annals*, II(5), pp. 123-130. <https://doi.org/10.5194/isprsannals-II-5-123-2014>
- Fazion, B., Treccani, D., Fregonese, L., Lombardini, N., 2024. HBIM structural model to evaluate building evolution and construction hypotheses: preliminary results. *ISPRS Archives*, 48-2/W4, 213–219. <https://doi.org/10.5194/isprs-archives-XLVIII-2-W4-2024-213-2024>

- Ferro, A., Lo Brutto, M., Ventimiglia, G.M., 2023. A Scan-to-BIM process for the monitoring and conservation of the Cultural Heritage: integration of thematic information in a HBIM model. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 48-M-2-2023, 549-556. <https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-549-2023>
- Frías, E., Previtali, M., Díaz-Vilariño, L., Scaioni, M., Lorenzo, E., 2022. Optimal scan planning for surveying large sites with static and mobile mapping systems. *ISPRS Journal*, 192, 13-32. <https://doi.org/10.1016/j.isprsjprs.2022.07.025>
- Garagnani, S., Cinti Luciani, S., 2011. The parametric model in architecture: Autodesk Revit's BIM technology. *Disegnarecon*, 4(7), 20-29
- General Services Administration, 2007. GSA BIM Guide Series 01. Published online at <http://www.gsa.gov/bim>
- Genovese, M.C., 2010. Francesco Valenti. Restauro dei monumenti nella Sicilia del primo Novecento. Edizioni Scientifiche Italiane, Napoli, 2010
- Gil, A., Arayici, Y., Kumar, B., Laing, R., 2024. Machine and Deep Learning Implementations for Heritage Building Information Modelling: A Critical Review of Theoretical and Applied Research. *ACM Journal on Computing and Cultural Heritage*, Volume 17, 3, 1-22. <https://doi.org/10.1145/3649442>
- Gollob, C., Ritter, T., Nothdurft, A., 2020. Forest Inventory with Long Range and High-Speed Personal Laser Scanning (PLS) and Simultaneous Localization and Mapping (SLAM) Technology. *Remote Sens.*, 12(9), 1509. <https://doi.org/10.3390/rs12091509>
- Guida, C.G., Limongiello, M.; Lorusso, A., Sanseverino, A., 2021. From 2D to BIM: Decay mapping projection via Visual Programming Script. *Esempi di Architettura*, 149-157.
- He, Y., Liang, B., Yang, J., Li, S., He, J., 2017. An Iterative Closest Points Algorithm for Registration of 3D Laser Scanner Point Clouds with Geometric Features. *Sensors*, 17(8), 1862. <https://doi.org/10.3390/s17081862>
- Historic England 2017 BIM for Heritage: Developing a Historic Building Information Model. Swindon. Historic England.
- Khalid, A. H., Araz, R. A., Ameer, S. M., Karzan, Abdulazeez, A., 2024. Digital preservation of heritage urban facades: An integrated approach using historic building information modeling and shape grammar analysis. *Digital Applications in Archaeology and Cultural Heritage*, 35, 2024, 2212-0548. <https://doi.org/10.1016/j.daach.2024.e00383>
- Kontoudaki, A., Georgopoulos, A., 2022. HBIM library development for a Doric temple column. *ISPRS International Archives*, XLIII-B2-2022, 1153-1158. <https://doi.org/10.5194/isprs-archives-XLIII-B2-2022-1153-2022>
- Jordan-Palomar, I., Tzortzopoulos, P., García-Valldcabres, J., Pellicer, E., 2018. Protocol to Manage Heritage-Building Interventions Using Heritage Building Information Modelling (HBIM). *Sustainability*, 10(4), 908. <https://doi.org/10.3390/su10040908>

ICOMOS International Scientific Committee for Stone (ISCS), 2008. Illustrated glossary on stone deterioration patterns, Ateliers 30 Impression, Champigny/Marne (France)

