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Interdisciplinary Method to Analyze Historical Water Resource Management Systems: The Case Study of *Masseria del Cristo* in Matera, Italy

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Abstract. The rural architecture of Matera preserves important traces of the historical heritage represented by integrated water resources management systems, which contributed to the inscription of the city on the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage List in 1993. The need to guarantee water supply led to theoretical and practical knowledge aimed at sustainable management of resources, both within the urban fabric of the Sassi and along the historical routes of transhumance. The farmhouse known as Masseria del Cristo, in the countryside of Matera, bears historical evidence of this heritage, unlike what is observable in urban areas due to the significant transformations undergone in recent decades. Excavated cisterns, settling tanks, dug channels and a semi-excavated cistern with a roof were detected through photogrammetric processes and represented through 3D digital models that are freely consultable online. Through the analysis of this specific case study, the contribution proposes an interdisciplinary multiscale method to investigate the relationship between historical water systems and the geomorphological and hydrological context in which said systems are located. The results of this process provide a solid starting point to guide proper practices for the protection, recovery and enhancement of this historical heritage.

Keywords: Interdisciplinary Multiscale Analysis, Historical Water Systems, Digital Survey, 3D Virtual Fruition, Rural Architectural Heritage.

1. INTRODUCTION

Digitalization processes play a central role in scientific research in the conservation and promotion of cultural heritage.

In recent years, the scientific community has shown a growing interest in developing innovative methodologies and techniques for the survey and analysis of detailed historical heritage information. These processes produce results useful for managing, designing and monitoring restoration interventions and functional recovery, as well as for enhancement and tourist promotion [1].

Structure From Motion (SfM) photogrammetric modeling, which uses frames acquired through cameras mounted on Unmanned Aerial Vehicle (UAV) devices, provides an innovative technology capable of returning high-quality information data, through rapid and simplified processes.

The photogrammetric survey enables the documentation of historical heritage at risk of disappearing and the development of 3D digital models for virtual fruition.

This study structures a multiscale analysis process to analyze systems of interception, channeling, collection and use of the water resource of a historical rural building, known as *Masseria del Cristo*, in the countryside of Matera (Southern Italy), ensuring its virtual accessibility through online 3D models which represent information banks to transfer knowledge. The choice of this approach stems from the need to properly know the intrinsic characteristics of such heritage, which is the product of historical practices aware of the relationship between architectural scale elements and the wider morphological and hydrological context in which they are located.

The *masserie*, historical farmhouses, are complex and heterogeneous architectural organisms, which constitute the key elements around the agricultural landscape of Southern Italy, organized on the latifundia and transhumance [2-3], from the Modern Age until the first half of the 20th century.

2. METHODS

This contribution presents a methodological approach to study the historical heritage represented by integrated water resource management systems in the area of the *Masseria del Cristo*, in Matera. The analysis of these systems, inserted in a rural context, which generally have not transformed as in urban areas, provides a systematic knowledge of traditional water supply practices and techniques. The proposed methodology permits to study this heritage through a multiscale interdisciplinary workflow, because the study of water resource management systems requires a broader view at the natural environment in order to understand the close link between human settlement, morphology and hydrology of the territory.

Rural architecture constitutes a substantial and invaluable component of the built heritage, not only within the boundaries of the case study presented but across the entire Italian territory. Until the aftermath of the Second World War, Italy remained a predominantly agrarian society. Consequently, the countryside was not only inhabited but also actively shaped and experienced, often even more intensively than urban areas. This historical condition, which finds parallels in many other European countries, gave rise to an exceptionally rich and diverse architectural landscape. The buildings that populate this landscape draw their distinctive features from a profound and enduring relationship with the surrounding environment.

The case study examined in this research was selected precisely because it embodies this legacy, offering an exemplary testimony to the ingenuity and skill of early builders. These individuals, despite the absence of modern tools and technologies, were remarkably capable of reading the landscape, harnessing local resources, and making thoughtful decisions about where and how to establish a settlement. Their choices reflect a sophisticated understanding of environmental conditions and reveal an inherent sustainability in their approach to construction.

The methodology developed in this study is based on a multi-scalar analysis that considers both the architectural artefact and its broader territorial context. This is achieved through the combined use of different technologies, including UAV devices for detailed architectural surveys and Geographic Information Systems (GIS) for large-scale spatial analysis. The latter makes use of data provided by various public administrations, enabling a broader understanding of the landscape dynamics at play.

Although each heritage site possesses its own unique characteristics, the proposed method proves effective in identifying the common features that define historical rural architecture. These features consist of a body of knowledge, practical expertise, and experiential wisdom that have been accumulated over centuries, allowing communities to develop meaningful and adaptive relationships with the natural environment.

By integrating archival and bibliographic research with architectural surveying, geomorphological and hydrographic analysis of the surrounding landscape, this study offers a comprehensive and interconnected reading of the built heritage. The resulting interpretation highlights causal relationships between the various factors involved, making it possible to understand the rationale behind past settlement and construction choices. These insights remain highly relevant today, providing valuable guidance in an era when environmental sustainability has become an essential goal for contemporary planning and design.

The proposed methodology is structured in the following steps:

1. *A bibliographical and archival search* that provides relevant information on the subject. The bibliographic search gives a global knowledge of the heritage under study and can provide interesting ideas for the analysis. At the same time, the information acquired through the consultation of historical archival documentation represents a necessary starting point for the next steps.
2. *State-of-the-art surveys* to acquire an accurate basis on which to carry out the analysis of the historical integrated water management systems.
3. *An interdisciplinary multiscale analysis* structured in two consequential steps of territorial and architectural research, allowing the case study to be framed within a larger area, identifying the close link between geological, morphological and hydrological characteristics and the integrated water resource management systems. The outcome concerns the detailed study of the different components of the system and their interrelations on an architectural scale.
4. *Open source virtual fruition*, made possible by selecting a platform on which to implement the 3D model generated in the previous steps, which can be freely accessed by users without any cost.

2.1 Bibliographical and archival research

The study of the bibliography was conducted through the consultation of scientific databases of Scopus, ResearchGate, Google Scholar and supported by the study of unindexed works related to the so-called *grey literature*. This phase enabled the acquisition of an in-depth understanding of the entire structure and the territorial context in which it was originally conceived. On the one hand, the consulted literature provided valuable insights into the morphological and geological features of the *Gravina di Picciano*, thus supporting the development of the scientific reflections presented in the subsequent methodological steps; on the other hand, it offered specific historical information regarding the evolutionary phases of the *masseria* and the functioning of the associated integrated water management systems.

The analysis of documentation enabled the validation of the historical information gathered through bibliographic research and its integration with new insights. This step was conducted through the consultation of several local archives, such as the State Archive of Matera (*Archivio di Stato di Matera*), the Diocesan Archive of Matera (*Archivio Diocesano di Matera*) and the RSDI Basilicata (Regional Spatial Data Infrastructure of the Basilicata Region) [4] online web platform. This step provided a solid basis for the analysis of this heritage and its characteristics in order to plan the survey and the analyses carried out at both territorial and architectural scales.

The *Masseria del Cristo*, or *Santissimo Sacramento*, stands on the *Piano di Chiatamura*, a plain area about 10 km west of the urban center of Matera, along a secondary branch of the ancient route from Matera to the Sanctuary of *Santa Maria di Picciano*, part of a vast network of historical farms and *jazzi* (typical structures for breeding and sheltering sheep) [5].

This architecture is located in the environmental context of the *Gravina di Picciano* stream, a left tributary of the *Bradano* river. The landscape is characterized by the contrast between the harsh bare limestone rocks along the steep banks of the stream and the clay cultivated with extensive arable land and olive trees. The *masseria* is located on a rocky outcrop exactly on the border between the limestone and clay, a few meters from the edge of the *Gravina*.

The historical sources related to the *Masseria del Cristo* appear limited, but they testify to its different configurations over time. Ancient documents call this district *Voccuzza*, or *Boccuzza* [5]. In this place, the *masseria* already appears at the beginning of the 17th century as a property purchased by the *Paolicelli* family, together with other possessions constituting a large estate, from the previous owner *Giacuzzi* family, which attests to its previous realization [6].

The probable original configuration of the building is stated in a document dated 11th September 1700 and released by the public officer (*tabulario*) of the city of Matera, *Don Giacomo Antonio Casamassima*. In this report, the manor is described as a farmhouse made up of a single brick slab with a pitched roof, a fireplace, an adjacent well and three enclosed courtyards. Construction began in 1706, when ownership passed from the *Paolicelli* family to the Confraternity of the *Santissimo Sacramento* of the Cathedral of Matera [6].

The building, used until the mid-20th century, preserves multiple traces of historical construction techniques and ingenious integrated water management systems. The peculiar characteristics and the critical state of conservation and accessibility, as well as the serious risk of definitively losing this heritage, motivated the choice of the case study.

This *masseria* shows itself in an almost unchanged condition, unlike what can be found in the historical urban fabric of the *Sassi*, significantly transformed during the recent decades.

2.2 Digital survey

The state-of-the-art analysis is a necessary action to understand the parts that compose a historical building, their characteristics and how they interact to enable the functioning of the whole artifact. The use of innovative technologies for the geometric survey ensures short acquisition times and high precision. For this reason, this study opted to use UAV photogrammetric and traditional survey techniques.

This step needs to be remotely programmed through the integrated software of the drone used or other external software. The on-site survey is carried out only afterwards. To improve the accuracy of the survey, well visible markers for Ground Control Points (GCPs) must be provided. The GCPs shall be evenly distributed in the survey area and well anchored to the ground, and they are intended to constitute the reference for aligning and georeferencing the data acquired. The above images are processed in specific software to obtain point clouds, which are further processed for the purpose of generating 3D digital models. Photogrammetric processes require careful acquisition of the frames, respecting the following parameters and precautions, for ensuring a successful acquisition and an accurate reconstruction of 3D models.

After acquiring all the information necessary to understand the subject, the authors conducted an on-site inspection. The preparation of this investigation directly affects the quality and accuracy of the data that will be collected subsequently.

A preliminary site survey was essential to identify potential interference and disturbance elements that could have adversely affected the acquisition phases. The accessibility of the site, the physical access to the area, the environmental and lighting conditions were assessed (natural lighting should be evaluated to avoid strong shadows and light variations that can complicate image processing) and finally the possible presence of disturbing elements such as crowds or moving elements which could interfere with the instrumentation used in the acquisition step.

Photogrammetric acquisition with UAV necessarily included the consultation of d-flight flight maps to verify airspace categories and determine any restrictions or permits required. The survey was remotely programmed through the integrated software of the drone Autel Robotics Evo II 6K [7], with which the photogrammetric in situ survey was subsequently conducted. To improve the accuracy of the survey, well visible markers have been set up for GCPs.

The GCPs were evenly distributed in the survey area and well anchored to the ground and served as a reference for aligning and georeferencing the data acquired. The acquisition of the frames has respected the following parameters and devices, ensuring the accurate reconstruction of the 3D models: frame overlap between 60% and 80%, both on longitudinal and transverse axis; different camera inclinations, enabling the capture of details that would otherwise remain in shadow; manually setting of shutter parameters, such as aperture, exposure time and ISO, which must be managed manually to ensure uniformity of image exposure; use of frames in their original entirety, without cropping or resizing operations.

The survey with drones has affected the factory in the farm and the external areas of relevance, for a total area of about 30,000 m^2, where a series of structures aimed at integrated management of water resources have been identified. The survey included a first UAV photogrammetric survey and a second traditional survey.

The first one enabled the capture of 1132 frames (Figure 1) and was conducted in the following steps:

1. Automated flight at 50 m from the level of the road access to the area, through which it was possible to obtain photos of context at the territorial scale, with a time of acquisition equal to about 10 minutes;
2. Automated flight at 40 m from the level of the access road to the area of the farm with photographic overlap of 80%, rectangular grid and zenith camera, with a time of acquisition of about 20-25 minutes;
3. Automated flight at an altitude of 20 m from the level of the access road to the area of the farm with a photographic overlap of 60%, rectangular grid and camera with inclination of 45° and with a time of acquisition of about 15-20 minutes;
4. Manual flight of detail at 5-10 m above the level of the road to the area of the *masseria* with a zenith camera and inclined at 45°, with a scan time of about 20 minutes.

The frames acquired through the previous photogrammetric survey step were processed in order to obtain a point cloud, which was in turn processed through the use of Agisoft Metashape software [8], following a series of basic preparatory steps to extract geometric information from photographs. The images acquired with the drone, as raw as possible and without distortion corrections, were imported into this software, which identifies common points in photographs, calculates, and determines the camera position for each image and optimizes the camera's calibration parameters. The result of this process is a "sparse point cloud" and a series of camera positions (Figure 2), which afterwards has been processed to obtain the "dense point cloud" (Figure 2), necessary for the generation of the 3D mesh

Figure 1. Aerial photography with UAV of the Masseria del Cristo at 40 m above the level of the access road to the area. © 2025, Daniele Altamura, Enrico Lamacchia.

(Figure 2c). Before the generation of the mesh, manual cleaning tools have been used to remove gaps in the reconstruction of the 3D model and correct anomalies. The mesh generation step is the process by which the previously obtained point cloud is transformed into a detailed and optimized 3D mesh using advanced triangulation algorithms (Figure 2).

The inaccessibility of the cisterns excavated into the rocky substrate (Figure 3), due both to the limited size of the intake openings and to their precarious state of preservation, has precluded the use of instrumental survey techniques employing drones or Light Detection And Ranging (LiDAR) systems, both of which require the physical presence of operators within the cistern itself. Consequently, the dimensions of the structures were derived through traditional survey methods using a laser distance meter and applying the triangulation technique. The data obtained reveal dimensions and typological features consistent with those of other similar artifacts found in the area, reflecting construction practices and techniques deeply rooted in the local building tradition [9].

2.3 Interdisciplinary multiscale analysis

To properly understand the intrinsic characteristics of any artefact, it is necessary to look at the context in which it is placed. Similarly, a thorough study of the architectural heritage requires a careful reading of its territorial context.

In the anthropic settlements of this area, the shapes of places guided practices aimed at supplying the resources necessary for survival and water management, leaving indelible traces that bear witness to the technical knowledge of the ancient inhabitants. The presence of complex integrated water resource management systems has led to a methodology that highlighted the relationships between geology, morphology and surface rainwater runoff, enabling the understanding of the path of the surface water and the mechanisms of water resource accumulation.

A multiscale approach was adopted to analyze the functioning of the integrated water resource management system and thus the interrelations between its different components.

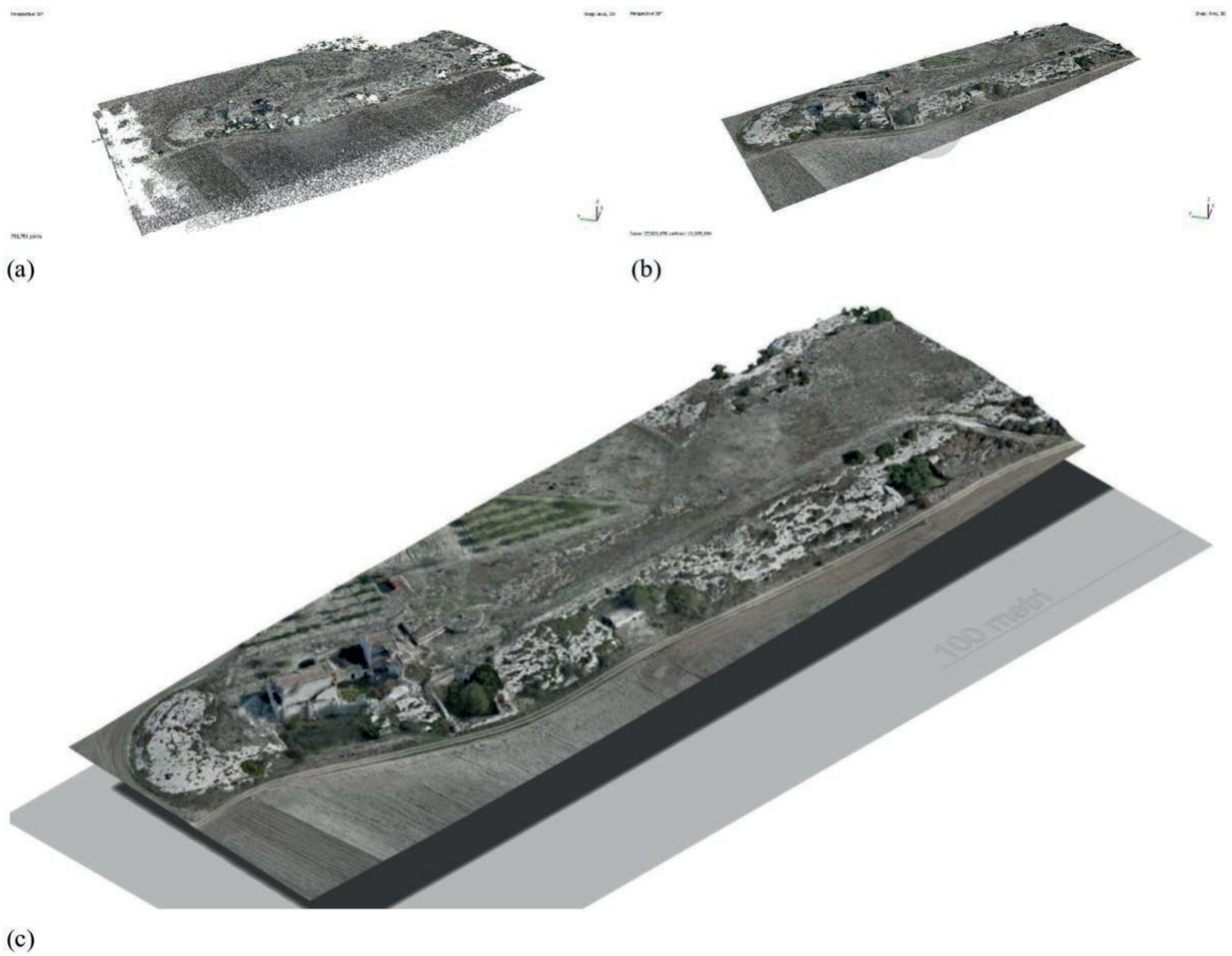


Figure 2. Sparse point cloud (a), dense point cloud (b), 3D mesh (c) in Agisoft Metashape. © 2025, Daniele Altamura, Enrico Lamacchia.

The hydrographic analysis was carried out using QGIS software [10], and a model was developed in the GIS environment. Surface runoff accumulation maps were produced starting from the DTM (Digital Terrain Model) data made available by the RSDI *Basilicata* platform [3]. This analysis permitted the comprehension of the mechanisms of water storage in the tanks, the configuration and operation of the individual components of the system and their interrelations.

The area of Matera can be considered the “physical boundary” between the Matera-Laterza Horst [11] to the north-east (*Murge* is the geographic name of this type of flat-topped carbonate hills in the Apulian district) and the bas-relief landscape molded in the clays of the foredeep to the south-west [11]. Further, this landscape is characterized by the presence of deep and narrow V-shaped valleys and/or gorges in the strict sense (i.e., with vertical sides), named *gravine* [12-13]. The *Masseria del Cristo* is located on a limestone outcrop 10 kilometers from Matera town, at an altitude of 250 m above sea level, not far from the *Gravina di Picciano* stream (Figure 4).

From a geological viewpoint, the study area is entirely included in the foredeep domain (*Fossa Bradanica*) of the southern Apennines, filled by a marine regressive stratigraphic succession made of clay, sand and conglomerate (from the bottom to the top), early Pleistocene in age. In the surroundings of *Masseria del Cristo*, the clay formation (*Argille subappennine*) is largely outcropping, locally covered by a few meters-thick eluvial-colluvial deposits. This formation stratigraphically overlies the bioclastic limestone of the *Calcarenite di Gravin*a, late Pliocene - early Pleistocene in age, cropping out along the sides of the canyon in which the *Gravina di Picciano* stream flows. Out of the gorge, the *calcarenite* emerges exclusively in correspondence with the elongat-

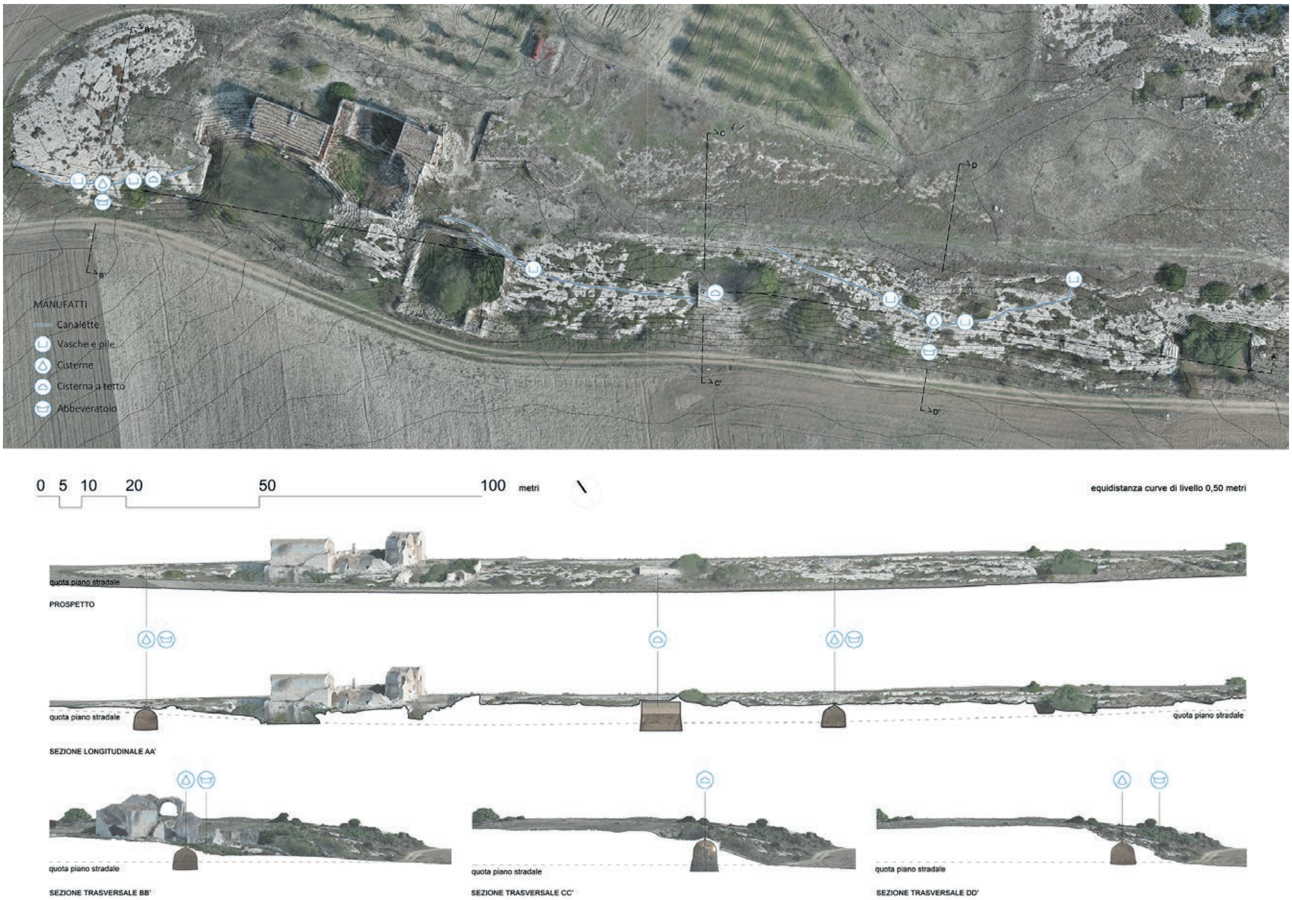


Figure 3. Plan, elevations and sections of the integrated water resources management system and analytical graphs of the interception, channeling, collection and use subsystems. © 2025, Daniele Altamura, Enrico Lamacchia.

ed relief trending Northwest–Southeast, upon which the *Masseria del Cristo* is situated.

Along the *Gravina di Picciano*, about 5-6 km to the south, the clastic limestone unconformably lies on the Upper Cretaceous limestones *Calcari di Altamura*, which constitutes the geological backbone of both the morpho-structural plateau of Matera and the whole Apulian foreland. Since the *Calcarenite di Gravina* does not exceed 30-40 m in thickness in the investigated area, a geological cross-section through the site can easily show the entire stratigraphic sequence, here affected by normal faulting [11, 13]. Indeed, the geological and geomorphological analysis reveals the presence of a set of Northwest–Southeast oriented faults, which are responsible for the genesis of the flat spur on which the *Masseria del Cristo* stands, and which have shaped the distinctive morphology of the area selected for the construction of the structure (Figure 5).

Some straight fluvial segments of the *Gravina di Picciano* stream display the same orientation (as, for example, the stretch immediately to the south of the limestone hump of *Masseria del Cristo*), being controlled by the same fault system. This stream is part of the Bradano river basin, which extends from Monte Carmine (*Appennino Lucano*) to the Gulf of Taranto and originates in the *Alta Murgia* Park close to the area of *La Disperata*, within the territory of the Municipalities of Spinazzola (in the province of Barletta-Andria-Trani), Poggiorsini and Gravina in Puglia (both in the province of Bari), at an altitude of 675 m above sea level [14]. The more modest basin of the *Gravina di Picciano* stream, considered for its lower limit of confluence in the *Bradano* river, has an extension of 425 km^2 and 28% of this is located within the administrative boundary of the Municipality of Matera [14] (Figure 6).

The hydrographic analysis carried out using QGIS software, based on the DTM data provided by the Basilicata Region through the online RSDI *Basilicata* platform, revealed that the cisterns were built in correspondence with the probable underlying Direct Fault. These cisterns collected meteor water carried by the western

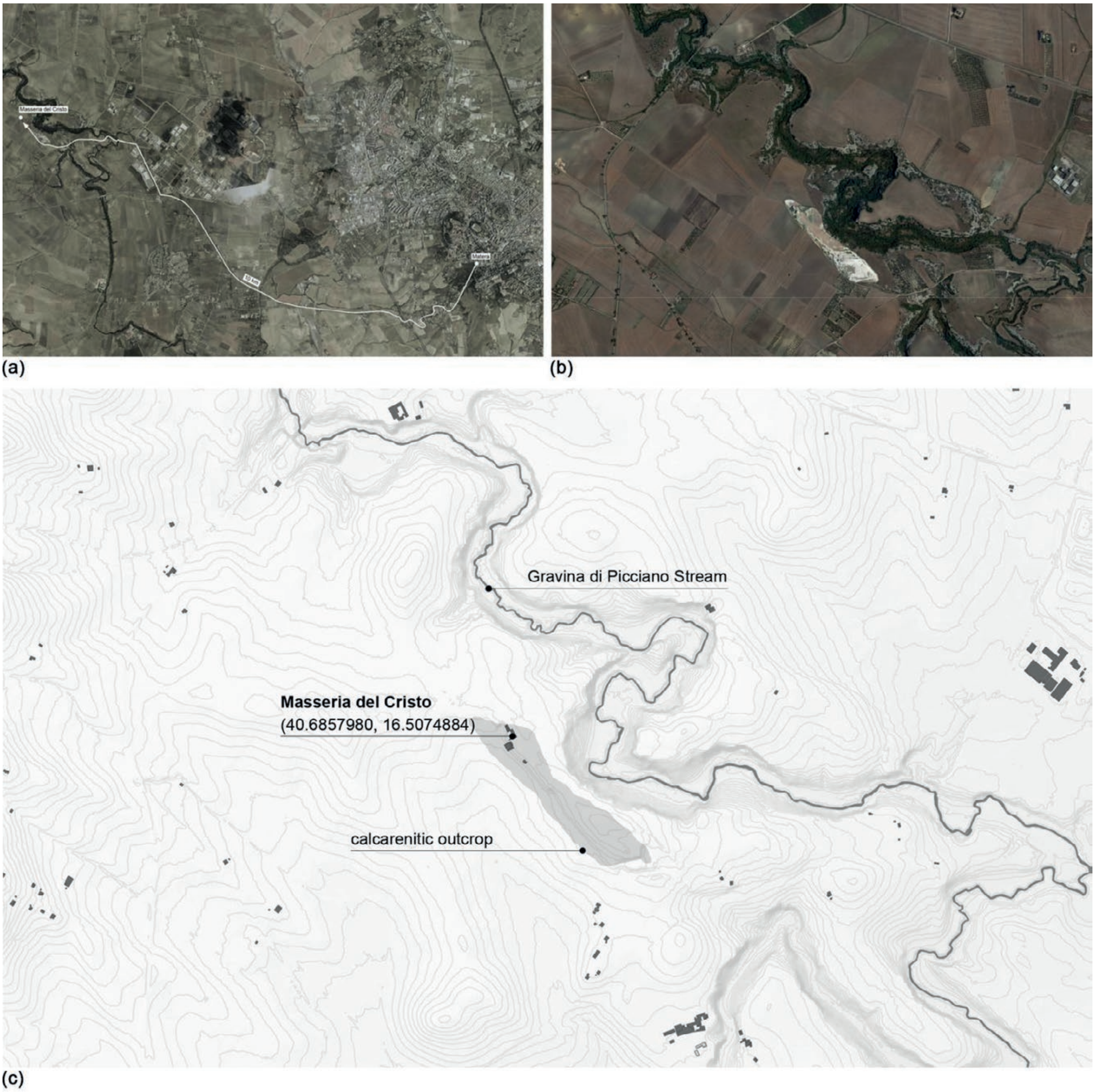


Figure 4. (a)Aerial photography of the Masseria del Cristo territorial context and access route from the town. (b) Aerial photography of the site. (c) Framing of the Masseria del Cristo with geographic coordinates of the artifact, the calcarenite outcrop and the Gravina di Picciano stream. © 2025, Daniele Altamura, Enrico Lamacchia.

waterproof clay surfaces of the Mountains of *Carbone*, *Picciano* and *Timbro*. The produced maps highlighting the relationship between morphology and surface run-off of the meteor water explain the reasons behind the choice of the site for the construction of the *Masseria del Cristo*. In fact, this building is located on the watershed of the corresponding hydrographic basin, and its position has allowed it to avoid flooding phenomena related to heavy rainfall and to ensure an extended view to control the surrounding territory (Figure 7).

