Supporting the Diagnosis and Functioning of Historical Buildings through measuring

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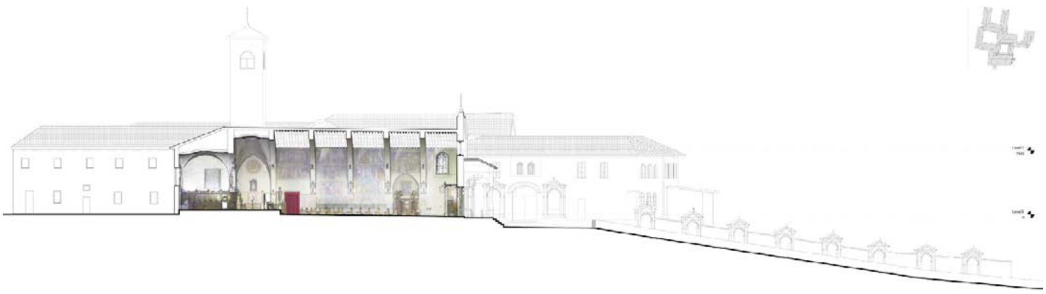
Abstract

The paper explores various aspects of HBIM implementation, starting from a Scan-to-BIM process to create a customized model for static preservation analysis, leveraging laser measurements to assess the structural integrity of heritage buildings and mitigate potential damage during periods of high occupancy. The proposed method was applied to the case study of a convent located in the Merate, Lecco, in northern Italy. The case is developed from a digital survey and a produced accurate virtual model. The research starts with understanding the morphology of the convent, providing a theoretical understanding of its architectural evolution. Different modeling techniques and workflows are compared in the modeling phase, considering the challenges posed by the intricate shapes and unique characteristics of Cultural Heritage. After the modeling phase, the thesis investigates the structural analysis of the main structures within the church, particularly through verticality analysis and surface deformation measurements. This analysis provides insights into the historical building's structural integrity and potential areas of concern.

Parole chiave
measuring, modelling, scan-to-bim, structural analysis, digital survey



Section of the digital model and point cloud of the convent. Elaboration by the authors.

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Introduction

Italy is grappling with a cultural heritage crisis as mass tourism overwhelms certain art cities and monuments, jeopardizing their preservation. Meanwhile, lesser-known towns and sites outside the tourist traffic suffer a slow decline. St. Augustine's path connects 50 Marian lesser -known sanctuaries in Lombardy, forming a unique shape resembling a rose, earning it the nickname "Way of Rose". The context is the broader European Cultural Routes initiative, the Council of Europe launched the "Cultural Routes" project [Council of Europe 1987] in 1987, aiming to share the values of European identity and culture through journeys across different countries and time periods.
One notable station along the route [Il Cammino Di S. Agostino 2024] is the Convent of Santa Maria in Sabbioncello. A general map of the path of St. Augustine with the location of the research case is shown (fig. 1). Along the route, travelers can explore various significant artistic and historical sites in the Brianza area, spread among Monza, Lecco, and Como.

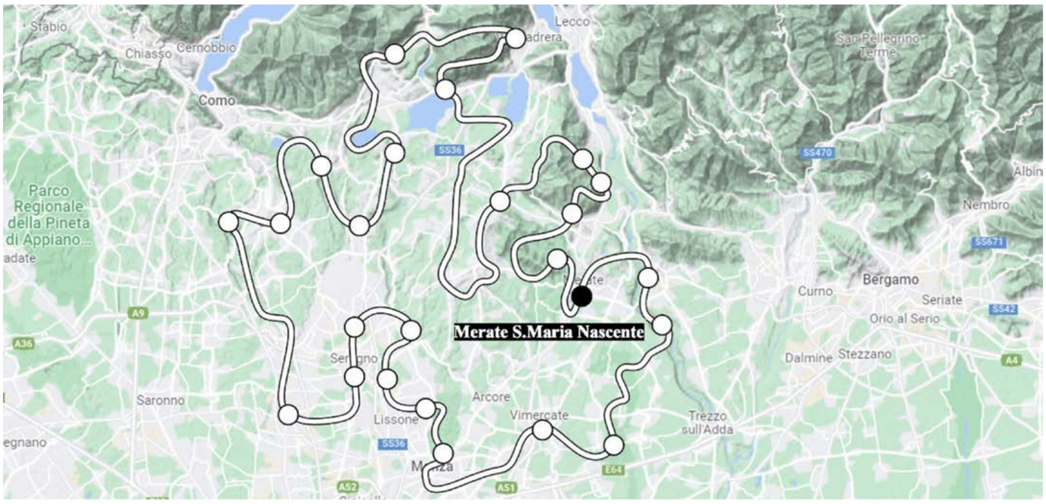

Fig. 1. Map of the path of St. Augustine with the location of case (Convento di Sabbioncello). Elaboration by the authors.

