# 3D Heterogeneous Dataset for Structural Analysis of Historic Buildings. A Discussion on Process Pipelines

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This paper presents a methodology for creating a comprehensive heterogeneous 3D dataset for the structural evaluation of a historic building by using both non-destructive and destructive surveys combined with historical information. The availability of adequate data on the actual conditions is crucial when assessing the seismic vulnerability and structural behavior of a historic building and validating the results. A reliable 3D dataset must accept different kinds of data, e.g., the results of destructive/non-destructive surveys, historical information, etc., which can be interrogated and enriched at any time. Therefore, creating such a 3D dataset may present several challenges in terms of data-gathering pipeline, comprehensiveness/redundancy, interpretation, organization, and integration with other heterogeneous data. The methodology we present in this paper includes 3D laser scanning, thermal imaging, and endoscopy combined with information regarding the state of conservation, construction history, materials, and techniques. We tested such methodology to create a dataset that was later used for Finite Element Modeling (FEM) to assess the seismic vulnerability of Diotti Palace, a neoclassical building that has been the seat of the Prefect of Milan since 1859. The results are analytically presented here. In conclusion, we highlight the pros and cons of the proposed methodology by means of a comparative discussion with the state of the art about 3D documentation pipelines for historic buildings and sites.

### Keywords:
Built heritage, data integration, workflows, 3D datasets, structural analysis.

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## 1. INTRODUCTION

The use of digital technologies has become a common practice in the field of Cultural Heritage (CH) to survey objects, buildings, and monuments of historical importance. Digital technologies provide new possibilities for CH preservation, archiving, restoration, data collection, recording, monitoring, structuring, analysis, interrogation, interpretation/communication, exploitation/valorization, and research/discovery [Arnold and Geser 2008; De Luca et al. 2006; Fassi and Parri 2012; Gomes et al. 2014; Soler et al. 2017]. An accurate and complete 3D survey, in particular, can play a crucial role in the analysis and interpretation of historic buildings [Grilli and Remondino 2019].

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This paper describes a methodology to obtain a comprehensive and extensive dataset for a more reliable and deeper structural analysis of historic buildings. The digitization pipeline of a historic building presented here is an attempt to develop a methodology that can meet the most important criteria defined by CIPA (Comité International de la Photogrammétrie Architecturale) for the documentation of CH [Quintero et al. 2017]. This methodology can specifically be valuable in cases where the purpose is to create a complete dataset for the structural or vulnerability analysis of built heritage. The pipeline focuses on the proper integration of data not only from different sensors (laser, thermographic, and photographic) but also from other sources such as historical images, reports on the state of conservation, and previously available drawings.

The developed methodology is supported by its application to a case study: Diotti Palace, a historic building that has been the location of the office of the Prefect of Milan, Italy, since 1859. The building, currently in a good state of conservation, shows some cracks on the internal and external surfaces, which can be traced back to the construction of the M4 underground metro line in Milan. To evaluate and understand the extent of these degradation phenomena, it was necessary to proceed with specific structural investigations, including a complete three-dimensional survey using laser scanner methodology, historical-archival analysis, and targeted diagnostic investigations.

It is to be noted that we propose a methodology to obtain a reliable 3D dataset that can later be used by the structural engineers to create Building Information Model (BIM) or to perform structural analysis through Finite Element Modeling (FEM). In the specific case study of Diotti Palace, the structural analysis was later performed by the experts in FEM, extracting useful information from the resulting dataset obtained through the proposed methodology. As this article is focused on the pipeline and comprehensiveness of generating 3D datasets for structural analyses, we do not report the later FEM analysis here.

The introduction briefly summarizes the state of the art of the 3D tools for the documentation of CH and compares some past experiences by identifying three criteria of evaluation. Section 2 is dedicated to the methodological definition of the work pipeline and includes a concise presentation of the case study, the tools used, and the data acquisition phase. Section 3 illustrates the results obtained for the creation of the three-dimensional dataset, the processing of two-dimensional graphic materials, and the integration of these with the data acquisitions from an endoscope, thermal camera, and historical analysis and on the state of conservation of the building. Section 4 is a brief discussion of the result achieved by applying the proposed methodology to the case study and its limitations.

## 1.1 3D tools for the documentation and analysis of Cultural Heritage

The 3D tools for digital surveys can be divided into two classes based on their operating principles. Active 3D devices project a coded light on the surface of the objects to be measured, which is then detected by a sensing device such as a camera or a photodetector. Passive 3D surveying methods, on the other hand, use ambient light to detect the features of the object being surveyed [El-Hakim et al. 1995].

The most widely used passive method for surveying historical buildings is digital photogrammetry, which can detect 3D features on the surface of an object by aligning 2D photographs taken from different points of view. In most cases, terrestrial photogrammetry is used to obtain geometric and high-quality texture details of CH objects of various scales. Aerial photogrammetry is often used for surveying large, complex, and inaccessible structures, such as upper parts of buildings, archeological landscapes, aqueducts, bridges, etc. In recent years, acquiring aerial photogrammetry data using Unmanned Aerial vehicles (UAVs) has proven to be a low-cost reliable alternative to classical manned aerial photogrammetry [Remondino et al. 2012]. 3D documentation and mapping of archaeological sites and historical structures are easily achieved with a low-altitude image-based UAV survey [Themistocleous 2020]. Typical examples of such UAV surveys are the monitoring of different layers of an ongoing excavation of archaeological sites [Sauerbier and Eisenbeiss 2010; Rinaudo et al. 2012] and 3D reconstruction of CH sites [Fiorillo et al. 2015].

Active 3D Terrestrial Laser Scanning (TLS) devices based on direct distance measurements such as Time-of-Flight (ToF) and Phase-Shift (PS) laser scanners have also been widely used in CH digitization [Lemmens 2011]. In these devices, the surface-to-sensor distance is measured by calculating the time required for light to travel from the sensor to the surface of the object and back. Direct distance measurement devices can be operated at a distance of a few meters to a few kilometers from the surface of the object being surveyed; therefore, they can be employed to measure large artifacts such as buildings, archaeological sites, or entire territories. The uncertainty of these devices range from a few millimeters to a few decimeters, an acceptable level of error when surveying large buildings. Laser Radar (LR) also uses the principle of direct distance measurement by evaluating the distance based on frequency-modulated light. In the case of LD, the measurement uncertainty can be reduced 20 times with respect to TOF laser scanners [Guidi and Frischer 2020].

The 3D data obtained from various forms of surveys can be used for the management and monitoring of buildings through different methods such as BIM and FEM. Laser scanning surveys generate a point cloud that can be utilized to generate BIM for seamless information management in the construction industry. BIM serves as a technological platform that allows professionals to collaborate throughout the entire lifecycle of a project, from planning to design, construction, and maintenance. This digital model integrates data from various sources, providing a holistic view of the building and its systems. For instance, it enables the coordination of architectural, structural, mechanical, and electrical systems in a construction project. The integration of laser scanning and BIM technologies has been extensively studied in recent years, with several applications being identified in the construction industry. For example, laser scanning can be used to create as-built models of existing buildings for renovation and retrofitting projects [Woo et al. 2010; Usmani et al. 2020; Razali et al. 2020]. The generated point cloud can also be used for clash detection and quality control during the construction phase, reducing the likelihood of errors and delays [Li et al. 2020; Tan et al. 2020]. Additionally, it can be used for building energy analysis, enabling the identification of energy inefficiencies and optimization of the building's energy performance [Valero et al. 2021; Zhao et al. 2021].

Recently, scan to BIM methodology has been applied to heritage buildings for restoration activities, monitoring, facility management, and structural analysis [Rocha et al. 2020; Yang et al. 2020]. HBIM (Heritage Building Information Modelling) can be used for the preservation, protection, and restoration of historical structures by facilitating accurate and efficient management [Allegra et al. 2020; Khan et al. 2022; Conti et al. 2020; Barontini et al. 2022; Costantino et al. 2021]. It can also be used for facility management of heritage buildings by creating a digital inventory of the building's components and monitoring their condition over time, aiding in the identification of potential maintenance issues [Machete et al. 2021; Tucci et al. 2019; Godinho et al. 2020]. By integrating information such as drawings, photographs, and materials, HBIM enables the creation of a 3D model that accurately reflects the building's geometry, including complex structural elements such as arches, vaults, and domes. It can also incorporate information on the building's materials, such as their mechanical and physical properties, which can be used to simulate the building's behavior under different load conditions. Therefore, HBIM has also been utilized to create a more accurate and efficient model for the structural analysis of historic buildings [Tsilimantou et al. 2020; Rolin et al. 2019; Antón et al. 2019].

A reliable HBIM can be created by improving the quality of the data acquisition phase for complex surveys and by optimizing the point cloud from laser scanning. For this purpose, a combination of terrestrial laser scanning, photogrammetry, and topographic surveys has been proposed in the literature [Alshawabkeh et al. 2021; Lo Brutto et al. 2021].