Starting from the analysis and surveys carried out, the subsystems of channeling, collection and use of the resource were identified, which, by using the morphology of the places, guaranteed the water supply (Figure

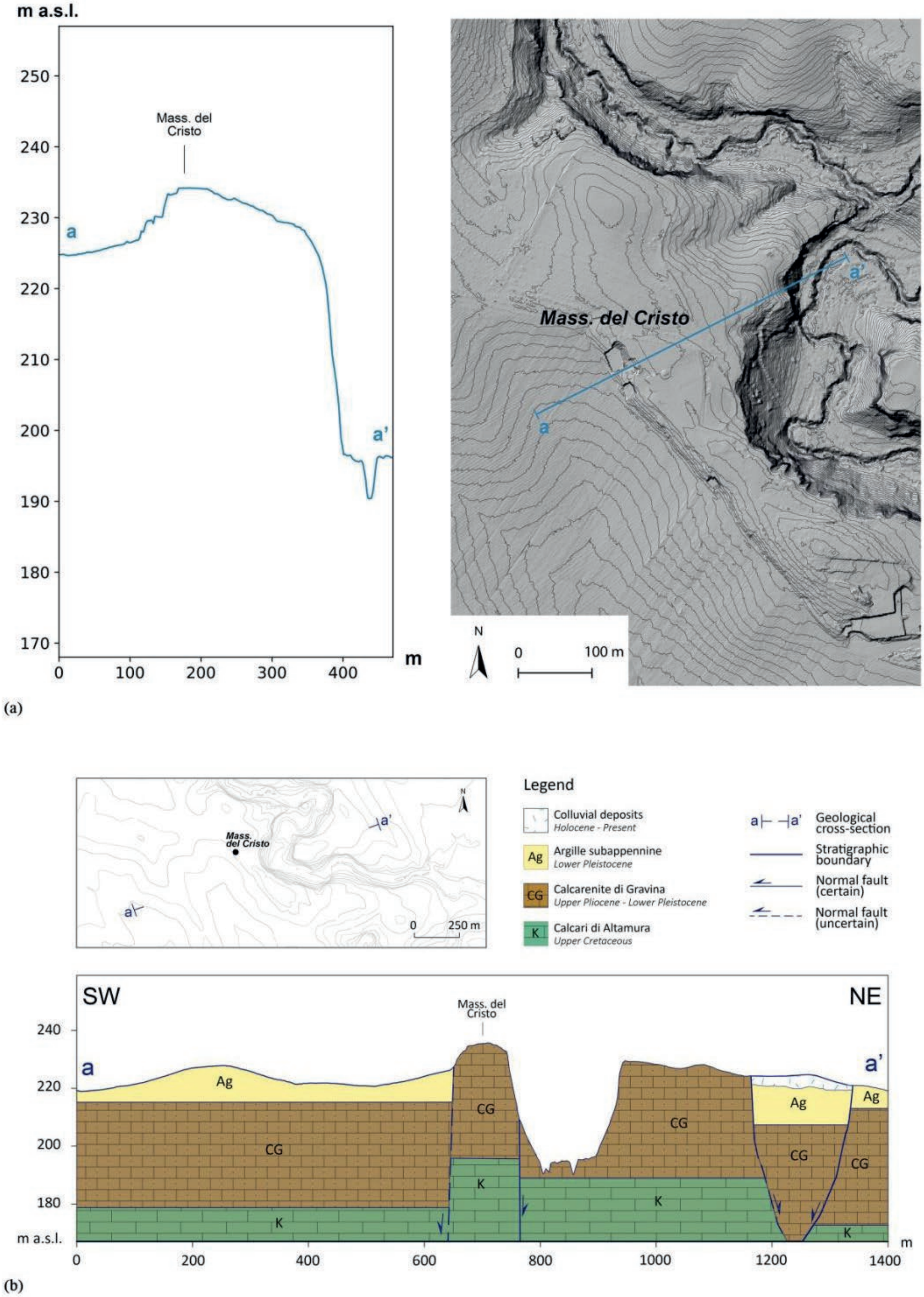
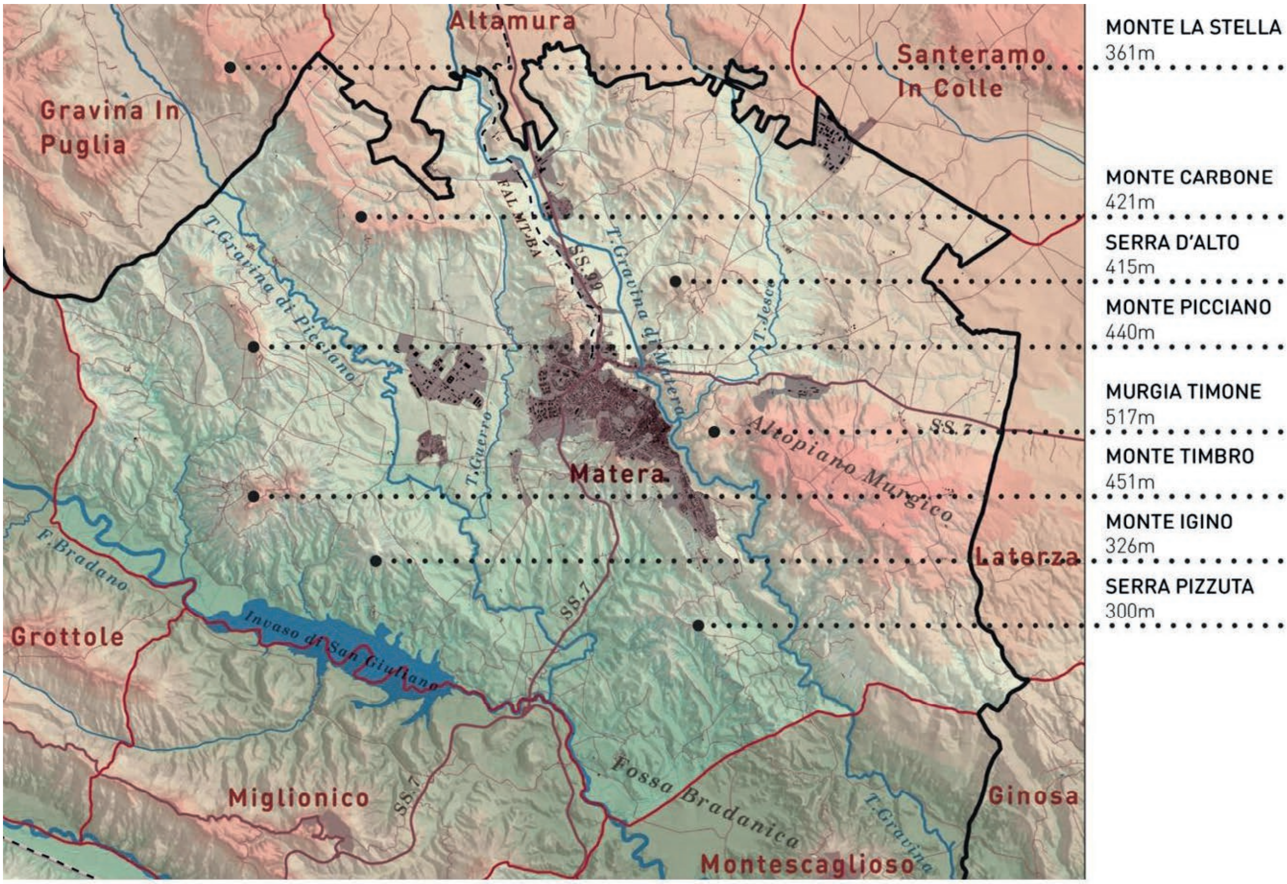
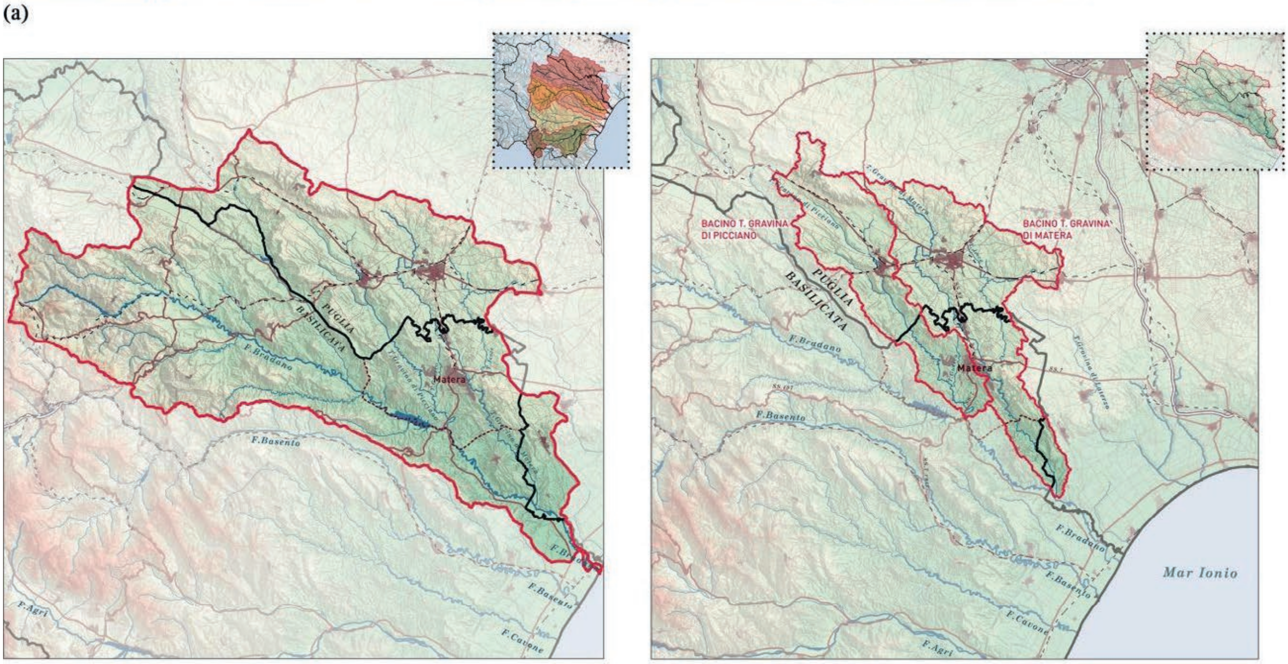


Figure 5. (a) Morphology of the area of Masseria del Cristo. (b) Geology of the area of Masseria del Cristo. © 2025, Marcello Schiattarella, Lucia Contillo.



(a)



(b)

Figure 6. (a) Morphological and hydrographical characteristics of Matera territory (from Ermini R., Spilotro G., 2022). (b) Bradano river basin, stream and Gravina di Matera stream basins (from Ermini R., Spilotro G., 2022). © 2022, Ruggero Ermini, Giuseppe Spilotro.

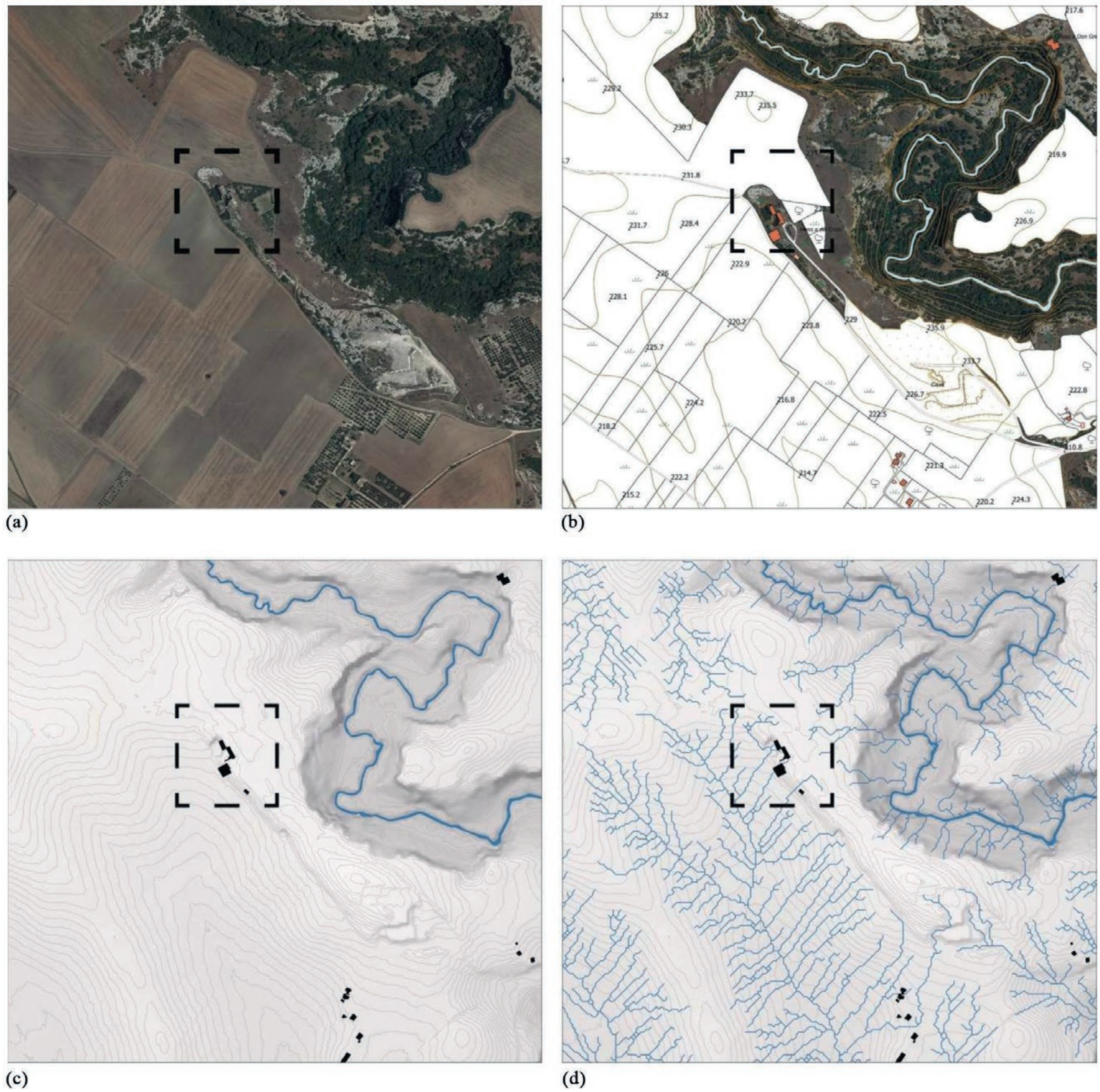


Figure 7. (a)Aerial photography of the Masseria del Cristo area. (b) Aerial photography with superimposed topographic CTR map (Carta Tecnica Regionale at the original 1:10,000 scale). (c) Morphology and stream. (d) Morphology, Gravina di Picciano stream and hydrospatial network. © 2025, Daniele Altamura, Enrico Lamacchia.

8). Rainwater is collected on the surface of bare limestone rock, in which channels of variable length are dug, between 20 and 50 cm wide and between 10 and 20 cm deep. These channels convey the water to storage “settling tanks” excavated in a parallelepiped shape of variable dimensions (Figure 8). Maintenance and cleaning were carried out by removing the sampling mouth itself.

The clarified water is subsequently transferred through other dug channels to three cisterns with an average depth of 6 m. There are two *bell-type cisterns* (Figure 9a-b) and one *semi-hypogeal with roof cistern* (Figure 9c).

The use of the resource occurred through direct withdrawal from the upper mouths using buckets lowered manually from above. The two *bell-type cisterns*

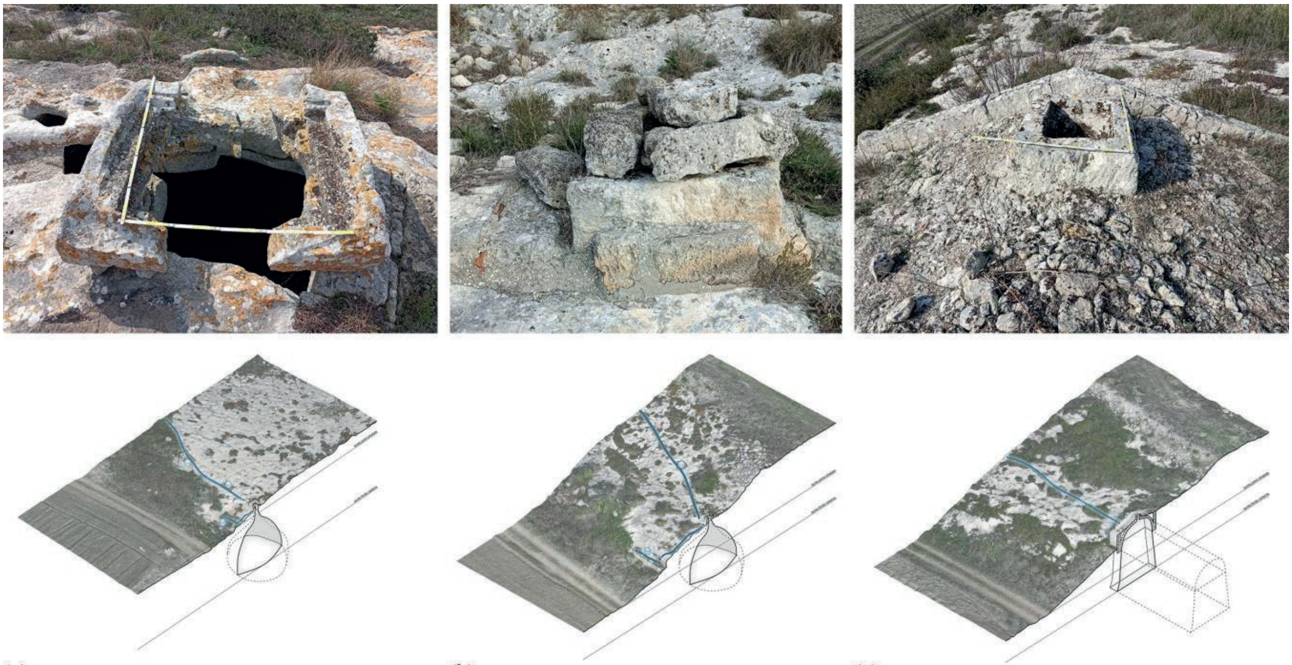


Figure 8. (a-b) Schematic axonometric split of the bell-type cisterns. (c) Schematic axonometric split of the semi-hypogeal cistern with roof. © 2025, Daniele Altamura, Enrico Lamacchia.

have an additional duct downstream of their mouth, which transfers excess water through a canal to the drinking trough excavated for animals.

2.4 Open source virtual fruition

The 3D model obtained through the processes described so far, as well as being functional to this specific study, is suitable for methods of enhancement and virtual fruition of this heritage.

In this way, this inaccessible heritage can be explored remotely through a virtual museum experience. Therefore, it was decided to upload it to the ATON open-source platform [15], created by the CNR (National Research Council), which allows users to visualize the model and interact with it in a virtual reality environment (Figure 10).

These tools offer an immersive approach to cataloguing material heritage for scholars and technicians and, at the same time, easy and engaging dissemination to a broad and non-specialized audience. Dissemination in this form is a starting point for raising awareness on the topic of heritage at risk and a guide for valorization processes [16].

3. DISCUSSIONS

In a general context in which the matrix of architectural shapes has been, for centuries, the adaptation to the natural substrate, each episode has evolved, starting from common practices, towards peculiar solutions. Understanding settlement phenomena on a territorial scale cannot therefore ignore the in-depth analysis of the individual pieces that compose it. This gives rise to the need to identify a research methodology, such as the one proposed in this study, which relates the individual case to its context. The *Masseria del Cristo*, despite the general precarious state of conservation, shows unaltered examples of systems for interception, canalization, collection and use of water resources of a rural architecture in Matera.

The analysis of historical water systems in the rural territory of Matera offers a valuable testimony to an empirical and profoundly interdisciplinary knowledge, developed and consolidated over centuries within local rural communities. Despite the absence of formal support from modern scientific frameworks, this vernacular wisdom proved remarkably effective in harnessing the geomorphological and geological characteristics of the landscape, thereby ensuring access to the resources needed for the survival and continuity of human settlement. Among these resources, water undoubtedly played

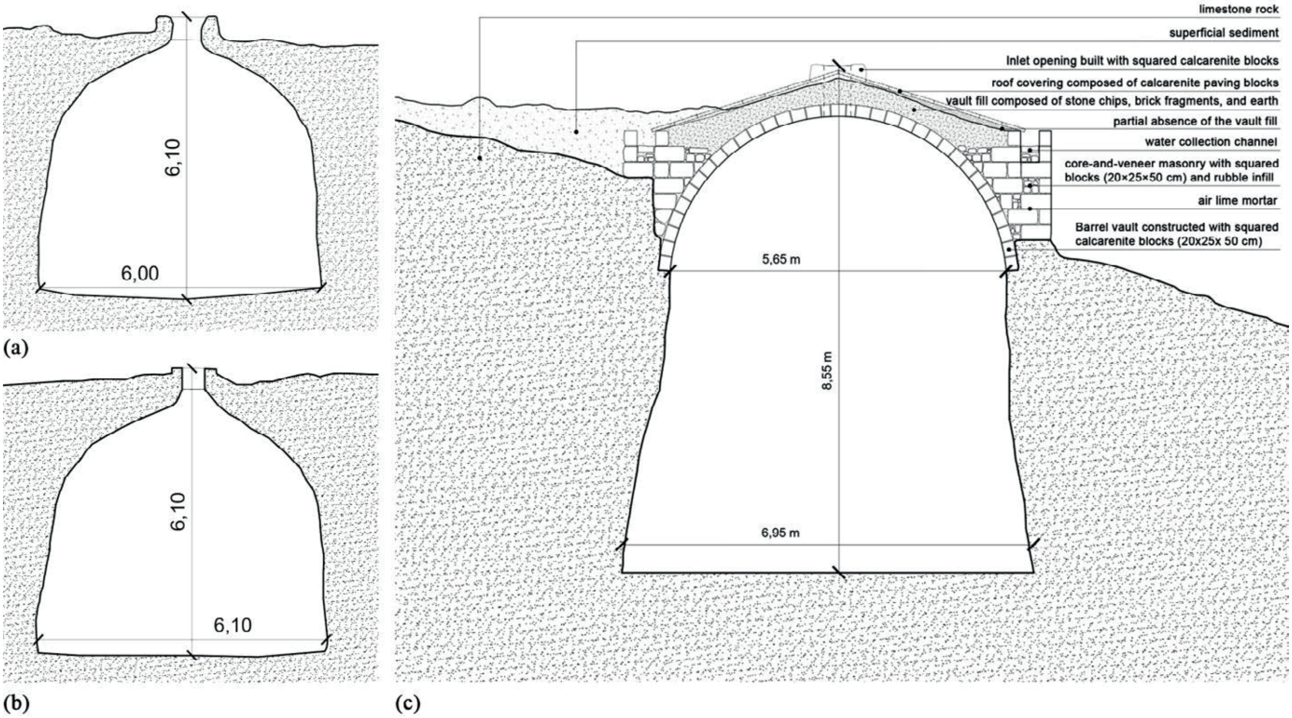


Figure 9. (a-b) Technological sections of the two “a campana” cisterns. (c) Technological sections of the “a tetto” cistern. © 2025, Daniele Altamura, Enrico Lamacchia.

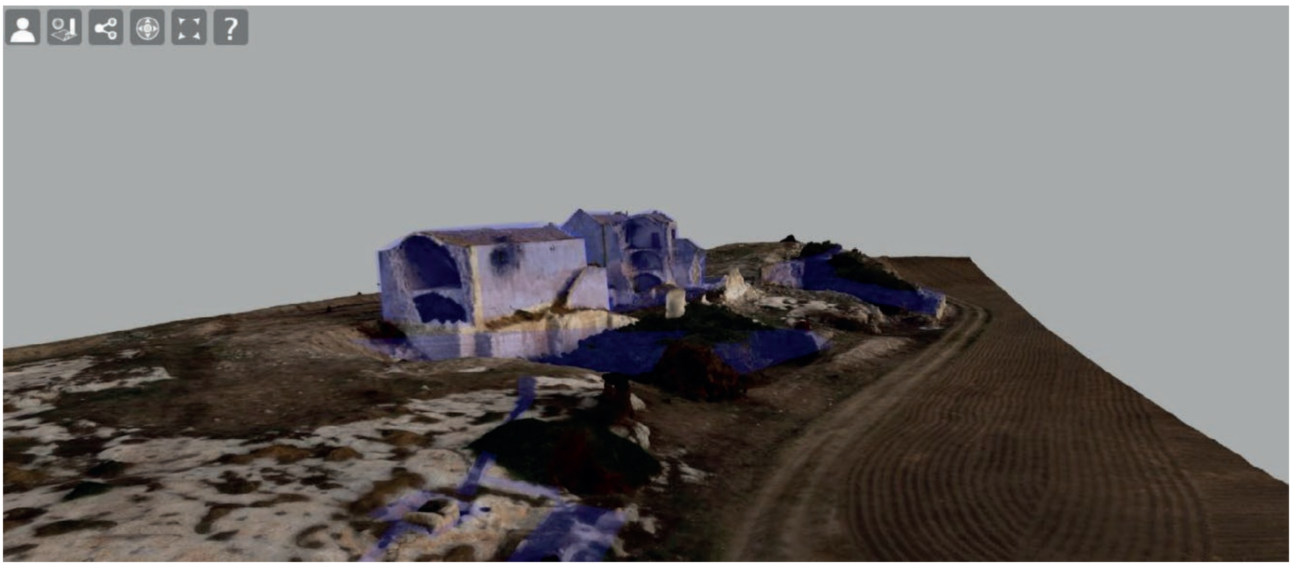


Figure 10. Navigation screen in ATON web platform: 3D model with highlighted selectable elements. © 2025, Daniele Altamura, Enrico Lamacchia.

a central and strategic role. This is clearly reflected in the sophistication and ingenuity of the systems identified through this research, which reveal a deep understanding of the natural mechanisms governing water circulation. The attention paid to the geological attributes of the context was not accidental but stemmed from precise empirical observations that guided both settlement choices and construction practices.

In particular, the decision to build the *Masseria del Cristo* upon a *calcarenite* rocky spur appears to reflect a rational assessment of the site's hydrogeological dynamics. This elevated position, in addition to offering defensive advantages and visual command over the surrounding territory, provided favorable conditions for intercepting and collecting rainwater and surface runoff. These processes were facilitated by the selective permeability of local lithological formations. The rocky spur, due to its form and composition, thus served not only a defensive function but also played a strategic role in water management, confirming the presence of a form of construction intelligence deeply rooted in the understanding of the environment.

Within this context, geomorphological analysis emerges as an indispensable tool for reconstructing the historical mechanisms of water procurement. The study of rock types and structures, stratigraphic discontinuities, and the permeability and porosity of lithic materials, along with the identification of infiltration and runoff dynamics, permits a scientifically rigorous reconstruction of settlement patterns and resource management strategies developed by rural communities.

In contemporary research, geological studies are essential not only for interpreting the hydraulic techniques of the past but also for evaluating their effectiveness, sustainability, and potential for adaptive reuse in current contexts. Stratigraphic surveys, petrographic analyses, topographical mapping, and digital hydrological modeling highlight the functional principles underlying these systems and the interactions between lithological structures and water flows. When integrated with historical and archaeological data, this knowledge provides a foundational basis for a comprehensive scientific approach to the preservation, restoration, and enhancement of rural hydraulic heritage.

Geology, therefore, not only offers a critical lens through which to interpret historical practices but also serves as a fundamental instrument for guiding informed and context-sensitive interventions aimed at the recovery, valorization, and potential reactivation of these systems. This approach aligns with broader goals of environmental sustainability and cultural continuity.

In this sense, the study of such water systems permits the recovery of meaningful fragments of traditional technical knowledge, as well as contributing to the recognition and appreciation of a form of territorial resilience. This resilience, shaped through a harmonious interaction with the natural environment, has ensured the long-term sustainability of rural settlements in the Matera region.

4. CONCLUSIONS

For these reasons, the case study constituted the test bed for validating the proposed multiscale analysis methodology, which can be replicated for further case studies, providing a solid starting point for recovery and enhancement practices. Obtaining a 3D digital model and its interactive online use offers a way to involve and raise awareness even among non-experts on the topic of historical architectural heritage, constituting an innovative method of teaching and dissemination.

The natural evolution of this research points toward the systematic and detailed cataloguing of additional heritage assets and architectural artifacts located within the same territorial context. These elements are to be examined using the same interdisciplinary and multiscale methodology adopted in the current study. Such an extension would permit a more profound understanding of each architectural object, considered in terms of its morphological, typological, and functional specificity. Furthermore, it would enable a more comprehensive interpretation of the relationships that these buildings maintain within the broader networks of settlements, hydraulic systems, and ecological structures embedded in the landscape.

This perspective marks a significant conceptual shift. Cultural heritage is no longer seen as a mere collection of distinct and independent elements, but rather as an organic and interconnected system, deeply rooted in the landscape and reflecting its multifaceted nature, encompassing historical, physical, environmental, and socio-economic dimensions. Within this framework, heritage is redefined as a layered and dynamic palimpsest in which each material component acquires a relational meaning, serving as tangible evidence of a longstanding and layered interaction between human communities and their surrounding environment.

