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BASILICA DI SAN GIACOMO IN COMO (ITALY): DRAWINGS AND HBIM TO MANAGE ARCHEOLOGICAL, CONSERVATIVE AND STRUCTURAL ACTIVITIES

M. Garramone [1], D. Jovanovic[1], D. Oreni [1*], L. Barazzetti[1], M. Previtali[1], F. Roncoroni[2], A. Mandelli[1], M. Scaioni [1]

[1] Dept. of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, via Ponzio 31, 20133 Milano, Italy
(manuel.garramone, dina.jovanovic, daniela.oreni, luigi.barazzetti, mattia.previtali, alessandro.mandelli, marco.scaioni)@polimi.it
[2] Polo territoriale di Lecco, Politecnico di Milano, via Previati 1c, 23900 Lecco, Italy – fabio.roncoroni@polimi.it

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ABSTRACT:

This paper aims at presenting the recording and modelling work developed in the framework of restoration and conservation activities for the Basilica di San Giacomo in Como, Italy, whose construction started in the 11th century**.** The project started in 2022 and involved the application of the Historical Building Information Model (HBIM) methodology through a Scan-to-BIM approach was assessed. High-detailed 3D survey techniques were used to acquire the specific shape of the church and annexed buildings. Then, through different modelling strategies, the HBIM environment allowed the representation of all the architectural elements. The purpose of this model is to have essential support to plan the restoration activities and to give the different experts involved a single three-dimensional tool for managing all the information during the development of the construction works. The possibility to update the model over time with geometric and non-geometric information will provide a powerful tool also for other future activities, such as the installation of a monitoring system that could reveal the displacements of bearing elements of the church.

1. INTRODUCTION

The conservation activities of the Romanesque church of the Basilica di San Giacomo (St. James) in Como, Italy, started at the beginning of 2022, thanks to a legacy left by a generous donator, and are still ongoing (Della Torre and Rajabi, 2022).
The documentation, the geometrical survey, the archaeological investigation, and the diagnostic activities represent the first step in the church's knowledge, together with the analysis of the materials.
That information is fundamental to understanding the transformations over the centuries of the different structures, and their actual state of conservation, as well as to plan and manage future activities and maintenance.