FEM analysis has also been a valuable tool for modeling and analyzing the behavior of historic buildings. FEM analysis is a numerical method that allows engineers to simulate the structural behavior of a building under different loading conditions by defining the material properties and boundary conditions of the building. The point cloud generated from 3D surveys can capture the detailed geometry of buildings, which can then be used to create an accurate FEM model. This approach enables engineers to identify potential structural issues, such as cracks, deformations, and settling of the foundation, to develop appropriate remedial measures to preserve the building's structural integrity and historical value [Fang et al. 2021; Sacco et al. 2023]. In most cases, the 3D survey data in the form of the point cloud can directly be used to create an accurate FEM model for complex buildings [Castellazzi et al. 2015]. The FEM model of historical buildings can then be used for the assessment of structural integrity, restoration, seismic assessment, conservation, preservation, monitoring, and maintenance. Scan-to-FEM analysis can also be used to evaluate the effectiveness of proposed structural interventions or retrofitting measures [Alfio et al. 2022].

An interesting approach presented in some studies [Ursini et al. 2022; Barazzetti et al. 2015; Oreni et al. 2014], uses the 3D metric survey of built heritage has been used to create an accurate HBIM model, which can then be used to analyze the structural behavior of the building using FEM analysis.

The generation of digital twins starting from the 3D survey to define a finite element model that can be exploited to predict future scenarios has also been presented in the literature [Funari et al. 2021].

## 1.2 3D digitization pipelines: experiences and research

The 3D tools for digital surveys can be divided into two classes based on their operating principles. Active 3D devices project a coded light on the surface of the objects to be measured, which is then detected by a sensing device such as a camera or a photodetector. Passive 3D surveying methods, on the other hand, use ambient light to detect features of the object being surveyed [El-Hakim et al. 1995].

CIPA is one of the major organizations for the documentation of CH monuments and sites. It has defined various criteria for the recording, documentation, and information management for all aspects of CH and encouraged the development of specialized tools and techniques in support of these activities [Quintero et al. 2017]. The most important criteria emphasize (a) the sensor and data integration [Rinaudo and Scolamiero 2021]; (b) the use of the most suitable technologies to capture different components of built heritage [El-Din Fawzy 2019]; and (c) achieving the redundancy in estimating the quality of the obtained 3D measurements [Patias and Hanke 2008]. Following these criteria, several experiments have been carried out to create pipelines for 3D data integration. One important examples is the integration of image and range-based techniques for providing complete and multi-scalar information about complex architectures as seen in the 3D digitization of the Pomposa Abbey in Italy [Russo and Manferdini 2014]. In this project, triangulation-based laser scanning was merged with the low-resolution models generated by photogrammetry to cover resolutions spanning from 0.25 to 250 mm [Guidi et al. 2009] and sensor integration were utilized to solve a typical problem in surveying the top of buildings with terrestrial technologies [Lasaponara et al. 2011; Meyer et al. 2015].

Different researchers have proposed 3D digitization and data integration pipelines for the documentation and analysis of historic buildings, CH monuments, and built environments of historic importance. Most of the presented works focus on the CH digitization pipeline with or without sensors and other data integration for digital documentation, reconstruction, and monitoring. Only a few studies explain the use of digitization for the structural analysis of built heritage. These, however, do not focus on the quality of the 3D dataset and the necessity of data integration from different sources. This is because structural analysis has traditionally been performed on rough digital models based on traditional surveys or existing geometrical drawings.

A scoping review shows that none of the digitization pipelines presented in the literature resulted in a comprehensive dataset. For this reason, we propose three essential criteria for comparative analysis:

- possibility to vectorize the points cloud to include the details necessary for structural analysis,
- flexibility to extract the constructive techniques and structural details of the building,
- redundancy of data for further investigations without the need for additional acquisitions.

Before further explanation of the proposed methodological pipelines, the criteria introduced above are employed to analyze some of the 3D digitization pipelines present in the literature. Their advantages and drawbacks based on the proposed criteria are reported in Table 1.

A proper mix of quantitative data from 3D surveys and other data from historical sources has proven to be good practice for the reconstruction of lost monuments and scenarios of CH importance, as suggested by [Micoli et al. 2018]. A methodology was proposed in this research to perform an accurate 3D survey of a lost monument with only a few remains by using ToF/PS terrestrial laser scanners and photogrammetry to add to sources of information coming from other disciplines of the humanities. The authors proposed utilizing sources of information including ancient visual representations of the monument, textual documents providing a description of the area in past times, archaeological decrees, archaeological reports, archaeological restrictions decrees, old photographs, and historical maps to reasonably determine a credible shape of the investigated monument.

*Table 1. Comparison of different pipelines for 3D digitization of CH.*

| Paper | Purpose | Case study | Data integration | | Scanning accuracy[1] | Spatial Resolution | Dataset limitations[2] | |
|---|---|---|---|---|---|---|---|---|
| | | | Survey data | Other data | | | | |
| [Micoli et al. 2018] | Diachronic reconstruction of lost monuments and scenarios | Roman Circus of Milan, Italy | ToF, PS laser scanners, and mobile mapping georeferenced through differential GPS and integrated with | Ancient maps, historical drawings, archaeological reports, archaeological restrictions decrees, and old photographs | Distance accuracy up to ± 3 mm | At least 1cm | a | ✓ |
| | | | | | | | b | X |
| | | | | | | | c | X |
| [Altuntas et al. 2016] | Three-Dimensional Digital Recording of Complex Historical Structures | Mevlana Museum in Konya, Turkey | PS Laser Scanning and ToF imaging | Image acquisition for texture mapping | Distance accuracy up to ± 2 mm | At least 1.9 cm | a | ✓ |
| | | | | | | | b | X |
| | | | | | | | c | ✓ |
| [Suwardhi et al. 2015] | Digital documentation of historical sites for web-based management and analysis | Borobudur temple in Indonesia | Multi-sensor multi-resolution photogrammetric techniques using UAV and terrestrial images | NA | An average accuracy of 0.25m | Multi-resolution sub-cm to 5cm | a | X |
| | | | | | | | b | X |
| | | | | | | | c | X |
| [Micoli et al. 2013] | Enhancing the actual knowledge of historical buildings to discover historical transformations | The Chartreuse of Pavia, Italy | Multi-resolution 3D laser scanning integrated with photogrammetry and orthoimages | Historical studies and other complementary information such as thermoluminescence dating, IR imaging, and historical analysis | Distance accuracy up to ± 3 mm | Multi-resolution from 2 to 20 mm | a | ✓ |
| | | | | | | | b | ✓ |
| | | | | | | | c | X |
| [Korumaz et al. 2017] | Identification of structural health of historic buildings with deviation Analysis and Finite Element numerical modeling | Eğri Minaret in Aksaray, Turkey | Field of View (FOV), Topographic Measurement integrated with Terrestrial Laser Scanner (TLS) | Previously available manual survey drawings | Distance accuracy up to ± 3 mm | At least 1cm | a | ✓ |
| | | | | | | | b | ✓ |
| | | | | | | | c | X |
| [Fortunato et al. 2017] | Assessment of the seismic vulnerability of historical buildings | Baptistery of San Giovanni in Tumba, Italy | TLS integrated with photogrammetry | NA | Distance accuracy up to ± 4 mm | Not reported | a | ✓ |
| | | | | | | | b | ✓ |
| | | | | | | | c | X |
| [Pepe et al. 2020] | A pipeline to obtain digital models for HBIM (heritage building information modeling) and structural analysis | San Nicola Church in Montedoro, and San Cono Bridge in Buccino, Italy | TLS integrated with photogrammetric techniques using UAV and terrestrial images | NA | Distance accuracy up to ± 1 mm | Multi-resolution from 1mm to 1cm | a | ✓ |
| | | | | | | | b | ✓ |
| | | | | | | | c | X |

[1] The reported values are based on the approximate accuracy of the instruments used for survey.
[2] a = Point cloud vectorization; b = Extraction of constructive techniques and structural details; c = Redundancy of data for further investigations.

3D data integration has also been proposed for creating datasets to digitally record the existing complex historical structures [Altuntas et al. 2016; Suwardhi et al. 2015]. In both these cases, the purpose was to accurately record the physical appearances in the form of realistic 3D models for record-keeping, management, and analysis. The intended results in these cases could be achieved by integrating different types of surveying sensors, including terrestrial laser scanners, terrestrial photogrammetry, and aerial imaging. Similarly, [Micoli et al. 2013] proposed a multidisciplinary data integration for enhancing the actual knowledge of a historical building to discover its transformations over time. The digital model was created by integrating multi-resolution 3D laser scanning and photogrammetry with contemporary information such as thermoluminescence dating, Infrared (IR) imaging, stratigraphy based on the architectural traces on the facades, and historical analysis. The resulting dataset was used to represent a synthesis of heterogeneous set of interdisciplinary information such as historical, architectonical, conservative and stratigraphic data associated with the historical building through a web-based information management system. Though multi-sensor and heterogeneous data integration have been implemented in these examples, the motivation for such data integration has not been the analysis of the structural health of built heritage.

Other studies have highlighted the importance of a proper 3D survey of buildings for carrying out structural analysis. To identify the structural health of a simple historical structure with deviation analysis and Finite Element numerical modeling, a topographic survey can be combined with a few laser scans from a ToF device as suggested by [Korumaz et al. 2017]. In this case, surveying was not allowed within the interior of the structure; therefore, the authors integrated the surveyed data with the previously available manual survey drawings using a mesh model based on the points cloud. In other cases, TLS has also been integrated with the photogrammetric data to generate more detailed models for the structural analysis of historical buildings [Fortunato et al. 2017; Pepe et al. 2020]. However, data integration from other sources has not been adopted in these cases. Generally, current studies have performed surveys on relatively simple structures, and proposed no pipelines for creating large 3D datasets that could be integrated with other heterogeneous data.