This condition of interrelation represents a fundamental characteristic of historical architecture in general, and of rural architecture in particular. Indeed, the latter embodies a form of deeply grounded construction wisdom that has been developed over centuries and transmitted across generations. It is an empirical and context-sensitive knowledge system, through which past builders devised sustainable solutions that were precisely attuned to the locally available resources and responsive to the geomorphological and climatic specificities of their environment.

Once validated within the context of the present case study, this methodological model proves not only to be transferable but also highly recommendable for application in other territorial contexts. It is grounded in consolidated processes of scientific inquiry and in technologies that are now widely accepted and employed by scholars, professionals, and institutional actors. Consequently, it offers promising avenues for broader applications at national and international levels, promoting an integrated strategy for the interpretation, conservation, and valorization of cultural heritage and landscapes. This approach is capable of reconciling scientific rigor with technological innovation and historical sensitivity, thus fostering a more sustainable and informed framework for heritage management in contemporary scenarios.

5. AUTHOR CONTRIBUTIONS

Conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing, visualization, supervision, project administration, funding acquisition.

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Information Management for Built Heritage: CDE and HBIM for Educational Buildings. The Case of the Pistelli School in Rome

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Abstract. The integration of Heritage Building Information Modeling (HBIM) with Common Data Environment (CDE) is essential for the efficient management and preservation of historical school buildings. This study explores their combined application through the case of the Ermenegildo Pistelli school in Rome. The methodology involves advanced surveying techniques, archival research, and digital modeling to create an accurate HBIM model, stored and managed within a CDE. The results highlight the role of public administration and stakeholder collaboration in ensuring effective data structuring, accessibility, and long-term conservation. Despite challenges in interoperability and digital literacy, the findings emphasize the importance of standardized workflows and stakeholder engagement in heritage management. Future research should enhance open-source solutions, improve training programs for public entities, and promote broader interdisciplinary cooperation. This study contributes to advancing digital strategies for the sustainable preservation of educational building heritage.

Keywords: HBIM, CDE, School Building, Built Heritage, Digital Preservation.

1. INTRODUCTION

The integration of advanced technologies in the management of school buildings plays a critical role in the context of contemporary educational environments. As institutions strive to create conducive learning spaces, the adoption of Heritage Building Information Modeling (HBIM) offers an effective solution. This approach not only facilitates the preservation of historical school buildings but also enhances the management of information related to their structural and functional attributes [1-2]. This paper explores the intersection of HBIM, school buildings, Collaborative Data Environments (CDE), and information management, highlighting their collective potential to optimize educational facilities.

The concept of HBIM extends beyond traditional Building Information Modeling (BIM) by incorporating the unique characteristics and historical significance of the building. This approach allows for the detailed documentation and analysis of school buildings, ensuring that their architectural integrity is maintained while simultaneously improving operational efficiency [3-4]. By leveraging HBIM, educational institutions can create a comprehensive digital representation of their facilities, enabling better decision-making regarding maintenance, renovations, and resource allocation.

The implementation of CDEs similarly plays a crucial role in enhancing collaboration among stakeholders involved in school building management. CDEs provide a centralized platform for sharing, facilitating communication, and streamlining workflows among architects, engineers, facility managers, and educators. This collaborative approach ensures that all parties have access to up-to-date data, thereby reducing the likelihood of errors and miscommunication during the planning and execution of the design. The integration of these platforms with HBIM can further improve school facility governance by providing a seamless exchange of relevant insights throughout the building's lifecycle. Effective information management is essential for optimizing the performance of educational facilities. The ability to collect, analyze, and utilize data related to building performance, occupancy, and environmental conditions can significantly impact the overall quality of the educational experience. By employing robust data-driven strategies, institutions can make informed decisions that enhance the functionality and sustainability of their facilities. This paper will examine various information management frameworks and their applicability to school buildings, emphasizing the role of data-driven decision-making in educational environments. The integration of HBIM and CDEs presents an opportunity to address the unique challenges associated with school facilities, particularly those of historical significance. In Rome, where the study is based, many educational institutions occupy buildings from different historical periods. Preserving these structures while adapting them to modern needs requires a careful balance. To illustrate effective strategies, this study will explore case studies showcasing successful implementations of HBIM and CDEs in school building management, highlighting best practices and key lessons learned.

1.1 HBIM for school buildings

HBIM integrates various data acquisition techniques, including terrestrial laser scanning (TLS) and photogrammetry, to create detailed 3D models of historical buildings [1-3]. The process typically involves several stages: data collection, point cloud generation, model creation, and the incorporation of historical and architectural information into a cohesive digital framework [4]. For instance, Liu et al. [1] emphasize the importance of interdisciplinary integration in developing HBIM models for ancient structures, including educational buildings such as the Rosenwald Schools in the United States. The application of HBIM in school buildings has been documented in various case studies, showcasing its utility in preserving educational building heritage. The digital documentation of the Tankersley School in Alabama utilized HBIM techniques to reconstruct the building's historical significance and architectural details [1]. This approach not only aids in restoration efforts but also serves educational purposes by providing a digital archive of the building's history and architectural features. Moreover, the integration of HBIM with virtual reality (VR) technologies has been explored to enhance the immersive experience of historical school buildings. This combination allows for interactive learning environments where users can explore the architectural heritage [5-6]. Such applications demonstrate the potential of HBIM to preserve and actively engage the public in historical educational sites.

The use of HBIM for school buildings facilitates comprehensive data management, allowing for the integration of various types of information, including architectural, historical, and structural data [7-8]. This holistic approach enhances the understanding of the building's lifecycle and informs conservation strategies. For instance, the use of HBIM in the management of the Master Gate of San Francisco in Portugal illustrates how detailed modeling can support diagnostic assessments and maintenance planning [2]. Secondly, HBIM promotes collaboration among stakeholders involved in heritage conservation, including architects, historians, and conservationists. By providing a shared platform for data access and visualization, HBIM fosters interdisciplinary cooperation, which is essential for effective heritage management [9, 10]. This collaborative aspect is particularly crucial in educational contexts, where multiple parties may be involved in the preservation of the buildings.

Despite its advantages, the implementation of HBIM in school buildings faces several challenges. The complexity of modeling intricate architectural details and the need for specialized skills in both heritage conservation and digital modeling can hinder widespread adoption [11-12]. Additionally, the integration of intangible cultural heritage aspects into HBIM models remains an area requiring further exploration [9, 13]. Future research should focus on developing standardized protocols for HBIM applications in educational building heritage, enhancing training programs for practitioners, and exploring the integration of emerging technologies such as artificial intelligence to automate certain aspects of the modeling process [14-15]. Furthermore, expanding the scope of HBIM to include community engagement initiatives could enhance public awareness and appreciation of historical school buildings. HBIM represents a transformative approach to preservation and management. By facilitating collaboration among stakeholders and integrating diverse data types, HBIM holds significant promise for advancing the preservation and management of educational built heritage.

1.2 Information management: platforms and uses

BIM implementation requires integrating the diverse professional roles involved in a project, facilitating efficient knowledge exchange. This approach ensures the continuous and accurate updating of available information, minimizing errors and optimizing processes. Specific tools, such as collaborative platforms based on open systems, are required to achieve these objectives. These platforms must support professionals in the architecture, engineering, and construction sectors in general, including Public Works Managers and contracting authorities, in the proper management of BIM models. This encompasses specialized aspects such as plant design, energy analysis, structural analysis, site management, maintenance of works, and much more. The integration of BIM and Common Data Environments (CDE) has emerged as a pivotal aspect of modern construction management and architectural design.

This literature review synthesizes current research on the interplay between HBIM and CDEs, highlighting their roles in enhancing collaboration, data management, and project efficiency. CDEs are essential for facilitating effective collaboration among stakeholders in BIM projects. They provide a centralized platform for data sharing, which is crucial for maintaining consistency and accuracy in project information. According to Patacas et al. [16], a well-structured CDE can significantly enhance the operational efficiency of BIM processes by ensuring that all participants have access to the latest project data, thus reducing the likelihood of errors and miscommunication. Furthermore, Min Ho Shin [17] emphasizes the necessity of standardized data definitions within collaborative environments, asserting that commercialized CDEs can streamline the implementation of BIM across various participants in the architecture, engineering, and construction (AEC) sectors. The use of CDEs not only improves data accessibility but also enhances data quality and interoperability among different systems. Sheehan et al. discuss how CDEs facilitate cross-study comparisons and data aggregation, which are vital for meta-analyses in clinical research, and these principles can be analogously applied to BIM environments. The standardization of data through CDEs allows for better integration of various tools and technologies used in BIM, promoting a more cohesive workflow. This interoperability is particularly important in projects involving multiple stakeholders, as it ensures that all parties are aligned in terms of data usage and project objectives. The development of frameworks for CDEs is crucial for their successful implementation in BIM projects. Patacas et al. [16] propose a framework that incorporates open standards and existing technologies to create a prototype CDE aimed at improving facilities management through BIM. This framework addresses the operational aspects of BIM and emphasizes the importance of a collaborative approach to data management. Similarly, Abbas et al. [18] highlight the necessity of a Master Information Delivery Plan (MIDP) within the BIM Execution Plan (BEP), which outlines the information deliverables and protocols necessary for effective collaboration in BIM projects.

Despite the advantages of integrating CDEs with BIM, challenges remain in achieving seamless collaboration and data management. The complexity of managing diverse data sources and ensuring data integrity across platforms can hinder the effectiveness of CDEs [19]. Future research should focus on developing stronger frameworks that address these challenges while enhancing user experience and data security in collaborative environments. Additionally, exploring the potential of emerging technologies, such as cloud computing and artificial intelligence, could provide innovative solutions for improving the functionality of CDEs in BIM applications [20]. CDE integration within BIM frameworks is essential for fostering collaboration, enhancing data quality, and improving overall project efficiency. As the construction industry continues to evolve, ongoing research and development will be crucial for addressing existing challenges and leveraging new technologies to optimize collaborative workflows.

These new workflows also bring some new issues to deal with, such as the critical need for improved collaboration, interoperability, and data security in heritage conservation efforts. As highlighted by Zhou et al. [21], who propose a framework that utilizes blockchain technology to enhance data security and collaborative efficiency. Furthermore, the role of CDEs in facilitating high-quality data exchanges and ensuring the effective management of heritage data is underscored by Oostwegel et al. [22], who emphasize the importance of openBIM standards in mitigating data loss during the digitalization of culturally significant buildings. Additionally, the potential of CDEs to support dynamic information integration, as discussed by Moyano et al. [23], illustrates the need for a comprehensive understanding of how these environments can streamline workflows and improve decision-making processes in HBIM applications.

1.3 Paper aim and research question

The integration of CDEs and effective information management strategies, within HBIM methodologies, holds significant promise for enhancing the management of school buildings. By embracing these technologies, educational institutions can create environments that support academic achievement and highlight the historical significance of their facilities. This paper aims to address some fundamental issues related to the use of CDE in HBIM applications, with a specific case study on a school building of public heritage in Rome, Italy, the Ermenegildo Pistelli Complex. The research unit cooperates for the historical-constructive investigation and performance verification of historic schools in Rome in a knowledge transfer path [24, 25]. The paper presents a consolidated workflow developed and used in collaboration with the Public Administration owner of a vast public patrimony of school buildings in the city of Rome, in particular those of the I Municipality. The following research question not only aligns with current trends in digital heritage management but also seeks to contribute to the development of best practices for implementing CDEs in the context of architectural heritage: How can the integration of CDEs enhance interoperability and data management in Heritage Building HBIM applications, particularly in the context of architectural heritage restoration design and their management?

2. METHODOLOGY

The research methodology presented in this paper, designed for the development of integrated planning and management processes of public school assets in alignment with and supporting the Public Administration, is structured into activities: 1. Data Collection and Data Processing (§ 2.1); 2. Data Restitution and Modelling Output (§ 2.2); 3. Management of CDE for HBIM (§ 2.3). The core of the process is represented by the last subsection concerning the use of the CDE. The chosen platform allows integrating the documentary aspects, technical documents, and information modeling, specifically to create a complete HBIM of all the fundamental aspects for the management of a public heritage. The methodology is illustrated in Figure 1.

2.1 Data Collection and Data Processing

The integrated survey involves both traditional and TLS (Terrestrial Laser Scanning) methodologies. The point cloud of the Ermenegildo Pistelli school building in Rome was created using Leica's RTC360 3D laser scanner. This device operates based on the high-speed time-of-flight principle, enhanced by Wave Form Digitizer Technology (WFD). This type of survey provides a precision of up to 5 millimeters and a maximum range varying between 800 and 1000 meters. The scanner can collect up to tens of thousands of points per minute (up to 2 million points per second) by directing the laser pulse across the surface of an object using a rotating mirror or prism. It also allows for data acquisition in less than 2 minutes per scan and provides an HDR spherical image with a resolution ranging from 6 mm to 10 m.

The scanner also enables automatic alignment of the point cloud based on real-time motion detection through a mobile device, which simultaneously offers a 3D and 360° visualization of a single scan or the entire point cloud. The automatic in-field registration without targets (based on VIS technology) and automated data transfer to the office further maximizes productivity, significantly reducing survey time.

The Leica Cyclone FIELD 360 app (version 5.2.1) was employed as part of Leica Geosystems' 3D reality capture solutions, connecting field-acquired data to the scanner and office data registration using Cyclone REGISTER 360 (version 2021.1.2 build r20092). In the field, users can acquire, register, and automatically review scan data and images. The reduced "noise" in the data results in sharper, high-quality scans rich in detail and ready for use in various applications. Combined with the Cyclone FIELD 360 software for automatic in-field registration, the Leica RTC360 scanner ensures high accuracy that can be verified directly on-site.

The survey of the E. Pistelli complex consisted of 157 scans, resulting in 272 connections between different setups. There is a 50% overlap between the scans, which makes the connections robust. The margin of error for the point cloud is 0.0005 m. It is therefore possible to conclude that the survey was carried out correctly.

In the process of reconstructing the building's original design, it is undoubtedly essential to conduct a cognitive investigation of the existing heritage, consulting and carrying out a careful analysis in several archives in Rome. In this specific case, the Capitoline Historical Archive, the Department of Infrastructure Development

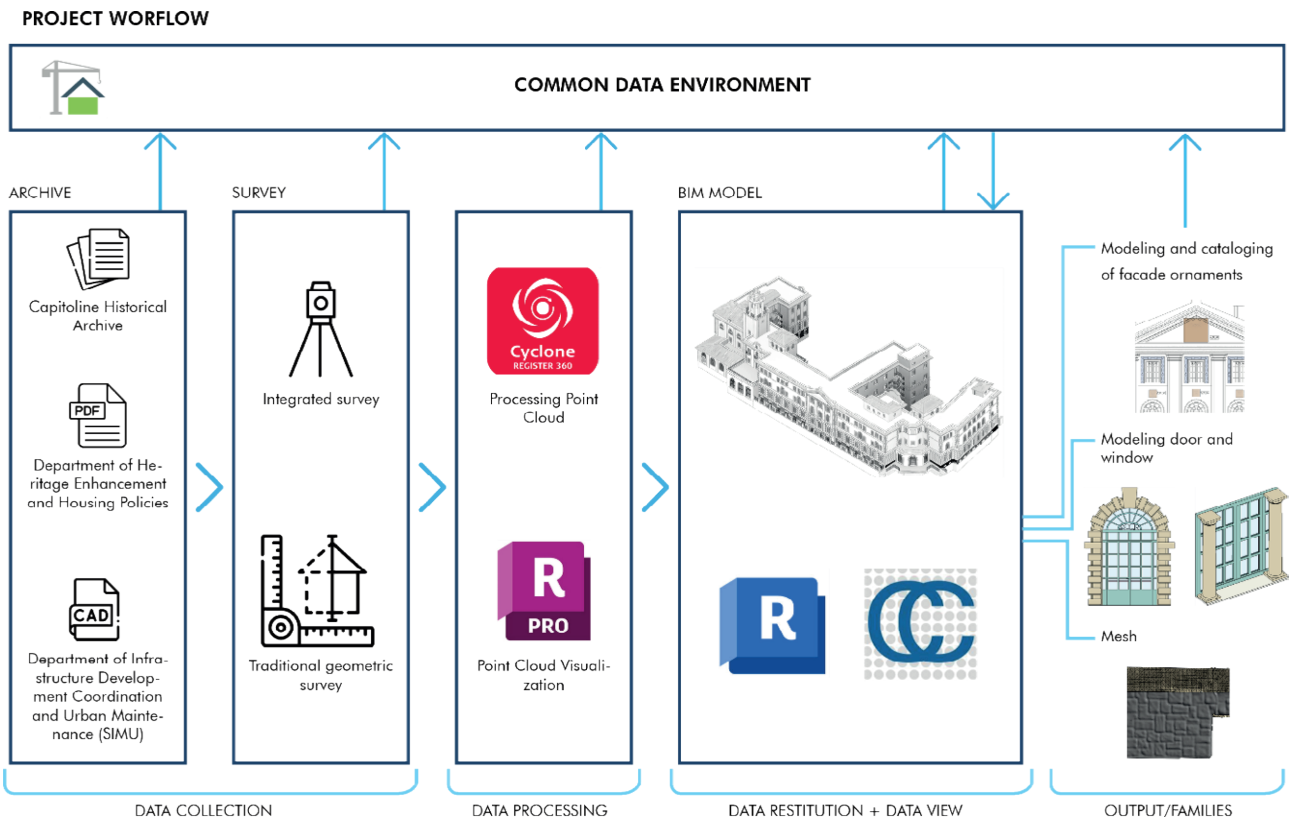


Figure 1. Methodology workflow.

and Urban Maintenance (SIMU), and the Department of Heritage of Rome Capital were consulted. From these results, it was possible to reconstruct and structure the model in several phases, mainly reconstructing the historical evolution of the building, consisting of extensions and adjustments to fire regulations. Through this phase of consulting the existing documentation, it was possible to simplify the subsequent phases of survey and modeling.

The survey campaign for the building was conducted over multiple days due to organizational constraints and the availability of the school. Once the survey campaign was complete, all scans were merged and aligned using the Cyclone Register 360 software (version 2021.1.2 build r20092). This software enables the merging of various point clouds, aligning them, and strengthening the connections between setups, i.e., the different scanning points. A separate point cloud was created for each survey day, and these were subsequently “cleaned” to remove noise and unwanted elements. After processing the point clouds, they were exported in the .rcp format, which is readable and compatible with Autodesk software.

A key feature of Leica’s RTC360 laser scanner is its ability to orient the model based on the geographic coordinates of the location. This ensures that the point cloud is automatically georeferenced, eliminating the need for additional steps once the data is processed in the office. The point cloud was then imported into Autodesk’s Recap software to be used for visualization, analysis, and sectioning according to specific needs.

2.2 Data Restitution: BIM Modelling

To create the BIM model of the Ermenegildo Pistelli Complex, the Autodesk Revit v2024 BIM Authoring software was selected. The first step involved identifying and semantically defining the various building components. The primary structural elements and detailed components were identified. The modeling process was developed in accordance with Italian regulation UNI 11337-part 3 and 4, and ISO 19650 standards, with the specific request from the Public Administration to achieve a Level of Development (LOD) E-F-G and a high granularity of Level of Information Need (LOIN) for windows, doors, and ornamental elements, to support future restoration and conservation interventions. LOD has evolved both in geometrical aspects (LOG – Level of Geometry) and information (LOI – Level of

Information). LOIN was articulated across three distinct dimensions: the geometric component (representation of shape, size, dimensional accuracy, and spatial positioning of elements), the alphanumeric (data expressed through characters, numerical values, codes, and symbolic identifiers necessary for classification and analysis), and the documentary component (structured set of historical records, technical drawings, and supporting documents associated with each modeled element). Specifically, all appropriate components were set up with the correct dimensions based on the surveys and accurately positioned. Thanks to the historical information gathered and the on-site survey, it was possible to recreate a highly accurate model. The majority of components were modelled as loadable families, while for some complex elements, conceptual mass modelling was employed, allowing for the creation of any shape. The parametric modelling of families facilitates their reuse, as families within the same category can be adapted by changing parameters, such as length. Each model component is assigned parameters defining its creation and demolition phases. These alphanumeric characteristics are managed within the model's database or schedules to produce thematic deliverables or interact more effectively with the information component, even remotely and using specialized tools. Information was added to the building model during and after its creation. A BIM model can incorporate extensive and multidisciplinary information, including: Building geometry, Materials and their properties, Images of various kinds of the investigated asset, Historical documentation, Traditional or high-definition surveys with point clouds, and other types of information. All this data is collected and managed within the BIM model, which functions as a three-dimensional and virtual database.

The main phases of the standard modelling process were: 1. Importing the point cloud into the modelling software, 2. Generating the primary geometries based on the point cloud, 3. Defining system families, 4. Creating, parameterizing, and inserting loadable families, 5. Creating local families.

2.3 CDE: Information Management

National (UNI11337 – part5) and international regulations (ISO 19650) describe the CDE as a virtual environment, such as a Cloud or Server, where all project stakeholders can store their work. This environment is organized and structured to track all activities, define roles and responsibilities, and provide up-to-date and comprehensive information to all participants. Within this context, the collaborative and integrative aspects typical of the BIM methodology take shape. This tool is central to the digital construction process because it allows digital models to fulfill their primary function: serving as the basis for integrated and shared decision-making.

A collaborative BIM platform (namely CDE) must provide a range of functionalities to enhance team productivity, stakeholder engagement, and achieve several benefits, including: 1) comprehensive control of construction processes (use of cloud infrastructures accessible from any device and by all operators, ensuring continuous supervision of processes); 2) defined roles and responsibilities (clear and precise assignment of roles and responsibilities to protect informational assets, ensure data security, and prevent fraud and errors); 3) action traceability (monitoring actions performed and recording revisions and modifications made to shared data among various stakeholders. Each user is granted specific permissions based on their role, ranging from read-only access to full editing rights); 4) review and approval (implementation of structured processes for the review, approval, and validation of documentation, facilitating control and sharing of updated document and model versions); 5) effective communication (promoting continuous communication among stakeholders through information coordination and management of the internal CDE, rather than external channels, such as email). Finally, the use of CDE permits automatic data backup, ensuring data recovery in case of partial or total loss.

In this research, it was possible to share and review all acquired materials and work progress using the Dalux software provided by the developer for the purposes of the research and study (Figure 2). This software, structured according to BIM regulations, allows project participants to manage file access, consult the project in its three-dimensional form while overlaying it with the point cloud, and create two-dimensional sections and plans directly from the viewer itself.

The digital archive thus constructed contains all documents organized into defined categories and sections. The database can be continuously updated over time. This ensures the orderly and ongoing management of documents by incrementally adding new ones as needed. The main advantages of managing an entire asset in this manner include: accessibility and retrieval of documents; measurement of the available archival assets; management and continuous updating; and stakeholder discussions on design objectives.

All the archive documentation, the 3D model of the building, and the elaborated point cloud were archived within the Dalux software. The peculiarity of this CDE is to update, comment, and keep track of all the people

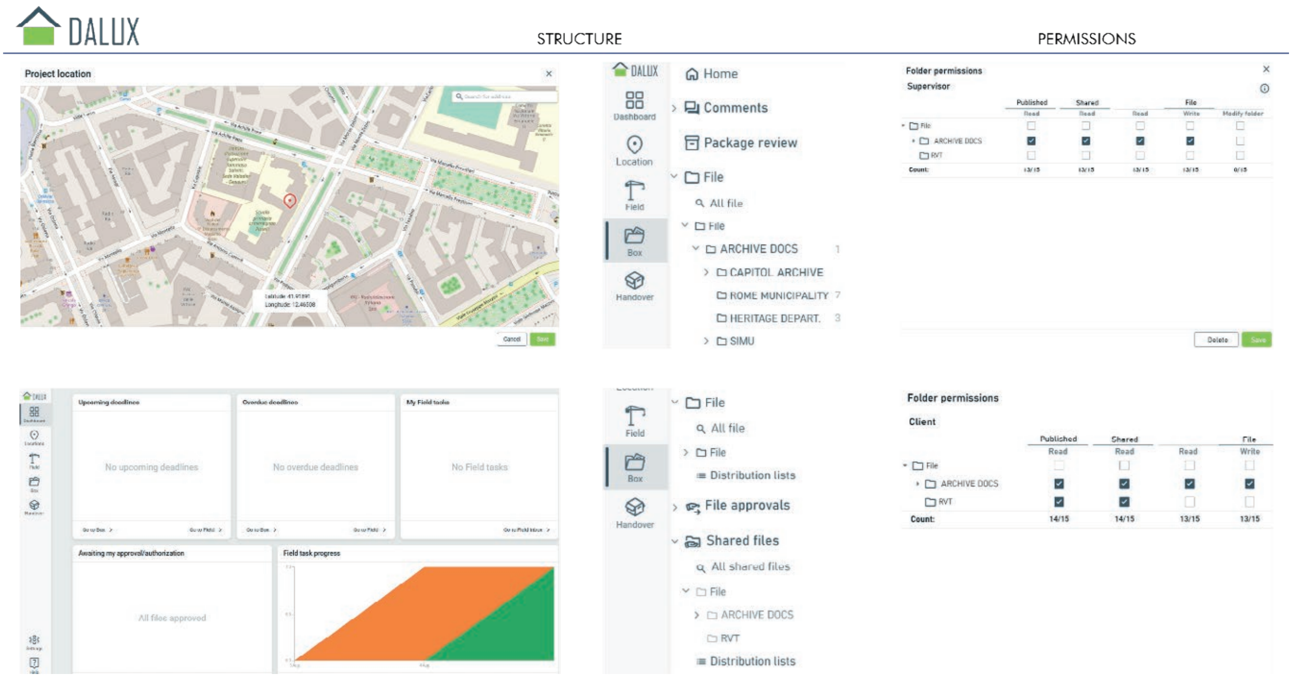


Figure 2. Structure of Dalux, CDE folders organized for the research and stakeholders permits.

and changes that make up the project. In particular, it is possible to keep track of the progress of the modeling thanks to the plugin that allows for instant connection of Revit and Dalux. Furthermore, in the Dalux viewer section, it is possible to view the overlapping of the model with the point cloud.

3. CASE STUDY: THE PISTELLI SCHOOL IN ROME

The case study is the Ermenegildo Pistelli school building, part of the Claudio Abbado Comprehensive Institute, which houses a kindergarten and elementary school. It is located in Rome's Municipality I, at Via Monte Zebio 35 (Figure 3). The building, large and C-shaped, is arranged along the perimeter of the lot, defining the entire frontage on Via Monte Zebio and extending along two sides to create two distinct angular spaces [26]. The corner between Via Monte Zebio and Via Cantore is notable for the low gymnasium structure, which visually balances the clock tower, and for the portal of one of the building's original entrances, which once separated the male and female sections of the school. Another corner, located at the intersection of Via Monte Zebio and Via Achille Papa, features a recessed entrance portico relative to the two main façades. This design harmoniously connects the two wings of the building and creates an inviting urban access space to the school. The internal garden could originally be accessed both from the building and through two side gates located on the wings of the building; today, only one gate remains, on Via Achille Papa.

The school building was designed according to modern criteria. The classrooms are spacious and bright, with large and tall windows that allow natural light and sunlight to enter. Gardens and terraces were conceived to enable outdoor teaching. However, following the subdivision of the courtyard, the original layout of the garden was lost, with most of the area now paved except for a small portion allocated to the kindergarten [26]. The building consists of three above-ground floors and a semi-basement, also featuring large windows on the main frontage. The interior spaces were organized based on solar orientation, with all classrooms facing southeast or southwest. The layout is serial, with rectangular classrooms of identical dimensions, each approximately 27 square meters.

The building's façades follow a classical design approach, with a clear hierarchy of floors. On the first floor, the central body windows feature a serliana motif, while the entrances are marked by arcaded porticos with round arches. The building's volume is complex and well-balanced, with a clear distinction among its various architectural components [26]. Distinct elements include the entrances with their terraces, the gymnasium, and the clock tower topped by a belvedere. The architecture

Figure 3. Historical and current pictures of Pistelli School. A) ICCD - Morpurgo Fund - inv. n. G016928 - Morpurgo, L. B. 1924, Cultural Association info.Roma.it - cod. 3896. C) Archivio Storico Luce. D) E) F) 2025, De Bellis, M.

is enriched with extensive use of stucco and decorative elements, enhancing its aesthetic value. The building was designed and constructed as an integral part of the new Piazza D'Armi district, now known as Piazza Mazzini. Morphologically, it has a traditional layout, adhering to the lot's shape and responding to the surrounding urban requirements. At the intersection of the tree-lined avenues of Via Monte Zebio and Via Achille Papa, the designer conceived a small resting area that expands the public space, providing a place of relief within the urban fabric.

The school building was designed in 1909 by architect G. Venturi. In 1924, following the signing of the contract, construction began under the supervision of the Gianicolense Cooperative Construction Company. By 1926, as the building neared completion, heating systems were installed. Prof. G. Jacobucci and Prof. B. Marescalchi were responsible for the façade decorations in 1928. In the same year, consolidation and underpinning work were required due to widespread structural settlements. The building works were officially tested and certified in 1932, and in the following year, the Fire Brigade Guard Post was constructed within the same block. The original design of the school was modified during construction, including lowering the level of the internal garden to match the basement floor. This change affected the internal façades and, functionally, altered access to the garden, which became primarily accessible from the basement level. In 1953, expansion plans for the school were drafted, involving the construction of the central block that divided the internal courtyard into two sections. The work commenced in 1955 and was completed in 1956. The expansion retained the proportions of the main building in terms of distribution and functionality but differed in terms of materials and, especially, window design. The architectural language of the façades was distinct, with a minimalist layout without decorative elements. In 1971, final testing was conducted for fire safety compliance, which included the construction of two external emergency staircases made of reinforced concrete. In 2019, the first-floor premises of the building, previously used by the former Opera Sante de Sanctis, were returned to their original use.