ISO 16757-1:2015: Data structures for electronic product catalogues for building services – Part 1: Concepts, architecture and model. Published online at <https://www.iso.org>

Italian Standardization Body (2017). *Evoluzione e sviluppo informativo di modelli, elaborati e oggetti* (UNI 11337-4:2017). <http://store.uni.com/catalogo/uni-11337-4-2017>

Lanzara, E., Scandurra, S., Musella, C., Palomba, D., di Luggo, A., Asprone, D., 2021. Documentation of structural damage and material decay phenomena in H-BIM systems. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 46-M-1-2021, 375-382. <https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-375-2021>

Liu, J., Azhar, S., Willkens, D., Li, B., 2023. Static terrestrial laser scanning (TLS) for heritage building information modelling (HBIM): A systematic review. *Virtual Worlds*, 2, 90–114. <https://doi.org/10.3390/virtualworlds2020006>

Lo Brutto, M., Dardanelli, G., 2017. Vision metrology and Structure from Motion for archaeological heritage 3D reconstruction: a Case Study of various Roman mosaics. *ACTA IMEKO*, 6 (3), 35-44. https://doi.org/10.21014/acta_imeko.v6i3.458

Lo Brutto, M., Sciortino, R., Garraffa, A., 2017. RPAS and TLS techniques for archaeological survey: the case study of the archaeological site of Eraclea Minoa (Italy). *ISPRS Archives*, XLII-2/W3, 433-438. <https://doi.org/10.5194/isprs-archives-XLII-2-W3-433-2017>

Lo Brutto, M., Iuculano, E., Lo Giudice, P., 2021. Integrating topographic, photogrammetric and laser scanning techniques for a Scan-to-BIM process. *ISPRS Archives*, XLIII-B2-2021, 883-890. <https://doi.org/10.5194/isprs-archives-XLIII-B2-2021-883-2021>

Lopez, F.J., Lerones, P.M., Llamas, J., Bermejo, J.G.-G., Zalama, E., 2018. A review of Heritage Building Information Modelling (HBIM). *Multimodal Technologies and Interaction*, 1-29, 2(2), 21. <https://doi.org/10.3390/mti2020021>

Lovell, L.J., Davies, R.J., Hunt, D.V.L., 2023. The application of Historic Building Information Modelling (HBIM) to Cultural Heritage: A review. *Heritage*, 6, 6691-6717. <https://doi.org/10.3390/heritage6100350>

Maiezza, P., Tata, A., 2021. Standard for geometric and informative reliabilities in HBIM models. *Disegnarecon*, 2021, 14.26: 15-1-15.10. <https://doi.org/10.20365/disegnarecon.26.2021.15>

Malinverni, E.S., Mariano, F., Di Stefano, F., Petetta, L., Onori, F., 2019. Modelling in HBIM to document materials decay by a thematic mapping to manage the Cultural Heritage: the case of “Chiesa della Pietà” in Fermo. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 42-2/W11, 777-784. <https://doi.org/10.5194/isprs-archives-XLII-2-W11-777-2019>