## 2. MATERIALS AND METHODS

### 2.1 Methodology

In the past, some pipelines have been proposed for creating surfaces suitable for modeling objects or structures starting from a 3D point cloud model obtained through geomatics surveys. For developing a complete 3D dataset for structural analysis, we propose a pipeline that fulfills the three criteria defined in section 1.2. The proposed dataset includes not only 3D points cloud from the actual survey but also other interdisciplinary information on the present health of the structure. The proposed pipeline is composed of three phases: data acquisition, processing, and integration (figure 1).

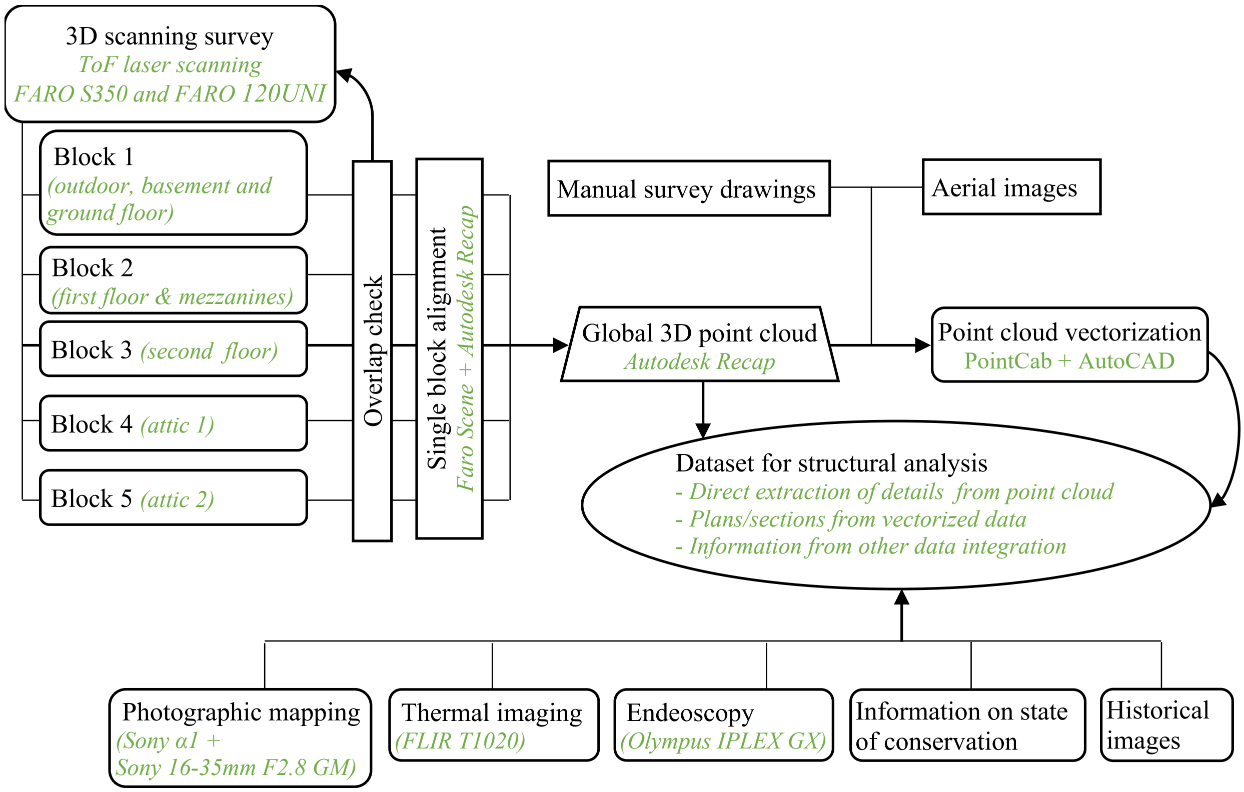



*Figure 1. The pipeline for creating a complete dataset for the structural analysis of historic buildings. The proposed general pipeline is presented in black text, while the green text represents the specific data acquisition, integration, and processing applied to the case study (section 2.2).*

The data acquisition phase is divided into several blocks so that the following data processing and integration steps can be carried out simultaneously within this step. It includes the acquisition of three-dimensional geometric data through laser scanning and the collection of other information on the state of conservation of the building. All the scanning activities must be accompanied by proper documentation to identify each recording; this identification includes a serial number, marking the position on manual survey drawings, noting the resolution, quality, intensity, color, and GPS coordinates, and any additional notes. The geometric registrations can be grouped into blocks such as all the external surfaces and several other blocks for the interior spaces of the building based on their location (ground floor, basement, first floor, second floor, attic). We also propose a direct survey of some important internal details for the subsequent treatment of the point clouds of the building and on-site verification of the acquired data using a portable computer. The surveyed data of each block can be simultaneously integrated with other historical data and other complementary information such as thermal imaging and Endoscopy, which would be useful for subsequent architectural and structural analysis of the building.

The second phase includes the alignment of the point clouds acquired in the first phase, control of errors generated by operations, application of filters for quality improvement, creation of the final points cloud, and graphical vectorization of the points cloud. The aligned points cloud can be used for automatically extracting the 2D plans and section drawings for the subsequent vectorization operations in any CAD (Computer-aided Design) software.

The final phase is the integration of all the acquired and processed data in the form of a complete dataset that can be further enhanced by adding other interdisciplinary data providing a possibility to extract any geometric or historical details for architectural and structural analysis of the building.

## 2.2 Case study

The methodology illustrated above is applied to the case study of Diotti Palace. This neoclassical historic building has been the location of the office of the Prefect of Milan, Italy, since 1859. The complex on which the Palace was built dates to the first half of the 17th century when it was the seat of the Collegio dei Padri Somaschi. The area was purchased by the lawyer Giovan Battista Diotti, who started construction works on the building in 1782 based on a project by G.B. Diotti himself and with the contribution of Giuseppe Piermarini. The complex underwent impressive changes and transformations with respect to the original configuration, due to the demolition of the nearby church of San Pietro in Monforte. This work allowed the construction of the second noble floor, the two extreme parts of the facade towards the garden, the central courtyard, and the restoration and general arrangement of the building. The building was sold to the Government of the Italian Republic in 1803 due to financial problems of the Diotti family and became the seat of the political section of the Austrian Government in 1815. The architect Pietro Gilardoni built the external facade on Corso Monforte in 1817, adding the current pronaos of fluted Doric columns surmounted by a balcony to the center of the same. The imposing external facade of the building is also composed of two lateral avant-corps and a central section characterized by a smooth ashlar decoration on the ground floor. On the main floor, the windows are decorated with lintels surmounted by triangular pediments, while on the second floor, the windows are decorated with simple stone frames. The main courtyard is much richer and more dynamic, featuring a portico with paired Doric columns, the first floor with paired pilasters, and the second with paired sculpted herms. Noteworthy inside the building are the paintings and decorations executed by the painter Andrea Appiani and by the theatrical decorator and set designer Clemente Isacchi and the main staircase with three flights with walls divided by pilasters. Finally, the Austrian Lieutenancy of Lombardy took office in the building in 1849, and in 1859, after the annexation to Italy, the Prefecture was established [Raponi and Scotti 2005; Bologna 1981; Lanza and Somarè 1993].

The complex was subject to further modifications over the last 150 years. Some vertical connections have been added to facilitate movement between the different levels of the building. Moreover, the internal environments have been further partitioned to maximize the spaces, with some portions of the building being subdivided in eight to create mezzanine floors suitable for offices. The building is currently in a good state of conservation. However, many cracks have been identified on the internal and external surfaces of the building. Comparing photographic images taken in 2018 with the current situation makes it possible to hypothesize that these degradation phenomena can be attributed to the construction of the M4 underground metro line in Milan. To evaluate and understand whether these degradation phenomena are still in progress or if they occurred only with the temporary vibrations of the M4 line construction and therefore the structure is stable again, it was necessary to proceed with targeted structural investigations.

For this reason, a three-dimensional survey using laser scanning methodology, historical-archival analysis, and targeted diagnostic investigations were carried out to form a dataset of information useful to the group of engineers who dealt with the static evaluation of the building. In addition to some specific publications on the history and evolution of the complex [Raponi and Scotti 2005; Bologna 1981; Lanza and Somarè 1993], the structure has been analyzed over the years both from the point of view of the state of conservation and from the geometric and morphological point of view. However, these studies and research are now dated and have not reached levels of detail that can be used for these investigations. The only drawings taken into consideration were the plans of the building. These were used to plan the three-dimensional survey as they were deemed reliable in regards to the location and subdivision of the rooms.

## 2.3 Materials (Instruments)

Different instruments and methodologies, aimed at the qualitative and geometric investigation of the structures, were used for data acquisition. More specifically, the first activities made it possible to understand the building from the material and the state of conservation point of view thanks to the investigation of the internal and external surfaces. The analysis was performed through the targeted inspection of all the rooms with the recording of photographic images of the walls or portions that had cracks. The photographic survey was performed using a full-frame mirrorless camera (Sony α1) [Sony Electronics INC. 2023a] equipped with a very bright wide-angle zoom lens (Sony FE 16-35mm F2.8 GM) [Sony Electronics INC. 2023b]. This configuration made it possible to acquire many high-resolution photographic shots (50.1 MP), which, in addition to mapping the surface situation of the walls, made it possible to implement further geometric knowledge of the building.