4. RESULTS

The results of the developed process are divided into three areas: 1) integrated survey, where archive documents, traditional techniques and TLS survey are merged to establish the basis for information modelling (§ 4.1); 2) information modelling for heritage, the HBIM process, with particular attention to the modelling of building components subject to cataloguing for subsequent redevelopment and restoration interventions

(§ 4.2); 3) conscious use of the CDE for the HBIM specifications, cataloguing the construction elements and the archival information (§ 4.3). The modeling in particular proposes different approaches depending on specific construction elements; some with more regular geometries can be parameterized with a defined procedure, while for those with more irregular ones, it is necessary to develop ad hoc strategies which, in the proposed case, combine the use of meshes with informative modeling.

The greatest challenge is certainly represented by the management of information for heritage buildings, where it is necessary to correctly store the archival information, create catalogues of the construction elements, and then generate the relative HBIM models, complete both from a geometric and an informational perspective. Furthermore, the possible and facilitated interaction between the stakeholders involved assumes a fundamental aspect in the phase of model development first, and of management of the heritage asset afterwards.

4.1 Integrated survey

The survey campaign for the building was conducted over multiple days due to organizational constraints and the availability of the school. Once the survey campaign was completed, all scans were merged and aligned. The 157 scans performed are shown in Figure 4. For a total of 2,158,318,110 points, which constitute the entire point cloud.

In order to outline the history of the building, it was necessary to consult as much archive material as possible (Figure 5). The only document in possession at the beginning of the work was the knowledge sheet of the building, drawn up by the architect P. Capolino. This document proved to be essential to understand, in general terms, all the aspects of the building, which allowed us to outline the subsequent historical investigations in the various archives of the Municipality.

The Capitoline Historical Archives of Roma Capitale preserves most of the documentation found on the case

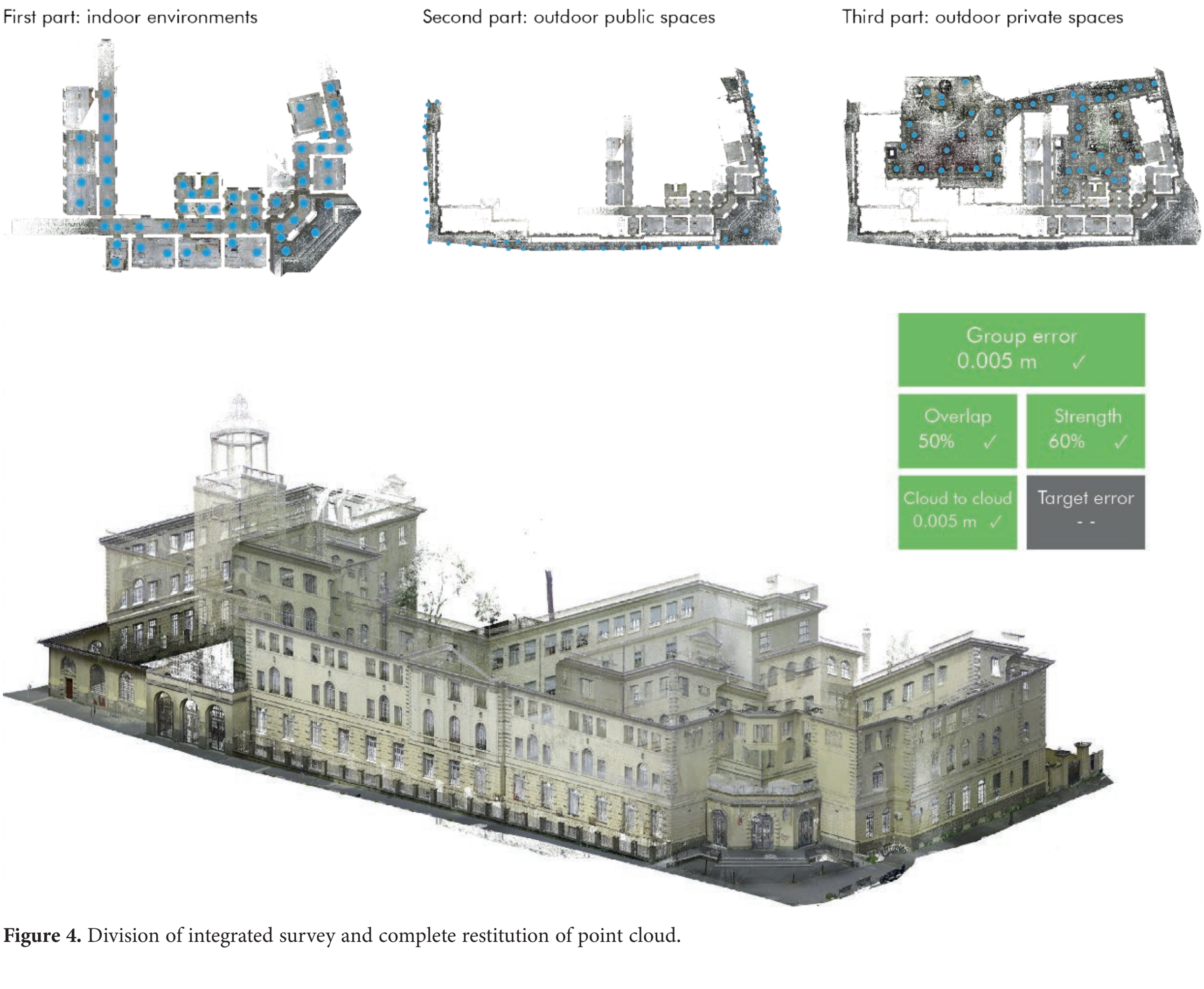


Figure 4. Division of integrated survey and complete restitution of point cloud.

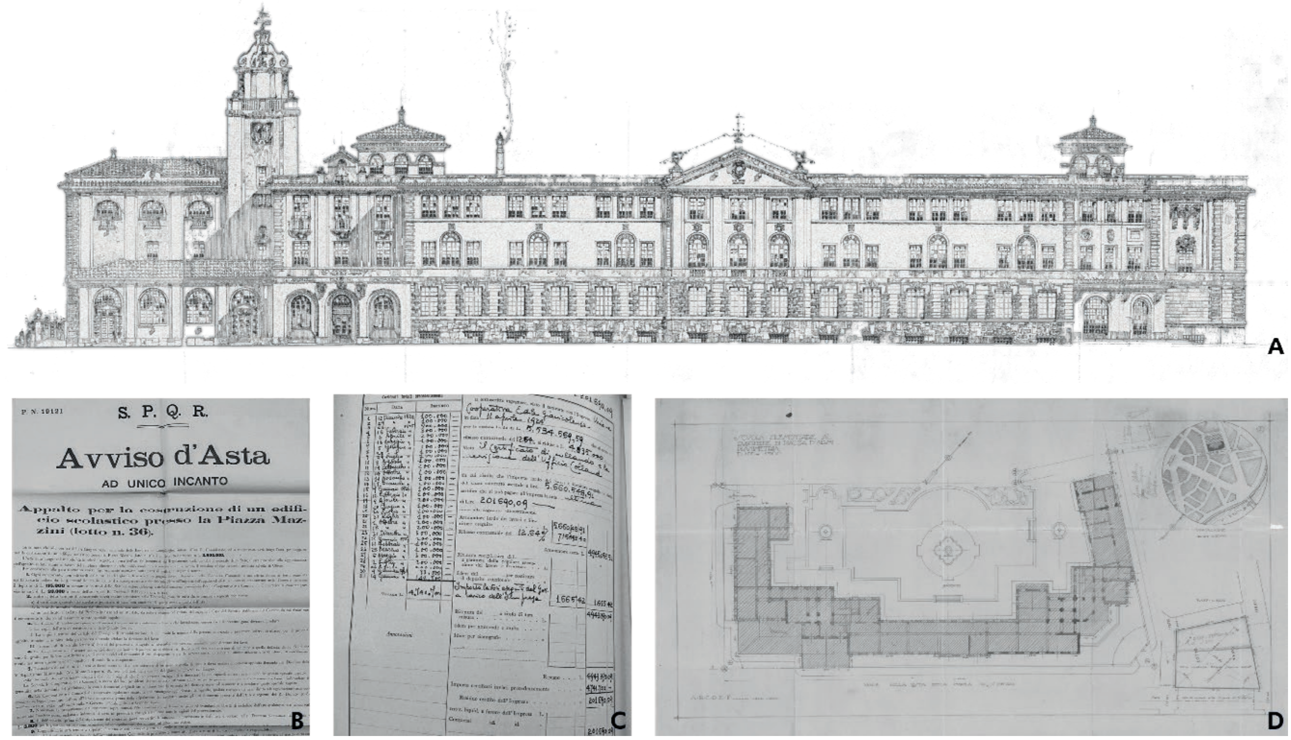


Figure 5. Archive documents. A) View of the elevation on via Monte Zebio, original design (1928). B) Tender for the construction of the E. Pistelli school (1924). C) Latest progress report of the E. Pistelli school (1932). D) Plan of the original design (1928). [Archives A, D: courtesy of the Department of Heritage Enhancement and Housing Policies of Rome- Dir. Acquisition Deliveries Conservatory - Conservatory Archive - pos. n. 486-XIX, folder 38; B, C: -courtesy of the Capitoline Superintendency of Cultural Heritage – Capitoline Historical Archive - Ripartizione V-Ragioneria Appalti Esauriti, b. 89, fasc. 231, sf. Bis]

study. Thanks to the archival sources, which also included design plans for the heating systems, it was possible to identify the different figures involved in the construction of the building and, at the same time, the problems faced during its construction. It was interesting to note how, after about a century, due to the war and the consequent increase in costs, a request was made by the construction company to review the prices, because both the labour and the materials had undergone increases. In addition, the Capitoline Archives also preserve the last progress report with the reservations made by the construction company for works not provided for in the contract and for increased costs. The accounting of the work also made it possible to identify the assignment of the decoration and sculpture work to the two professionals in charge, a document that proved crucial in cataloguing the façade elements.

The Department of Heritage Valorization and Housing Policies of Rome Capital preserves the original design layouts of the building. Furthermore, it was possible to view the documents relating to the expansion of the building, and consequently, it was possible to reconstruct its history, namely the planning that took place in 1953, the construction that began in 1955, and ended in 1956.

To conclude the historical investigations on the building, an inspection was also carried out at the Department of Infrastructure Development and Urban Maintenance of Rome Capital (SIMU), where the latest interventions carried out on the school are archived, including maintenance of the systems and checks of compliance with fire regulations. In addition to the verification documentation of the building, it was also possible to recover the plans of the building in CAD format, whose last update dates back to 2010.

4.2 HBIM Model and Building Components Informative Modelling

The modeling process followed the consolidated Scan2BIM process, where the elaborated point cloud served as a scaffolding on which to model the building. The historical analysis elaborated through archival sources also allowed us to obtain essential information for information modelling.

An explicit request from the public administration was to pay attention to the valuable elements of the school, which had to be modeled with great attention to detail (always both geometric – LOG – and informative – LOI). Among these, in the case study analyzed in the paper, the following certainly stand out (Figure 6): the geometric rustication of the ground floor, the irregular rustication of the basement, the vaults of the ground floor, the ornamental elements of the façade, and the windows and door frames (internal and external ones). In particular, on these last two elements, it was considered essential to develop a filing system that would allow the information to be stored in order to proceed with a restoration (for the ornaments) and a performance requalification with conservation of the historical-constructive values (for the windows and door frames).

A critical aspect of this study was the approach to modelling the external and internal windows and door frames. Staying within the constraints of Revit's built-in libraries proved nearly impossible, especially considering the unique elements required, such as the fixtures and frames in this case. These elements, inherently unique, are difficult to simplify into generalized categories because they were specifically designed and constructed for particular applications. Additionally, they often reflect the craftsmanship and modifications introduced over time. For the windows, it was decided to create specific families for each type, nesting them based on their components and decorative elements while geometrically simplifying them as much as possible. A closer inspection of the building reveals a division of the façades into three distinct architectural orders, each corresponding to a specific type of fixture. The fixtures are more ornate at the lower levels and become progressively simpler on the upper levels. Furthermore, on each façade, the decorations of the fixtures differ, making it necessary to identify each façade of the building using letters of the alphabet. Overall, the building contains 435 windows and French doors, along with 227 internal and external doors.

In the HBIM modeling of the E. Pistelli school, the development of the digital model was structured according to the Italian regulation UNI 11337 for LOD and the ISO 19650 standard for LOIN. The overall model reached a geometric development corresponding to LOD C-D (according to Italian UNI 11337), ensuring sufficient accuracy for general analysis and decision-making pro-

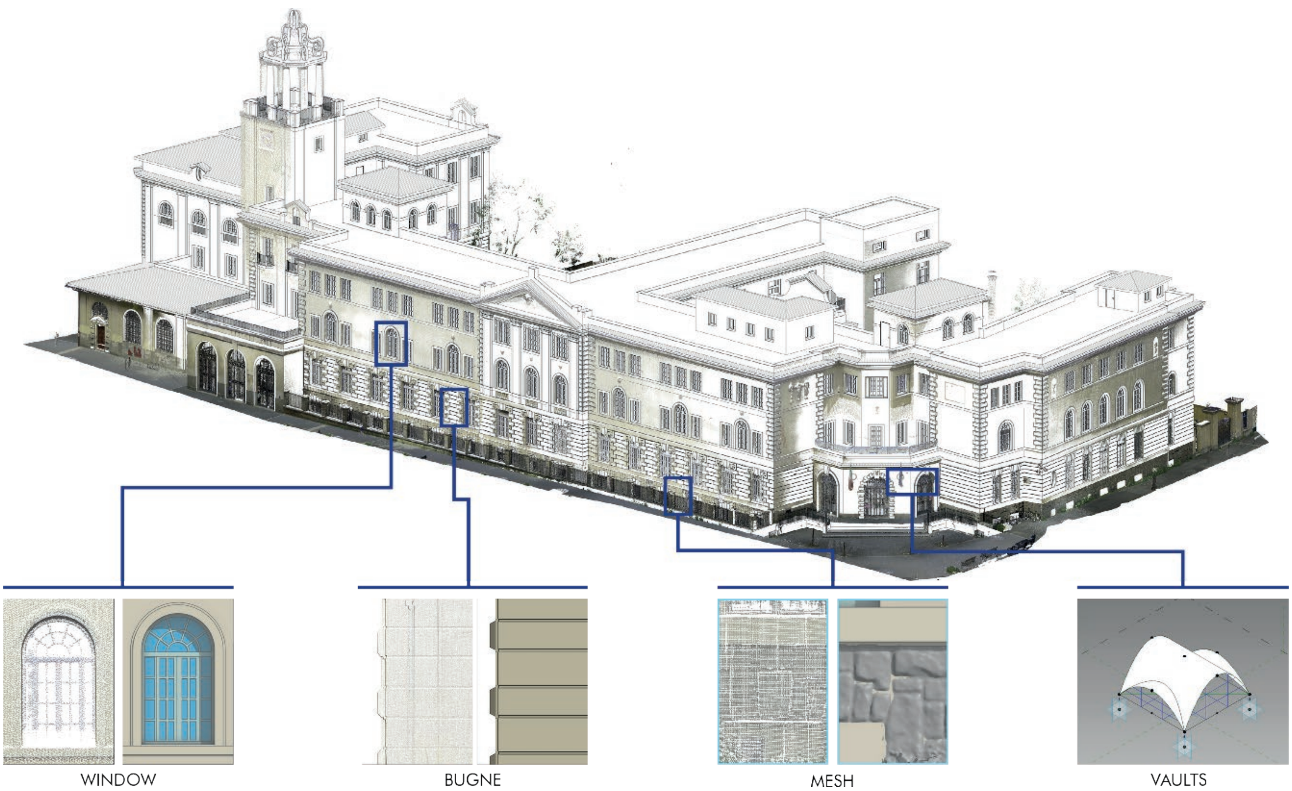


Figure 6. HBIM model and specific informative objects elaborated.

cesses. However, for specific components explicitly prioritized by the Public Administration (i.e., windows, doors, and ornamental elements), the geometric modeling (LOG) attained a higher level of detail, corresponding to LOD E-F. These elements were modeled with a high degree of morphological accuracy, often through bespoke parametric families and mesh modeling to capture irregularities and artisanal features. From an informational perspective (LOI), the objective was to reach LOD F-G for selected components, with a focus on comprehensive metadata supporting maintenance, restoration planning, and performance assessment. The LOIN defined for the project required high granularity of information, including historical references, construction features, material properties, typological classification, and performance-related data. This level of detail enabled an accurate and interoperable dataset aligned with the asset management needs of the Public Administration, supporting long-term conservation strategies and integration into broader heritage information systems.

A great deal of cataloguing work was carried out on the doors and windows (Figure 7). Given the number and the difference in types for each façade, first, the elevations were distinguished with a letter (from A to L). Secondly, they were coded with an acronym IE (external frame) and a number regarding the different typologies. The modelling followed the same cataloguing, so the informative family was named with the cataloguing IE - NN (code-number) and then each different family (which therefore corresponds to a typology different from frame).

As with the windows, another distinctive feature of the façade of the E. Pistelli school is the rusticated finish on the external walls. The ornamental and rusticated masonry follows the same principle as the fixtures: more elaborate on the lower levels adjacent to the street and progressively simpler as the height of the building increases. Rustication is present on all façades of the building, except for the new construction, which is devoid of any decorative elements. For all the rusticated elements that characterize the ground floor façade of the building, a highly realistic modeling approach was achievable, given their regular geometry (Figure 8). The same principle was applied to other elements of the façades, such as string courses and quoins.

Almost all the interior spaces on the ground floor are covered by vaults. It was discovered that the majority of the vaults are ribbed, but the building also features barrel vaults with lunettes and dome vaults. Since Autodesk Revit does not have a specific command for creating vaulted ceilings, several methods were experimented with to reproduce and catalog the various vaults present in the rooms of the building, to evaluate which methodology could be considered the most effective, reliable, and easiest to implement.

In order to create a model as faithful to reality as possible, and given that the spaces covered by the vaults have different geometric dimensions, it was decided to use adaptive component families as the basis for modeling the vaults. This type of family adjusts to the irregularities that typically characterize existing buildings.

For the elaboration of the more complex ornaments of the façade, in order to provide a comprehensive interpretation, it was decided to approach them through the development of meshes (Figure 9). This choice was also influenced by the fact that modeling programs typically assume the design of a new building, where the geometries are perfectly aligned and free of irregular elements. In the specific case of the E. Pistelli school, the elements in question were the fountain, located in the internal courtyard of the school, and the rustication of the raised basement. The latter, in fact, features rustication that does not follow a precise and repeated geometric pattern, in addition to being made of an equally irregular surface, which overall adds movement to the façade. Moreover, this type of decoration is characteristic of the neighbourhood and the period of construction, and consequently, it was deemed essential to represent it. The software used for data processing was Autodesk's Recap and Cloud Compare.

4.3 Use of CDE for HBIM applications

The use of CDE is a real challenge in the information management of the built heritage. In the research project presented, the Dalux platform was selected for a series of specific functions that allow for expanding the capabilities of the HBIM as much as possible. The process according to which the CDE is structured is the classic one, divided into 4 phases by technical regulations: WIP - SHARED - PUBLISHED - ARCHIVED. The information passes to the next step depending on the approvals provided by the actor of the building process responsible for validating each phase. Commercial CDE platforms have undergone significant developments and can lend themselves significantly to implementation in the HBIM process if used consciously.

They certainly present a series of fundamental functions in the HBIM process, such as: cataloguing in a single storage of all the information relating to the building, even if in different formats; the interaction between the stakeholders involved, in particular the public administration, still not very familiar with the logic of BIM modeling, but instead more willing to interact with

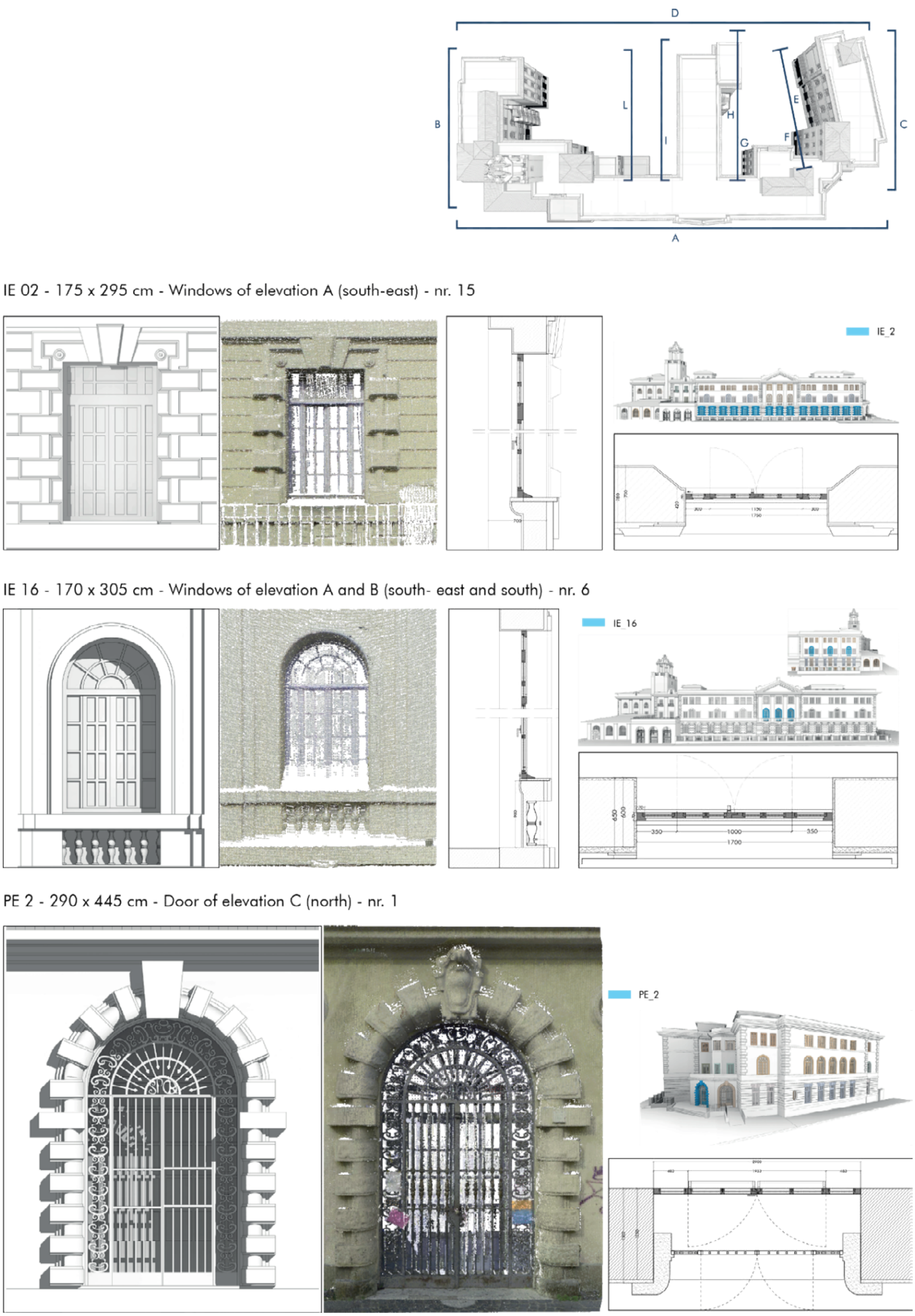


Figure 7. Windows and door informative modeling.

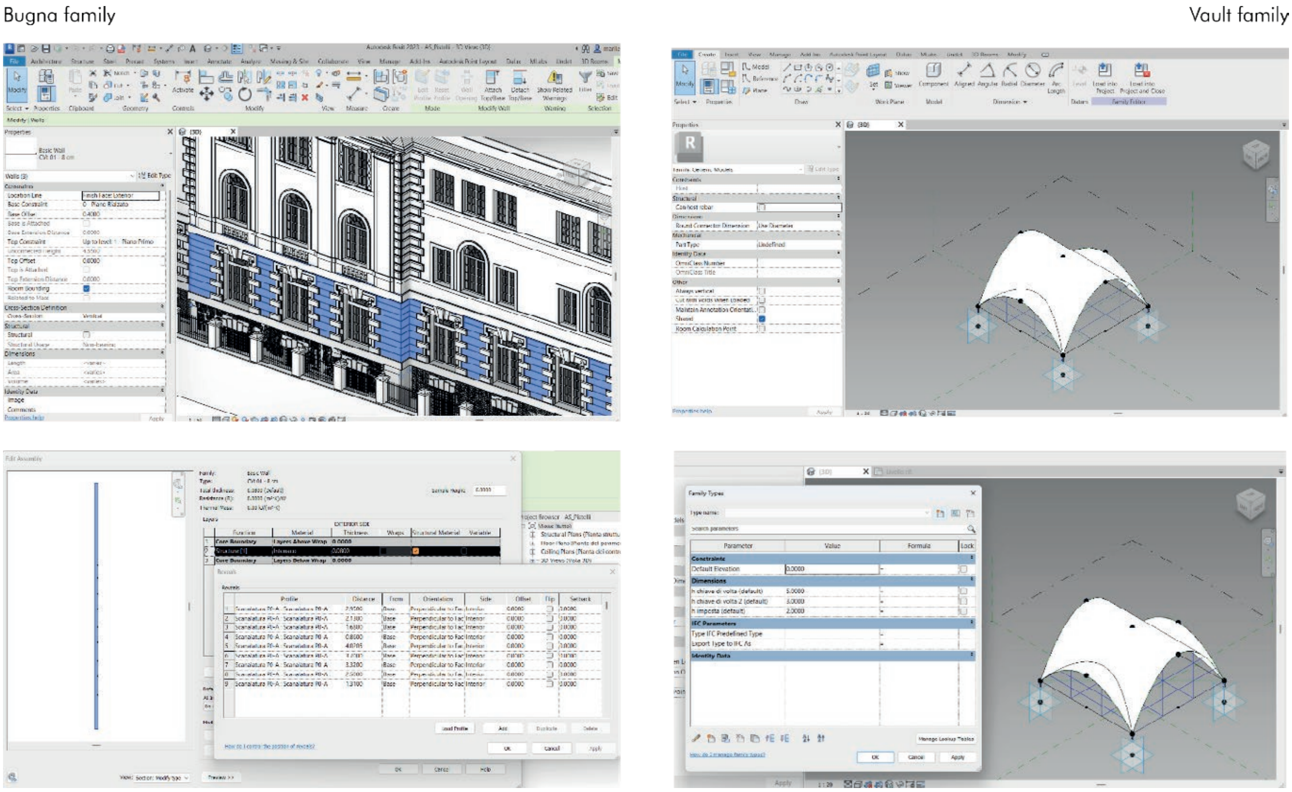


Figure 8. Regular bugne modelling and parametrization in the HBIM model and vaults specific families modelling

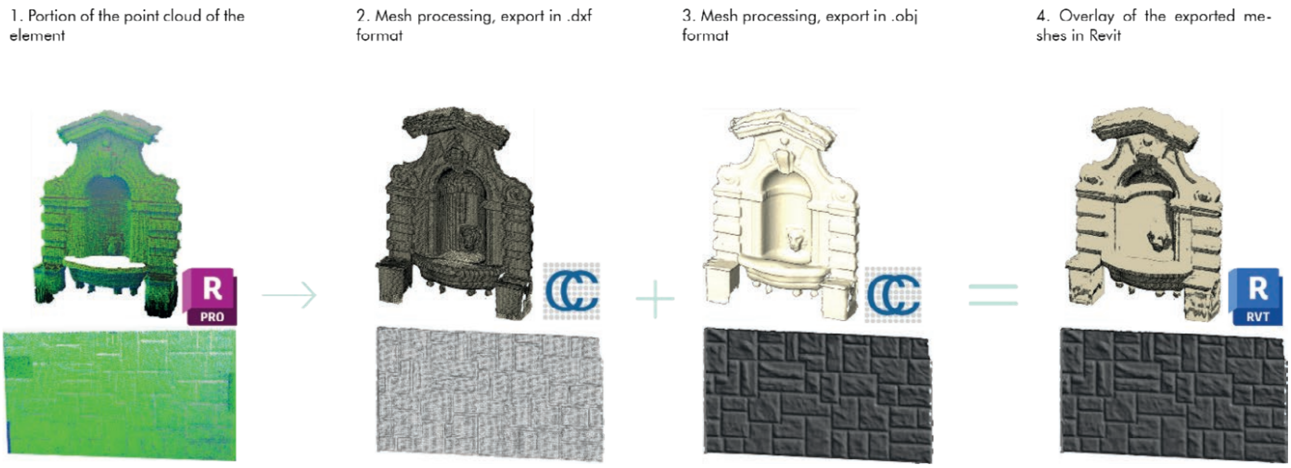


Figure 9. Ornaments modelling workflow.

BIM Viewers and management platforms; the possibility of verifying responsibility and completion of tasks and activities; and finally the cataloguing of construction elements through the detailed explanation of information models and other documentary sources.