- Martinelli, L., Calcerano, F., Gigliarelli, E., 2022. Methodology for an HBIM workflow focused on the representation of construction systems of built heritage. *J. Cult. Herit.*, 55, 277–289. <https://doi.org/10.1016/j.culher.2022.03.016>
- Martinez-Carricondo, P., Carvajal-Ramirez, F., Yero-Paneque, L., Aguera-Vega, F., 2021. Combination of HBIM and UAV photogrammetry for modelling and documentation of forgotten heritage. Case study: Isabel II dam in Níjar (Almería, Spain). *Herit. Sci.*, 9, 95. <https://doi.org/10.1186/s40494-021-00571-8>
- Masciotta, M.G., Sanchez-Aparicio, L.J., Oliveira, D.V., Gonzalez-Aguilera, D., 2023. Integration of laser scanning technologies and 360° photography for the digital documentation and management of cultural heritage buildings. *Int. J. Archit. Herit.*, 17, 56–75. <https://doi.org/10.1080/15583058.2022.2069062>
- Mateus, L., Fernández, J., Ferreira, V., Oliveira, C., Aguiar, J., Gago, A. S., Pacheco, P., Pernão J., 2019. Terrestrial laser scanning and digital photogrammetry for heritage conservation: Case study of the historical walls of Lagos, Portugal, 2019. <https://doi.org/10.5194/isprs-archives-XLII-2-W11-843-2019>
- Matrone, F., Lingua, A., Pierdicca, R., Malinverni, E. S., Paolanti, M., Grilli, E., Remondino, F., Murtiyoso, A., Landes, T., 2020. A benchmark for large-scale Heritage point cloud semantic segmentation. ISPRS Archives, XLIII-B2-2020, 1419-1426. <https://isprs-archives.copernicus.org/articles/XLIII-B2-2020/1419/2020>
- Mengiste, E., Prieto, S.A., De Soto, B.G., 2022. Comparison of TLS and photogrammetric 3D data acquisition techniques: Considerations for developing countries. *ISARC, Proceedings of the International Symposium on Automation and Robotics in Construction*, Bogotá, Colombia, 12–15 July 2022; IAARC Publications: Pittsburgh, PA, USA, 2022; Volume 39, pp. 491–494
- Miky, Y., Alshawabkeh, Y. Baik, A., 2024. Using deep learning for enrichment of heritage BIM: Al Radwan house in historic Jeddah as a case study. *Herit Sci* 12, 255. <https://doi.org/10.1186/s40494-024-01382-3>
- Mongitore, A., 1739. Dell' Istoria sagra di tutte le Chiese, Conventi Monasteri, spedali et altri luoghi pii della città di Palermo. Manoscritto, BCP, Qq E 5
- Moropoulou, A., Labropoulos, K.C., Delegou, E.T., Karoglou, M., Bakolas, A., 2013. Non-destructive techniques as a tool for the protection of built cultural heritage. *Construction and Building Materials*, 48, 1222-1239. <https://doi.org/10.1016/j.conbuildmat.2013.03.044>
- Moyano, J., Nieto, J.E., Nieto, J. A. L., Bruno, S., 2021. Semantic interpretation of architectural and archaeological geometries. Point cloud segmentation for HBIM parametrisation. *Automation in Construction*, 130. <https://doi.org/10.1016/j.autcon.2021.103856>
- Moyano J., Carreno Euan E., Nieto J., Gil-Arizon I., Bruno S., 2022. Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project. *Automation in Construction*, 123. <https://doi.org/10.1016/j.autcon.2022.104551>
- Murphy, M., McGovern, E., Pavia, S., 2007. Parametric vector modelling of laser and image surveys of 17th century classical architecture in Dublin. In D. Arnold, A. Chalmers, F. Niccolucci (Eds.), *Proceedings of VAST 2007, Future Technologies to*

Empower Heritage Professionals, The 8th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage, (pp. 79-84). Aire-la-Ville (CH): Eurographics.

Murphy, M., McGovern, E., Pavia, S., 2009. Historic building information modelling (HBIM). *Structural Survey* 27 (4), 311–327. <http://dx.doi.org/10.1108/02630800910985108>

Murphy, M., 2012. *Historic Building Information Modelling (HBIM). For Recording and Documenting Classical Architecture in Dublin 1700 to 1830*. (Tesi di dottorato, School of Engineering Trinity College Dublin, Department of Civil, Structural & Environmental Engineering)

Murphy, M., McGovern, E., Pavia, S., 2013. Historic Building Information Modelling – Adding intelligence to laser and image-based surveys of European classical architecture. *ISPRS Journal of Photogrammetry and Remote Sensing*, 76, 89-102. <https://doi.org/10.1016/j.isprsjprs.2012.11.006>