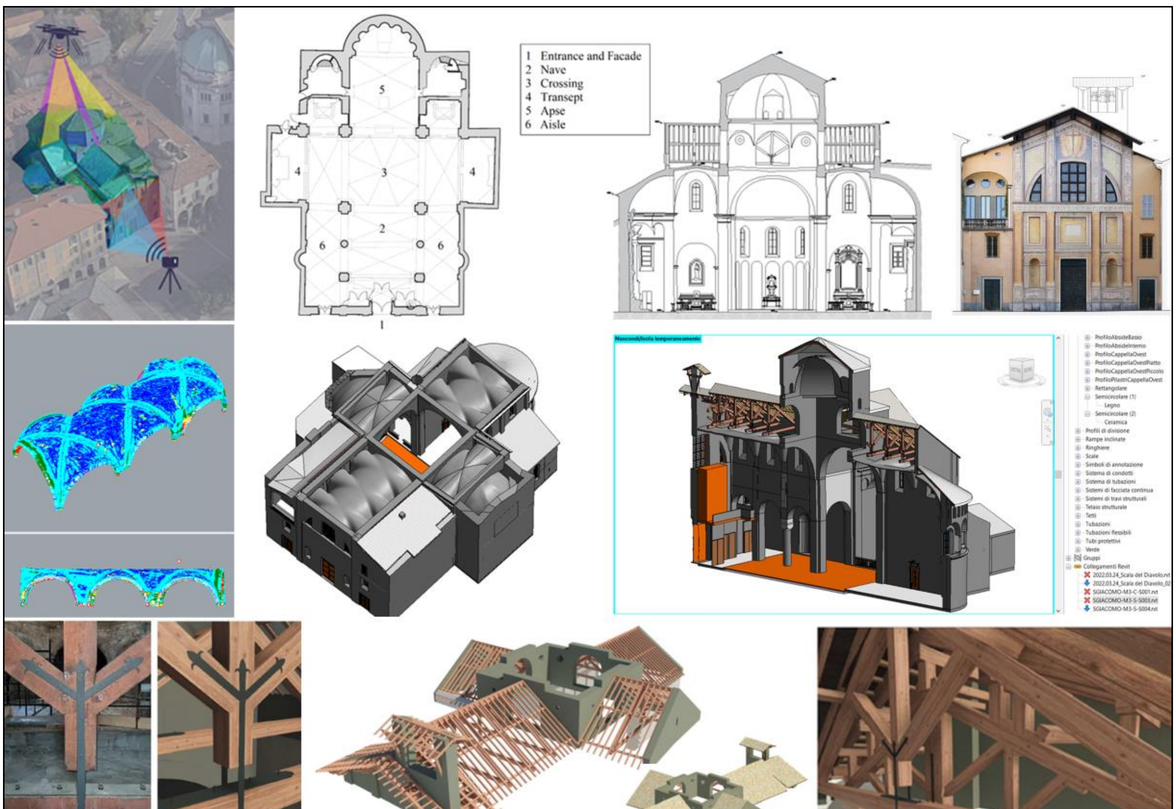

Figure 1. San Giacomo church: From digital recording to measured drawings and HBIM.

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The aim of the general project is to restore the Basilica to obtain a space that could be added to the new museum of Como Cathedral, creating a cultural system able to enhance the entire cultural heritage of the church. Thus, the project required an active and complex collaboration between different specialists and experts, among which historians, restorers, architects, archaeologists, and engineers.
Different activities have been planned for the church structures, from the conservation of the painted surfaces to the strengthening of the roof wooden elements and of the semi-circular columns of the apsis.

Starting from the historical information and the previous drawings available, the new studies and surveys of the church were done with the aim of creating the essential support to plan the restoration and to give the different experts involved a single three-dimensional tool for managing all the information during the construction activities. Therefore, according to the different needs of the expert groups, a Historical Building Information Model (HBIM) of the church was created, to connect all the different data available, to be implemented during the restoration activities (Oreni et al., 2014).

Figure 1 illustrates the different phases of the surveying work carried out, which involved acquiring and processing digital information with terrestrial laser scanning and digital photogrammetry, and the creation of measured drawings and a HBIM of the church.

2. HISTORICAL NOTES

The St. James church was founded by Bishop Rainaldus during the 11th Century next to the Cathedral and the Bishop Palace (*Broletto*), in the middle of the walled city of Como. Historians agree that St. James was part of the Cathedral complex from the Middle Ages until the 16th Century, representing the symbolic and operational centre of the political life of the town. Until 1580, the Basilica had a much longer nave than today, closing off the public square towards the Cathedral (Figure 2). There are several hypotheses regarding the presence of one or more bell towers on the façade, the position of which was certainly aligned with the one of the *Broletto* palace (Catalano, 2004).

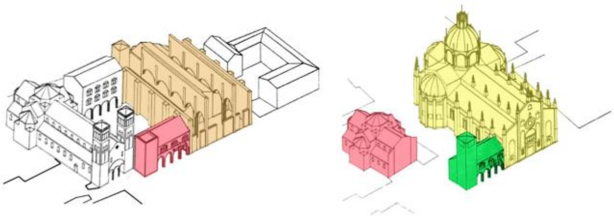

Figure 2. Archaeological hypothesis about the shape of the church and the transformation that occurred from the Middle Agea until the 16th Century (modified from Cani, 2016).

During the Middle Ages, numerous buildings sprang up next to the church, and its importance gradually declined in favour of the nearby Cathedral. This process continued up until 1578 when the severe state of decay resulted in the decision to demolish part of the building. The church was thus halved in length, with the demolition of fine bays, and in the following decades, the Baroque transformation of the remained part of the ancient medieval church began. In 1585 a new façade was built to close the truncated nave, following a design by the architect Giovanni Antonio Piotti da Vacallo. This painted façade, which still exists today, is characterized by its faux marble decoration and large thermal window, with the "Triumph of the Cross" depicted at the top of the façade, between the two roof pitches.

Today the only remaining 16th Century truss is the one positioned close to the façade. On the walls of the nave area, stratigraphic signs related to the cut made to shorten the church and insert the new façade masonry are immediately recognizable. In this area the height of the roof is lower than the rest of the roof, making the transformation that took place even more evident, as shown in Figure 3.