First of all, the possibility of interacting between the interested stakeholders has allowed sharing information, revisions, and comments on all shared aspects: archival information, technical representations, point clouds, and models (Figure 10), and also visualizing by overlapping them. Each comment can also be assigned to a process

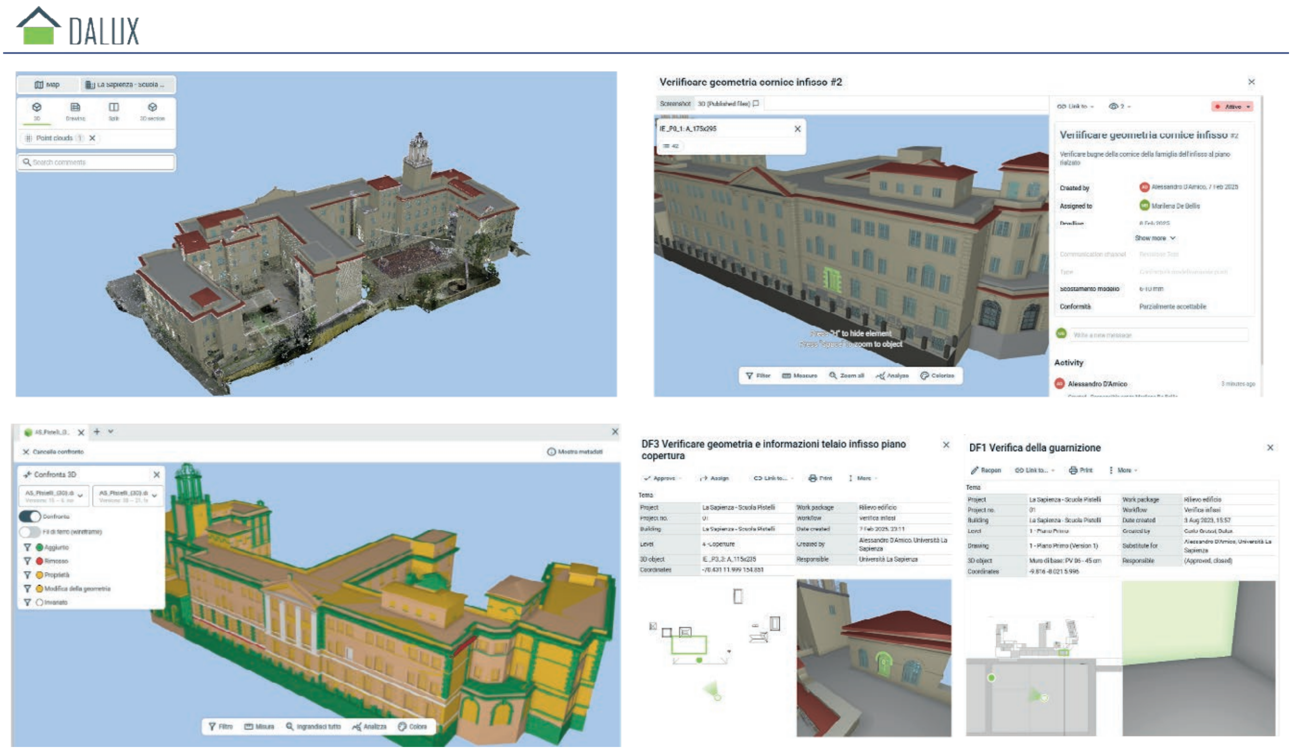


Figure 10. CDE HBIM management and Stakeholders' interaction.

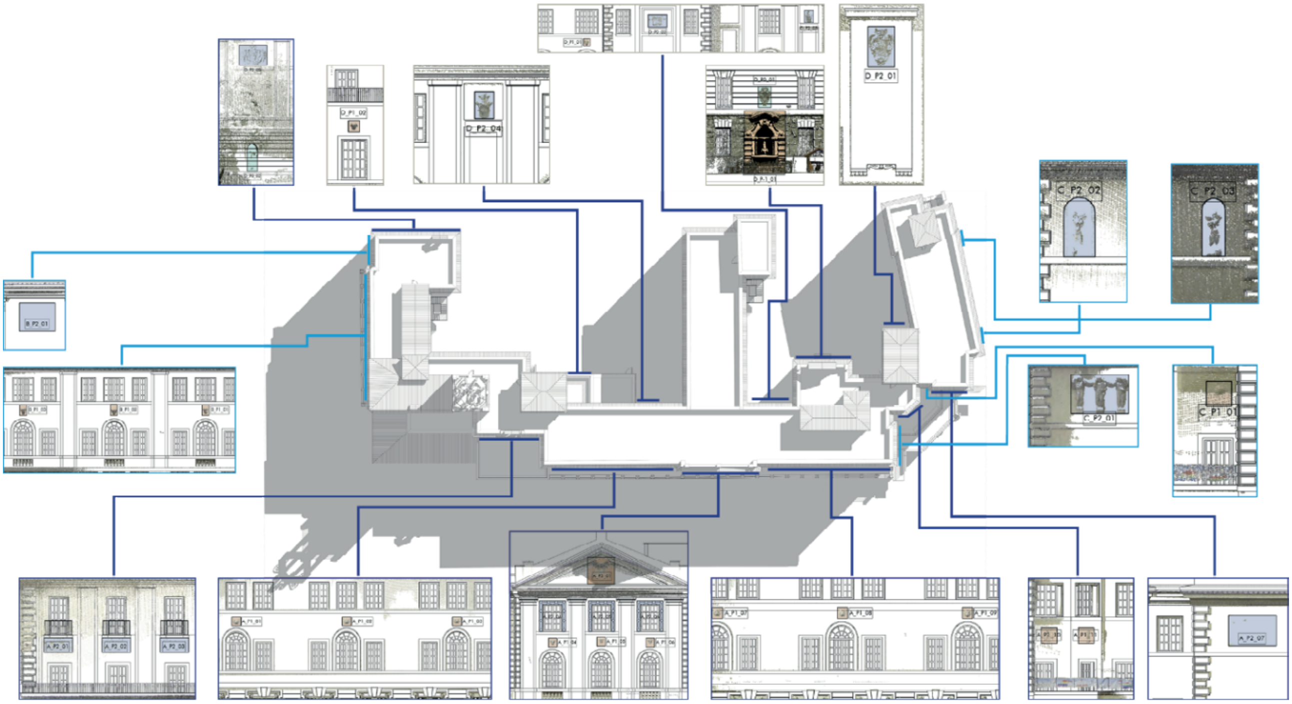
actor and has a deadline. In this way, it is always possible to verify responsibilities and implementation times of the activities (Figure 10). Secondly, a fundamental aspect is to verify the progress of the information modeling, comparing the versions uploaded by the operators. In Figure 10, it is possible to view the HBIM model divided by colours depending on the updates (i.e., red: removed; green: added; yellow: modified).

Finally, the cataloguing for the detail elements (described specifically in 4.2 for the fixtures) is reported with all the aspects of the digital archive produced within the CDE in Figure 11 for the façade ornaments. The archive is translated into a table that reports the label of the modeled element, explanatory comments, geometric aspects, and archival descriptions; to these are added photographs of the survey carried out and meshes extracted from the point cloud. This procedure allows for a complete archive of the aspects necessary for the analysis and possible restoration of the construction elements, and is open, since it can be implemented at any time, with data and documents relating to specific analyses that the public administration will want to conduct (e.g., material, degradation, performance analyses for the fixtures, etc).

5. DISCUSSIONS

The findings of this study highlight the significant advantages of integrating HBIM with CDE for the information management of built heritage, and in particular, with a case study on school buildings. The methodology exposed allowed for a comprehensive approach to digital documentation, fostering interdisciplinary collaboration among the stakeholders (architects/engineers, historians, real estate and facility managers, and public administrators). The integration of advanced surveying techniques, including TLS, ensured a high level of precision in data collection, which was instrumental in creating a robust and information-rich HBIM model of the Ermenegildo Pistelli school in Rome.

The use of CDEs proved to be a pivotal component of the research, facilitating seamless communication and data exchange among stakeholders. By structuring the digital environment according to standardized workflows, it was possible to efficiently manage historical documentation, architectural and construction modeling, and collaborative decision-making. The research also demonstrated the effectiveness of cataloguing construction elements and archival information within the HBIM framework, offering a replicable model for other heritage preservation projects.



SHEET ORNAMENTS ELEMENTS				
LABEL	COMMENTS	L	H	DESCRIPTIONS
A_P0_01	Stemma porta d'ingresso	70	100	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_01	Formella decorativa	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_02	Formella decorativa	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_03	Formella decorativa	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_04	Formella testa di dama	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_05	Formella testa vecchio	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_06	Formella testa di dama	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_07	Formella decorativa	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_08	Formella decorativa	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_09	Formella decorativa	70	70	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P1_10	Medaglioni con bassorilievo	65	65	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
A_P1_11	Medaglioni con bassorilievo	65	65	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
A_P2_01	Conchiglia balcone	200	75	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P2_02	Conchiglia balcone	200	75	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P2_03	Conchiglia balcone	200	75	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P2_04	Formelle finestra	220	153	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P2_05	Formelle finestra	220	153	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P2_06	Formelle finestra	220	153	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
A_P2_07	Bassorilievo	250	150	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
A_P3_01	Stemma principale timpano	175	200	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
B_P1_01	Formella testa vecchio	60	90	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
B_P1_02	Formella testa di dama	60	90	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
B_P1_03	Formella testa vecchio	60	90	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
B_P2_01	Bassorilievo	200	150	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
C_P1_01	Medaglioni con bassorilievo	65	65	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
C_P2_01	Bassorilievo figure allegoriche	285	170	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
C_P2_02	Nicchia e putto	110	150	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
C_P2_03	Nicchia e putto	80	150	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
D_P0_01	Stemma	95	120	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci
D_P0_02	Nicchia e putto	95	175	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi
D_P1_01	Formella decorativa	60	60	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci

D_P2_01	
TYPE	Stemma
L	130
H	170
DESCRIPTION	1926, elementi decorativi, materiale: cemento, Prof. Giovanni Jacobucci

C_P2_01	
TYPE	Bassorilievo figure allegoriche
L	285
H	170
DESCRIPTION	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi

A_P2_07	
TYPE	Bassorilievo
L	250
H	150
DESCRIPTION	1926, opere di scultura, materiale: cemento, Prof. Bernardo Marescalchi

Figure 11. Scheme of ornaments modelling and information storage into the CDE.

The study also encountered limitations. One of the primary challenges was the complexity of modeling intricate architectural details and integrating them with historical data in a structured manner. The use of HBIM methodology proved to be effective in documenting tangible aspects of the building, but the inclusion of intangible cultural heritage remains an ongoing challenge. The reliance on authoring software, such as Autodesk Revit and Dalux, may also pose constraints in terms of interoperability and long-term data accessibility.

Furthermore, the process of historical data collection presented obstacles due to fragmented archival records, requiring efforts to piece together a coherent reconstruction of the building's evolution. The accuracy of the final model is inherently dependent on the quality and availability of archival materials, which may not always be sufficient. Another limitation is the adoption of CDEs by public administration entities, which often lack the necessary technical expertise to fully utilize these digital tools. The study underscores the need for tailored training programs to enhance the digital competencies of heritage management professionals.

To address these limitations and expand upon the research findings, significant future directions can be proposed. The development of standardized protocols for HBIM applications in educational heritage management could also improve consistency and facilitate broader adoption. Further research should focus on enhancing the interoperability of HBIM and CDEs through open-source platforms and standardized data exchange formats. This would mitigate the challenges associated with proprietary software and ensure long-term accessibility and usability of heritage data. Additionally, community engagement initiatives could be developed to involve local populations in heritage conservation efforts, ensuring that HBIM applications align with broader societal and cultural objectives.

The debate on data ownership, in terms of security and protection, certainly remains open. In accordance with the actual legislation (UNI 11337), the responsibility for the CDE is assigned to the client, who can either manage it directly or delegate this function to an external entity. The client specifies the procedures for managing the flow of information to and from the CDE in the Information Specification, also defining the parties responsible for and/or custodians of the CDE. The regulations establish a general framework for the information flow within the CDE. The presented work could allow a framing in the proposed framework, also of the issues of data management to support the public administration for the future conservation and sharing of information.

6. CONCLUSIONS

The study highlights the significant role of integrating HBIM with CDE for the efficient management and preservation of historical school buildings. The case study of the Ermenegildo Pistelli school in Rome demonstrated that HBIM not only enables accurate digital documentation of architectural and historical features but also enhances data structuring for long-term conservation. The involvement of public administration and stakeholders played a fundamental role in ensuring the effective storage, management, and accessibility of models and data within the CDE. By fostering collaboration among architects, engineers, historians, and facility managers, the structured digital workflow facilitated informed decision-making and optimized heritage management processes. Despite challenges related to the complexity of architectural modeling, data interoperability, and the digital literacy of public entities, this research underscores the necessity of robust digital strategies in heritage conservation. Future efforts should focus on enhancing interoperability through open-source platforms, developing training programs for public administration, and promoting stakeholder engagement to ensure sustainable and inclusive heritage management practices.

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9. AUTHOR CONTRIBUTIONS

A.D. Conceptualization, Methodology, Validation, Writing - Original Draft, Supervision, Project administration, Funding acquisition; M.B. Visualization, Investigation, Surveys, Formal analysis; E.C. Writing - Review & Editing, History of construction supervision.

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A Solver-efficient Computational Fluid Dynamic Approach for the Thermal Performance Analysis of Ventilated Façades

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Abstract. The paper deals with the use of Computational Fluid Dynamics (CFD) for the thermal performance analysis and optimisation of prefabricated Timber-Concrete Composite (TCC) ventilated façades. TCC envelopes are composed of an internal insulated timber-frame wall coupled to an external concrete slab, separated by a ventilated air cavity. Such systems join the properties of engineered timber (good seismic behaviour, low thermal conductivity, environmental sustainability, and ease of system integration) with those of concrete (high thermal inertia, excellent durability and fire resistance). There is very limited knowledge on the performance of TCC facades, especially for what concerns their thermal behaviour. For this reason, a TCC ventilated façade located in the north of Italy was monitored over one year, and the results collected were used to calibrate and validate a CFD model. A new solver algorithm was developed to speed up the CFD simulations, allowing up to 45 times faster analysis compared to conventional solvers. Thanks to this improvement, the final model is suitable to be used for time-efficient thermal analysis (a full-day real-time simulation takes approximately 23 minutes), limiting the expensive and time-consuming construction of mock-ups. The CFD model developed is suitable for the thermal performance analysis and optimisation of TCC ventilated facades, but also for generic ventilated facades with external massive cladding, both in the case of new and existing buildings.

Keywords: Ventilated façade, CFD, Energy efficiency, Timber-concrete composite façade, Building monitoring.

1. INTRODUCTION

In recent years, the construction industry has witnessed significant growth in the adoption of engineered timber products, both for new and existing buildings. This is primarily due to their good characteristics, such as excellent seismic performance, good thermal insulation, environmental sustainability and good behaviour under fire. Additionally, timber is highly compatible with prefabrication processes and systems integration, and can be easily disassembled at the end of its lifecycle [1]. On the other side, its limitations are mainly related to its fragile stress-strain behaviour, hygroscopic properties and low durability if not adequately protected [2].

In the realm of building envelopes, lightweight timber facades typically exhibit lower thermal inertia and acoustic insulation than higher-mass alternatives. On the other hand, massive timber solutions involve considerable use of virgin materials and high costs. To address these limitations and enhance performance in terms of structural behaviour, acoustic properties, fire resistance, and durability, timber structures are often combined with concrete, resulting in timber-concrete composite (TCC) systems [3].

TCC facades generally consist of an internal insulated timber wall coupled with an external concrete slab, which acts as a protective barrier against adverse weather conditions [4], particularly extreme events like hailstorms and windstorms. These hybrid facades merge the advantages of timber – i.e., light weight, excellent thermal insulation, sustainability, ease of prefabrication and systems integration, aesthetic appeal – with the benefits of concrete – i.e., mechanical strength, high thermal inertia, good acoustic insulation, durability, fire resistance, application of heavy claddings (e.g., tiles or stone) – [5].

Beyond timber-based construction, another widely studied topic is the use of ventilated facades and their advantages in terms of thermal, acoustic, and watertightness properties [6].

TCC technology can be applied to ventilated facades. In this case, the presence of an air cavity between the timber wall and the concrete slab is needed to separate the external (potentially humid) concrete slab and the internal insulated timber wall, which must always be dry to prevent material degradation.

A comprehensive evaluation of the thermal performance of ventilated facades remains a key focus in current research. These systems interact in complex ways with the external environment, necessitating experimental investigations and CFD analyses to model the airflow within the cavity [7]. Over the past two decades, numerous studies explored the thermal behaviour of ventilated facades through experimental and numerical approaches [7-8]. Typically, these studies involve experimental monitoring, followed by analytical or CFD-based assessments. However, only a limited number of these CFD studies validate their findings against experimental data. Experimental monitoring, barring unexpected sensor errors, tends to yield reliable results, but these are closely tied to specific case studies [9]. On one hand, analytical methods have a long-established history and are known for their reliability, as evidenced by numerous studies. These methods involve simplified processes grounded in physical correlations, whose validity has been repeatedly confirmed over time [10]. On the other hand, CFD simulations provide a higher degree of detail, but are relatively new and less extensively validated, leading to greater uncertainties and the need for experimental validation [4]. One of the primary challenges in applying CFD techniques within the building physics domain is the significant computational power required [11]. This limitation has historically confined CFD studies to steady-state analyses or very short dynamic periods [12-14]. Despite these challenges, CFD's ability to deliver highly precise information about flow fields makes it a valuable tool for evaluating the impact of design details in ventilated facades. For instance, research has examined airflow around venetian blinds [15], facade openings [16], and various shading systems [17].

The integration of experimental analysis and CFD modelling is widely regarded as the most comprehensive and accurate approach to evaluating the thermal behaviour of ventilated facades [9]. This combination was considered for the current investigation of ventilated facades with external massive cladding. Specifically, a TCC envelope was examined, a topic with limited prior research [4, 18], and for which no rigorous CFD modelling studies have been identified.

The objective of the research was to develop a solver-efficient CFD model for analysing the thermal performance of ventilated façades. Specifically, the first sub-goal was to implement the model and a novel solver algorithm to speed up the simulation process compared to conventional solvers. The second sub-goal was the model calibration and validation against experimental results, which were previously collected during the façade monitoring over one entire year [19].

The innovative aspect of the research is the implementation of a fast and accurate CFD model for the thermal performance prediction and optimization of ventilated facades with massive cladding, which can be used for new or refurbished buildings.

2. METHODS

For the development of the CFD model, the prefabricated TCC ventilated façade system in Figure 1. was considered. It is composed of an internal timber frame structure coupled with an external 50 mm thick reinforced concrete slab, separated by independent vertical ventilated air cavities. The concrete slab has sealed

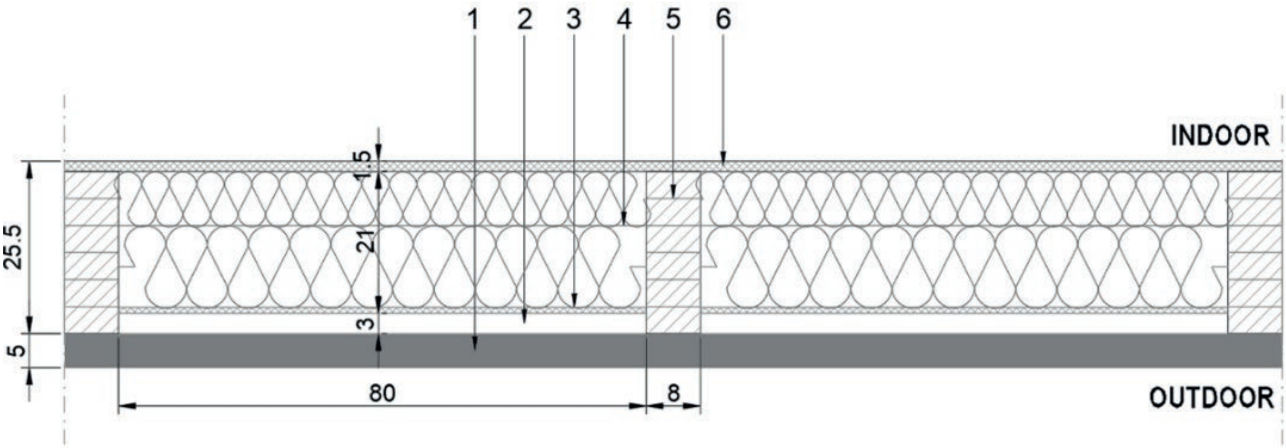

Figure 1. Horizontal section of the TCC façade studied (units in cm). The layers are: (1) reinforced concrete slab, (2) ventilated air cavity, (3) OSB panel, (4) rockwool insulation (100 kg/m3), (5) timber-frame structure, and (6) OSB panel. © Pastori S.

joints, which means that each air cavity is connected to the external environment only at the bottom and top of the façade. The height of the air cavity depends on the building elevation and the presence of windows and/or protruding slabs.

The thermal behaviour of the TCC façade was preliminary monitored experimentally, to collect all the data needed for calibrating the numerical model. For this purpose, a 3-storey building with a TCC ventilated envelope was built and monitored for over a year in the north of Italy. In this case, the ventilated façade's height is equal to two storeys of the building (the ground floor has a different envelope system), which is the minimum height that allows gaining some benefits from the natural ventilation inside the cavity of the façade, according to the literature. The monitoring started in August 2022 and ended in August 2023 [19]. The collected data were then used to set, calibrate and validate the CFD model, which was developed using the open-source software OpenFOAM [20]. All simulations were run on a computer with Dual XEON 6x CPUs and 48 GB of RAM.

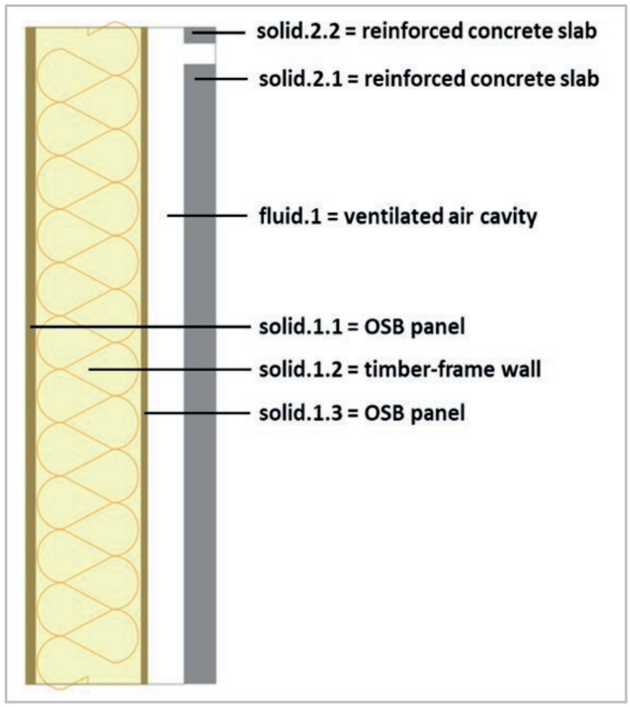

Figure 2. Two-dimensional CFD model developed with indication of the solid and fluid regions. © Pastori S.

2.1 Geometry of the model

A two-dimensional analysis was performed to keep the model as simple as possible. This choice was compatible with the envelope configuration, since the air flows through many vertical independent façade cavities characterized by limited width (800 mm), hence horizontal air flow is negligible. For this reason, a 2D model that neglects the third spatial dimension was considered adequate for the study purpose. The model geometry developed is shown in Figure 2.

2.2 Physical properties of the model

The thermo-physical properties assigned to each material (i.e. each region) in the CFD model are reported in Table 1. The materials' characteristics were taken from the technical datasheets of the products used for the envelope.

Table 1. Physical properties of the regions of the CFD model.

Solid regions					
Region	Density (kg/m³)	Thermal conductivity (W/mK)	Specific heat at constant pressure (J/kgK)	Emissivity	Absorptivity
Solid.1.1 – Internal OSB panel	550	0.100	1600	0.8	0.8
Solid.1.2 – Timber-frame insulated wall	100	0.035	1030	0.8	0.8
Solid.1.3 = External OSB panel	600	0.100	1600	0.8	0.8
Solid.2.1/.2.2 = Concrete slab	2400	2.00	1000	0.5	0.5

Fluid region						
Region	Density (kg/m³)	Thermal conductivity (W/mK)	Specific heat at constant pressure (J/kgK)	Dynamic viscosity (Pa·s)	Molar mass (kg/kmol)	Prandtl number
Air (properties at 30°C)	Variable, function of temperature (incompressible ideal gas)	0.02588	1007	$1.872\ 10^{-5}$	28.966	0.728

2.3 Boundary conditions

The boundary conditions applied to the model are shown in Figure 3. The trends of the variables T_air,i (indoor air temperature), T_air,e (outdoor air temperature), qr_incident (incident solar irradiation on the façade), and V_air,e (air velocity at the bottom inlet of the cavity) were taken from the experimental monitoring. The values of hi (convective-radiative coefficient of indoor environment), he (convective-radiative coefficient of outdoor environment), Rse (surface resistance of outdoor environment) were taken from the Standard ISO 6946 [21]; the values of T_outlet (air temperature at the top outlet of the cavity), P_outlet (air pressure at the top outlet of the cavity), V_outlet (air velocity at the top outlet of the cavity) are calculated by the software during the simulation.

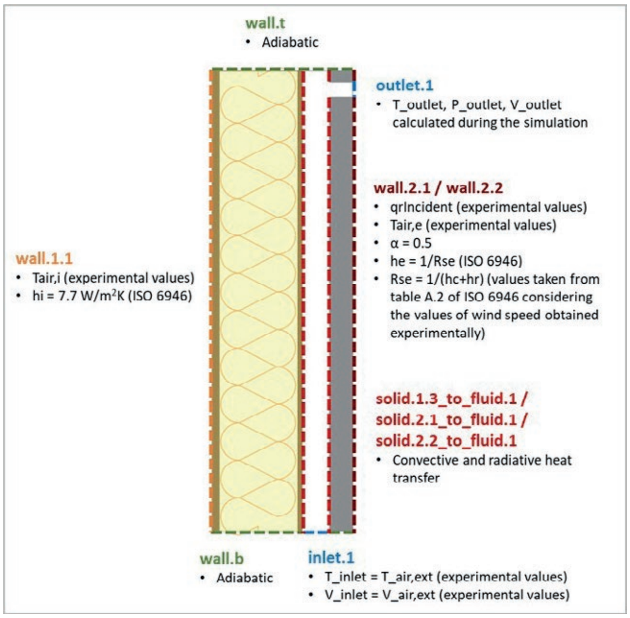

Figure 3. Main boundary conditions applied to the CFD model. © Pastori S.

2.4 Mesh

A mesh refinement study was developed to identify the best model discretization in terms of accuracy of the results and computational cost/time. Three meshes were tested by setting a simple simulation case, and the accuracy of the results obtained from the simulations was compared.

The meshes tested were:

- m0001_baseMesh
- m0002_baseMeshx1.5
- m0003_baseMeshx1.5x1.5

The number of cells for each mesh is equal to the number of the previous one multiplied by 1.5 in both vertical and horizontal directions. As expected, the results obtained show that the grid refinement produces slightly better accuracy, but with higher computational time. In this specific case, the mesh refinement does not produce consistent differences in the results, while the time needed for the computation increases considerably (see Table 2). For this reason, the coarser mesh (m0001) was chosen and used for all the simulations (Figure 4).

The first simulation (t0001) was run for 96 hours (4 days) to evaluate the amount of time needed by the model to catch the correct temperature trends. According to the results, 48 hours were enough for that, thus the second case (t0002) was run for 48 hours. The third simulation (t0003) was stopped just after 24 hours due to the huge computational time required to end the analysis.

2.5 The new "frozen-unfrozen flow" solver

At first, the conventional solver "chtMultiRegionFoam" was used. This solver allows for coupling a transient fluid flow with heat transfer between regions, buoyancy effects, turbulence, and radiation. It follows a segregated solution strategy, which means that the equations for each variable characterizing the system are solved sequentially and the solution of the preceding equations is inserted into the subsequent equation. The coupling between fluid and solid regions follows the same strategy: first, the equations for the fluid are solved using the temperature of the solid of the preceding iteration to define the boundary conditions for the temperature in the fluid. After that, the equation for the solid is solved using the temperature of the fluid of the preceding iteration to define the boundary condition for the solid temperature. This iterative procedure is executed until convergence is achieved. For each fluid region, the compressible Navier-Stokes equations are solved; for the solid regions, only the energy equation has to be solved. The regions are coupled by a thermal boundary condition.

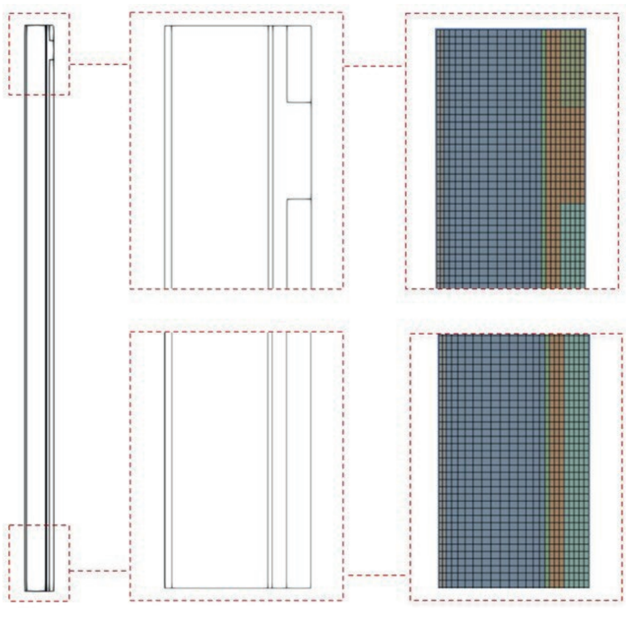

Figure 4. CFD model geometry and mesh. © Pastori S.