NBIMS_US_V3 Complete standard reference, 2011. <https://www.nibs.org>

NBS, 2011. National BIM Report March 2011. RIBA Enterprises Ltd. <https://www.thenbs.com>

NBS, 2020. *10th National BIM Report*. <https://www.thenbs.com>

Nieto-Julián, E., Bruno, S., Moyano, J., 2024. An Efficient Process for the Management of the Deterioration and Conservation of Architectural Heritage: The HBIM Project of the Duomo of Molfetta (Italy). *Remote Sensing*, 16(23), 4542. <https://doi.org/10.3390/rsVolk et al., 201434542>

Nikoohehmat, S., Peter, M., Oude Elberink, S., Vosselman, G., 2017. Exploiting Indoor Mobile Laser Scanner Trajectories for Semantic Interpretation of Point Clouds. *Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, IV-2/W4, 355–362. <https://doi.org/10.5194/isprs-annals-IV-2-W4-355-2017>

Oreni, D., Brumana, R., Della Torre, S., Banfi, F., Barazzetti, L., Previtali, M., 2014. Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila). *ISPRS Annals*, II(5), pp. 267-273. <https://doi.org/10.5194/isprsanals-II-5-267-2014>

Patricolo, G., 1880. La chiesa della Trinità di Delia presso Castelvetro, monumento del XII secolo scoperto il 31 Marzo 1880. In *Archivio Storico Siciliano*, V, Palermo 1880, 51-66

Patricolo, G., 1883. *Il monumento arabo scoperto in febbraio 1882 e la contigua chiesa di S. Giovanni degli Eremiti*. In «ASS», n. s., anno VII, Palermo 1883, 170-183

Penjor, T., Banihashemi, S., Hajirasouli, A., Golzad, H., 2024. Heritage Building Information Modelling (HBIM) for Heritage Conservation: Framework of Challenges, Gaps, and Existing limitations of HBIM. *Digital Applications in Archaeology and Cultural Heritage*, e00366. <https://doi.org/10.1016/j.daach.2024.e00366>

Pepe, M., Costantino, D., 2021. UAV Photogrammetry and 3D Modelling of Complex Architecture for Maintenance Purposes: the Case Study of the Masonry Bridge on the Sele River, Italy. *Periodica Polytechnica Civil Engineering*, 65(1), 191–203. <https://doi.org/10.3311/PPci.16398>