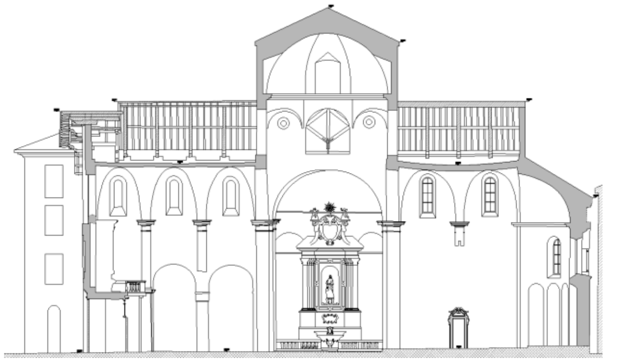

Figure 3. Longitudinal Cross Section of the Church.

In 1672 the parish of St. James was assigned by Pope Clement X to the fathers of the Congregation of the Oratory of St. Philip Neri. Almost a century later the demolition of the first part of the church, radical interventions were made to the building, completely distorting its original form and proportions. Columns were transformed into large pillars, cross vaults were built in the nave, the side apses were closed, transforming them into sacristies, and the floor level was raised (Catalano, 2004).
In 1798 and 1800 the French suppressed the Congregation, and all its property was requisitioned and put up for sale. In the following years St. James, reopened for worship and became a subsidiary church of the Cathedral. The different phases of transformation of the church over the centuries are well documented by the studies and surveys conducted by Fernand de Dartein in 1872-1874 (Leoni, 2015), see an example in Figure 4.

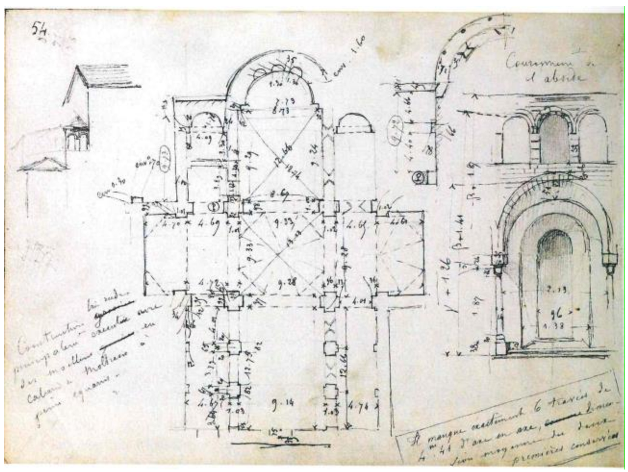

Figure 4. Fernand De Dartein, 1 July 1872 (Guarisco et al., 2015, p.156).

A pretty hard restoration of the church was conducted in 1970, which put into light many different medieval elements, removing several layers added later (Guarisco et al., 2015). Restoration work became necessary because of the imminent

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risk of collapse of the *tiburium*. Thus, this part was restored to its primitive octagonal plan and mullioned windows, traces of which had been found, and the eight tuff *oculi* were reopened in its masonry. The trusses were replaced, raising them, and restoring them to their ancient inclination, to recover the four large arches at the base of the *tiburium*, through which the trusses themselves could be glimpsed. The roofing of the northern arm of the transept was also rebuilt.

Today the church consists of three naves, whose bays are covered by cross vaults, and are marked by columns with Romanesque capitals, a transept, and a semi-circular apsis with niches (Figure 5). The church is incorporated within a complex and articulated block, which resulted in more involved surveying operations.

Figure 5. Internal views of the Church, the naves and the central apsis.

3. DIGITAL RECORDING STRATEGY

The complex geometry of the church required a combination of photogrammetric and terrestrial laser scanning (TLS) data, which were registered in a common reference system using ground control points – GCPs (Murphy et al., 2013). As mentioned in the previous sections, the church is completely encapsulated (on three sides) by other buildings and has a single direct access only on the main façade. Therefore, a geodetic network was installed and measured to connect those parts only accessible from the other surrounding buildings (including private buildings, shops, bars, and restaurants), which resulted in the progressive combination of several acquisition campaigns.

The overall workflow for data acquisition is shown in Figure 6 and is based on the traditional recording methods used for heritage buildings and sites.