The morphological analysis of the complex was performed using two 3D Terrestrial Laser Scanning (TLS) devices based on Phase-Shift (PS) measurements, the FARO Focus 3D 120 Uni and FARO Focus 3D S350 [FARO 2023]. Laser scanners using this technology allow faster and more accurate acquisitions than ToF scanners and, in recent years, have overcome the initial problem of the maximum reachable extension achieving up to about 350 meters [Suchocki 2020; Previtali et al. 2014; Rüther et al. 2009]. Furthermore, the PS devices are small in size and therefore useful in complex and articulated situations, where easy handling and low weight play a fundamental role in long and extensive acquisitions. Although the two devices were released on the market about ten years apart, the accuracy of the data captured has remained very similar [FARO 2023]. In fact, the FARO Focus 3D 120uni has a ranging error of ±2mm (defined as the systematic measurement error around 10m and 25m) and a ranging noise between 0,3mm and 0,5mm (calculated at 90% reflectance with a noise-compression algorithm and a distance between 10m and 25m), while the FARO Focus 3D S350 has a ranging error of around ±1mm and a ranging noise of around 0.3mm.

Finally, two survey methodologies were used to define the building's construction technologies. The first analysis investigated the thermal characteristics of the surfaces through a non-destructive device, the FLIR T1020 thermal imaging camera [Teledyne FLIR LLC 2023]. The second investigation methodology, in this case destructive, used a video endoscope, the Olympus IPLEX GX [Evident 2023], to identify the material change inside the walls, especially in the underground portions of the building. Combining these two types of analysis made it possible to implement the knowledge gained from the historical-archivist analysis relating to the materials and construction techniques used in the entire complex. In particular, the thermal imaging camera proved to be particularly useful as it was able to identify temperature differences down to <20mK (thermal sensitivity/NETD at 30°C) for clear and low-noise results [Teledyne FLIR LLC 2023].

## 2.4 Data acquisition

### *2.4.1* Three-dimensional data acquisition

A careful design and planning of the registration points preceded the data acquisition. Considering the size of the complex, which consists of approximately 19,000 gross sqm of flooring and about 4,500 sqm of outdoor spaces, this phase was essential to balance the number and arrangement of scans to be made. The recordings phase started with all the external fronts visible from the entrance floor, acquiring about 250 complete scans. For the spaces located inside the building, an intense survey campaign was carried out. The survey produced the following registrations: 580 scans for the basemen, 550 scans for the ground floor, 530 scans for the first floor and mezzanine floors, 500 scans for the second floor, and 400 scans for the attic floor. In total, around 2800 complete scans were acquired for defining all the internal spaces of the building.

As the survey was only required to obtain the geometric description, the acquisitions were therefore made in reflectance mode (scales of gray, without color) to speed up the registration and subsequent processing operations and avoid the excessive weight of the three-dimensional dataset. The only exceptions were a few colored scans conducted in interior spaces with complex decorations on the walls or the roofs.

The location of the rooms, their geometric and architectural characteristics, and the presence of numerous fixed and movable furnishings, did not allow a broad view of the spaces. This led to a preference for a very dense acquisition, with a pitch of about 3-4 meters between scans. This setting was further reduced to 2 meters in most of the storage rooms in the basement and for smaller or morphologically/architecturally complex rooms located on the upper floors. All recordings were performed with a rotation of 360° around the vertical axis and 300° around the horizontal axis, positioning the instrument at a height between 0.50 and 1.60 meters from the ground. The resolution parameters were defined based on the characteristics of the portions to be surveyed, the extension of the area, and based on the distance of the instrument from the surfaces, while the settings for the quality of the survey remained unchanged. For example, the first scans made outside the building were recorded using a higher resolution setting in comparison to the subsequent acquisitions made inside where a lower resolution was preferred due to the reduced distance between the instrument and the surfaces to be acquired.

### *2.4.2* Thermal imaging and Endoscopy

Following a careful analysis of the historical-archival documentation and the results of the analysis carried out in previous years, the thermal and endoscopic investigations involved only certain portions of the building. These acquisition activities were mostly concentrated where information was incomplete, or on the most technologically articulated portions of the building. The thermal images were mainly recorded in spaces that were difficult to understand only through direct vision; for example, the painted and/or decorated vaults of the rooms, some wholly plastered surfaces or elements of the basement, the areas that presented morphologically or dimensionally anomalous configurations, and some portions of the building that were highlighted by the team of structural engineers. Altogether, well over 50% of the detectable spaces and at least one or more rooms per homogeneous area were investigated. The spaces with recently built false ceilings (many rooms on the second floor and some on the ground and first floors) were not surveyed since the thermography could not provide any results of the vault hidden by a false ceiling. The thermal shots were recorded at maximum resolution after calibrating the sensor's emissivity and were captured along with a photographic image in real RGB colors of the same portion. This allowed a perfect overlap between the thermal image and the RGB image for a more precise analysis of the results. The thermal investigations were carried out during two different periods of the year, in July and at the end of September, and in passive mode (i.e., without the contribution of artificial heating or cooling sources). In the first session, the rooms were in the phase of maximum heat, while in the second session, natural ventilation of the rooms was opted for to favor the thermal transient.

Endoscope tests were mostly concentrated in the basement areas. This choice stems from both the nature of the building and the limits of permitted analysis, as it is a protected historic building. Furthermore, the spaces in the basement were the least known or studied, and therefore, required specific investigations the most to identify the technological and material stratigraphy. For this reason, ten points of analysis were identified with the team of structural engineers, relating to the stratigraphy of the wall portions and vaulted ceilings. After making the approximately 100cm holes for the endoscopy and cleaning the canal, the endoscopic probe was used to acquire video and static images at different depths.

## 3. RESULTS

The three-dimensional data from laser scanning, along with the graphic vectorization of point clouds and integration with other heterogeneous data, resulted in a complete dataset for the structural analysis of the case study as proposed in the methodology.

### 3.1 Three-dimensional data from laser recordings

In parallel with the on-site survey operations, the single point clouds recorded during the acquisition phase were verified from the point of view of reliability and subsequently filtered to improve their quality through the elimination of false points, incorrectly acquired points, or artifacts present through portable and desktop workstations. Since the instruments are capable of acquiring data up to a distance of about 120 or 350 meters (variable depending on the model used) [FARO 2023], it was necessary to remove all the non-essential points, the redundant points, and those relating to the non-object portions of the relevant activities, to optimize the result.

Considering the preliminary processing results, the alignment and registration phase was carried out by macro-blocks to evaluate the effective coverage of the acquisitions, the reliability, the general density of the clouds, and the correct connection and positioning between the different levels of the building. The individual point clouds were thus pre-aligned through the cloud-to-cloud alignment method together with an automatic analysis with a top view, returning positive results, an average density greater than 25,000 points per square meter, and linear/angular errors below the restitution scale (1:100).

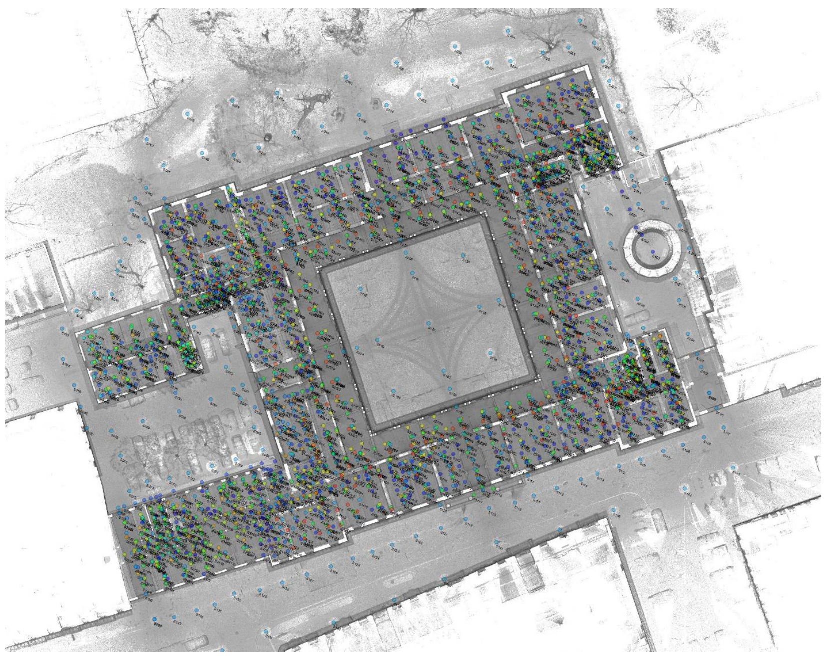
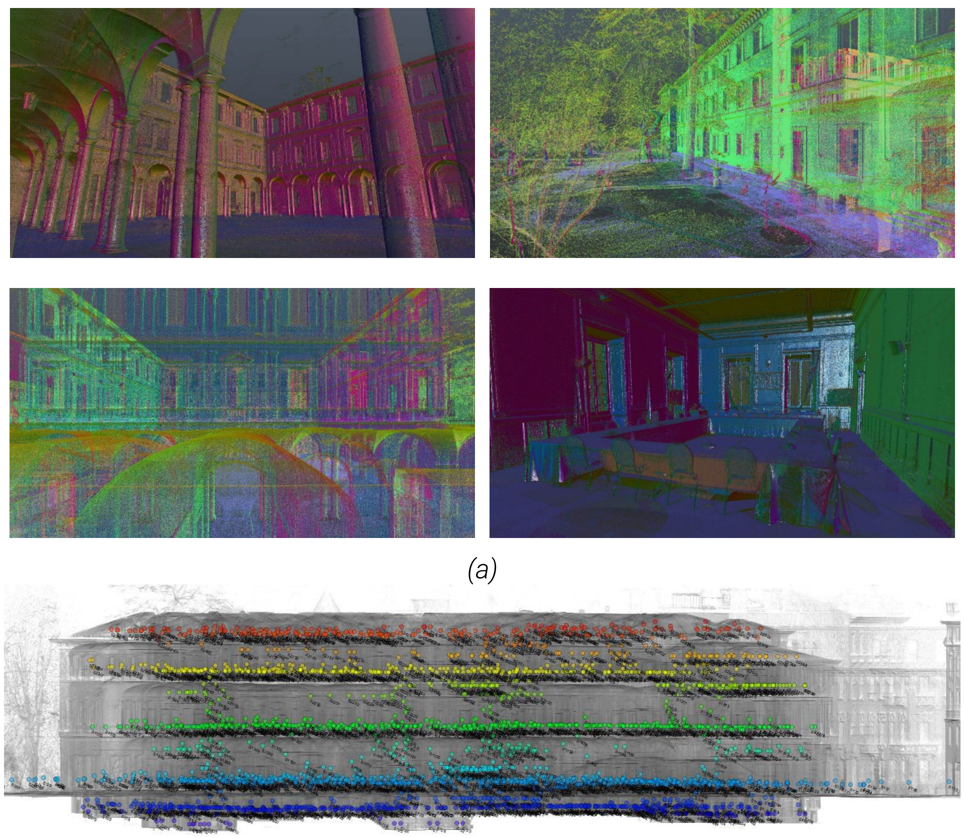