Starting from that, a novel solver algorithm called the "frozen-unfrozen flow" was developed to speed up the simulations, by switching the solution mode to "frozen" (i.e. no update of the velocity and pressure fields, allowing large time steps) and "unfrozen" (i.e. solution of all transport equations, with normal time steps) sequentially. The normal time step in the "unfrozen" mode is determined by the Courant number and the solid diffusion numbers, while the time stepping in the "frozen" mode is set based on user input. Figure 5. shows the schematic view of this algorithm: it starts with the initial time ($\tau_{initial}$)and several cycles with unfrozen (red zones) and frozen (blue zones) mode are repeated till the end of the simulation. For stability reasons, a transition mode (grey zones) is considered when the flow mode is switched between "frozen" and "unfrozen".

2.6 Testing of the new solver

New cases were created to test the new solver performance, varying the length of frozen and unfrozen periods of time, respectively τ_{frozen} and τ_{unfrozen}, in a systematic way to explore the effect of these numerical parameters on the accuracy of the results (i.e. the temperature values obtained in the model) and the time needed for the computation. The new cases were compared to a baseline case, t0001, identical to the new ones but run with the old solver. Table 3 resumes the results obtained from the new cases. All the simulations were run for 24 hours real time.

As expected, the simulation speed increased by increasing the ratio τ_{frozen} /τ_{unfrozen}, while the accuracy did not appear to be inversely proportional to the speed.

Table 2. Mesh refinement study.

Mesh refinement					
Simulation	Mesh	Solver	Time simulated	Time needed for running simulation	Temperatures that differ more than 0.2K from t0001
t0001	m0001 (7152 cells)	chtMultiRegionFoam	96h (345000 s)	67.5h	/
t0002	m0002 (14850 cells)	chtMultiRegionFoam	48h (172800 s)	100h (+196% t0001)	1.4%
t0003	m0003 (33075 cells)	chtMultiRegionFoam	24h (86400 s)	314h (+1761% t0001)	5.7%

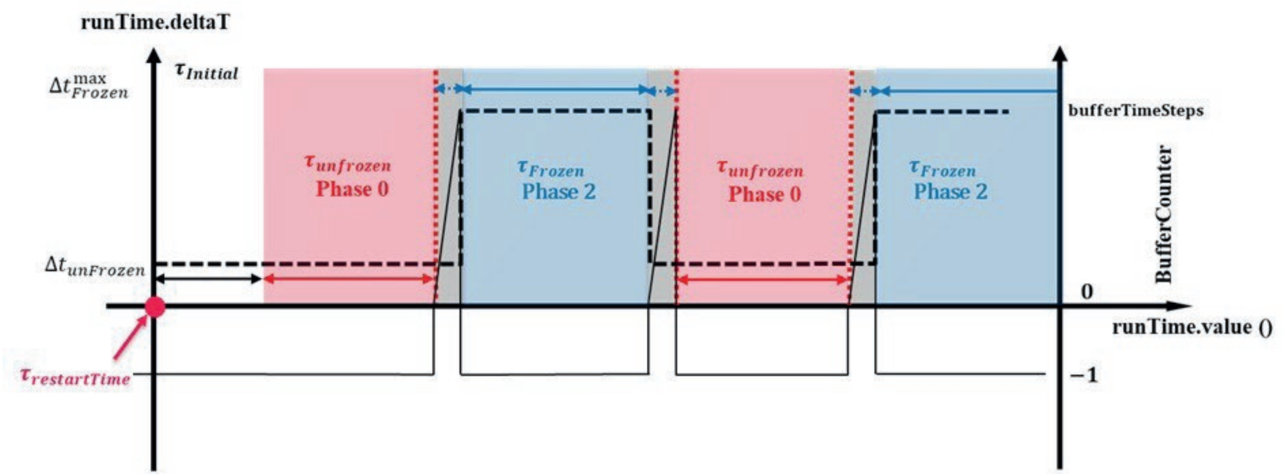

Figure 5. Schematic view of the new "frozen-unfrozen flow" solver algorithm. © Pastori S.

2.7 CFD model calibration

The calibration process was developed by comparing the results obtained from the CFD model with the experimental data collected. It consisted of changing the physical and numerical parameters used in the modelling until the CFD results were aligned with the experimental ones.

For this process, the experimental data collected during summer days with clear sky (from the 23rd to the 27th of August 2022) for the south-oriented building façade were considered. The solver chtMultiRegionFoam was used for the calibration process, since the "frozen-unfrozen flow" solver was still under development.

2.8 CFD model validation

After calibrating the CFD model against experimental results obtained during summer days with a clear sky, the model was tested again considering different weather conditions. This process serves as model validation and is necessary to see whether the developed model also works under different boundary conditions. In this case, the experimental data collected during summer days with an overcast sky (registered from the 17th to the 21st of August 2022) were considered. The façade considered was again the south elevation of the building. For the present research objective, the validation process to test the model accuracy was performed considering only one new case. A more in-depth study should involve a greater number of cases for model validation, testing the calibrated model by changing several parameters (e.g. cavity depth, different weather conditions, etc.).

3. RESULTS

In this chapter, the results obtained by running the CFD model developed are presented and discussed. Fig-

Table 3. Cases run for testing the new solver and finding the optimal settings considering the trade-off between speed and result accuracy.

Case	tauFrozen/ tauUnfrozen	Simulation speedup compared to t0001	Max temperature difference (°C) from t0001	% of values that differ more than 0.2°C from t0001	% of values that differ more than 0.5°C from t0001	% of values that differ more than 1°C from t0001
t0011	5s/5s = 1	x 1.8	-2.61 (outlet.1)	12.9%	7.6%	3.9%
t0012	10s/5s = 2	x 2.7	3.61 (outlet.1)	15.5%	8.0%	4.1%
t0013	15s/5s = 3	x 3.5	-2.87 (outlet.1)	16.6%	7.7%	4.3%
t0014	50s/5s = 10	x 9.4	3.20 (outlet.1)	12.4%	2.8%	1.0%
t0015	100s/5s = 20	x 16.5	2.66 (outlet.1)	12.6%	2.9%	1.3%
t0016	500s/5s = 100	x 45	3.43 (outlet.1)	20.8%	9.9%	4.5%

ure 6. shows the graphical comparison between the temperatures measured experimentally and those predicted by the calibrated CFD model. The calibrated model (t0116) was able to predict the façade thermal behaviour with a very limited error compared to the experimental values obtained. The error was calculated for each surface of the wall as the difference between the mean temperature measured experimentally on that surface and the one calculated on the same surface by using the CFD model. For the error calculation, only the last 24 hours of each simulation were considered to exclude inaccurate values due to the initialization process at the beginning of each CFD case. The error obtained between experiment and CFD is: 0.19°C for TR, 1.3°C for TO, 0.8°C for TC and 0.9°C for TC_ext. Thus, the mean error between the values measured experimentally and those obtained from the CFD model is 0.8°C.

3.1 Validated model

The calibrated model (t0116) was then tested considering different boundary conditions, in order to evaluate the accuracy of the prediction, also for a different case. For this reason, a new case (t0216) was set up by changing the weather conditions to summer days with an overcast sky. Figure 7 shows the comparison between the CFD results and the experimental data. In this case, the error obtained between experiment and CFD is: 0.22°C for TR, 0.8°C for TO, 0.6°C for TC and 0.6°C for TC_ext. Thus, the mean error between the values measured experimentally and those obtained from the CFD model is 0.6°C, slightly lower than the previous case.

3.2 Prediction of the thermal behaviour

After the CFD model validation, some of the input parameters might be changed (e.g. façade geometry, materials, weather conditions, etc.) to understand their influence on the façade's thermal behaviour and study an optimised envelope configuration.

For example, the emissivity of the OSB panel facing the ventilated cavity was changed, and the results were analysed. The objective was to evaluate and quantify the effect of an increased reflectivity of the inner surface of the ventilated cavity – that can be obtained by painting the OSB panel with a reflective paint or by placing a reflective foil on it – on the envelope's thermal behaviour, considering summer days with a clear sky.

The comparison between the calibrated model (t0116) and the new case with increased reflectivity (t0316) is shown in Figure 8. What can be noticed is that an increase from 0.2 to 0.8 in the reflectivity value can produce a 3°C reduction of TO maximum peaks and a 1°C increase of the lowest peaks. The results show a change in the heat flux entering the building from 10 W/m^2 to -10 W/m^2 over the day.

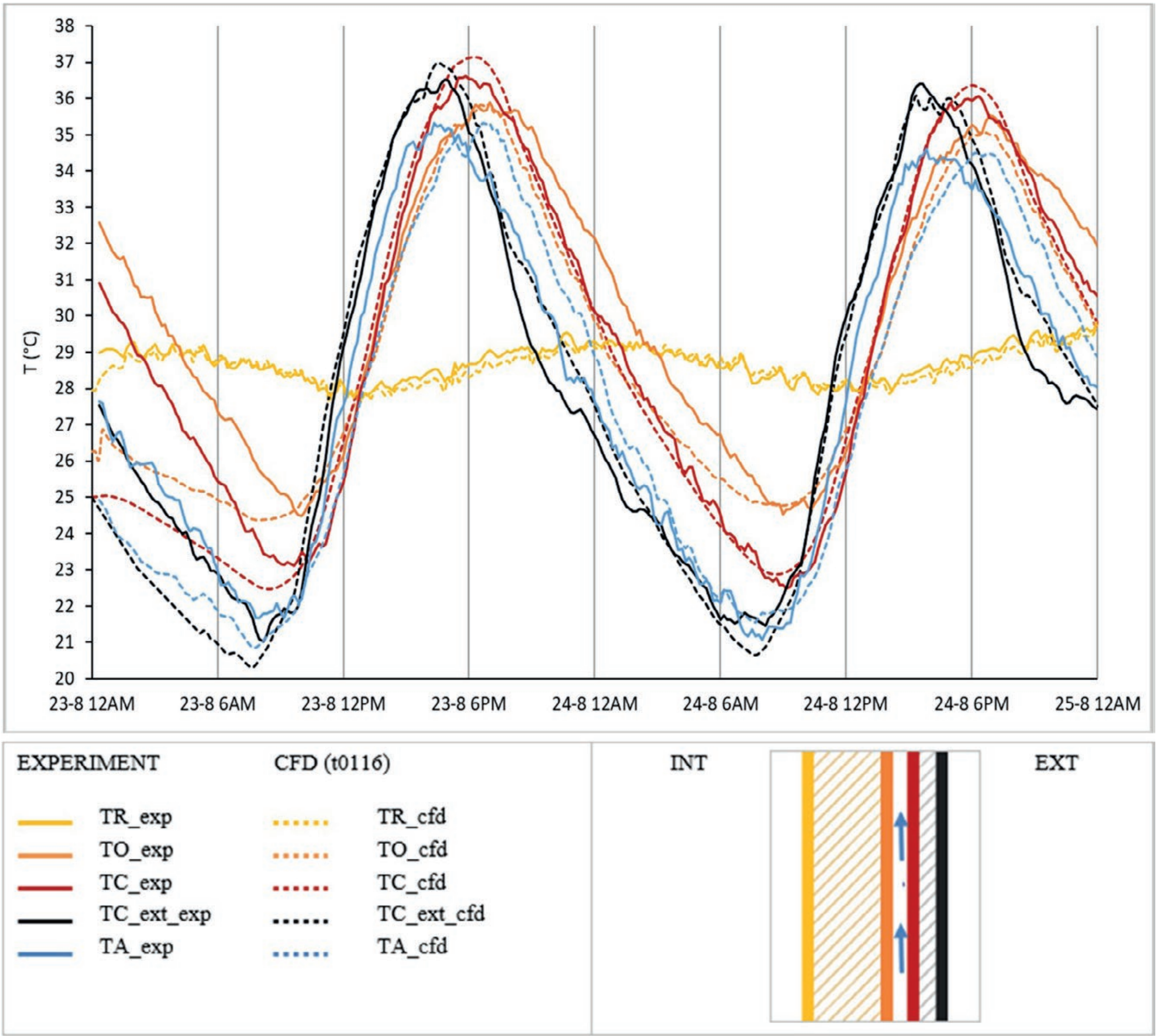

Figure 6. Comparison between the temperatures from the experimental monitoring and those given by the CFD model, considering a façade facing south and summer days with clear sky. © Pastori S.

4. CONCLUSIONS

The research presented focuses on the development of a solver-efficient multi-region 2D CFD model for the thermal analysis and optimisation of ventilated façades with external massive cladding. The CFD model was calibrated and validated against the data collected during the experimental monitoring of the timber-concrete composite ventilated façade of a new building located in the north of Italy (described in [19]). Several CFD models for the thermal analysis of ventilated façades were found in the literature, however they were all tested to study ventilated façades with thin external cladding. In contrast, the current research focused on the development of a CFD model for ventilated façades with external massive cladding.

The model was set by using the open-source software OpenFOAM [20] to make it accessible to everyone. Also, it was developed in two dimensions to be as simple as possible and it was enhanced in terms of computational effort: a mesh refinement study was performed to select the optimal discretization. Finally, a new "frozen-unfrozen flow" solver was implemented to allow faster simulations while still maintaining good accuracy of the results. In case the

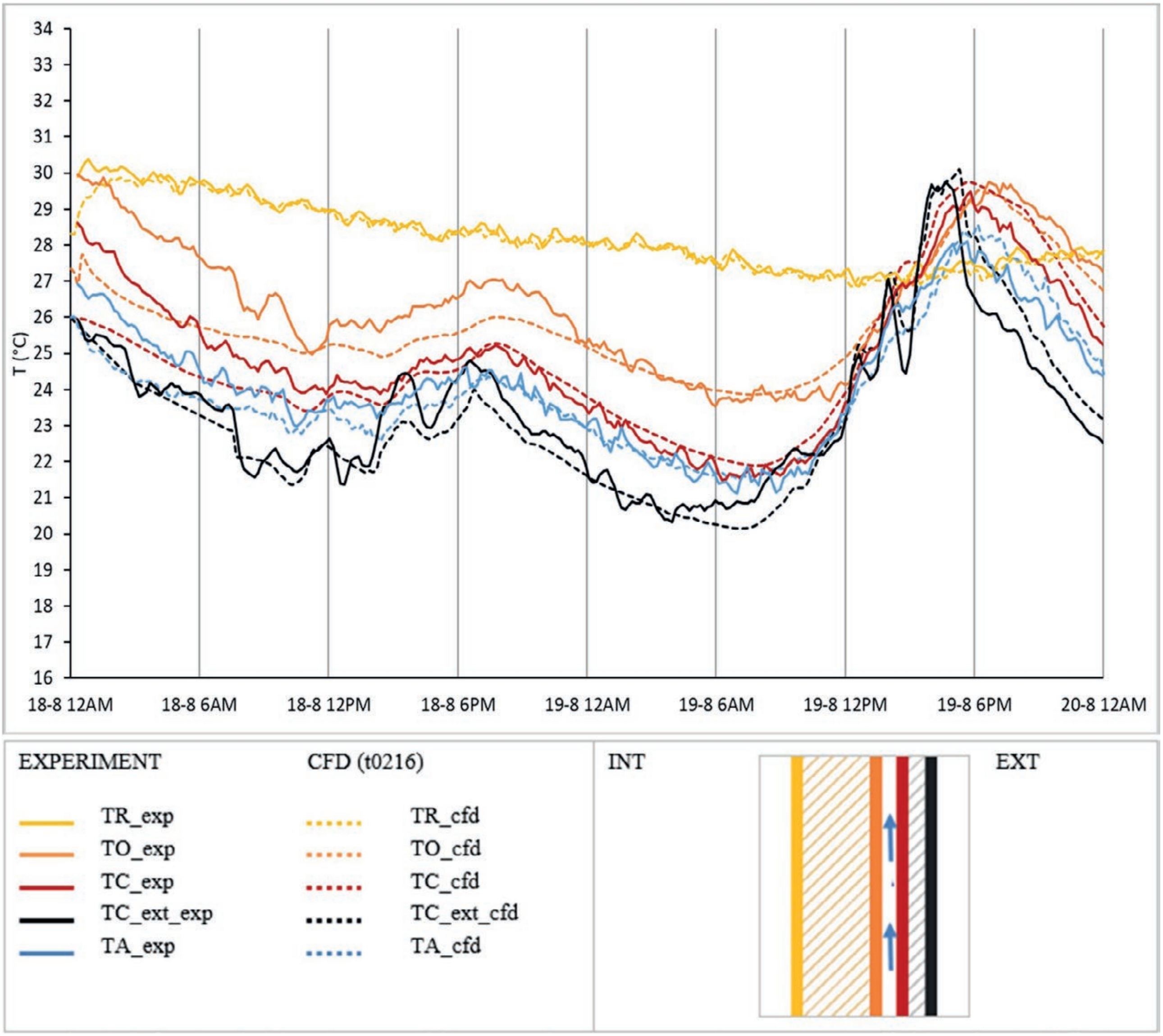

Figure 7. Comparison between the temperatures from the experimental monitoring and those given by the CFD model, considering a façade facing south and summer days with overcast sky. © Pastori S.

"frozen–unfrozen flow" solver is used, the simulations are much faster than using the original solver: considering simulations for 24 h real-time, the new solver can increase the speed of the simulation up to 45 times, keeping an acceptable margin of error in the results. This significant acceleration is impressive when considering the relatively simple modification of the algorithm.

The calibrated CFD model obtained can be used to assess the thermal performance of TCC ventilated façades in different configurations (e.g., a different air cavity depth, concrete slab thickness, colour and material of the surfaces, orientation, ventilation type, etc.), allowing the optimization of the building envelope solutions, partially avoiding the expensive and time-consuming construction of mock-ups. Accurate research in this respect might be interesting for system manufacturers, in order to further develop their products to comply with the different project requirements, and for designers, to better choose and specify the systems to be used. Certainly, experiments for validation remain key for benchmarking a CFD model prediction. However, the new opportunities offered by calibrated CFD models for façades more than balance the efforts needed to create them from our perspective.

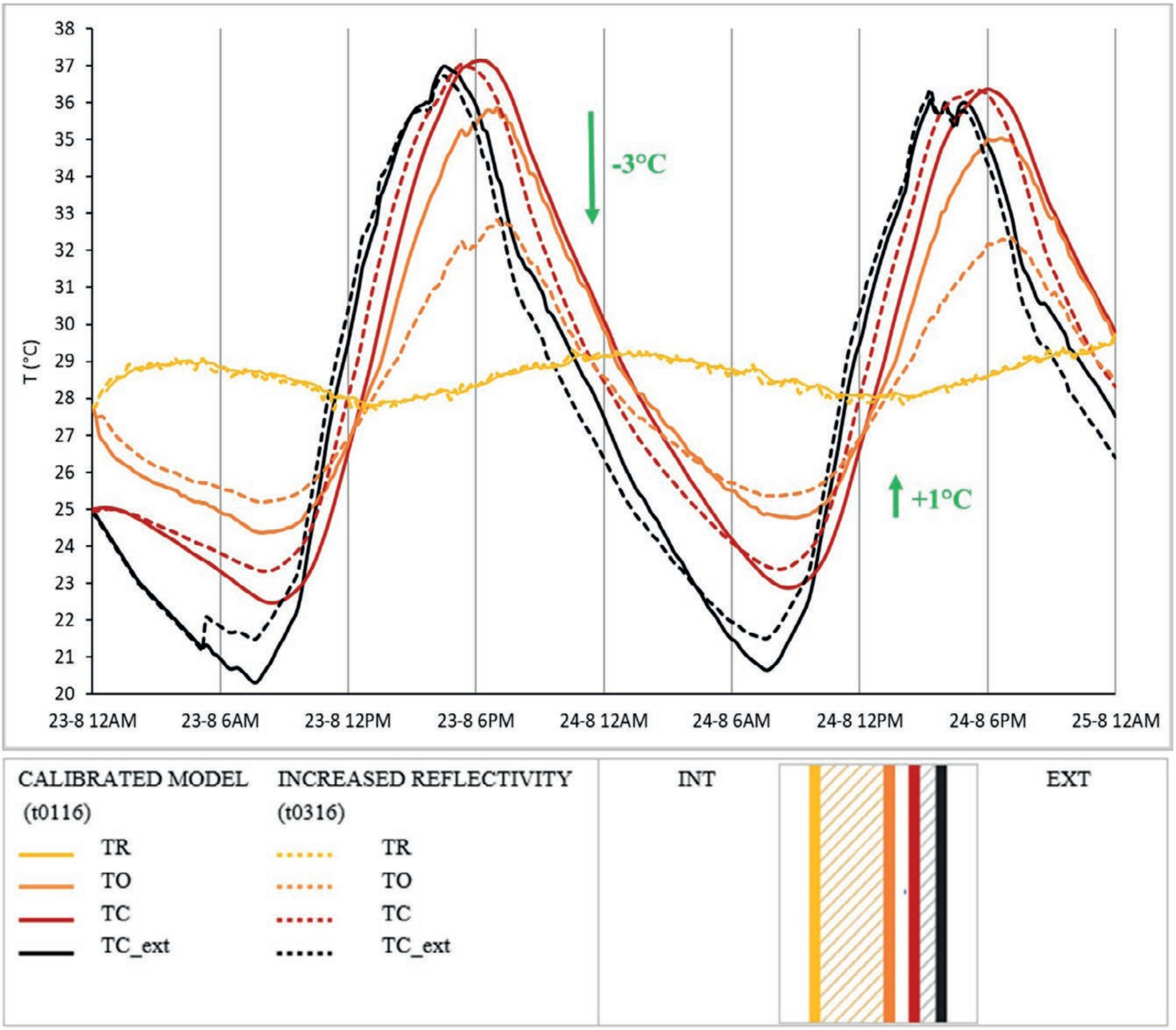

Figure 8. Comparison between the temperatures predicted by case t0116 (calibrated CFD model) and t0316 (case with increased reflectivity of the OSB panel into the ventilated cavity). © Pastori S.

Additionally, the study represents an important step towards digital twins for TCC ventilated façades, since the calibrated CFD model can make predictions faster than real-time [22]. For example, the model might be used together with advanced control strategies to minimize a building's energy consumption. A 1:1 digital twin of the façade is required, which might necessitate the digitalization of existing buildings. Future work might address these limitations, e.g., through a refined validation study or a sensitivity analysis with respect to the assumed boundary conditions to mitigate these limitations.

At a broader level, the research aims to contribute to the knowledge regarding the thermal performance of ventilated façades composed of an internal lightweight wall structure and an external massive cladding.

5. AUTHORS CONTRIBUTIONS

Conceptualization, P.S.; Methodology, P.S.; Software, P.S.; Validation, P.S.; Formal Analysis, P.S.; Investigation, P.S.; Data Curation, P.S.; Writing – Original Draft Preparation, P.S.; Writing – Review & Editing, P.S. and S.G.; Visualization, P.S. and S.G.; Supervision, M.E.S. and L.A.; Project Administration, M.E.S. and L.A.

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Sustainable Strategies for Knowledge of Built Heritage: Graphic Methods for Vaulted and Arched Masonry Structures

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Abstract. Traditional materials and construction techniques are of central importance for knowledge and, subsequently, the protection of existing building heritage, including historical and monumental sites. The evaluation of the static consistency of existing structures can be carried out in a coherent and accurate manner only by starting from an in-depth knowledge of the geometric, physical and mechanical characteristics of the building's structural elements. In recent years, we have witnessed an exponential increase in the use of advanced technologies for graphic representation and subsequent structural analysis, especially in the study of existing buildings. For a real and concrete application of the results, these representations must be critical and functional for understanding the building rather than merely serving as graphic virtuosity. In this framework, the graphic methodologies to be applied, in support of digital data, in simplified procedures for a preliminary knowledge of the buildings, their technological configuration and static behaviors have been studied in depth. It is important to point out that the historic built heritage, unlike the modern built heritage, is characterized by the strong presence of vaulted and arched elements, with columns and piers of various shapes and materials; for this reason, models and procedures of graphic analysis based on the limit analysis and the theories of Jacques Heyman have been applied. The method is first applied and verified on a single historical monumental building to test its limits and potential and then applied to other case studies. The results show that the graphical and analytical analysis of structures is a valid and reliable tool for analyzing buildings in order to understand their structural behavior, since, even if the model is simplified, it is possible to obtain results that are strongly correlated with the behaviors of the structures and can guarantee good accuracy and adequate safety margins.

Keywords: Built heritage, Structural analysis, Graphic method, Morocco, Construction techniques.

1. INTRODUCTION

The culture of the valorization and preservation of Cultural Heritage, or in general of building recovery, has always recognized the "built environment" as the bearer of a quantity of Values that are defined but changeable according to the historical epoch with respect to this, it is necessary to define decisions on the possibilities of intervention in order to respond to the continuous and constant need for maintenance and also transformation of this heritage [1]. In recovery, reuse and refurbishing projects, the impact of modernity can also take on destructive aspects. There are several studies from which the need to address recovery emerges, refunctionalisation and infrastructural integration, through an understanding of the urban environment and the opportunity to define a cultural guideline, a sort of code of behavior that allows for the re-inhabitation of this architectural heritage. Bringing the structures back to life in accordance with the requirements of modern living, without altering their consolidated characteristics over time, with interventions correlated to the original constructive, typological, functional and technological characteristics, is indispensable, but at the same time, particular attention must be paid to the integration and sustainability of the new interventions [2]. In this cultural context, the analysis of existing structures, in particular historical and monumental buildings, in general implies confrontation with masonry constructions, made of a material in which a resistant structure is often not clearly recognizable. This depends on the building's geometry, the distribution of stiffnesses and masses within it, the temporal succession of construction works and subsequent modifications, the acting loads, and sometimes the presence of structural cracks and material damage, which may be more or less evident [3]. In these fields, the study and numerical modeling of the structure, also of the FEM. type, cannot be separated from analysis tools that allow us to describe it through a first decomposition and subsequent independent schematization of single parts of the construction (arches, vaults, piers, walls, etc.), otherwise the instrument of critical control of the results would be missing. The analysis of the static condition of existing structures and historic and monumental buildings can therefore only be conducted consistently and correctly based on a thorough knowledge of the geometric, physical and mechanical characteristics of the building's structural elements [4]. The latter consists of building materials and techniques that vary considerably in relation to both the geographical area and the era of construction, as well as the various historical stratifications. Consider also the difficulty in representing and managing the large and complex knowledge related to the non-geometrical aspects of the historical heritage with the problems related to meeting the requirements of semantic representation of the built heritage [5]. For this reason, they must be evaluated on a case-by-case basis with a careful examination of the building in its entirety through geometric measurements, surveys, and non-destructive testing [6]. Researching, investigating and discovering what the orders and rules of good building are, is a subject that has been addressed in the debate of the scientific community, but it proves to be more topical than ever if we consider, in Italy alone, the wide diffusion and peculiarity of building techniques, autochthonous materials, specificity of workers, unique to urban contexts that are never standardized, such as historic centers. In such diversity, difficult to standardize, the meaning of intervening "according to the rules of the art" acquires the meaning of "doing with care and precision", following dimensional, constructive and formal language rules dictated in some cases also by a component of indeterminacy, the result exclusively of man's need for survival [7]. Within this debate, therefore, an attempt is made to establish the definition of a "methodological strategy" that can connect the recovery intervention essentially aimed at the reinterpretation of pre-existing structures, with a reading of historical forms and materials. The pivot around which the entire discussion revolves is the definition of a method for transferring knowledge from the past to meet the demands of the present, while considering future demands and needs. A suitable methodological approach, therefore, is the key to ensuring the processual continuity of the built heritage. This approach allows us to interpret and read the existing building heritage in the light of contemporary needs; millennial history must confront the demands of the current lifestyle. It is therefore important to continue to implement and develop different methodological approaches that propose, in addition to preserving the image of pure matter, innovative formal and technological solutions starting from the basics of static knowledge of masonry constructions, tackling, in a simple and innovative way, the study of the behaviour of both the most important monuments and the most common works, in a unitary vision that crosses engineering and architecture [8]. In this perspective, knowledge of the artifact as an object of analysis must be obtained by exploiting all the most modern and advanced technologies, such as the use of drones, 3D laser scanners, etc., aimed at the most complete and comprehensive graphic rendering possible. However, at the same time, such representations must be both critical and functional to the understanding of the artifact, rather than merely a display of graphic virtuosity. From another perspective, the widespread use of finite element models, facilitated by the characteristics of increasingly prevalent IT tools, requires particular attention and care. The modeling of existing buildings, and of those in masonry with historical and monumental interest, is indeed very complex, especially in relation to the possible schematizations for the realization of the model and the choice of the mechanical characteristics of the materials. Based on geometric and dimensional measurements, even if carried out with high accuracy, it is of fundamental importance to thoroughly investigate the building and increase its knowledge, both in order to create a mathematical model congruent to the behavior of the structures, to correctly interpret it, and to verify the results. For each structural element, the geometry and nature of the materials must be known, because only this can allow obtaining a first configuration that is essential for a full understanding of the overall static functioning of the building. This process of first approach, so indispensable for the real and complete knowledge of the artifact, is effectively realized through analysis using graphic methods, based on the limit analysis and the theories of Jacques Heyman [9-10]. As further study, if necessary, through subsequent steps, it is then possible to arrive at the finite element (FEM) modeling of both the individual elements and the whole structure, in a critical way, ensuring a check of the input and output data, to reduce the risk of incorrect interpretations of the results of the mathematical model. To test the potential and limits of the proposed graphic method, it was applied in advance to a case study that was well-suited to the purpose. A historical building in ordinary, regular and compact load-bearing masonry was analyzed, which presented typological, constructive and structural elements, typical of historical buildings such as arched structures, i.e. vaults and arches, piers, metal chains, etc. The chosen artifact also proved to be very suitable both for the applications of Heyman's theories and for detailed and meticulous FEM finite element modeling. The choice went to the "Logge di Banchi" in Pisa, Italy. The graphic method, once validated through the case study, was then applied as part of a broader, international, multidisciplinary research project to the monumental gate called "Bab Agnaou" of the historic walls of the city of Marrakech in Morocco.