The first phase of the work consists of the installation of a permanent geodetic network, using different typologies of permanent points (mainly retro-reflective targets and points materialized on stable metal elements on the square.) The network was then measured with a Leica TS30 theodolite, and Least-Squares adjustment provided 3D point coordinates with a precision better than ±2-3mm. Some points in the square were also measured with differential GNSS techniques using an Emlid Reach RS2 receiver and the correction service SPIN3 GNSS. The adopted method for data acquisition was VRS (Virtual Reference Station) with corrections received via the Internet.

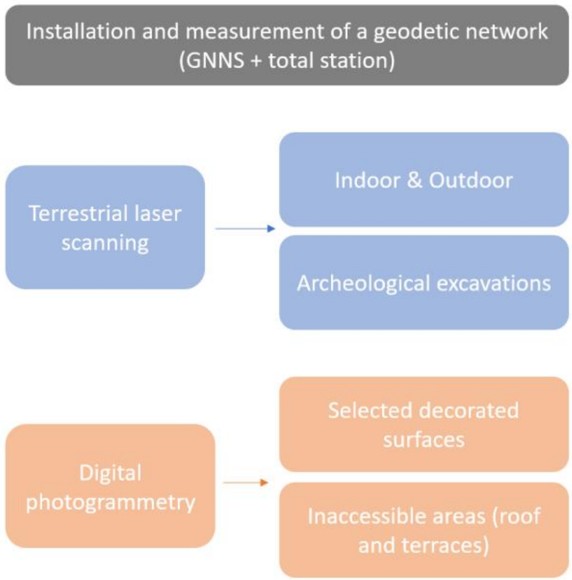

Figure 6. The main methods used for the digital documentation of the church.

The reference system for GNSS measurements is ETRF2000-RDN (epoch 2008.0), and geodetic coordinates (latitude, longitude) were converted into the cartographic grid with the UTM projection (North-Est), Zone 32N. The ellipsoid elevation was transformed into the orthometric value using the geoid model ITALGEO 2005 provided by the IGMI (Italian Geographic Military Institute). The set of points measured in both the cartographic reference system and the local network was used to georeferenced the entire local network using a rigid 3 parameter transformation (for East and North), and a simple translation for the elevation value. As can be seen, we decided to exclude the scale correction (in this case the scale factor is 1) to ensure consistent measurements between TLS point clouds and the georeferenced network. The analysis of transformation residuals resulted better than ±30 mm, which is consistent with the expected precision of GNSS-VRS coordinates.

A set of more than 300 laser scans was then acquired and registered with a precision of about ±3-4mm, providing (almost) complete coverage of the entire complex, including spaces with difficult accessibility, such as the vaulted roof.
Data registration was carried out with targets, mainly spheres and checkerboards. Several targets were also measured with the theodolite, resulting in the opportunity to register scans directly in the network reference system. Two laser scanners were used to speed up data acquisition: a Faro Focus HDR130 and a Faro Focus s70.

Scans were also acquired from windows and terraces of the buildings around the church so that the external elevations were also directly scanned, providing information about wall thickness. Additional laser scans were then acquired inside the church to record the archaeological excavations, integrating the dataset acquired by a team of archaeologists, and revealing the foundations of some selected columns. Some illustrative images of the terrestrial acquisition are shown in Figure 7.

Some additional (smaller) geodetic networks were also necessary to integrate spaces not accessible during the first phase of the survey. As mentioned, other buildings surround the church, and access to specific areas was subject to additional constraints. Additional laser scans were then acquired depending on the availability to access private buildings. In this sense, the opportunity to use a combination of TLS data registered with additional GCPs acquired with second-order networks (adjusted using GCPs of the overall network) allowed for reducing the acquisition time, which was an important factor in capturing these additional spaces.

Figure 7. Some images showing the acquisition phase by terrestrial laser scanning (TLS).

Eventually, an unmanned aerial vehicle (UAV) survey was carried out to capture a photogrammetric block covering the highest external part of the church and the roof. At the time of digital recording, a lifeline was still unavailable on the roof, preventing access to the upper parts of the church. The flight was carried out according to European and Italian regulations. Based on a Structure-from-Motion approach (Barazzetti et al., 2009), a dense point cloud of the roof and a high-resolution orthophoto of the entire area were obtained. During bundle block adjustment, some laser scanning and theodolite points were used as GCPs.

Figure 8. Point clouds produced based on UAV-Photogrammetry showing the church and the surrounding buildings.