*Figure 2. Alignment of external and internal point clouds, highlighting individual scan points.*

The scan registration of the internal spaces returned average linear errors of less than 10mm due to the large overlap between the scans and the limited dimensions of the rooms. These factors have contributed to the containment of the error propagation allowing an excellent accuracy of the LS internal reconstruction, unlike what happened in the external portions. The alignment and registration of the external spaces have given rise to major problems, especially in the portion characterized by medium and low vegetation. The maximum error detected was about 25mm in correspondence with surfaces partially hidden by vegetation, while the average accuracy of the LS external reconstruction was around 18mm. The preliminary analysis of the data highlighted the correctness of the individual recordings and confirmed the acquisition method (figure 2).

The high number of scans and the acquisition time extension did not allow the association and definitive registration of the approximately 2800 scans in a single group from the beginning. For this reason, as suggested in the proposed methodology section 2.1, the following alignment macro-blocks were created:

- block 1: outdoor spaces, basement level, and ground floor;
- block 2: first floor, mezzanines, vertical connections with the ground floor, and connections with external spaces;
- block 3: second floor, mezzanines, and vertical connections with the first floor;
- block 4: attic level of the two lower buildings to the west;
- block 5: attic level of the main body of the building.



*(b)*

*Figure 3. (a) Perspective images of the point cloud from the exterior and internal spaces of the building; (b) lateral orthographic view of the complete aligned point cloud with individual scan points highlighted.*

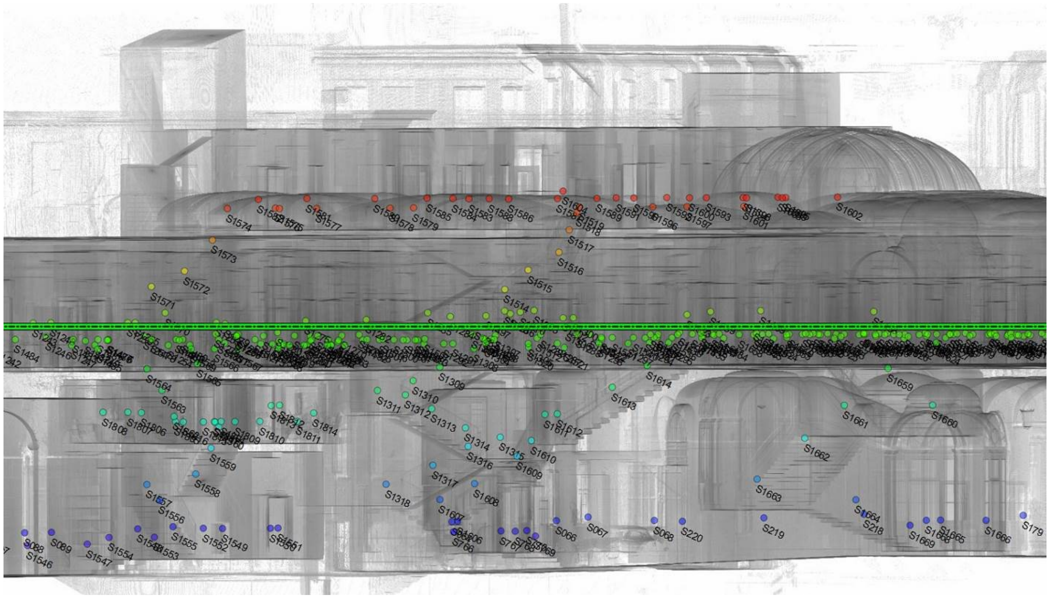
The five blocks thus formed, possessing common areas and surfaces, allowed further checks of geometric coherence and made it possible to create a single three-dimensional dataset containing all the geometric information acquired. Also in this case, the macro-blocks were aligned through the cloud-to-cloud method together with an automatic analysis with a top view, returning positive outcomes, densities, and linear and angular errors as before (Figure 3).

The complete three-dimensional dataset was then decimated in the portions where it had significantly higher-than-average densities. It was useful to facilitate the subsequent phases of exporting the points on horizontal and vertical planes in terms of processing time and amount of information. It was possible to project all the points of the dataset onto spatially determined horizontal planes to bring out all the morphological characteristics necessary for the definition of the geometries of the rooms and architectural elements. We opted for two types of projection, the first on the ground and the second towards the ceilings. The operation made it possible to verify the complete coverage of the internal surfaces and further validated the acquisition method and process. This processing phase also made it possible to export the levels used as a metric basis for the creation of the vector drawings of the entire building.

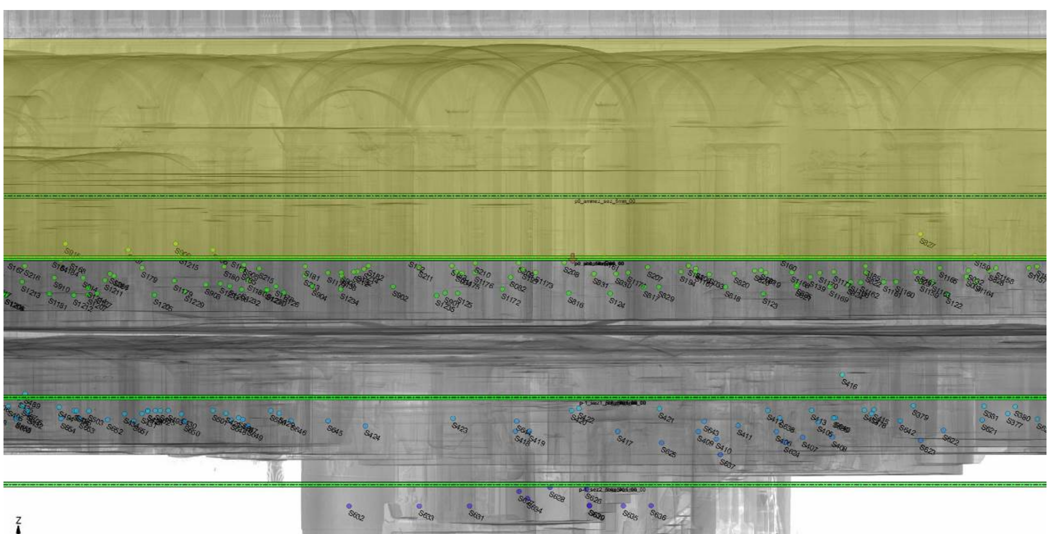
The list of levels extracted in the planimetry included:

- horizontal section/profile of the cloud at about +120cm from the walking surface: the portion of points involved does not exceed 5mm in thickness (figure 4a);
- projections of the points on the ground on the horizontal section plane: export of different projection levels based on the altimetric and morphological characteristics of the environments;
- overturned projections of the ceiling points on the horizontal section plane: similarly to the previous point, export of different projection levels based on the altimetric and morphological characteristics of the rooms (figure 4b).

All the projections on the ground and towards the ceilings on the horizontal cutting planes constitute individual metric work environments characterized by univocal roto-translations of the geometric components to allow a full overlapping of the levels that make up the building, thus maintaining the possibility of interacting with the same coordinate system.



(a)



(b)

*Figure 4. (a) Detail of "Block 2" in frontal orthographic view. The horizontal plane of the section/profile placed at about 120cm above the walking surface of the first floor is highlighted in green; (b) detail of "Block 1" in frontal orthographic view. The horizontal planes of the section/profile are indicated in green. The area of the projection of the points including the entire extension surface is highlighted in yellow.*

The same export method was also followed for the drawings in elevation, sections, and facades. For the internal sections of the building, 7 vertical cutting planes have been identified as capable of fully defining the morphology of each room on the various levels (Figure 5). For the elevation sections of the external facades, all the points of each facade of the building were projected onto vertical planes parallel to the fronts affected by the operations (Figure 5).