Research Aim

To protect, preserve, and restore the individual stations along the path, it is crucial to carefully know the buildings; you can select survey procedures and modeling methodologies to carefully measure the architecture we face [Paris et al. 2022; Achille et al. 2015]. It is essential for all stakeholders to possess a deep understanding of the structural behavior and construction methods employed to build the place they want to explore [Cali et al. 2022; Wei et al. 2017; Wong et al. 2014]. To achieve this, a specific survey approach is implemented, encompassing potential transformations over time and structure statute [Rocha et al. 2017; Rolin et al. 2019]. The digital model facilitates initial structural verification by employing approximate numerical calculations based on the dimensions of structural components, shapes, and material properties. During the digitization process, advanced digital survey and representation techniques are employed, including terrestrial laser scanners [Bevilacqua et al. 2017; Battini et al. 2017] and photogrammetry. These techniques enable a scan-to-BIM [Allegra et al. 2017] process, integrating modeling techniques [Biason et al. 2019]. The resulting HBIM models can be tailored for static measurements and preservation analysis, utilizing laser accuracy to evaluate static conditions [Croce et al. 2022; Pepe et al. 2022] and prevent damage to heritage buildings during crowded times [Salvador et al. 2020].
The so accurate digital surveys can be utilized to create models to support structural analysis facilitating in-depth analysis and documentation of cultural heritage sites [Massafra et al. 2022].

The integration of digital modelling into monitoring systems has been extensively studied, highlighting its wide range of applications and benefits. An effective method to localize a mobile 3D LiDAR sensor on BIM-generated maps [Ying et al. 2022] has been developed considering geometric and semantic properties.
This enhances the accuracy and efficiency of data collection and localization in building monitoring.
A bridge web platform that connects an IoT platform with the informative model of a building has been developed [Desogus et al. 2021].
This integration allows for real-time data exchange, monitoring, and analysis, enhancing the building's performance and management.
Through this research, the goal is to contribute to preserving and effectively maintaining historical structures by employing advanced surveying techniques, digital modeling, and integrating innovative technologies for analysis and monitoring purposes.

Fig. 2. Site plan (a) minor cloister (b), main cloister (c), church nave (d), frescoes (e), main structure (f). Elaborations by the authors.

Material and method

The convent (fig. 2) is in the town of Merate, Lecco, in northern Italy. Over the following decades, the church underwent several renovations works, preserving its historical significance. In 1508, a new church in late Gothic style replaced the original structure; in 1540, a sacristy, refectory, kitchen, and bell tower were added. In 1588, a new presbytery was built. The convent faced suppression during Napoleon's reign in 1810 but was repurchased in 1884, becoming part of the Lombard province of the Friars Minor in 1898 [Europe in the XIX 2024].
The convent comprises multiple buildings arranged around two quadrangular cloisters, with wings opening onto two courtyards to the north.
To achieve a comprehensive representation of the church's structure, a two-stage point cloud scanning process was implemented. The first involved the utilization of a laser scanner structured with time-of-flight registration a Leica RCT360 [Leica RTC360 2024] whose VIS (Visual Inertial System) technology facilitated the placement of scans in a local reference system. The second session involved the use of a mobile scanner BLK2GO scanner [Leica BLK2GO 2024] to capture the courtyard on the southern side of the church as well as the two cloisters on the northern side [Del Duca et al. 2023].
The first scanning path originated from the northeastern road and seamlessly extended into the interior of the church (fig. 3). Cyclone REGISTER 360 [Leica Cyclone REGISTER 360] a 3D laser scanning point cloud registration software was used to import, align, clean and export project data collected by Leica Geosystems sensors.