2. METHODS

The proposed approach for understanding and analysis of masonry structures with vaults and arched structures consists of the following steps. Starting from the basis of global and local geometric measurements, the buildings must be studied in depth to increase their knowledge. For each structural element, the geometry, nature of the materials and the constructive technique must be studied. In particular, the constructional logic of vertical structures (walls and masonry fixtures), horizontal pusher structures (arches and vaults in masonry) and non-pushing (wooden roof slabs) must be studied. Based on these analyses, the first framework for understanding the overall static functioning is possible to obtain. Moreover, it is possible to identify the structural elements to be analyzed in detail successively. In this phase of knowledge about the building, the presence of structural damage and degradation phenomena could be investigated. The analysis of the structural elements is carried out using graphic methods based on limit analysis and on the theories of Jacques Heyman. To conduct the graphic analysis, the structure must be decomposed by identifying its significant modules. It's important to highlight that, in line with Heyman's hypothesis, the path of analysis of the structure proposed is based on a model with non-reactive tensile masonry. The masonry has a tensile strength that is not considered in this type of modeling. A simplification is therefore carried out, which, however, is in favor of safety. It is considered an ultimate limit state, but in reality, considerable resources of the structure given by the real tensile strength of the masonry are neglected. Moreover, more specifically regarding the analysis of masonry arches, it is useful to underline that, in addition to considering them free of tensile strength, we consider them as free in space. In reality, they are constrained in the vertical plane by the masonry, which prevents changes in shape and, therefore, the onset of instability phenomena, which are the main causes of the collapse of arched and vaulted structures. This allows the arch to have almost infinite compressive strength, limited only by the crushing resistance of the material, as seen in Heyman's hypothesis [11-13]. As far as the vaulted structures are concerned, even if in a minor way, they are limited in the shape change from the backward, which, if it is of good workmanship and of suitable materials, is very effective. Moreover, in the analysis of the vault, carried out in sectors, the contribution that each sector offers to the other and the global contribution that their union offers is neglected. From the above, it is clear that the results obtained from the previous analyzes are useful for understanding the behavior of the structural elements, operating strongly in favor of safety [14].

2.1 Analysis of structures from graphic-synthetic to FEM methods: case study "Logge di Banchi" in Pisa

The complex of the "Logge di Banchi" in Pisa (Figures 1-2) is placed at the center of the city, on the historical commercial axis where the palaces of political and administrative life are located. The current configuration of the "Logge di Banchi" is the result of the succession of various transformative interventions that occurred during the 400 years of the building's life. It consists of three main parts: (1) the ground floor consisting of the Lodges built in 1603, presumably based on a design by Bernardo Buontalenti, (2) the first floor partly made up of the original 17th-century first floor, which was later transformed and raised in 1865 by the architects Cervelli and Piccoli called "State Archives" and (3) the basement floor built in the early twentieth century and named "Albergo Diurno Cobianchi". The ground floor is preserved intact in the structures and architectural elements that characterize it; the plan is rectangular, measuring approximately 33 × 19 m, with a height of 22 m [15].

2.2 Analysis of structures with graphic-synthetic methods

Each internal module (Figure 3), enclosed between the four separately tested stone reinforcement arches,

Figure 1. "Logge di Banchi" in Pisa. Façade view and internal view of the loggia.

Figure 2. Technical Drawings of "Logge di Banchi". Front and back elevation - Cross and longitudinal section.

formed by a lunette barrel vault, has been divided into 6 equidistant parts with a width of about 45 cm. Due to this schematization, each lunette is divided into six sectors, and the barrel vaults are divided into 12. Also, for stone and masonry arches, a graphic and analytical analysis was carried out for the determination of the stress states. Piers constituting the lodges can be classified, according to their position and geometric structure in plan, into three main types: "L", "I", and "T". For each type of pier, the rays and the relative central ellipse of inertia and the central inertial core were determined through graphic and analytical methods. For each strip, the graphic analysis was carried out by obtaining a funicular polygon of forces such as to be as close as possible to the arch axis line and in any case contained within the arch. (Figure 4).

2.3 FEM analysis of partial and global models

Based on the analysis of the structures with synthetic graphical methods, then the creation of a model FEM of the same structures has been realized. The stress and deformation states of the elements have been investigated in relation to the hypotheses made, through various schematizations of load application, boundary constraints, and types of FEM elements used for modeling the different types of structural elements. The numeri-

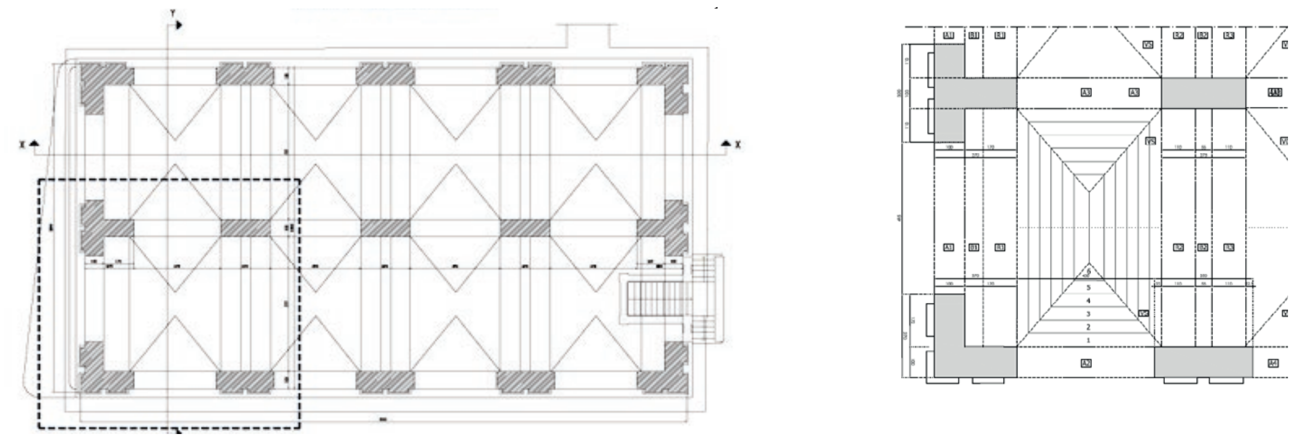


Figure 3. Plan of the "significant module".

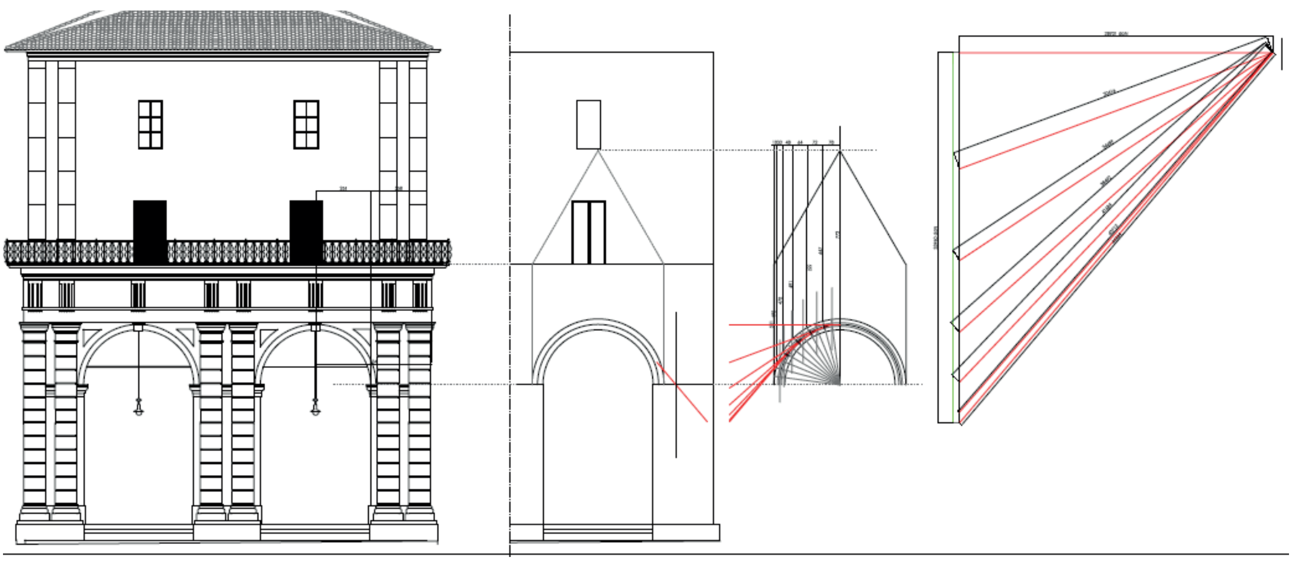


Figure 4. Search for the "A2" arch pressure line.

cal analysis of the structures was performed with the “Straus 7” [16]. The construction of the finite element model has been realized, without the aid of “auto mesh functions”, directly constructing every structural element (arches, vaults, springers, walls, etc.) based on geometric measurements, observations and considerations made in situ. In the model, only the above-ground structures were represented, leaving out the foundation structures but schematizing their constraints (Figure 5).

2.4 Case study “Bab Agnaou in Marrakech” (Morocco)

The simplified graphic method, studied, analyzed and validated with FEM analysis in the case study of the “Logge di Banchi” in Pisa, has been applied, at an international level, to the Bab Agnaou, a monumental gate that is part of the historic walls of the ancient Medina of Marrakech (UNESCO site), Morocco. The study presented here is a synthesis of a much broader research carried out within the framework of an agreement between Department of Energy, Sys-tems, Land and Construction Engineering of the University of Pisa (D.E.S.T.eC) and École Nationale d’Architecture de Marrakech (ENAM) signed since 2018 to develop joint studies in the field of Architecture, Urban Space and Technological Development. Bab Agnaou (Figures 6-7) is one of the best-known monumental gates in Marrakech and its construction is attributed to the Almohad caliph Abu Yusuf Ya’qub al-Mansur and was completed around 1188 and 1190. The gate was the main public entrance to the Royal Kasbah (citadel) in the southern part of Medina. The function of the gate was primarily decorative, given its location already inside the city walls and was originally flanked by two bastion towers crowned with merlons [17-19].

The passage inside was a bent entrance passing through a large, vaulted vestibule. The flanking towers and the covered vestibule, however, have since disappeared, and the archway of the gate has been partly filled in with a smaller and simpler brick arch. Since its construction in the 12th century, the gate seems to have undergone fairly frequent restorations (Figure 8), three of which are archived: a) the restoration of the eighteenth century, during the reign of Sultan Sidi Mohammed Ben Abdellah (1757-1790) in which the arch of the gate opening was reduced in width and height; b) the restoration in 1930 during the French protectorate; c) the restoration in 1960 which only proofs left are photos and testimonies of former craftsmen [18].

Bab Agnaou, with its sumptuous stone decoration, consists of 4 successive semicircular arches, which appear to be superimposed on each other (Figure 9). It is also very common in mosques to have a purely oriental arch in which the two semi-arches extend downwards below the plane of the centres. The analysis procedure proposed for the case study of the “Logge di Banchi” in Pisa was also applied to the arch in question. The load-bearing brick arch was analysed in detail, assuming it, for the sake of safety, as a support for the structures above. Operationally, for the graphic analysis, the arch was schematised as a round arch, (radius 1500 mm) and subsequently divided into 30 ashlars, with 5 mm joints (Figure 10).

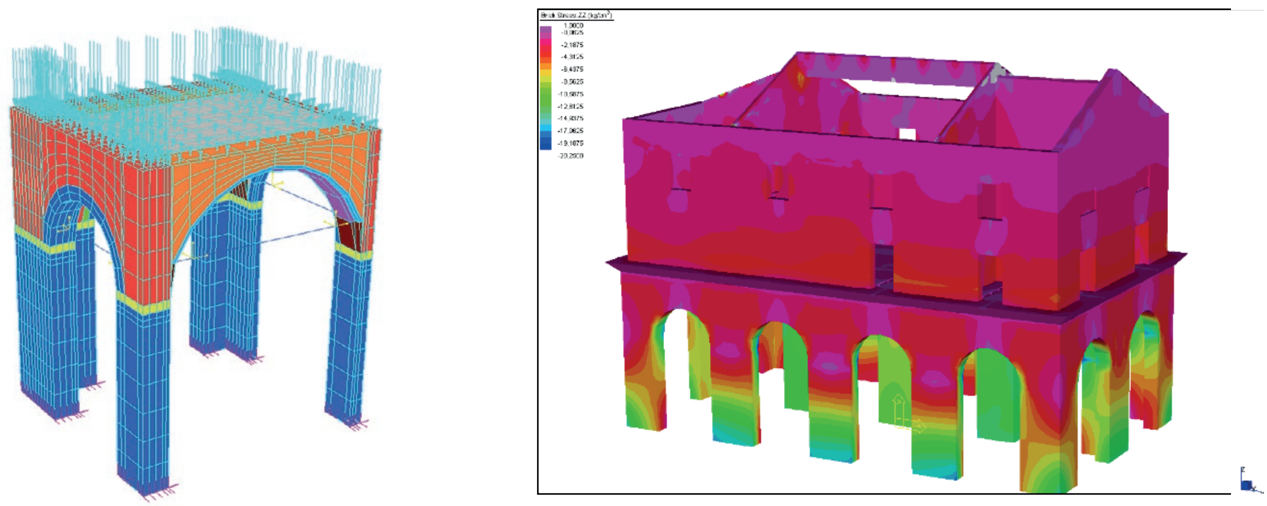


Figure 5. Exemplary representation of the FEM model of the “local significant module” (axonometric view of structural elements, loads and nodes) and “global model” (axonometric view of the structural analysis results - ZZ stresses).

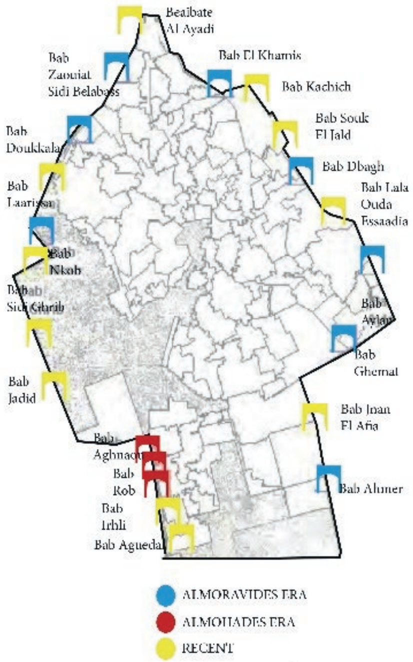


Figure 6. Location of Bab Agnaou and historical periods of the gates on the left, and other places of interest on the right.

3. RESULTS

The results obtained in the research can be divided into two parts, one for each of the two case studies analyzed. In detail, we can make a first, more theoretical and in-depth consideration on the Pisa case regarding the proposed simplified method, and a second, more practical and expeditious one regarding the possible applicability in a more operational field. With reference to the case study of the "Logge di Banchi" in Pisa, it is possible to observe that, comparing both the qualitative and the numerical results obtained both with the graphical and analytical analyses and with the FEM analyses, we note good correspondence, even if with slight differences due to the schematizations carried out in both types of analysis. The main source of the differences in the results of the two types of analysis is the schematization of the constitutive bond of the masonry material; in graphical analysis, masonry is schematized as a non-resistant linear elastic material, and in the finite element analysis, the material is schematized as linear elastic but also endowed with tensile strength. These results represent the two extremes or the lower and upper limits within which will certainly be understood the real behavior of the masonry, of the structural elements, and of the global structure, being the masonry material endowed with one, even if minimal, tensile strength.

Analyzing these results in detail, however, some singularities can be fully justified based on the aforementioned premises; in particular, a difference in the stress state of the chains is observed, higher in the FEM analysis compared to the graphical analysis. This is presumably due to the different stiffness of the structures and the contributions taken into consideration, or better depends on the fact that in the graphic analysis the acting forces are determined by analyzing the vaulted structures by sectors, separated from each other, the separated arcs, the walls applied as separate loads and then added together but without taking into consideration the mechanical loads that are actually present between them. The FEM model also takes into account this interaction between structural elements and their portions, although considering the material as having tensile strength, and therefore slightly modifying the results. Moreover, the spandrel of the vaults is, in the first case, considered as a load on the structures, while in the second case, although equipped with different stiffnesses to limit the effects, it is an integral part of the structures and therefore considered both as a weight and a structure interacting with the vaults. In conclusion, we can consider the global model faithful to the expected behavior of the structure only if it is interpreted in light of the previous considerations.

Regarding the findings from the case study of Bab Agnaou in Morocco, however, we can say that the graph-

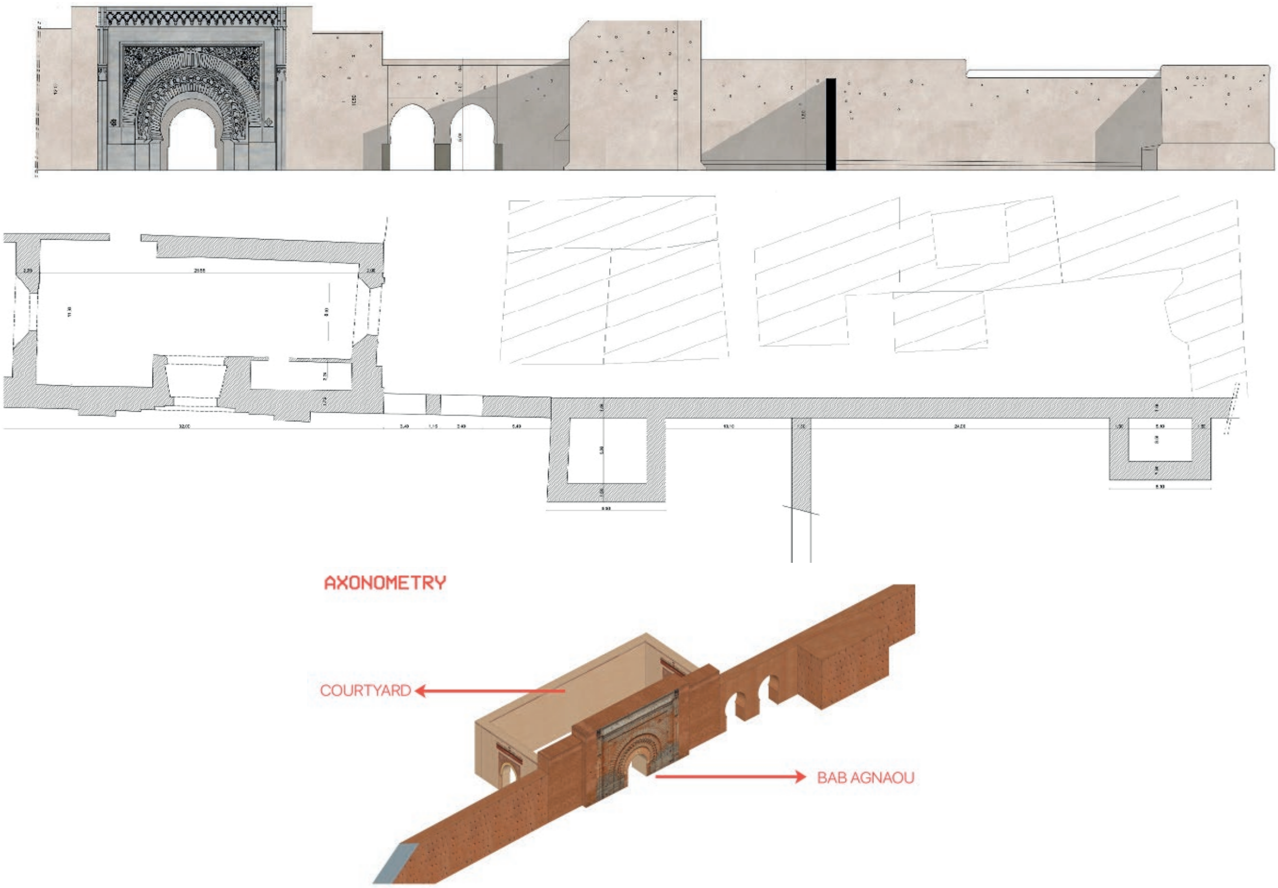
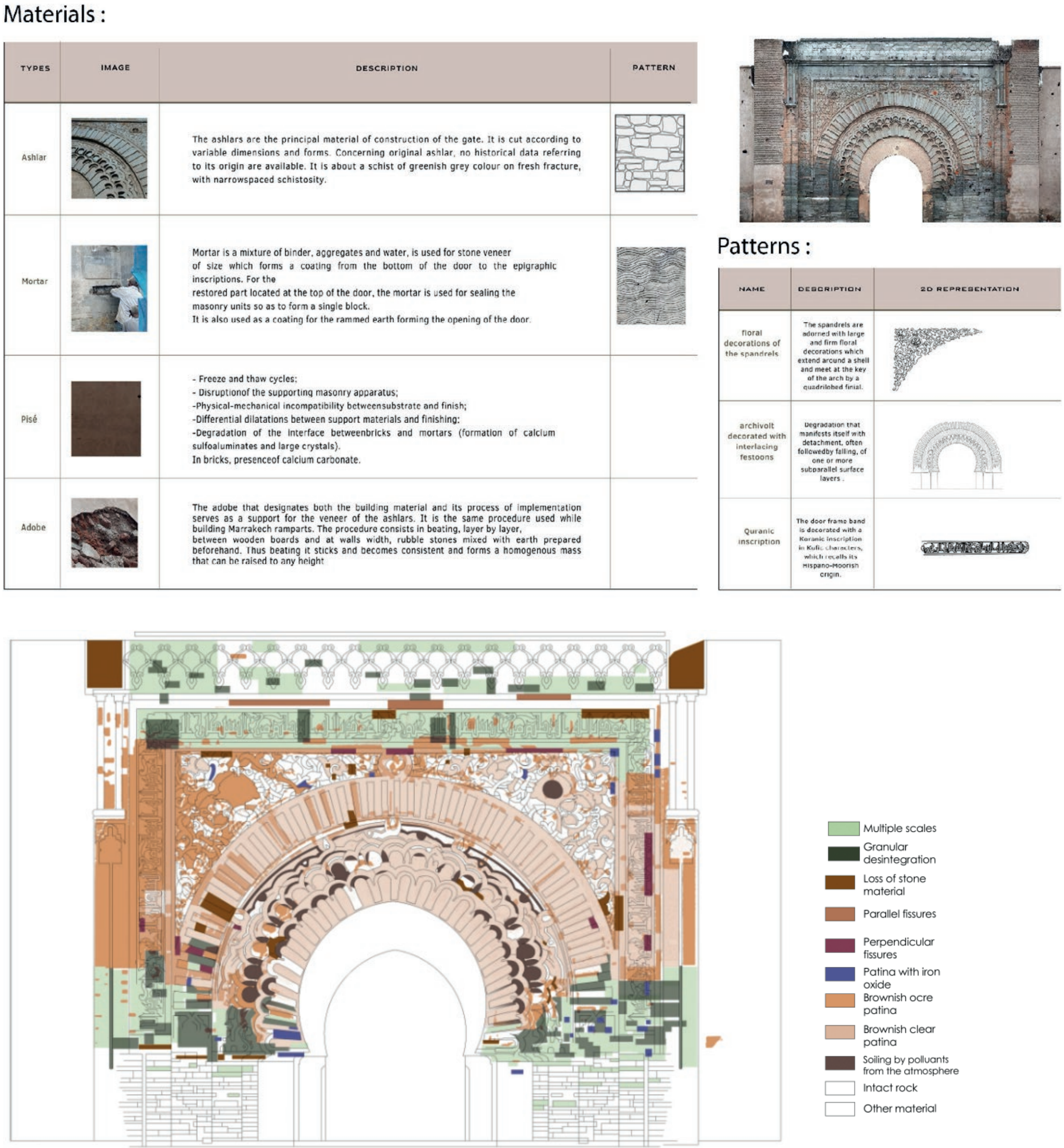


Figure 7. Façade, plant and the axonometry view of Bab Agnaou gate.

Figure 8. Bab Agnaou gate after the end of the renovation.



Materials :

TYPES	IMAGE	DESCRIPTION	PATTERN
Ashlar		The ashlars are the principal material of construction of the gate. It is cut according to variable dimensions and forms. Concerning original ashlar, no historical data referring to its origin are available. It is about a schist of greenish grey colour on fresh fracture, with narrowspaced schistosity.	
Mortar		Mortar is a mixture of binder, aggregates and water, is used for stone veneer of size which forms a coating from the bottom of the door to the epigraphic inscriptions. For the restored part located at the top of the door, the mortar is used for sealing the masonry units so as to form a single block. It is also used as a coating for the rammed earth forming the opening of the door.	
Pisé		- Freeze and thaw cycles; - Disruptionof the supporting masonry apparatus; -Physical-mechanical incompatibility betweensubstrate and finish; -Differential dilatations between support materials and finishing: -Degradation of the interface betweenbricks and mortars (formation of calcium sulfoaluminates and large crystals). In bricks, presenceof calcium carbonate.	
Adobe		The adobe that designates both the building material and its process of implementation serves as a support for the veneer of the ashlars. It is the same procedure used while building Marrakech ramparts. The procedure consists in beating, layer by layer, between wooden boards and at walls width, rubble stones mixed with earth prepared beforehand. Thus beating it sticks and becomes consistent and forms a homogenous mass that can be raised to any height	

Patterns :

NAME	DESCRIPTION	2D REPRESENTATION
floral decorations of the spandrels	The spandrels are adorned with large and firm floral decorations which extend around a shell and meet at the key of the arch by a quadrilobed finial.	
archivolt decorated with interlacing festoons	Degradation that manifests itself with detachment, often followedby falling, of one or more subparallel surface layers .	
Quranic inscription	The door frame band is decorated with a Koranic inscription in Kufic characters, which recalls its Hispano-Moorish origin.	

Figure 9. Analysis of the construction materials and decorations, top. Degradation analysis map, bottom.

ic method, with its potential and limits as tested and highlighted in the case study in Pisa, is easy to apply when inserted within a study of artifacts. By applying traditional cognitive methods, historical analysis, geometric survey, material analysis and degradation, etc., the graphic analysis, rapid and expeditious, constitutes a further useful element of knowledge that provides elements both in terms of seismic vulnerability and the degree of static safety of the structures. From this enriched cognitive framework, useful elements can

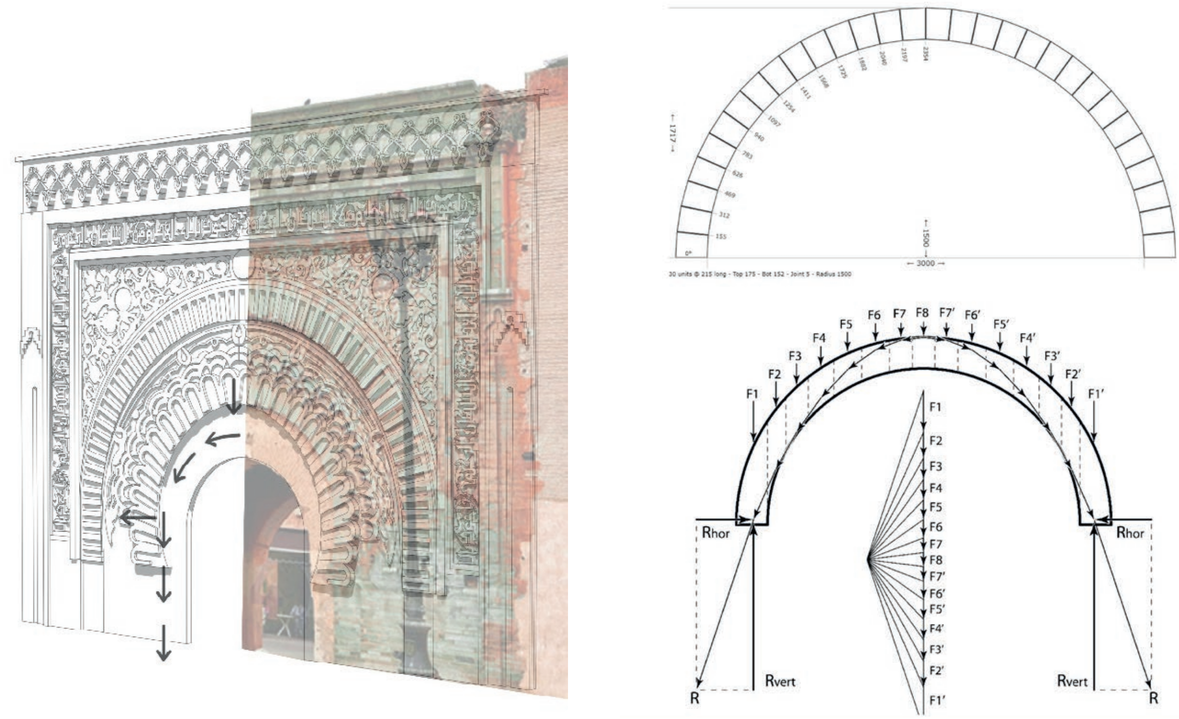


Figure 10. Analysis of the arch of Bab Agnaou gate with the graphic method.

emerge more clearly for the planning of possible future interventions on the artifact, both for reuse and refunctionalisation and for management and scheduled maintenance.

4. CONCLUSIONS

On the basis of the above considerations, it is possible to draw some general conclusions regarding the methods of investigation and analysis used in this case study. The analysis of the static consistency and of the eventual evaluation of the seismic vulnerability of the existing structures, in particular of the historical and monumental buildings, can be carried out in a coherent and correct way only starting from a deep knowledge of the history and of the geometric, physical and mechanical characteristics of the structural elements. To obtain this, a preliminary and in-depth knowledge of the building in its entirety is necessary, through historical documentation, geometric measurements, investigations, tests, etc.