The final residuals on a set of check points were about ±5-6 mm, which is sufficient to produce metric deliverables at a scale of 1:50.
An image of the final point cloud is shown in Figure 8, demonstrating how the church is encapsulated on three sides by other buildings. The point cloud was then used together with other deliverables of the project to design and install a lifeline and position the crane during the restoration activity.

4. DRAWINGS AND HBIM MODELLING FOR THE MANAGEMENT OF RESTAURATION ACTIVITIES

The accurate surveying data were first used to create two-dimensional representations of the church, at scale 1:50. These drawings were fundamental for the experts to design the restoration and consolidation works and to define in a timely manner the position and attachments of the internal and external scaffolds. Similarly, the request expressed by the design team, was to have a complete HBIM model of the church available, so that all site data could be managed in a single digital environment, which must be interoperable and continuously updatable. In fact, some works and diagnostic survey operations (e.g., archaeological) take place simultaneously and require real-time updating of graphic and information documents.

To this aim, data acquired on-site, and processed into point clouds, were used for the HBIM model. This approach is called Scan-to-BIM (Murphy et al., 2009). It can be defined as the process of combining photogrammetry and laser scanning to develop an informative model by employing BIM software (Rashdi et al., 2022). Although Scan-to-BIM provides the most efficient, less time-consuming, and non-invasive data acquisition (Buill et al., 2020), using the point cloud for the modelling phase is still considered a bottleneck (Chiabrando et al., 2017). The main reason is the scarce flexibility of BIM tools in managing irregular and complex architectural shapes. This implies that the uniqueness of elements must be recognized, interpreted, and modelled by the expertise of operators (Aricò et al., 2023). Moreover, since automated and semi-automated methods of components detection in point clouds are still under development (Donato et al., 2017), manual methods are used to segment point clouds, extract elements, and model objects.

Considering this scenario, once the laser scanner point clouds were filtered and cleaned, a modelling strategy was defined considering the Level-of-Detail (LoD) to achieve and the tolerated approximation. To create a model usable for different analyses, a nominal scale of 1:100 was taken as a reference. Accuracy was quantified by adopting the concepts of Graphic Error (G.E., the smallest detail that can be represented at a given scale; at 1:100 scale G.E. = 20 mm) and Tolerance (2 or 3 times the G.E. value).

The result is an accuracy (tolerance) of 40÷60 mm. Moreover, operational specifications were defined before any modelling steps, specifying a unique coding system for digital models, elements, and materials. In particular, after the semantic decomposition of point clouds, elements were listed considering technological units derived from the UNI 8290 standard (UNI - Ente Italiano di Normazione, 1981), see Figure 9.

CLASSES TECHNOLOGICAL UNITS	CATEGORY / TECHNICAL ELEMENT	CODE
Foundations	Wall	FOMu
	Pillar	FOPi
	Plinth	FOPi
Vertical structures	Wall (load-bearing)	SVMu
	Partition wall (non-load-bearing)	SVPa
	Column (base + shaft + capital)	SVCo
	Pillar (base + shaft + capital)	SVPi
	Parasta	SVPa
Horizontal structures	Floor	EOPa
	Vault	SOVo
	Arc	SOAr
	Dome	SOCu
	Terrace	SOTe
	Balcony	SOBa
Vertical connection elements	Stairs	CVSc
	Ramp	CVRa

Figure 9. Examples of technological units, categories, and codes of the architectural elements.

To create complex parametric elements, such as vaults, columns, and capitals, geometric modelling modes were chosen from time to time that allowed the true dimensions and characteristics of the objects to be faithfully represented. All in such a way as to maintain even geometric irregularities and deformations where present. The modelling process has been divided into three main strategies reflecting the increasing complexity of the elements:

1. Modelling directly from the point cloud;
2. Extracting 2D CAD drawings to use as modelling profiles;
3. Generating NURBS (Non-Uniform Rational Basis Spline) surfaces to model irregular objects.