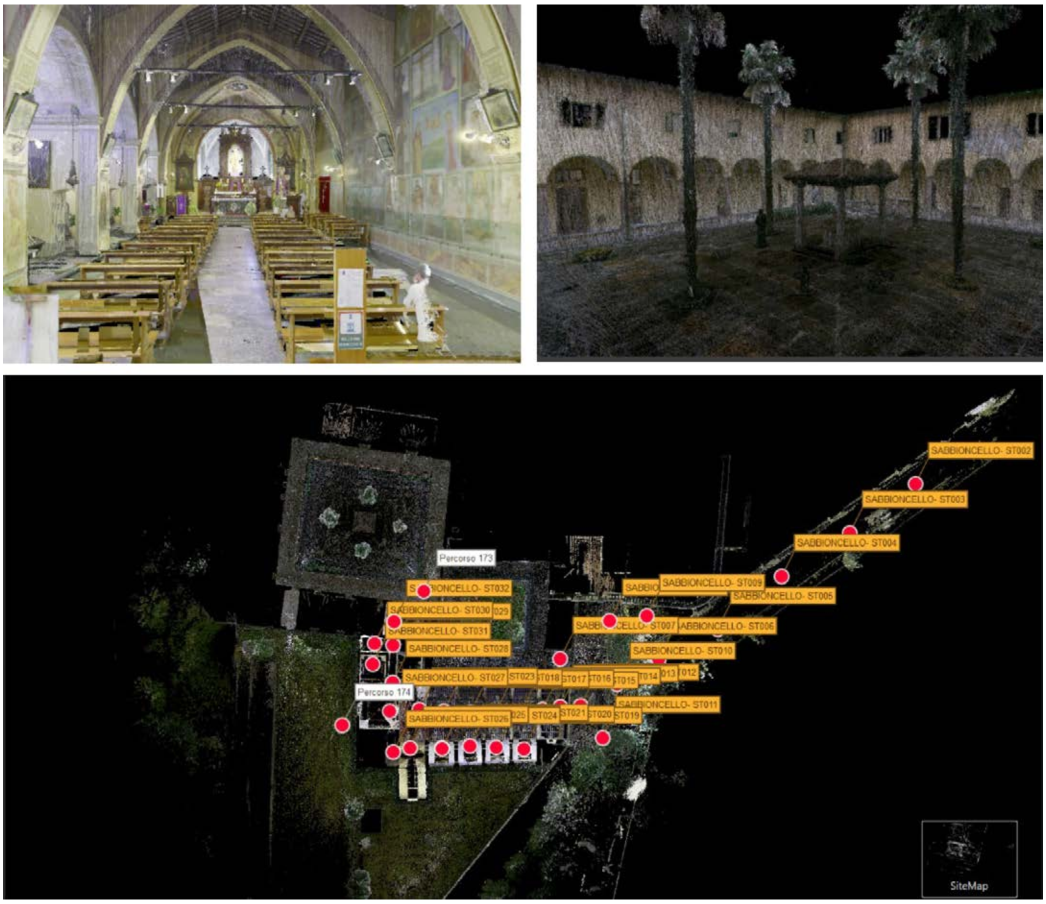

Fig. 3. First session point cloud of main church (a), second session point cloud of main. Elaborations by the authors.

The average error related to the scan alignment (Cloud-to-Cloud) was measured at 0.001m, ranging from 0.000 m to 0.020 m.

Space	Number of Scans	Number of points	Average number of points per scan	Overlap (%)	Strength (%)	Cloud-to-Cloud (m)
Exterior	10	905,569,405	90,556,940	60	69	0.001
Interior	21	2,338,661,525	111,364,834	66	67	0.001
Total	31	3,244,230,930	104,652,610	64	66	0.001

Tab. 1. Leica RCT360 laser scanner statistics

The second point cloud data was obtained through scanning using BLK2GO. The process involved handheld device operation, where the machine automatically recorded video while being walked through. The size of the raw point cloud data was 1.44 GB. The resulting dataset consisted of over 100 million points (122,500,542).

Space	Number of points	Trajectory duration (s)	Trajectory length (m)
Cloisters	79,499,015	465	309.8
Churchyard	43,001,527	320	196.2
Total	122,500,542	785	506.0

Tab. 2. BLK2GO laser scanner statistics.

The integration of the point cloud data from the two scanning sessions was a crucial step in creating a cohesive representation of the entire church. The entire point cloud data was imported into Autodesk ReCap software, where manual removal of objects like people, trees, and vehicles was carried out.
This optimization process helps reduce file size and improve efficiency. In this case, the original file size of 51 GB has been optimized to 6.49 GB, resulting in a substantial reduction in data size.