- Pepe, M., Alfio, V. S., Costantino, D., 2022. UAV Platforms and the SfM-MVS Approach in the 3D Surveys and Modelling: A Review in the Cultural Heritage Field. *Applied Sciences*, 12(24), 12886. <https://doi.org/10.3390/app122412886>
- Pepe, M., Garofalo, A. R., Costantino, D., Tana, F. F., Palumbo, D., Alfio, V. S., Spacone, E., 2024. From Point Cloud to BIM: A New Method Based on Efficient Point Cloud Simplification by Geometric Feature Analysis and Building Parametric Objects in Rhinoceros/Grasshopper Software. *Remote Sensing*, 16(9), 1630. <https://doi.org/10.3390/rs16091630>
- Pierdicca, R., Paolanti, M., Matrone, F., Martini, M., Morbidoni, C., Malinverni, E. S., Frontoni, E., & Lingua, A. M., 2020. Point Cloud Semantic Segmentation Using a Deep Learning Framework for Cultural Heritage. *Remote Sensing*, 12(6), 1005. <https://doi.org/10.3390/rs12061005>
- Pocobelli, D. P., Boehm, J., Bryan, P., Still, J., Grau-Bovè, J., 2018. Building Information Models for monitoring and simulation data in Heritage Buildings. *ISPRS Archives*, XLII-2, pp. 909-916. <https://doi.org/10.5194/isprs-archives-XLII-2-909-2018>
- Pritchard, D., Rigauts, T., Ripanti, F., Ioannides, M., Brumana, R., Robert Davies, R., Avouri, E., Clifffen, H., Joncic, N., Osti, G., 2021. Study on quality in 3D digitisation of tangible Cultural Heritage. In *Proceedings of the Joint International Event 9th ARQUEOLÓGICA 2.0 & 3rd GEORES*, Valencia, Spain, 26–28 April 2021; pp. 1–7. <http://dx.doi.org/10.4995/arqueologica9.2021.12113>
- Quattrini, R., Malinverni, E.S., Clini, P., Nespeca, R., Orlietti, E., 2015. From TLS to HBIM: high quality semantically-aware 3D modelling of complex architecture. *ISPRS Archives*, 40(5/W4), pp. 367-374. <https://doi.org/10.5194/isprsarchives-XL-5-W4-367-2015>
- Quattrini, R., Pierdicca, R., Morbidoni, C., Malinverni, E.S., 2017. Conservation-oriented HBIM. The BIM explorer tool. *ISPRS Archives*, Volume XLII-5/W1, 275-281. <https://doi.org/10.5194/isprs-archives-XLII-5-W1-275-2017>
- Radanovic, M., Khoshelham, K., Fraser, C., 2020. Geometric accuracy and semantic richness in heritage BIM: A review. *Digit. Appl. Archaeol. Cult. Herit.*, 19, 1-11. <https://doi.org/10.1016/j.daach.2020.e00166>
- Rashdi, R., Martínez-Sánchez, J., Arias, P., Qiu, Z., 2022. Scanning Technologies to Building Information Modelling: A Review. *Infrastructures*, 7, 49. <https://doi.org/10.3390/infrastructures7040049>
- Rinaudo, F., Scolamiero, V., 2021. Comparison of multi-source data, integrated survey for complex architecture documentation. *ISPRS Archives*, 46-M-1-2021, 625–631. <https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-625-2021>
- Rocha, G., Mateus, L., Fernández, J., Ferreira, V., 2020. A Scan-to-BIM Methodology Applied to Heritage Buildings. *Heritage*, 3(1). <https://doi.org/10.3390/heritage3010004>
- Roman, O., Avena, M., Farella, E. M., Remondino, F., Spanò, A., 2023. A semi-automated approach to model architectural elements in Scan-to-BIM processes. *ISPRS Archives*, XLVIII-M-2-2023, 1345-1352. <https://isprs-archives.copernicus.org/articles/XLVIII-M-2-2023/1345/2023>