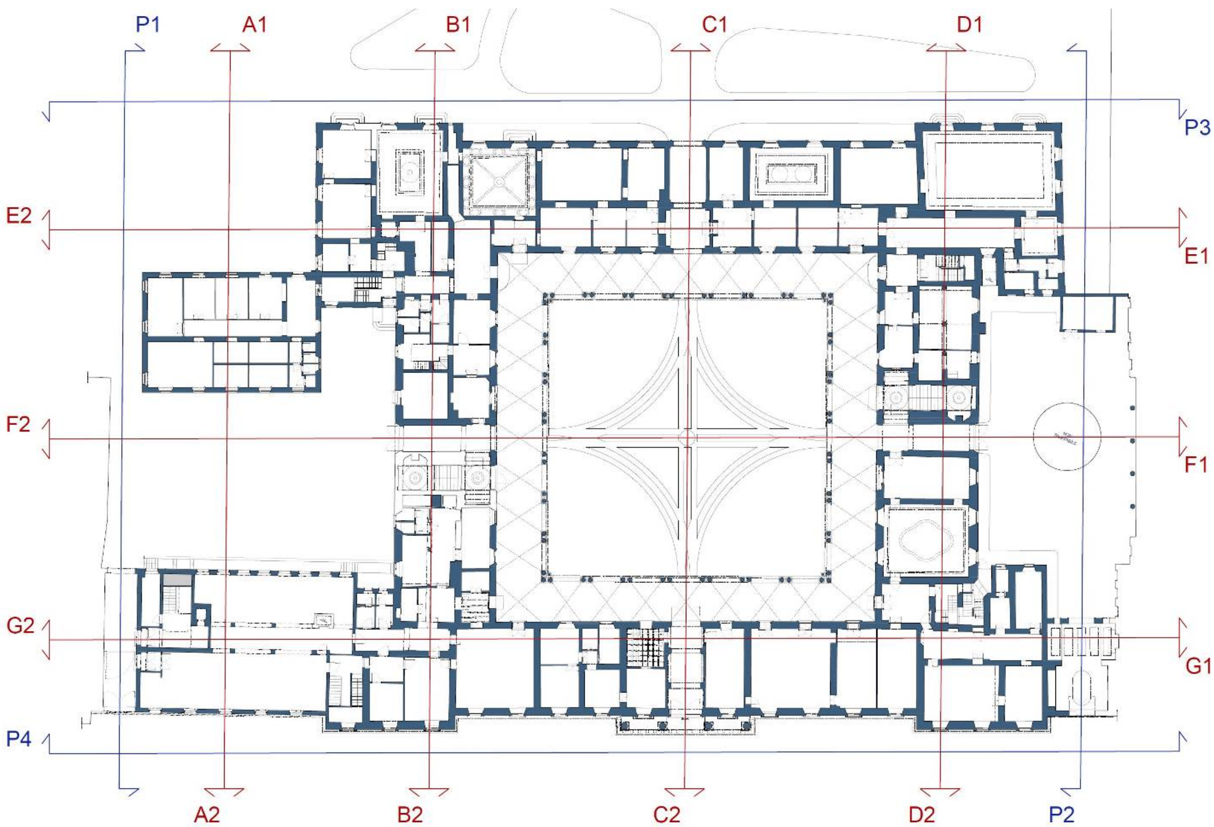



*Figure 5. Indication of the vertical section planes: double-sided sections and elevations, based on the planimetric basis of the ground floor.*

In this way, 4 drawings in elevation were generated capable of defining the geometric characteristics of all the external surfaces. As before, all the elevation projections constitute single metric work environments characterized by unique roto-translations of the geometric components.

For each vertical section plane, the following levels have been exported:

- vertical section/profile of the cloud as per the diagram in Figure 6: the portion of points involved does not exceed 5mm in thickness;
- projections of the points on the vertical section plane: export of different projection levels based on the morphological characteristics of the rooms and the building (Figure 6).

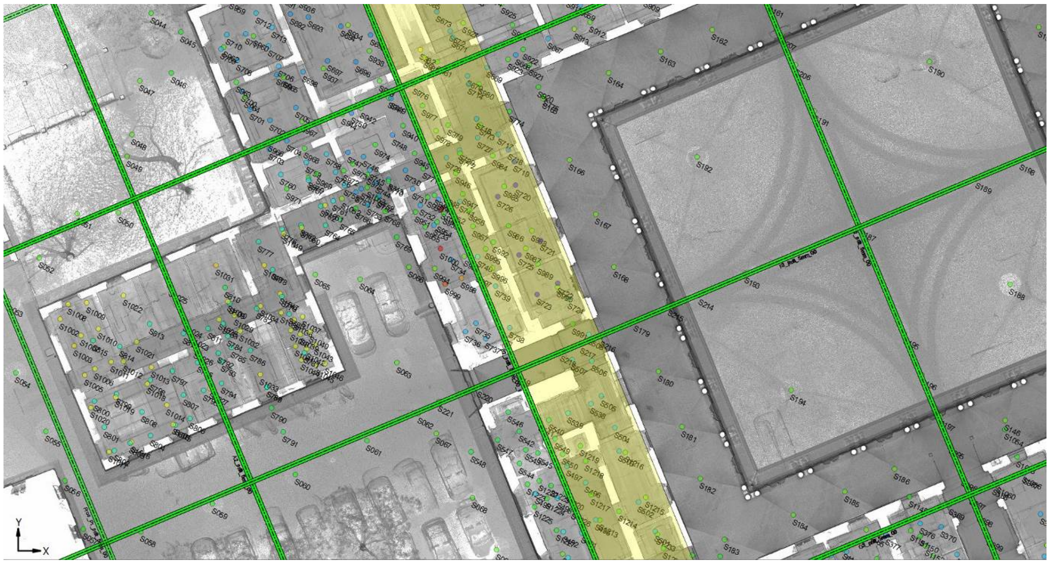


*Figure 6. Detail of "Block 1" in zenithal view. The vertical planes of the section/profile are indicated in green. The area of the projection of the points including the entire extension surface is highlighted in yellow.*

## 3.2 Graphic vectorization of points cloud

The elaborations and extractions carried out in the previous step allowed the creation of a unique two-dimensional dataset as a base for the subsequent vectorization operation. We initially proceeded with the unification of all the exports referring to each single section plane, horizontal or vertical, systematizing the levels in the AutoCAD environment.

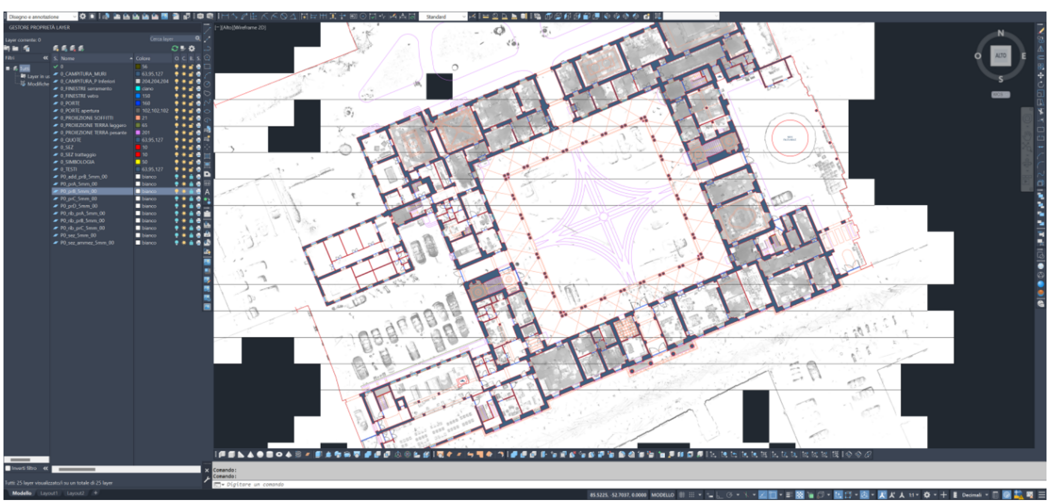
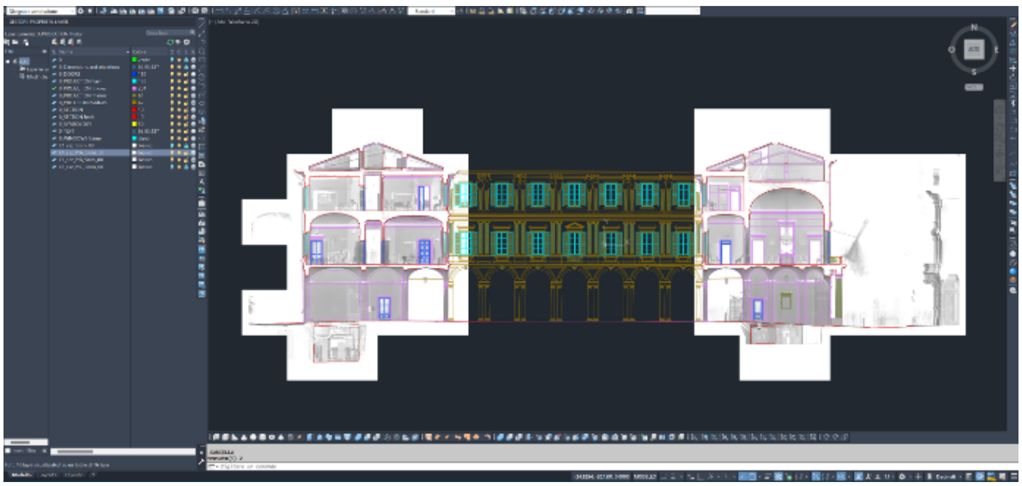