Tab. 3. Merged laser scanner statistics.

Space	Number of Scans	Number of points	Average number of points per scan	Overlap (%)	Strength (%)	Cloud-to-Cloud (m)
Total	33	3,366,731,472	102,022,165	60	66	0.001

The cleaned point cloud file was further processed to extract for analysis on static conditions. This part will take the main church as an example to illustrate the research. To reach the topic of static preservation starting from laser measurement, the point cloud was sliced to determine some parts that formed seven planes (surface W1 is in the interior side of the north, surface W2 is in the interior side of the wall at the entrance) and five arches named A1-A5 (fig. 4). The workflow can be further applied in the other parts, such as two cloisters to evaluate the convent more fully.

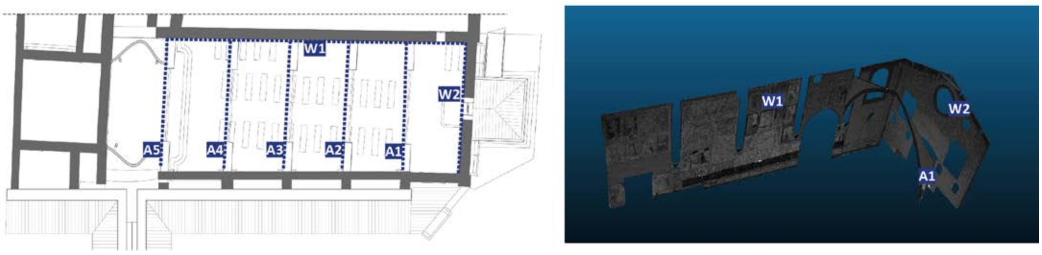

Fig. 4. The position of selected wall surface and point cloud of W1, W2 and A1 surface. Elaboration by the authors.

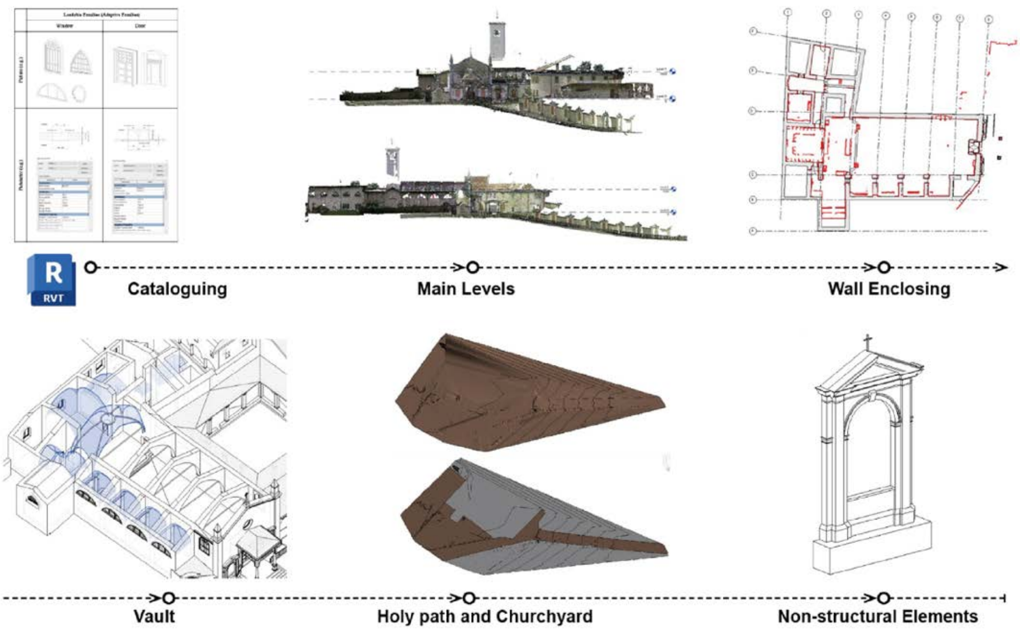

Fig. 5. Workflow of 3D modeling.
(a) Cataloguing: Elements are catalogued into different families.
(b) Main Level: Define the main level. Level one is set at the indoor level of the entrance.
(c) Wall enclosing: Define the grid system.
(d) Vault: Build different types of irregular vaults.
(e) Holy path and Churchyard: Model the terrain.
(f) Non-structural elements: Model specific non-structural elements. Elaboration by the authors.