4.1 Technical 2D drawings

Two-dimensional drawing is a traditional instrument for documentation of the cultural heritage. Technical drawings can present the hierarchy of elements and the way they are positioned and built. They were produced on a scale of 1:50 using *Autodesk AutoCAD*® software, version 2022. Complex structures, decorative elements, and historical stratigraphy visible in the church required different materials to produce technical drawings. Next to the point cloud, which provided the main data about the geometry of the space, photogrammetric techniques were applied to produce orthophotos and draw the roof plan and the frontal façade. These orthophotos were able to present details in the required scale and to give information about the material and state of conservation of the external surfaces of the building. Additionally, other collected material has been consulted for the creation of accurate and complete technical drawings. This refers to the use of photographic material, videos obtained with a 360° camera (see Barazzetti et al., 2020) and a drone (i.e., drone was used for high places in the interior such as the cupola and for the exterior, it surveyed context and roofing) and *in-situ* survey to obtain direct measurements, which can compensate for ‘blind spots’ in the laser scanner recording. The process of data interpretation and comparison with other collected information was required. This part of the work is necessary prior to entering the modelling phase of complex elements that could not be surveyed only from TLS point cloud.

Nevertheless, the point cloud allowed the greatest flexibility to create a digital twin of the church that could be sliced to the view of interest. In the potentially numberless technical drawings that could be produced, the working group targeted those that will be used for the preservation activities that will take place. The cross-sections, plans and elevations were determined together with the project team that will work on the restoration and engineers working on the historic structural consolidation. They were specifically focused on a few features - strengthening the roof structure, apse and spiral staircase – thus the cross-section and plans were made accordingly. In total, five drawings of the façade elevations were produced, to which for the main façade and roofing plan the orthophotos were integrated. Six cross-sections were done in the transversal and longitudinal direction, presenting the internal structure and relation with neighbourhood buildings. Cross-sections were used to demonstrate the complexity of decorative elements of the church and, most importantly to display structural elements which are not visible from the interior of the church. This refers specifically to the roof constructions, where the accessibility is limited and the survey can be aggravated due to the number of wooden truss elements, uneven or decayed flooring, narrow space, and insufficient lighting conditions. In these situations, photographic acquisition and direct measurements are necessary to be collected, as a complementary material to the point cloud for making technical drawings in scale 1:50 (Figure 10).

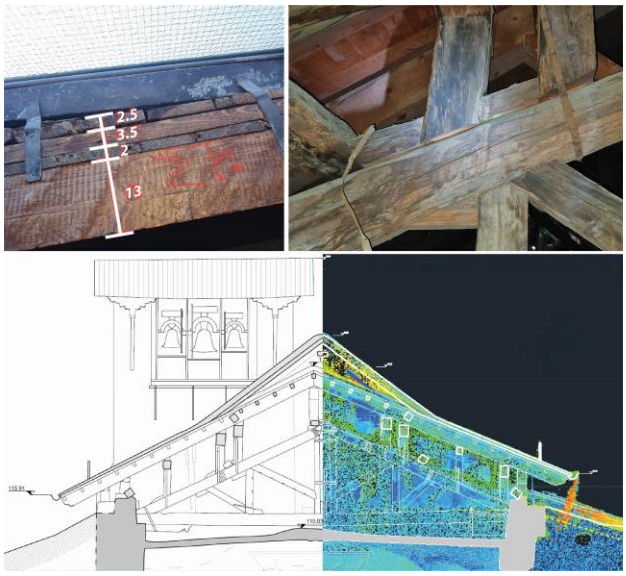

Figure 10. Direct measurements and photographs were additional material necessary to accompany the point cloud for producing technical drawings of the oldest wooden truss roof.

4.2 Modelling Process

The BIM model of the case study was developed through the *Autodesk Revit*® software, version 2022. The ‘*Insert Point Cloud*’ tool allowed the linkage of the point cloud to the software and to use it as the essential reference for the modelling process. Then, a group of grid lines (to delimit the perimeter of the building and its internal division), levels (such as the ground floor, roof planes, domes, and vaults planes, etc.) and significant section planes (such as in correspondence of long and cross axes of the churches, etc.) were defined. The proper modelling phase started from the apsis to the principal façade, from the ground floor to the roof. Essential elements (i.e., walls, floors, stairs, and roofs) were prioritised to have a preliminary volume of the Church. They were modelled directly from the point cloud (Figure 11).