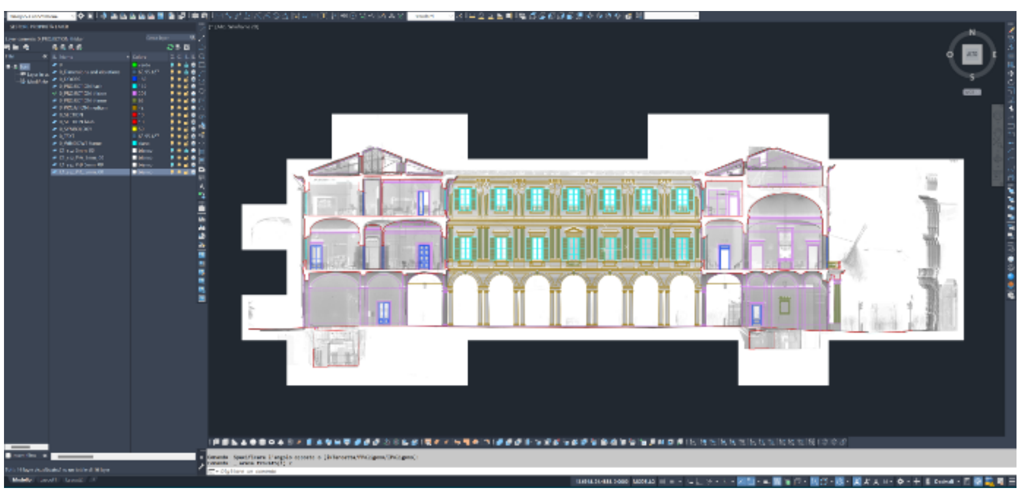
*Figure 7. AutoCAD file representing the union of the extractions of the ground floor of Diotti Palace. On the left is the list of all the levels extracted from the point cloud that has allowed vectorial processing in the planimetry. An intermediate level of ground projection is displayed on the right.*

These levels were loaded maintaining the same point of origin to allow certain overlaps between the different horizontal section planes. For the extractions on vertical planes (internal sections and external elevations), we proceeded in the same way, keeping the altimetric position of the point cloud extractions constant and absolute to allow for evaluations or checks. For each vector file referring to the drawings in the planimetry, the levels in the section/profile were first inserted, then the levels in the ground projection, and finally those in the ceiling projection (Figure 7).

For the elevated drawings, the section/profile level was initially entered and then the different projection levels were loaded (Figure 8).



*(a)*



*(b)*

*Figure 8. File in AutoCAD environment for merging the extracts of the "C1" section. On the left is the list of all the levels extracted from the points cloud that has allowed the vector processing in elevation. (a) The level in partial*

*projection is displayed on the right (surfaces within 8 meters of the vertical section plane); (b) the level in complete projection is displayed on the right.*

Considering the degree of detail to be achieved, the morphological complexity of the architectural structures, and the geometric articulation of the external and internal decorations, double extraction for each level was carried out. The first is characterized by pixels corresponding to 5mm in real scale and the second with pixels corresponding to 2mm in real scale. This method has allowed greater identification of all the elements, thus increasing the reliability of the vectorization.

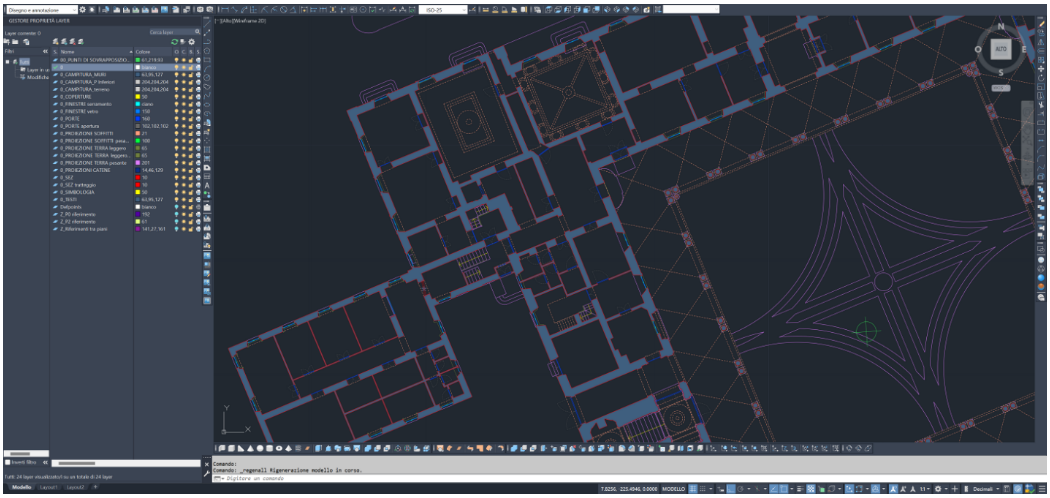
On these planimetric bases and in elevation, the different layers and the most suitable graphic design for defining the geometries of the building in relation to the necessary level of detail (1:100) were identified. In general, the tools and graphic codes of architectural design for historical buildings were used, as summarized below [type of line, color, thickness]:

- walls section: continuous line, black, th. 0.30 mm;
- hidden walls section: dotted line, black, th. 0.30 mm;
- doors and windows section: solid line, black, th. 0.09 mm;
- heavy front/ground projection: continuous line, black, th. 0.13 mm;
- light ground/frontal projection: continuous line, black, th. 0.09 mm;
- ground/frontal detail projection: continuous line, black, th. 0.05 mm;
- projection of the ceilings: dotted line, grey, th. 0.13 mm;
- door space: dotted line, grey, th. 0.10 mm.

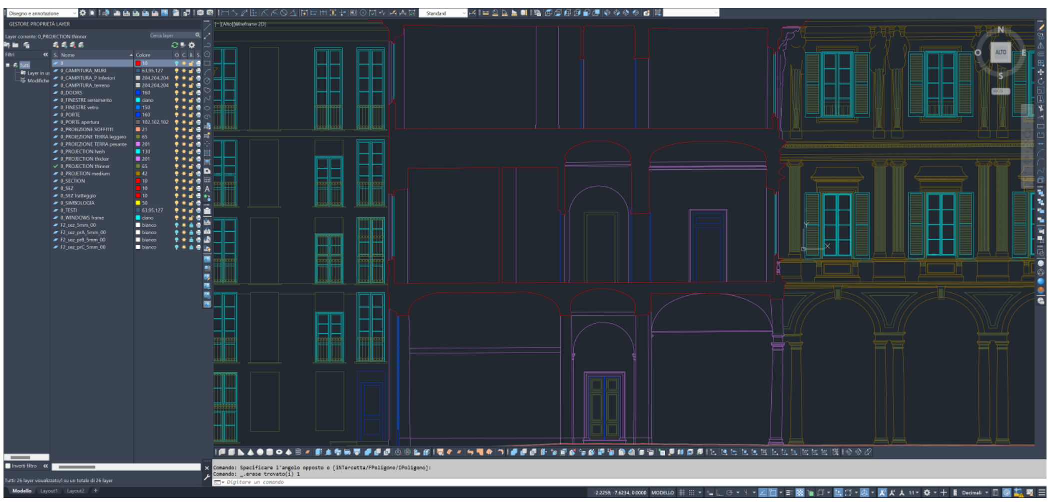
The area of the section of the wall was indicated through a solid continuous background to allow immediate recognition of the wall section in the horizontal or vertical section plane. The portions of hidden walls, cut by the horizontal or vertical planes were indicated by a black dotted line with a thickness of 0.30 mm. Therefore, the color and thickness previously used for the sectioned visible structures are maintained, varying only in the type of line. This system was used only for the completely covered/hidden portions of the walls. These geometric indications for hidden portions were the result of analysis and direct measurements carried out in the internal rooms of the building and based on some points of the three-dimensional cloud. In the absence of information, the geometric indications of hidden walls were hypothesized through analogy with respect to similar and comparable spaces or situations both structurally and morphologically.

The level of simplification of the geometries followed the degree of detail of the representation, therefore, the elements or details of dimensions smaller than 3 cm were not represented, while the characteristics of dimensions between 3 cm and 6 cm were simplified in order not to weigh down or make the reading of the graphics unclear. Even the morphological discontinuities or the effects of some degradation phenomena (for example, decay and erosions) on the geometries followed the same simplification approach. However, this method has not affected the reliability and accuracy of the section, the reliability level of the survey remains unchanged by the simplification operations.

The two-dimensional elaborations produced entirely covered the external and internal surfaces of the building, including the decorative apparatus, without representing the fixed and movable furnishings present (Figure 9).