Once the data integration process is carried out, 3D modelling phase is followed [Lopetz et al., 2017]. The 3D model (fig. 5) serves multiple objectives. In the field of cultural heritage, it is common practice to employ digital survey tools that provide accurate and efficient means of obtaining structural geometry information [Min Koo, 2019]. These tools enable the acquisition of geometric data, typically in the form of point clouds, which can then be utilized for the creation of 3D models in HBIM software and even support structural analysis [Grussenmeyer et al., 2019].
The main structure of the church consists of five three-pointed brick arches and wooden purlins. Based on the point cloud data, it was observed that the axes were not perfectly parallel or perpendicular, but rather inclined at slight angles. On-site visual inspections of the roof structure revealed that it was relatively intact and did not exhibit significant damage.
These arches are inclined at a certain angle relative to the longitudinal walls and are primarily constructed with a thickness of approximately 600mm. The upper section of the arches is connected to the roof and bears the weight of the beams (fig. 6).
In the process of modeling the church, the following characteristics were identified:

- The plane grids were not parallel or perpendicular to each other.
- In the vertical direction, certain wall structures exhibited non-vertical orientations, with noticeable tilts at certain angles. The wooden roof structure also displayed deformations.
- The church interior featured numerous vaults, which presented irregular shapes, possibly due to construction errors or structural deformations.

These observations of Convento di Sabbioncello prompted further investigation into the structural deformations.

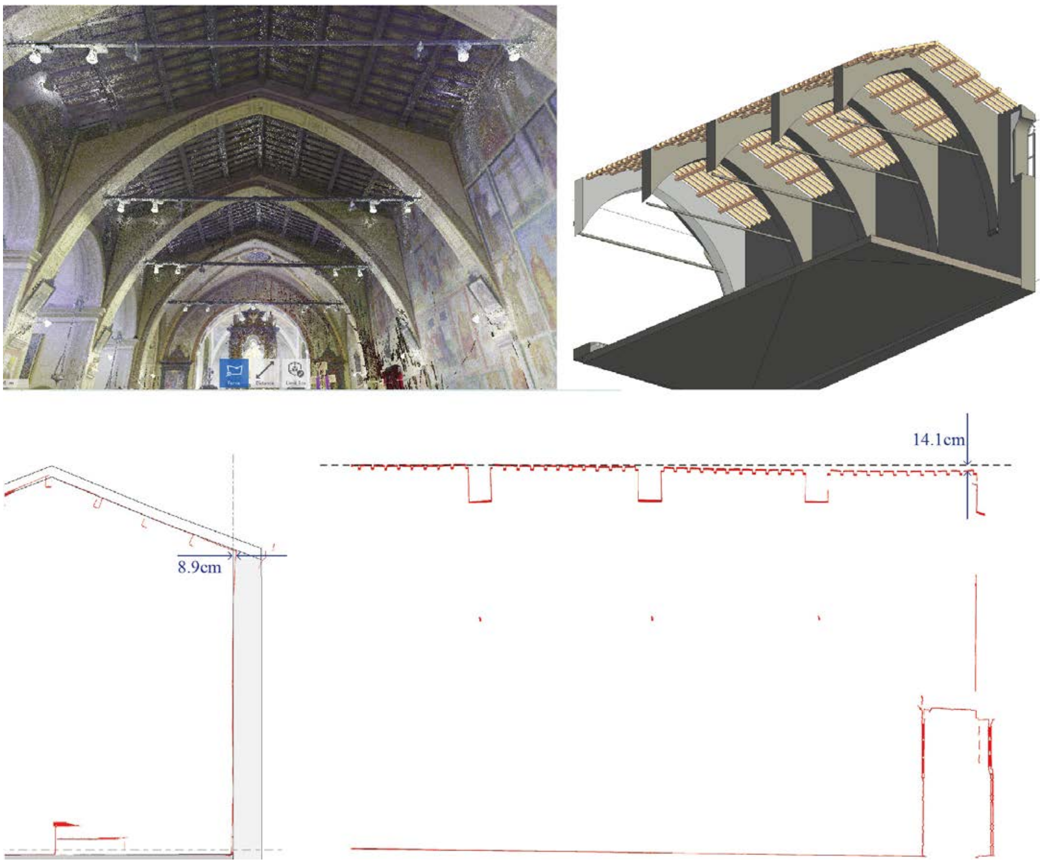

Fig. 6. The point cloud and axonometry view of structure (a), deformation in cross section and longitudinal section (b). Elaboration by the authors.