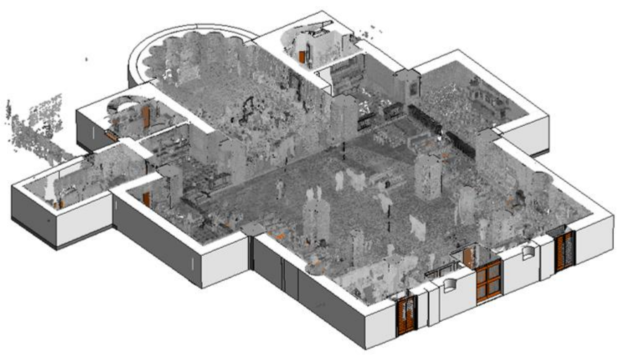

Figure 11. Point Cloud and external/internal walls.

The apsis was an exception: the walls curvature, the variable thickness and the out-of-plumb required a different approach. Firstly, the wall was sliced at different heights (a section every meter), creating two-dimensional profiles. Then, a ‘*Mass*’ element was obtained joining the different profiles, and a ‘*Wall by Face*’ was created. In the end, ‘*Void Forms*’ were used to obtain the niches. As for the apse, most architectural elements of the church are excluded by the default BIM objects, and alternative non-standard modelling ways must be found. This has resulted in different secondary features modelled as loadable families, created and implemented one by one based on the uniqueness of the element. Thanks to the potential of the family editor, it is possible to create deformed, irregular, or far from an ideal geometry element typical of cultural heritage buildings. For example, openings (windows and doors), cruciform pillars, cornices, trusses, balustrades, and other details were created starting from 2D elements’ profiles extraction (Figure 12).

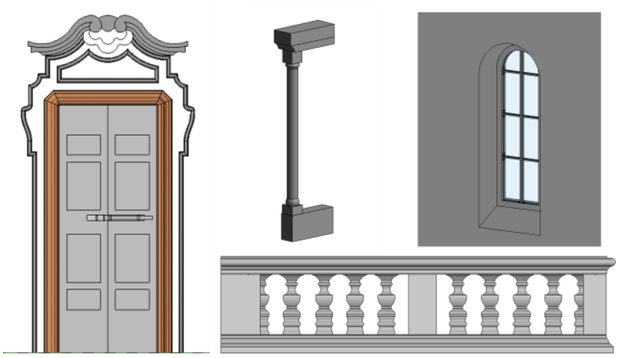

Figure 12. Some secondary features (door, column, window and balustrade) modelled starting from 2D profiles.

The third modelling strategy, the generation of NURBS surfaces, increasingly used in the HBIM field (Özeren and Korumaz, 2021), allows to represent faithful geometry details for complex architectures (Diara, 2022). In the case of San Giacomo church, the need to describe the correct shape and the possible deformations to perform structural analysis has led to the use of this method to create vaults and domes in detail (Figure 13).

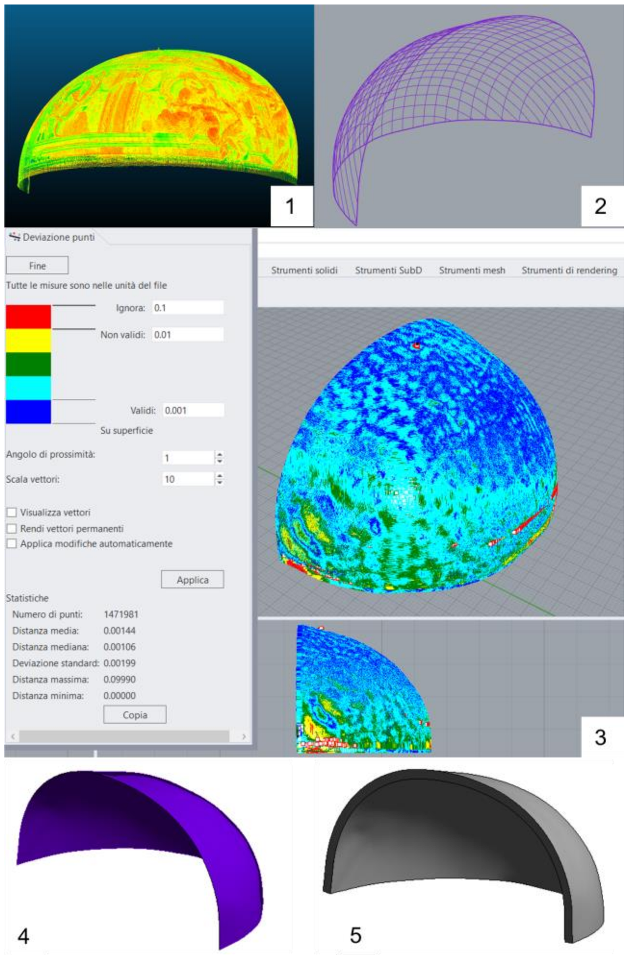

Figure 13. Dome modelling process: 1) Point Cloud; 2) NURBS surface; 3) Surface validation; 4) Mass element; 5) Dome model.