- Ryding, J., Williams, E., Smith, M. J., Eichhorn, M. P., 2015. Assessing Handheld Mobile Laser Scanners for Forest Surveys. *Remote Sensing*, 7(1), 1095-1111. <https://doi.org/10.3390/rs70101095>
- Sacchi, L., 2016. Il punto sul B.I.M. / On B.I.M., *Disegnarecon*, 9(16), 1.1-1.8.
- Sakellaris, E., Siountri, K., Anagnostopoulos, C.N., 2022. Conservation of Greek Neoclassical Facade Elements Through Their Integration in a HBIM Library. In: Moropoulou, A., Georgopoulos, A., Doulamis, A., Ioannides, M., Ronchi, A. (eds) *Transdisciplinary Multispectral Modelling and Cooperation for the Preservation of Cultural Heritage*. TMM_CH 2021. Communications in Computer and Information Science, vol 1574. Springer, Cham. https://doi.org/10.1007/978-3-031-20253-7_9
- Sammartano, G., Spanò, A., 2018. Point clouds by SLAM-based mobile mapping systems: Accuracy and geometric content validation in multisensor survey and stand-alone acquisition. *Appl. Geomat.*, 10, 317–339. <https://doi.org/10.1007/s12518-018-0221-7>
- Sammartano, G., Previtali, M., Banfi, F., 2021. Parametric generation in HBIM workflows for SLAM-based data: discussing expectations on suitability and accuracy. Proceedings of the joint international event 9th ARQUEOLÓGICA 2.0 & 3rd GEORES, Valencia (Spain). 26–28 April 2021, 374-388. <https://doi.org/10.4995/Arqueologica9.2021.12155>
- Sampaio, A., Martins Gomes, A., Sanchez-Lite, A., Zulueta, P., Gonzalez-Gaya, C., 2021. Analysis of BIM Methodology Applied to Practical Cases in the Preservation of Heritage Buildings. *Sustainability*, 13(6), 3129. <https://doi.org/10.3390/su13063129>
- Santagati, C., Lo Turco, M. Garozzo, R., 2018. Reverse information modeling for historic artefacts: Towards the definition of a level of accuracy for ruined heritage', in *ISPRS Archives*, XLII, 2, 1007. <https://doi.org/10.5194/isprs-archives-XLII-2-1007-2018>
- 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*, 36, 102804 2021. <https://doi.org/10.1016/j.jasrep.2021.102804>
- Santoni, A., Martín-Talaverano, R., Quattrini, R., Murillo- Fragero, J. I., 2021. HBIM approach to implement the historical and constructive knowledge. The case of the Real Colegiata of San Isidoro (León, Spain). *Virtual Archaeology Review*, 12(24), 49-65. <https://doi.org/10.4995/var.2021.13661>
- Saricaoglu, T., Saygi, G., 2022. Data-driven conservation actions of heritage places curated with HBIM. *Virtual Archaeology Review*, 13(27), 17–32. <https://doi.org/10.4995/var.2022.17370>
- Sattanino, E., 2018. I LOI nelle scale di LOD USA, UK, ITA, *Ingenio*, <https://www.ingenio-web.it/18926-i-loi-nelle-scale-di-lod-usa-uk-ita>
- Saygi, G., Remondino, F., 2013. Management of Architectural Heritage Information in BIM and GIS: State-of-the-Art and Future Perspectives. *International Journal of Heritage in the Digital Era*, 2(4), 695-713. <https://doi.org/10.1260/2047-4970.2.4.695>