Results

This chapter focuses on analyzing static conditions based on the digital data including the evaluation of wall verticality and measurement of surface [Lorenzoni, 2013]. The acquired point cloud data were imported into CloudCompare, that was utilized for in-depth structural assessment. This part will take the main church as an example to illustrate the research. The workflow can be further applied in the other parts, such as two cloisters to evaluate the convent more fully [Robles, 2019].

For this case, the following process was followed:

- The point cloud was sliced to determine some parts that formed seven planes (one surface on the interior side of the wall at the entrance, one surface on the interior side of the north, and five arches).
- Afterwards, the plane best fitted to the previous point cloud was generated.
- Finally, given that the raw surface was leveled, the inclination angle of the normal vector of each plane was measured with respect to the world axes, indicating that the two planes formed specified degrees with respect to the axis.

Based on the analysis data, the verticality of multiple wall locations (W1, W2, A1, A2, A3, A4, and A5) was assessed. The data obtained includes the verticality values, average inclination, standard deviation, and best-fitting plane angles. It allows for evaluating the degree of vertical alignment and potential variations among the analyzed walls.

Location	Point Number	Verticality	Average	Standard Deviation	Best Fitting Plane Angle
W1	1,740,921	0.0126	0.9541	0.0586	88.88deg.
W2	703,216	0.0159	0.9727	0.0410	89.99deg.
A1	803,008	0.0113	0.9799	0.0158	90.00 deg.
A2	411,172	0.0141	0.9798	0.0188	89.82 deg.
A3	449,449	0.0144	0.9762	0.0244	89.36 deg.
A4	397,275	0.0149	0.9805	0.0212	89.84 deg.
A5	673,439	0.0147	0.9771	0.0180	89.98 deg.

Tab. 4. The verticality statistics of W1, W2, A1-A5.

The graphical representations provide a concise summary of the verticality analysis, allowing for a clear comparison of the wall locations.

In this research, the effectiveness of the employed methodology for evaluating structural surface deformation was assessed using the "RANSAC shape detection" plane on point cloud data in ".e57" format. The analysis focused on multiple locations, including W1, W2, A1, A2, A3, A4, and A5. The results obtained from this evaluation are visualized in the histogram and summarized in the following table (fig. 7).

The "Standard Deviation" column represents the measure of surface deformation, with lower values indicating less variation in the deformation. The "Min. Distance," "Max. Distance," and "Average Distance" columns provide information about the spatial extent of the deformation, with values reflecting the distances between the detected plane and the point cloud data. These distances were found to range from 0.00 to a maximum value depending on the location (fig. 8). Additionally, the "Max Error" column presents the maximum error observed in the deformation measurement. This value indicates the largest deviation between the actual structural surface and the plane created by the RANSAC shape detection algorithm.

Tab. 5. The deformation statistics of W1, W2, A1-A5.

Location	Standard Deviation	Min. Distance	Max. Distance	Average Distance	Max Error
W1	0.0586	0	0.1707	0.0248	0.0853
W2	0.0141	0	0.0772	0.0091	0.0386
A1	0.0185	0	0.0765	0.0095	0.0382
A2	0.0151	0	0.0768	0.0062	0.0384
A3	0.0149	0	0.0775	0.0068	0.0395
A4	0.0112	0	0.0779	0.0042	0.0394
A5	0.0128	0	0.0790	0.0068	0.0395

The all-standard deviation values ranged from 0.0112 to 0.0586, indicating varying levels of deformation across the locations. This suggests that some areas exhibit more significant deformations than others. The minimum and maximum distance values provided insights into the extent of deformation, with each location having its own range of distances between the detected plane and the point cloud data. The average distance values ranged from 0.0042 to