Starting from the point cloud, each vault and dome was isolated and extracted. Then, through the *CloudCompare* software (ver. 2.14), each point cloud was subsampled to reduce the point cloud density and make them more manageable. Simplified point clouds were imported into the freeform modeller software *Rhinoceros* (ver. 7) and NURBS surfaces were created, interpolating profile lines and point clouds (Banfi, 2019). These surfaces were validated by measuring their distance from the point clouds. Once the correct results were obtained, NURBS surfaces were imported into *Revit* as a “*Mass*” element and, again, the “*Wall by Face*” command was used to create the architectural elements.

All the single elements were created and added to the model. A separate file was used to model the surrounding context and different buildings placed on the three sides (Figure 14).

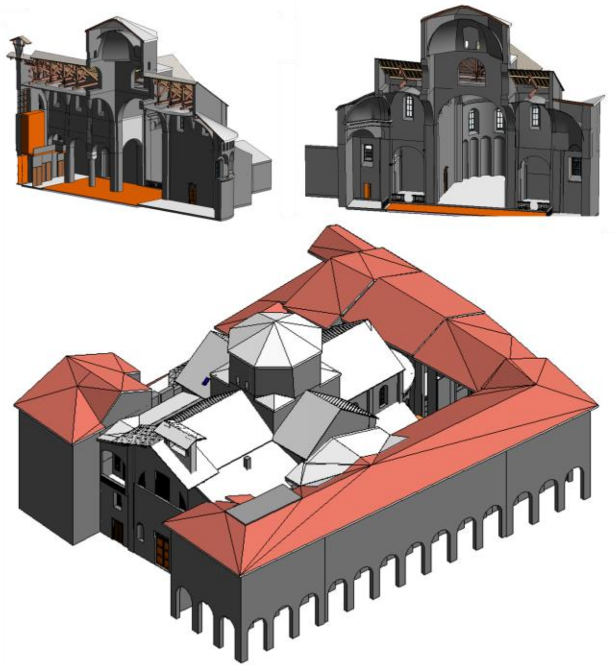

Figure 14. San Giacomo church: sections and context.

5. INSTALLATION OF A MONITORING SYSTEM

Another goal of the project is to install a monitoring system that could reveal the displacements of bearing elements of the church, providing a time series of vertical movements with a precision of about ±0.1mm. An important consideration deserves to be mentioned. The monitoring system of the church was also related to the larger system already available in the area, which tracked the movements of the Duomo di Como (Cathedral of Como) and the square for more than 20 years, resulting in a collection of monitoring time series. The system was also connected to the levelling network of the town of Como, which has been severely affected by land subsidence due to water extraction up to the 70s. In particular, the area where the Basilica di San Giacomo stands has been intensively affected by this phenomenon, due to the weakness of the terrain resulting from the historical stratifications of the town (Nappo et al., 2020). A reconstruction of all available and reliable general levelling measurements in the city (see Colombo et al., 1998) was done, and partially compared with synchronous medium resolution InSAR data based on ERS1/2 constellations (Eskandari, 2022). This part is presented and discussed in Eskandari and Scaioni (2023).

6. CONCLUSIONS AND FUTURE ACTIVITIES

The possibility of having available, in addition to the classical two-dimensional representations, an accurate three-dimensional HBIM model is an undoubted advantage for architects and engineers involved in the design and management activities of the construction site. The construction site will begin with the consolidation and restoration of the apsidal area, the wooden roofs, and the access staircase to the attics. Nonetheless, the updated three-dimensional model, supplemented by information of various kinds, will be able to be used for all those enhancement and dissemination activities that will represent the last moment of this long construction site, that of opening to the population a building that has remained mostly closed for many years.

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