- Scianna, A., La Guardia, M., 2019. Survey and Photogrammetric Restitution of Monumental Complexes: Issues and Solutions—The Case of the Manfredonic Castle of Mussomeli. *Heritage*, 2, 774–786. <https://doi.org/10.3390/heritage2010050>
- Shao, J., Zhang, W., Mellado, N., Wang, N., Jin, S., Cai, S., Luo, L., Lejemble, T., Yan, G., 2020. SLAM-aided forest plot mapping combining terrestrial and mobile laser scanning. *ISPRS Journal*, 163, 214-230. <https://doi.org/10.1016/j.isprsjprs.2020.03.008>
- Shen, J., Ren, R., Dib, H.N., McGraw, T., Habib, M., 2021. Machine Learning Segmentation and Classification Algorithm to Support Simulated Point Cloud As-Built Model Applications. *Computing in Civil Engineering 2021*, 942-949. <https://ascelibrary.org/doi/abs/10.1061/9780784483893.116>
- Simeone, D., Cursi, S., Acierno, M., 2019. BIM semantic enrichment for built heritage representation. *Autom. Constr.*, 97, 122–137. <https://doi.org/10.1016/j.autcon.2018.11.004>
- Tisserye, P., 1995. Un'abbazia basiliana del XIII secolo. Santa Maria della Grotta a Marsala: Lo scavo e i materiali. In *Archeologia e architettura*; Ediprint: Siracusa, Italy, 1995; Volume 1, p. 247
- Tomaselli, F., 2023. Palermo-Patricolo: il ripristino dell'architettura dei Normanni nel programma del riscatto ottocentesco della città. Unipapress, Palermo, 2023
- Torregrossa, T., 2013. San Giovanni degli Eremiti a Palermo. Edizioni Caracol, Palermo, 2013
- Tucci, G., Bonora, V., Conti, A., Fiorini, L., 2017. High-Quality 3d Models and Their Use in a Cultural Heritage Conservation Project. *ISPRS Archives*, 42, 687–693. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-687-2017>
- Tucci, G., Conti, A., Fiorini, L., Corongiu, M., Valdambrini, N., & Matta, C., 2019. M-BIM: a new tool for the Galleria dell'Accademia di Firenze. *Virtual Archaeology Review*, 10(21), pp. 40-55. <https://doi.org/10.4995/var.2019.11943>
- UNI, 2017. *Evoluzione e sviluppo informativo di modelli, elaborati e oggetti* (UNI 11337-4:2017). <http://store.uni.com/catalogo/uni-11337-4-2017>
- Valenti, F., 1921. Progetto dei lavori urgenti abbisognevoli per completare il rinsaldamento delle strutture murarie ed eseguire i due tetti delle navatine della chiesa normanna di San Giovanni dei Leprosi in Palermo. ACS, DGABA, Div. I, 1920-1924, BN 1358
- Van Nederveen, G.A., Tolman, F.P., 1992. Modelling Multiple Views on Buildings, *Automation in Construction*, 1(3), pp. 215-224. [https://doi.org/10.1016/0926-5805\(92\)90014-B](https://doi.org/10.1016/0926-5805(92)90014-B)
- Volk, R., Stengel, J., Schumann, J., 2014. Building Information Modelling (BIM) for existing buildings. Literature review and future needs. *Autom. Constr.*, 38, 109–127. <https://doi.org/10.1016/j.autcon.2013.10.023>
- Volpe, M., 2007 Manutenzione e restauri in una fabbrica medievale siciliana. La chiesa della SS. Trinità di Delia nel 1527 e nel 1742. In *Lexicon. Storie e architettura in Sicilia*, 4, 53–56

- Wang, C., Cho, Y. K., Kim, C., 2015. Automatic BIM component extraction from point clouds of existing buildings for sustainability applications, *Automation in Construction*, 56, pp. 1-13. <https://doi.org/10.1016/j.autcon.2015.04.001>
- Wang, Q., Guo, J., Kim, M., 2019. An Application Oriented Scan-to-BIM Framework. *Remote Sens.*, 11, 365. <https://doi.org/10.3390/rs11030365>
- Wu, C., Yuan, Y., Tang, Y., Tian, B., 2022. Application of Terrestrial Laser Scanning (TLS) in the Architecture, Engineering and Construction (AEC) Industry. *Sensors*, 22(1):265. <https://doi.org/10.3390/s22010265>
- Xin, Y., Wang, R., Wang, X., Xiao, Z., Lin, J., 2022. High-Resolution Terrain Reconstruction of Slot Canyon Using Backpack Mobile Laser Scanning and UAV Photogrammetry. *Drones*, 6, 429, 1-23. <https://doi.org/10.3390/drones6120429>
- Zeitouni, S., Asslan, H., 2025. Adopting the HBIM system as a basis for preserving the architectural heritage in the city of Aleppo (Al-Matbakh al- Ajami building as a case study). *International Journal of BIM and Engineering Science (IJBES)*, published online May 2025. <https://doi.org/10.54216/IJNS.xxxxxxx>
- Zhang, W., Qi, J., Wan, P., Wang, H., Xie, D., Wang, X., Yan, G., 2016. An Easy-to-Use Airborne LiDAR Data Filtering Method Based on Cloth Simulation. *Remote Sensing*, 8, 501. <https://doi.org/10.3390/rs8060501>
- Zlot, R., Bosse, M., Greenop, K., Jarzab, Z., Juckes, E., Roberts, J., 2014. Efficiently capturing large, complex cultural heritage sites with a handheld mobile 3D laser mapping system. *Journal of Cultural Heritage*, 15, 670–678. <https://doi.org/10.1016/j.culher.2013.11.009>