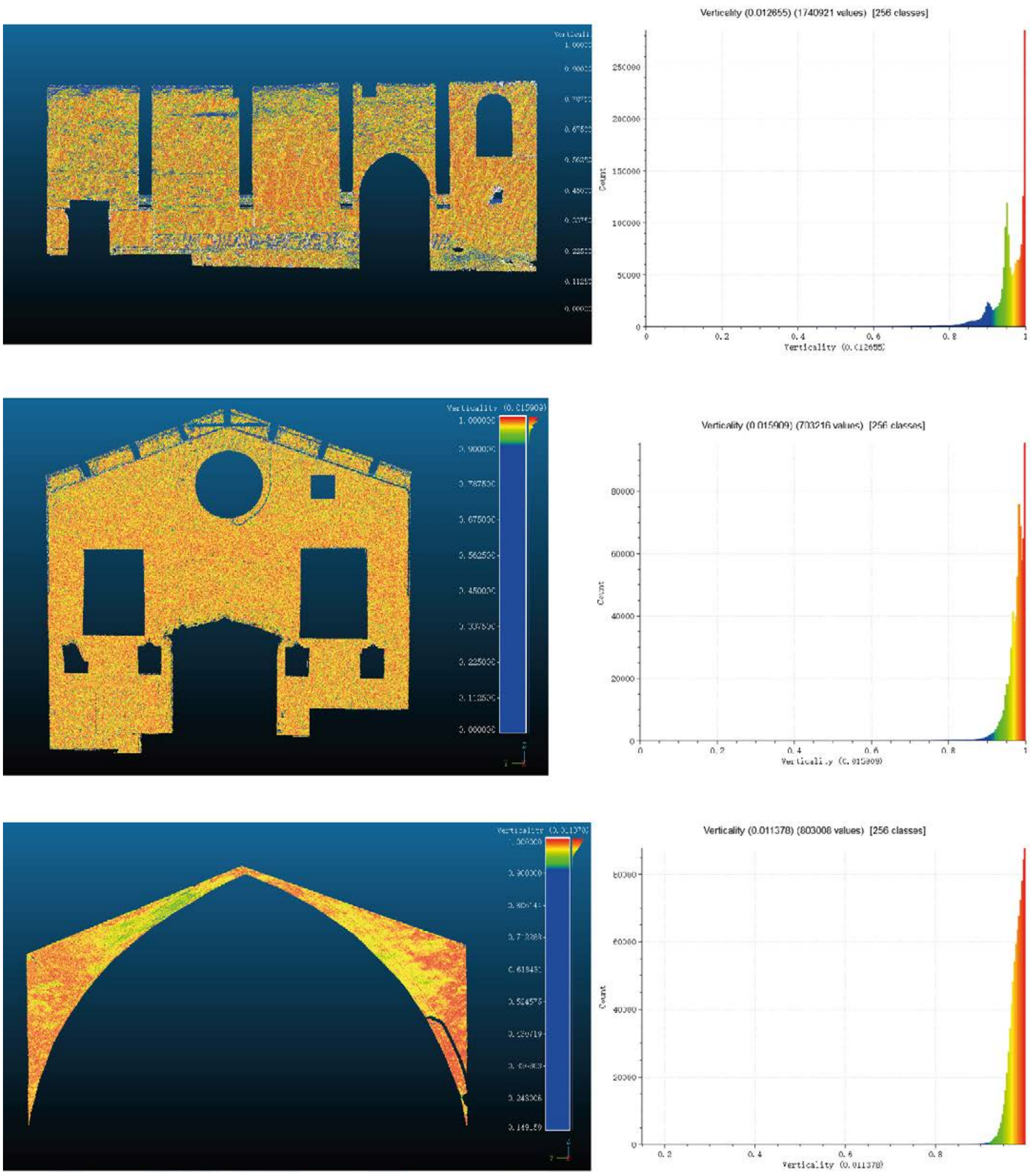

Fig. 7. The heat map and histogram of verticality. W1 wall (a), W2 wall (b), A1 arch (c). Elaboration by the authors.

0.0248, representing the overall magnitude of deformation observed. Furthermore, the maximum error values, ranging from 0.0382 to 0.0853, identified localized areas with substantial deviations from the actual wall surface.