*(a)*



*(b)*

*Figure 9. (a) Detail of the ground floor plan in AutoCAD environment; (b) detail of the "F2" section in the AutoCAD environment.*

## 3.3 Data integration: thermography and endoscopy

The geometric dataset in the three-dimensional and two-dimensional versions was of great use, allowing the anchoring and positioning of the information from the other analyses performed by the work team. The results of the historical-archival research have been localized in the plans at different levels, allowing a clear identification of the complex's evolutionary phases and the architectural and structural elements involved. This made it possible to think even at a high level, reconstructing the evolutionary profile on a reliable metric basis. The geometric survey was also implemented by the analysis of the crack pattern of the building created through a photographic mapping of the surfaces that showed cracks of any kind. The expeditious analysis of the structural elements has also broadened the morphological knowledge of the building to return a general framework of the construction techniques used, providing information on the state of conservation of the materials and structures and possible critical issues in terms of structural resistance. The aim, in this case, was to complement and broaden the understanding of the 3D survey by linking it to the results of historical-archival research and the mapping of cracks, creating a knowledge base for creating a structural model of the building. This analysis made it possible to document the materials of the load-bearing structures and the wall textures through visual observation of the elements, taking into consideration the accessibility of the places and the effective level of understanding that can be reached. The investigations were carried out inside the building and involved the most interesting spaces from a structural point of view due to the presence of cracks or because they straddle buildings belonging to different historical periods. The basement has been completely inspected, both because it is easily accessible and because most of the structures are visible.

On the other hand, the ground, first, and second floors have only been partially analyzed as the structures appear to be hidden by the decorations or furnishings. It was decided to examine the spaces near different historical phases for these floors. Of great interest was the attic, which had some parts of wooden trusses cut when the roof was rebuilt in the 1990s. The main criticality of the analysis lies in the lack of some information that it was not possible to deduce visually, especially where the thickness of the walls varied a lot. For this reason, it was decided to implement the knowledge baggage through thermographic and endoscopic investigations.

In the specifics of these last two types of analyses, we first verified the acquired thermographic images and created thermal mosaics to represent the mapped surfaces (Figure 10) for the images taken from the same point of view. All the single thermal images and subsequent mosaics have been simply placed into the 3D geometric dataset and named according to the layout of the rooms. The aim was to provide useful data mainly for the identification of the texture of the vaults and walls without any metric purpose. Each image shows the date and time of acquisition, the GPS coordinates, the size in pixels, the range used during the acquisition, the indicative temperature measured by the instrument, and the emissivity used. The images acquired in the second session of thermal tests returned clear and useful results for understanding the masonry techniques thanks to the high thermal transient (warm walls and decreasing external temperatures). The images have allowed the identification of the texture of the vaults in wooden carpentry or in masonry and the wooden or later-cement floors, above all, for the first and second levels of the building. The rooms located in the basement instead gave a lesser response as the temperature of the walls and the environment was practically in balance due to the few openings to the outside and the thickness of the walls.

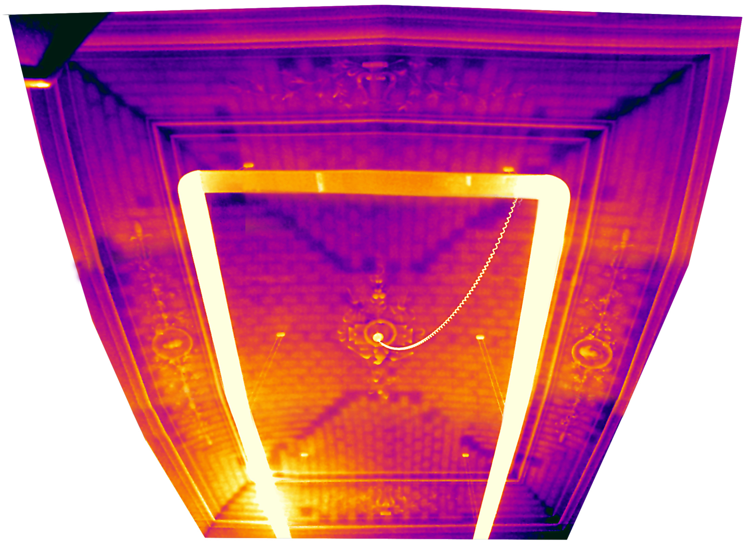


*Figure 10. Thermal mosaic of one of the rooms with the vaulted brick ceiling.*

Finally, the endoscope acquisitions were reprocessed and selected in such a way as to extract the information useful for the characterization of the masonry stratigraphies (Figure 11). Above all, the endoscopic tests were carried out in the basement of the building, where the historical-archival information was incomplete, and the thermal images returned insignificant data. The analysis concerned the load-bearing walls against the ground and the vaults dividing the basement from the ground floor, clearly showing the identified materials.


*Figure 11. Image of an endoscopic test carried out in the masonry of the basement (view from the inside out). The material change between the brick and the ground is highlighted.*

## 4. DISCUSSION AND CONCLUSIONS

The pipeline to create a complete dataset for structural analysis of a complex historical building proposed in this article was tested on the case study of Diotti Palace. By fulfilling three essential criteria suggested in this article, the proposed pipeline shows an advantage over the other 3D pipelines in the literature to digitize the built heritage (Section 1.2). This pipeline is based on common 3D surveying and data integration techniques, but the proposed methodology of data acquisition/integration and the validation of the robustness of the resulting dataset through the suggested criteria will contribute to providing guidelines for future works in the preservation of built heritage.

The dataset obtained from this process must be considered as a container of three-dimensional metric information to which information coming from other sources has been anchored. Specifically, the implementation through historical-archival investigations, thermographic analysis, and endoscopy has played a crucial role. The process has in fact made it possible to organize, manage and share all the data within a defined environment. This semi-structured information dataset relatable to each other also made it possible to offer an overview of the current conditions of the architectural components of the complex and to reconstruct the evolutionary/construction phases that influenced the building.

The resulting dataset from this study satisfies the three essential criteria (defined in Section 1.2) to be considered for producing a complete dataset useful for later structural analyses. The first criterion is the possibility of vectorizing the 3D data in detail. The 3D dataset generated for the case study was used to produce vectorized drawings of the whole building (Section 3.2) including 4 elevations, 7 double sections, 4 floor plans, a plan of the attic level, and a roof plan. The vectorized drawings were later proved to be sufficient for a detailed structural analysis of the building with FEM.

The second criterion is related to the flexibility of the dataset to provide comprehensive information about the building's constructive techniques and structural details. The dataset produced by applying the proposed methodology to the case study also meets this criterion. A 3D dense point cloud shown in section 3.1, with at least two scans in each ambient of the whole building including interior details and exterior surfaces, offers the possibility to extract any structural detail for later analysis. All the spaces are characterized by the same degree of resolution and uncertainty and can therefore be compared. Thus, the dataset allows exporting of the data subsets at the same resolution and density, which is useful for the detailed analysis of the historic built heritage.

The third criterion is to produce redundant data that can be used for further investigations, if required at a later stage, without a need for additional data acquisitions. The dataset created for the structural analysis of the case study in this article accomplished this criterion by creating redundant 3D point cloud data integrated with different quantitative and qualitative data. The results reported in Section 3 demonstrate that by using the proposed methodology, we were able to create a dataset that has an abundance of data which might not be required in all the cases, but is valuable in cases where additional information is required at later stages without carrying out further surveys. Such a dataset is easily shareable and interpretable after the data acquisition step. In the specific case of Diotti Palace, for example, additional information on the materials and state of conservation required by the structural engineers was easily extracted several times from the completed dataset.

The 3D dataset in the case of Diotti Palace was produced by using the proposed methodology of data collection and integration with other heterogeneous data, which turned out to be complete to perform later FEM analysis.

As suggested in the proposed pipeline, the 3D dataset was integrated with further data for the case study (Section 3.3), which provided an additional opportunity to gather further information on the constructive details of the complex building. The data integration from thermography and endoscopy allowed us to add information on the technological characteristics of the building positioned in specific and known points of the building.

Data from aerial cartography was also integrated to make up for the lack of surveyed information. Considering the central positioning of the case study building with respect to the center of Milan and the particularly delicate function of the building (being a Prefecture), it was difficult to acquire geometric information on the roof slopes using a drone. Some geometric information was acquired from the high spaces of the building. However, there were not sufficient results for the vectorization of the roofs. Therefore, reliable, and recent aerial maps were used to integrate the missing portions. Geometric/construction data obtained from historical research and drawings held by the Prefecture of Milan were also very useful for better understanding the roof eaves.

Furthermore, the photographic mapping of the internal and external surfaces added additional value because it could be directly connected to the 3D dataset, which allowed us to contextualize and locate details and additional information on the photographic images.

Nonetheless, a redundant dataset such as the one presented in this article presents some drawbacks, specifically regarding the additional time required for 3D survey planning, data acquisition, and processing. Therefore, we suggest adopting the proposed pipeline to be used only in the cases where: (a) the purpose is to measure the structural vulnerability of a complex building; (b) the sharing of large datasets among different professionals is required without additional surveys for specific needs; and (c) the subsequent integration of data from heterogeneous sources might be required.

Overall, this article highlights the importance of creating a comprehensive dataset that can later be used for a complete structural analysis of complex historical buildings. We proposed three essential criteria that determine such comprehensiveness of a 3D dataset. By carefully planning the 3D survey campaigns, heterogeneous data collection, and data integration, a rich dataset can be produced. Such a dataset is efficient for providing all the necessary information that might be required at later stages to evaluate the structural vulnerability of historic structures. We believe that the proposed methodology could significantly contribute to providing good guidance for planning surveys and optimizing the pipelines of creating large datasets for the structural analysis of complex historical buildings.

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