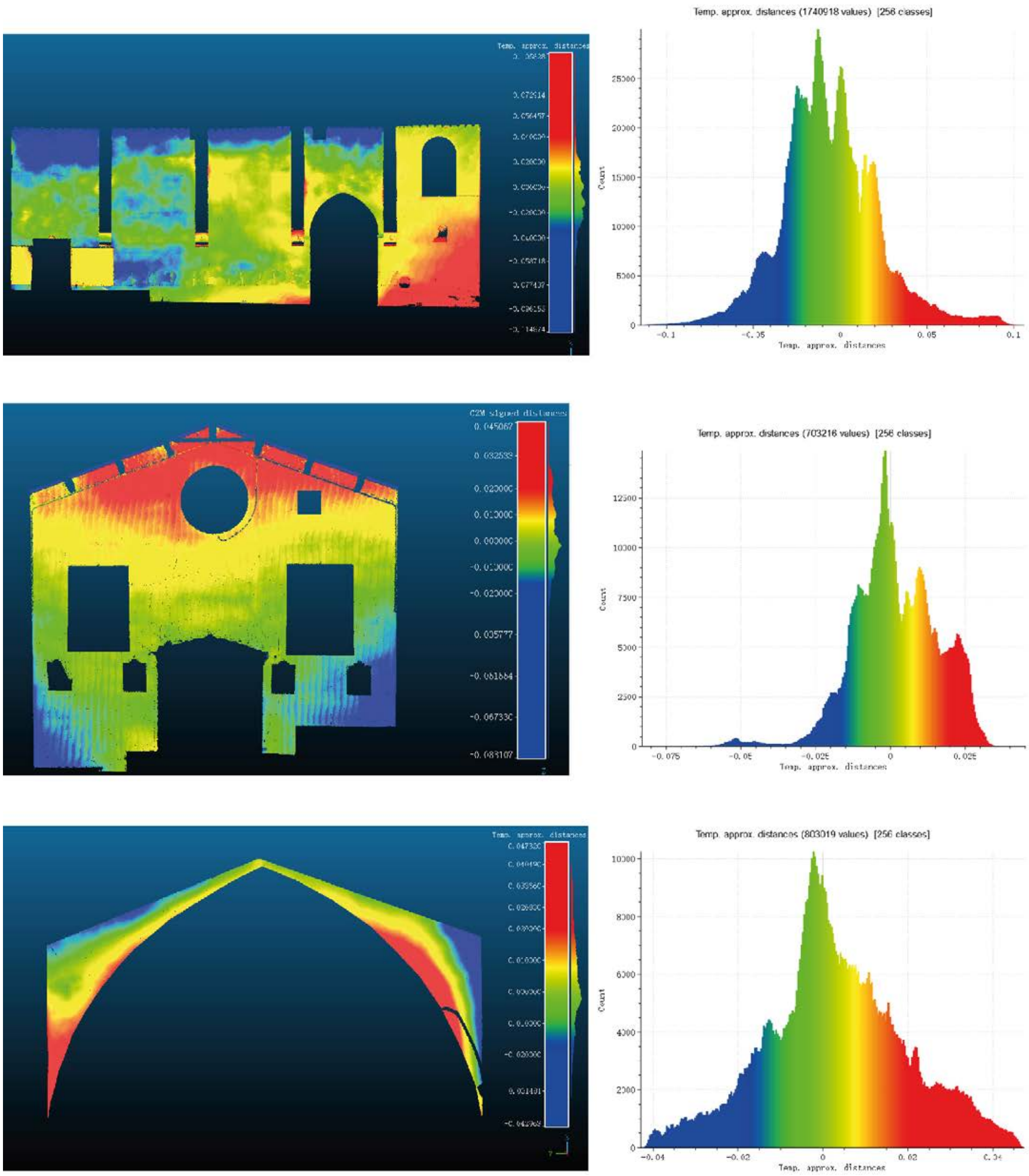

Fig. 8. The heat map and histogram of deformation. W1 wall (a), W2 wall (b), A1 arch (c). Elaboration by the authors.

Discussion and conclusions

The research illustrates the process of the survey and specific modeling to reach the topic of information for static preservation, which consists of analysis of static conditions starting from laser measurement and the possibility to avoid consumption of frescoes due to eventual crowder times in the church. Classified as a part of Structural Health Monitoring (SHM) system, static systems monitor the long-term time evolutions of specific quantities (such as inclination of walls, relative distances).

For the analysis of static conditions, the geometric state of the structure can be documented on various dates. With respect to the analysis results on verticality and wall deformations, it is

possible to visually observe the inclination and deformations of the walls using heatmaps and bar charts. In this case, the walls exhibit some degree of flexibility rather than rigid bodies because of the masonry composition of the walls. The structural condition of the church is found to be in good shape, with the maximum inclination angle being approximately 1.1° and the largest deformation measuring around 0.2m. The analysis of this data enables the detection and recording of pathologies, which can then be incorporated into the inventory system.
Finally, a five-year plan is proposed to check the static conditions of the whole complex. The goal is to establish the static conditions diagnosis of the whole patrimony of the churches on Saint Augustin path to prevent damages and definitive deterioration.

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