Being able to read the supporting elements, making their schematization and the consequent modeling is often very complex and challenging to interpret. On the contrary, through the use of graphic-synthetic and analytical methods based on the method of limit analysis and the theories of Jacques Heyman, it is possible to obtain a first detailed picture of the building. It allows access to understanding the functioning of structures, starting from the main elements such as arches, vaults, springers, and walls, to gain a comprehensive understanding of the structure as a whole. Therefore, the use of graphical and analytical analysis is not only an excellent tool for assessing the static consistency of structures, with the advantages and limitations illustrated above, but also and above all an excellent tool for the knowledge of monumental historical building artifacts, even in the case of complex constructions. In a second phase, through a finite element analysis, all results obtained through graphic and analytical procedures is analyzed to investigate local phenomena and behaviors that are difficult to analyze using only a global model. Starting with considerations and evaluations based on rigorous graphical and analytical analysis of the structures, FEM with particular levels of detail can be realized, aimed at local investigations on even complex buildings. It is objectively difficult in structures such as the structure under study to analyze all global and local aspects with a single FEM model as modeling very complex and not easy to implement both from the point of view of the creation of the model (elements to be modeled, hierarchy of structures, etc.), and from the point of view of the interpretation of the results obtained. From this perspective, the graphic and analytical analysis of structures represents a valid and reliable tool for analyzing buildings and investigating their structural behavior, serving as a starting point for further and more sophisticated analyses, both local and global. Finally, it should be remembered that the above graphical methods of analysis are applied in the context of a series of hypotheses about the materials, the constitutive bonds, the structural behaviors and the rupture mechanisms that are clearly in favor of safety. Based on these considerations, this method makes it even more interesting because, in the face of simplifications on the model, it's possible to obtain results that are both strongly correlated with the behavior of the structures and able to guarantee good precision and adequate safety margins. By enriching traditional methods of building knowledge with simplified and rapid graphic analysis methods, a further useful element of knowledge is constituted, providing valuable information for planning interventions aimed at both reuse and refunctionalization, as well as management and scheduled maintenance.

5. AUTHORS CONTRIBUTIONS

Conceptualization, E.L, V.P., G.S. and A.T.; methodology, E.L, V.P., G.S. and A.T.; software, E.L, M.M., V.P., G.S. and A.T.; validation, E.L, G.S. and A.T.; formal analysis, E.L, V.P., G.S. and A.T.; investigation, E.L, M.M., V.P., G.S. and A.T.; data curation, E.L, G.S.; writing—original draft preparation, E.L, V.P., G.S. and A.T.; writing—review and editing, E.L, G.S.; visualization, E.L, V.P., G.S. and A.T.; supervision, E.L, G.S. and A.T.; All authors have read and agreed to the published version of the manuscript.

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Mining Users' Perceptions Through Sentiment and Emotion Analysis to Address Heritage Conservation Strategies

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Abstract. Monitoring architectural heritage is a crucial step in the planning of proper conservation strategies and resource allocation. Current protocols rely on periodic, though infrequent, expert-led inspections, which assess the state of conservation of heritage assets and inform intervention priorities. However, public perceptions, which may suggest alternative courses of action, are seldom considered. This study proposes an innovative methodology integrating public feedback into heritage monitoring via Natural Language Processing (NLP). The framework, applied to '70s heritage sites in Italy's Marche region, integrates Aspect-Based Sentiment Analysis (ABSA) and Aspect-Based Emotion Analysis (ABEA) to systematically analyze user-generated content, identifying heritage-related aspects and classifying sentiment (positive, negative, neutral) and emotions (e.g., joy, anger) from Google Maps reviews. Heritage-specific targets were first identified in user reviews using spaCy-based tokenization. Sentiment classification (positive, negative, neutral) was performed using a pre-trained Bidirectional Encoder Representations from Transformers (BERT) model, while emotions (joy, anger, sadness, fear) were identified using the FEEL-IT algorithm. User perceptions were effectively retrieved, revealing a generally positive sentiment and joy as the most dominant emotion. This approach enables large-scale monitoring based on continuously updated user feedback, which can be integrated into current monitoring protocols to adopt a more comprehensive decision-making approach.

Keywords: Architectural heritage, Heritage monitoring, Resources allocation, User sentiment, User emotion.

1. INTRODUCTION

Monitoring architectural heritage is essential to guarantee proper knowledge to inform decision-making and the allocation of financial resources for conservation interventions. Continuous surveillance allows for the early detection of potentially critical issues, enabling timely, targeted actions. Strategies that adopt a *preventive* rather than *curative* approach help avoid delayed restoration efforts, which often fail to address underlying issues and require substantial public funding [1].

Currently, monitoring protocols are managed by public administrations, which rely on experts to assess the state of conservation of heritage buildings through structured reports. Their evaluations constitute the base knowledge for stakeholders responsible for decision-making [2].

However, these documents often fail to reflect the actual status of the assets and become outdated as soon as they are compiled. This is not only due to the evolutionary nature of the built environment, but also to the infrequent site inspections by technicians.

Although seldom considered, the potential of strategies that involve end-users in monitoring and planning actions has been explored and supported by several studies and directives [3]. In fact, involving the general public not only fosters a democratic approach but also offers a more comprehensive perspective, highlighting overlooked issues or suggesting alternative courses of action for decision-making. Moreover, public engagement also provides an opportunity to monitor the outcomes of actions taken (or not taken) in heritage conservation and management.

Heritage architecture is a topic of widespread interest among the public, whose opinions are frequently reported on social media platforms in the form of short texts, comments, or reviews. The internet thus serves as a large and dynamic repository of unstructured data, which is continuously updated and provides near-realtime and unbiased information. Thanks to Artificial Intelligence (AI) technologies, and in particular to Natural Language Processing (NLP) techniques, it has now become possible to exploit this huge amount of user-generated content [4].

Increasingly popular applications of NLP are represented by Sentiment Analysis (SA) and Emotion Analysis (EA). SA, also called *Opinion Mining*, is the computational study of people's opinions, allowing for the detection of sentiment orientation (positive, negative or neutral) or sentiment intensity (e.g. sentiment polarization on a scale from 1, most negative, to 5, most positive). EA provides more detailed insights, detecting and classifying user emotions into distinct classes (e.g. joy, anger, sadness and fear, but they can vary depending on the adopted psychological model) [5-6].

Although widely used to assess user satisfaction in products and services, SA and EA have seen limited application in the construction sector, where they remain in their early stages.

For instance, D'Orazio et al. [7] employed different SA models to process user-generated reports from a computerized maintenance management system for a stock of university-administrated buildings and to define an intervention priority scale. A comparative analysis of the models' efficiency was performed, and the potential of such tools for this kind of tasks was confirmed. In a subsequent study, D'Orazio et al. [8] used a similar approach to prioritize maintenance requests, but included EA to categorize perception into joy, anger, fear and sadness categories, providing deeper insights.

In the context of heritage architecture, Rosin et al. [9] applied the SA model VADER (Valence Aware Dictionary for Sentiment Reasoning) [10] to online user reviews of the maritime museums network *Arca Adriatica*, examining how visitors' feedback could enhance management strategies. Mendes et al. [11] proposed instead the use of VADER to process Tripadvisor reviews of two Iberian monuments, identifying triggering factors of negative sentiment; the study revealed that maintenance actions restricting access to the site constitute the main cause of dissatisfaction among tourists.

SA can be performed at different levels. Ginzarly et al. [12] applied SA at the sentence level to the TripAdvisor reviews of two Monuments in Lebanon to categorize their perception as positive or negative and thus provide insights on cultural values and attributes expressed by users. Valdivia et al. [13] detected the sentiment polarity for three Spanish monuments by applying an Aspect-Based Sentiment Analysis (ABSA) on Tripadvisor reviews, identifying negative aspects and issues that required intervention by cultural managers.

While document level SA detects the overall sentiment for a document, and sentence level SA for a single phrase, ABSA aims at identifying what users exactly appreciate or not [5]. Within a document – or even a single sentence – multiple thoughts may actually be expressed (e.g. the sentence "The museum has fascinating exhibits, but the staff is unhelpful" conveys a positive sentiment for the aspect "museum", but a negative one for "staff"). Focusing the SA and EA on the selected *target* is crucial for obtaining reliable results. ABSA still represents a challenging field for research, due to the complexity of linguistic structures, such as sentences which present negations or which are factual but still imply opinions. Additionally, the lack of sufficient domain-specific training data constitutes further difficulties.

A proper revolution in the field came with the introduction of pre-trained models based on transformer technology: among them, it is recalled BERT (Bidirectional Encoder Representations from Transformers) language model [14]. Introduced by Google in 2017, BERT uses an encoder based on self-attention mechanisms and incorporates Masked Language Modelling (MLM) and Next Sentence Prediction (NSP), which enhanced the comprehension of word relationships and of the general context. Its versatility allows for fine-tuning across a range of tasks, including SA.

The advancements hereby presented offer just a brief glimpse into the potential of applying SA and EA tools to user-generated content related to architectural heritage, which currently lacks well-defined frameworks or methodologies [15].

This study aims to present a novel methodology which leverages pre-trained BERT-based models to perform ABSA and EA on user-generated reviews concerning architectural heritage. The results will provide an overview of user perceptions of the assets which are not influenced by non-architectural aspects (e.g. the function of buildings), and deeper insights will be given by the detection of conveyed emotions. The presented approach intends to offer a novel monitoring strategy which is more comprehensive and can complement current protocols and favor public engagement.

This paper is structured as follows: Sect. 2 describes methods, starting from the illustration of the proposed methodology (Sect. 2.1) and a description of the case study selected to test it (Sect. 2.2); Sect. 3 presents data resulting from the analysis along with its discussion; Sect. 4 concerns conclusions and future possible implications of the present research.

2. METHODS

2.1 Aspect-Based Sentiment and Emotion Analysis methodology

The proposed Aspect-Based procedure for SA and EA was tested on user-generated textual reviews from Google Maps related to heritage sites in Italy's Marche region. This dataset provides the basis for demonstrating the framework's applicability. Information regarding the selection of heritage sites and the collection of user-generated content will be described in greater detail in Section 2.2.

The methodology can be synthesized in three phases (Figure 1), which are briefly described here and will be detailed in the following sections:

1. *Heritage target detection* (Sect. 2.1.1): the NLP model spaCy was employed to detect words (tokens) within the text of reviews related to the heritage domain. These tokens represented the *targets* for the aspect-based analysis, enabling the recognition of segments of sentences to be processed by SA and EA algorithms.
2. *Sentiment Analysis* (Sect. 2.1.2): a pre-trained BERT model was employed for the SA of the previously identified segments of reviews' sentences. Sentiment scores of pieces of text were aggregated to obtain a single score for the analyzed heritage item.
3. *Emotion Analysis* (Sect. 2.1.3): the FEEL-IT [16] model was used to provide further insight on sentiment polarity and categorize segments into emotion classes (joy, anger, fear, sadness).

2.1.1 Heritage target detection

Two key steps characterize this phase: (i) identifying heritage-related tokens in the review texts, and (ii) isolating sentence segments containing these tokens.

To this aim, the use of the Python library spaCy was chosen [17]. SpaCy is an NLP library which supports more than 75 languages, including Italian, the language used in the analyzed reviews. One of its main features consists of breaking texts into basic units (tokens) and

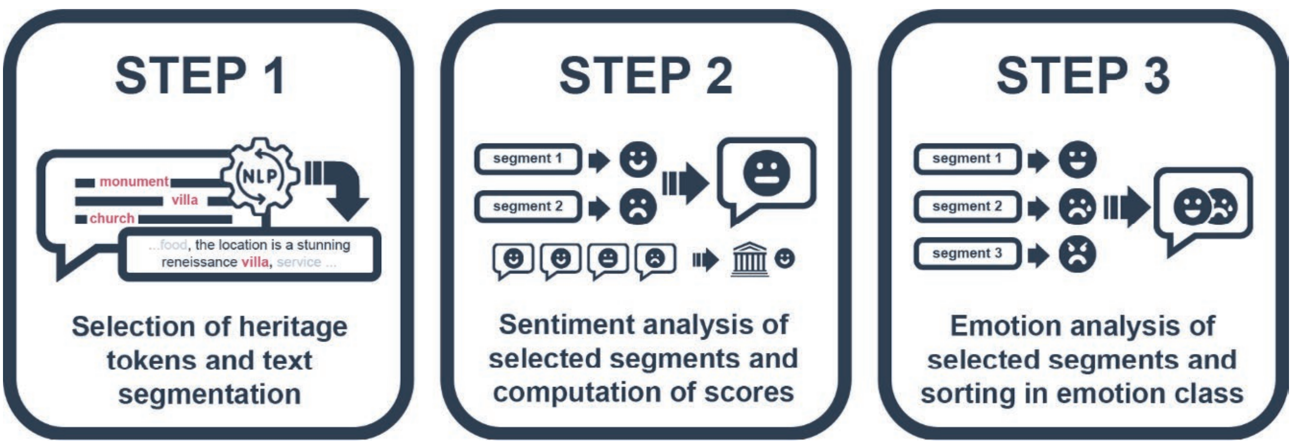

Figure 1. Representation of the three main phases at the base of the proposed methodology. © 2025, D'Orazio et al.

assigning a label (noun, adjective, etc.) to each through Part of Speech (POS) tagging.

By leveraging this function, words representing subjects or direct objects of sentences were detected, as they typically correspond to the parts of sentences most closely associated with opinions. The combination with the default Python module Collection allowed for the creation of an ordered list of terms, from the most to least frequent. The final selection of items followed these criteria: (i) architectural heritage related words or its physical surroundings (e.g. "gardens"); (ii) terms referring to immovable works of art or historically significant furnishings that contribute to the site's value (e.g. "sculptures", "altars"); (iii) terms associated with user experiencing the sites (e.g. "visit").

The identified terms served as targets to identify the parts of the review sentences to be isolated for later analysis. The boundaries of these segments were defined by the presence of punctuation marks or conjunctions (POS tagging identified), as these usually represent the borders of completed thoughts.

This passage allowed isolating parts of reviews related to heritage topics in the text (Table 1).

2.1.2 Sentiment Analysis

The SA processing of the previously identified sentence segments (Sect. 2.2.1) was performed using the pre-trained model BERT-base-multilingual-uncased-sentiment [18] from the Hugging Face platform. As the name itself suggests, the main features of the model are its capability to support multiple languages, including Italian, and to be unaffected by the use of uppercase or lowercase characters. The main reason that favored its selection was the provision of sentiment scores on a 5-star scale, analogous to the star ratings directly assigned by users, useful for a later comparison between the detected and the expressed perceptions of the users about the assets.

After analyzing each segment in a single review, their mean was calculated to obtain a single score for all of them. Once all the review scores had been computed

Table 1. Example of words (subject and direct objects) retrieved by spaCy and example of the selection of terms related to heritage and the associated sentence segments for the heritage site Church of Portone, in Senigallia. © 2025, D'Orazio et al.

Heritage Architecture	List of all detected tokens (subject and direct object) with frequency (within brackets) – English translation	List of tokens selected for the individuation of segments – English translation	User	Example of review – English translation
Church of Portone	parish priest (3); church (2); atmosphere (2); title (1); function (1); consideration (1); celebration (1); parish (1); theatre (1); lectures (1); vision (1); punishment (1); share (1); chapel (1); tabernacle (1); architecture (1); parking (1); works (1); youth (1); favourite (1); confessor (1); peace (1); name (1); enchanting (1)	<u>Building related:</u> church; chapel; architecture <u>Works of art/furniture:</u> tabernacle; works <u>Users experience:</u> atmosphere; sorrow; favourite; enchanting	User_01	Nice place. The church is nice and cosy. There is an atmosphere of recollection just entering it. It is a reference point for the community. The parish is very active in social work. The theatre next door often hosts themed conferences. I recommend watching them. It is well worth it.
				Selected segments for analysis
				"The church is nice and cosy"; "There is an atmosphere of recollection just entering it"; "It is well worth it"
				Segments excluded from analysis
				"Nice place"; "It is a reference point for the community"; "The parish is very active in social work"; "The theatre next door often hosts themed conferences"; "I recommend watching them"
			User_02	7.15 p.m. Sunday Mass. Full of people, priest engaging and smart. Singing few and well done. The architecture is simple. Outside there lots of parking spaces.
				Selected segments for analysis
				"The architecture is simple"
				Segments excluded from analysis
				"7.15 p.m. Sunday Mass"; "Full of people"; "priest engaging"; "smart"; "Singing few"; "well done"; "Outside there lots of parking spaces"

Figure 2. Calculation of a single sentiment score for an asset. © 2025, D'Orazio et al.

in this way, the sentiment score for the heritage item was obtained by averaging the scores of the corresponding reviews (Figure 2).

To categorize reviews into sentiment polarity classes, scores 1 and 2 were considered negative, 3 neutral, and 4 and 5 positive.

2.1.3 Emotion Analysis

Parallel to SA, the segments were processed with the model FEEL-IT to classify the emotions conveyed in the texts. FEEL-IT is a fine-tuned UmBERTo model (itself a fine-tuned version of BERT for Italian language) trained on tweets annotated with labels corresponding to the four basic emotions: joy, anger, fear and sadness [19].

Each of the segments identified in the first phase (Sect. 2.2.1) was processed using the selected algorithm. Just as a single sentence can convey both positive and negative sentiments, it can also express multiple emotions simultaneously. Since emotions are qualitative rather than quantitative, it was not possible to apply a procedure similar to the one used for calculating sentiment scores to derive a single result value (Sect. 2.2.2). Handling multi-opinionated sentences remains a significant challenge in this context [6, 20].

Therefore, the results of EA are presented as computed, with multiple emotion labels for each review.

2.2 Case study

The selected case study on which the proposed methodology was tested consists of catalogued heritage architecture located in the region of Marche in Italy. Italy is one of the richest countries in terms of heritage, and the region Marche alone counts more than 1000 monuments, 106 castles, 15 fortresses, thousands of churches and 72 theatres, as well as presenting the highest museums-population ratio and UNESCO sites [21].

The Italian authority responsible for heritage protection is the Ministry of Culture (MiC), which operates through peripheral offices, such as territorial Superintendencies for Archaeology, Fine Arts, and Landscape (SABAP, *Soprintendenze Archeologia, Belle Arti e Paesaggio*), in charge of the conservation and promotion of heritage sites.

These cultural stakeholders base their activities on data provided by platforms which collect information on protected sites. The heritage items selected for this study were sourced from the General Catalogue of Cultural Heritage [22]. This platform is managed by the MiC's Central Institute for the Catalogue and Documentation (ICCD) and organizes data collected on structured sheets during periodic on-site cataloguing campaigns conducted by local authorities (superintendencies, provinces, etc.), which include information on the state of conservation of assets [23].

The complete dataset for Marche's architectural heritage from the General Catalogue, comprising 6835 sites, was retrieved from the MiC open data platform at dati.beniculturali.it [24]. For each site, data such as the unique national ID, name, coordinates, state of conservation, notes on conservation status (e.g., causes of decay), and dates of compilation and updates were retained. This dataset represents official data collected by experts following official monitoring protocols.

Subsequently, a further selection was made from the official dataset to identify heritage items provided with user-generated content. The majority of the buildings listed in the catalogue are privately owned, precluding access to visitors and thus impeding discussions on social media.

Google Maps was chosen as the platform for retrieving user data. As a vast repository of location-specific information, it includes heritage sites and allows users to contribute content, such as five-star ratings, textual reviews, and even attached photos.

Matching items from the General Catalogue of Cultural Heritage and Google Maps could only be done by manual search. Automated procedures were hindered by the presence of inconsistencies in items' names (e.g. naming conventions as the use of "S." for "Saint" for churches and convents) or in coordinates data. Setting a tolerance distance to address the latter issue only made it worse, as the proximity of buildings in historic centers increased the risk of mismatches.

The final dataset of user-generated content comprised 70 items, including ratings, textual reviews, and usernames of the authors (hidden to protect their privacy), all scraped using the Google Chrome extension Instant Data Scraper. As most of the reviews were in Italian, the few reviews in other languages were extracted in their automatically translated form to maintain consistency within the dataset (multilingual SA is a possibility, but it is not the focus of this study).

The reduction from the 6835 items of the official catalogue dataset to the 70 of the user-generated content dataset is due to two main factors. First, the majority of the architectures listed in the official catalogue are private, preventing users from visiting them. Second, ministerial records also include *minor heritage* sites (it is noteworthy that Italian law protects public buildings over 70 years old), often less appealing to the general public and resulting in fewer reviews.

The results obtained by applying the methodology described in Section 2.1 to the case study dataset are presented in the following Section 3.

3. RESULTS

First considerations concerning the results obtained from the application of the proposed methodology for ABSA were conducted by comparing sentiment scores with the ratings directly assigned by users in the review process.

At first glance, the distribution patterns of the graphs are quite similar, confirming the methodology's effectiveness in capturing user perceptions, which is, for the most part, positive. However, some differences remain. The ABSA score histograms show fewer items in the most extreme categories (1- and 5-star ratings), with a higher concentration in the middle range. This suggests that ABSA tends to present less *extreme* perceptions, likely because the analysis focused on heritage-related aspects, excluding other factors that might have led to more polarized opinions.

Further analysis incorporated these results alongside findings from the Aspect-Based Emotion Analysis (ABEA). While, as noted in Sect. 2.2.3, it is not possible to force multi-emotion results into a single category, the most common emotion per heritage asset was retrieved to provide a qualitative overview of ABEA. Joy emerged as the dominant emotion, far surpassing the others. Given that joy is universally recognized as positive, while anger and fear could be considered negative emotions [19], ABEA also proved effective in capturing user perceptions. It is important to note that sadness does not always represent a negative emotion. For instance, in this case study, some reviews expressing nostalgia were categorized as sadness. These reviews did not convey negativity but rather a sense of affection and longing for something lost over time. Nevertheless, joy remains the most frequently detected emotion, far surpassing sadness in the ABEA results.

All these considerations are based on the data presented in Figure 3.

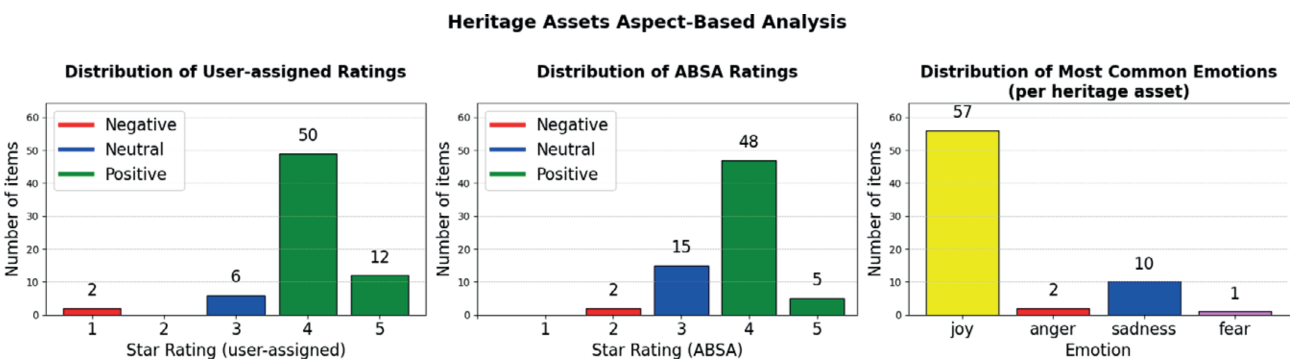

Figure 3. Histograms representing the distribution of ratings directly assigned by users (left), of resulting scores of the ABSA (center) and most common emotions for heritage assets (right). To sort results into sentiment polarity classes 1- and 2-star ratings were considered as negative, 3 as neutral and 4- and 5-star as positive. © 2025, D'Orazio et al.

Deeper insights are provided by dividing in categories the heritage architecture dataset based on the destination of use of buildings. The categories include directional buildings (4 items), fortifications (5), schools (4), monuments (1), museums (4), productive buildings (1), churches and monasteries (39), receptive structures (8), public buildings (1), theatres (2), and historic villas (1). Again, the distribution of user-assigned ratings (only the ones associated with the processed textual reviews), ABSA scores and ABEA results were analyzed in parallel. By making this distinction, it was easier to highlight cases worthy of attention.

One of the most notable cases is represented by the Post Office building of Ancona, the only one falling under the public building category. This item received the most negative evaluations by users, averaging just 1 star, which increased only to a 2-star score after ABSA processing of reviews (Figure 4). This shift may be attributed to the aspect-based approach; however further examination of the texts revealed that even when targeting the analysis through the use of heritage-related tokens (e.g. "place", "war"), users primarily expressed complaints about the service provided at the office (Table 2). This is further supported by the ABEA analysis of the reviews, which clearly indicates a predominance of anger in the examined texts (Figure 4).

Another interesting example is provided by the former Mancini furnace in Pesaro (productive buildings category). This site received only two reviews, averaging a rating of 4, as shown in Table 3. The first review (User_01) is paired with a highly positive rating from the author but was assessed as neutral by the ABSA, likely because the text is mainly descriptive, with the user implicitly expressing an appreciation for the allure of ruins. ABEA offers additional interpretations: the review conveys sadness in relation to the site's abandonment, anger over the decay caused by plant overgrowth, and fear regarding the dangers involved in accessing an opening to enter. This last emotion does not directly pertain to the asset's conservation status but rather to a dangerous action involving the site. While not strictly linked to conservation, such observations can provide valuable insights into how people experience a heritage asset in its current state of decay. The second review (User_02) shows a close alignment between the user's rating and the ABSA score, while the ABEA interpretation reflects sadness over the structure's lack of redevelopment.

Figure 5. provides a graphical representation of the data discussed above.

Final assessments compared the results of the proposed methodology for ABSA regarding user perceptions with expert evaluations on the state of conservation, as recorded in the official catalogue.

To achieve this, terms used in the ICCD sheets were categorized as positive, negative, or neutral, consistent with the ABSA results. As shown in Table 4, terms such as "good" and "excellent" were classified as positive, terms describing damage or explicitly negative conditions ("bad", "very bad") were classified as negative, and references to ongoing work or terms not fitting the other two categories were considered neutral. The term "ruin" was classified as negative, as it can be considered a synonym of "collapsed" from a conservation standpoint; however, it is worth noting that a ruin can have historic value and be in an optimal state of conservation [25].

Exploiting coordinate data, all items were mapped and marked with a color depending on the respective category (Figure 6). Results of the ABEA were excluded from this analysis due to the complexity of reporting multi-emotion-labelled data on a map.

The first observation is that the official record presents the most negative view of heritage conditions, particularly in the southern and inland areas of the region. By contrast, ABSA reflects a more positive outlook, with only two negative cases. These two cases, the Post Office of Ancona and the San Decenzio Cemetery in Pesaro, were given positive evaluations by experts but were further analyzed through user reviews. In the case of the Post Office, reviews primarily criticize the postal service, as discussed earlier in this section; for the cemetery, users reported various signs of structural decay (Table 5), which were further reflected by the predominance of anger and sadness resulting from the ABEA. Examination of the catalogue's compilation date revealed it to be from 2004, highlighting the outdated nature of the official records.

For sites marked by experts as in a negative state of conservation but classified as positive or neutral by ABSA, the conservation status notes in the official records were examined. It was found that the damages leading to these negative expert evaluations were largely caused by the 2016 earthquake that affected the southern part of the region. Although these records were more recent (averaging around 2018), they did not reflect recent restoration and refurbishment efforts that have since made these structures accessible to visitors.

4. CONCLUSIONS

Ensuring continuity in monitoring operations is crucial for the safeguarding of heritage and fosters preventive protocols. In addition to preserving cultural values,

Table 2. Example of reviews for the Post Office building of Ancona: the presented texts clearly show that, even when focusing the analysis on selected segments, these consist of complaints. © 2025, D’Orazio et al.

Heritage Architecture	Unique national ID	Selected tokens	User	User-assigned rating	ABSA score	Example of review – English translation	ABEA emotions
Post Office building	1100216467	post; war; place	User_01	1/5	5/5	You guys go to the sub-offices, here you wage war. Absurd	anger
			User_02	1/5	2/5	They don't answer the phone and the biggest shame is that no office in the yellow pages of the same building in Lagro XXIV Maggio has the working seriousness to pick up the phone and the smartest ones hang up the fax […] Now work, people, there are those who are laid off and would like a job [in Italian “posto di lavoro”, workplace] like yours that would make this company much better, increasingly in a state of decay	sadness
			User_03	1/5	2/5	No one answers the phone, maybe the place is abandoned. Good service, that's love for one's work	sadness

Figure 4. Top: histograms representing the distribution of ratings directly assigned by users (left) and of resulting scores of the ABSA (right) for the Post Office building of Ancona; Bottom: Representation of the emotions associated with each of the analyzed reviews’ sentence segments for the Post Office building. © 2025, D’Orazio et al.

Table 3. Reviews for the former Mancini furnace of Pesaro. © 2025, D'Orazio et al.

Heritage Architecture	Unique national ID	Selected tokens	User	User-assigned rating	ABSA score	Example of review – English translation	ABEA emotions
Former Mancini furnace	1100221349	furnace; plants; brambles; ruins; opening	User_01	5/5	3/5	Together with xxx and xxx, I went to explore the disused Mancini furnace. Plants - unfailingly brambles - besieged the ruins. We do not give up and make our way through the thorns and mosquitoes. We reach an opening that is not too high, we cross it and we are inside	Anger, fear, sadness
						I went to explore the disused Mancini furnace	sadness
						Plants - unfailingly brambles - besieged the ruins	anger
						We reach an opening that is not too high	fear
			User_02	3/5	4/5	A ruin awaiting targeted redevelopment.	sadness

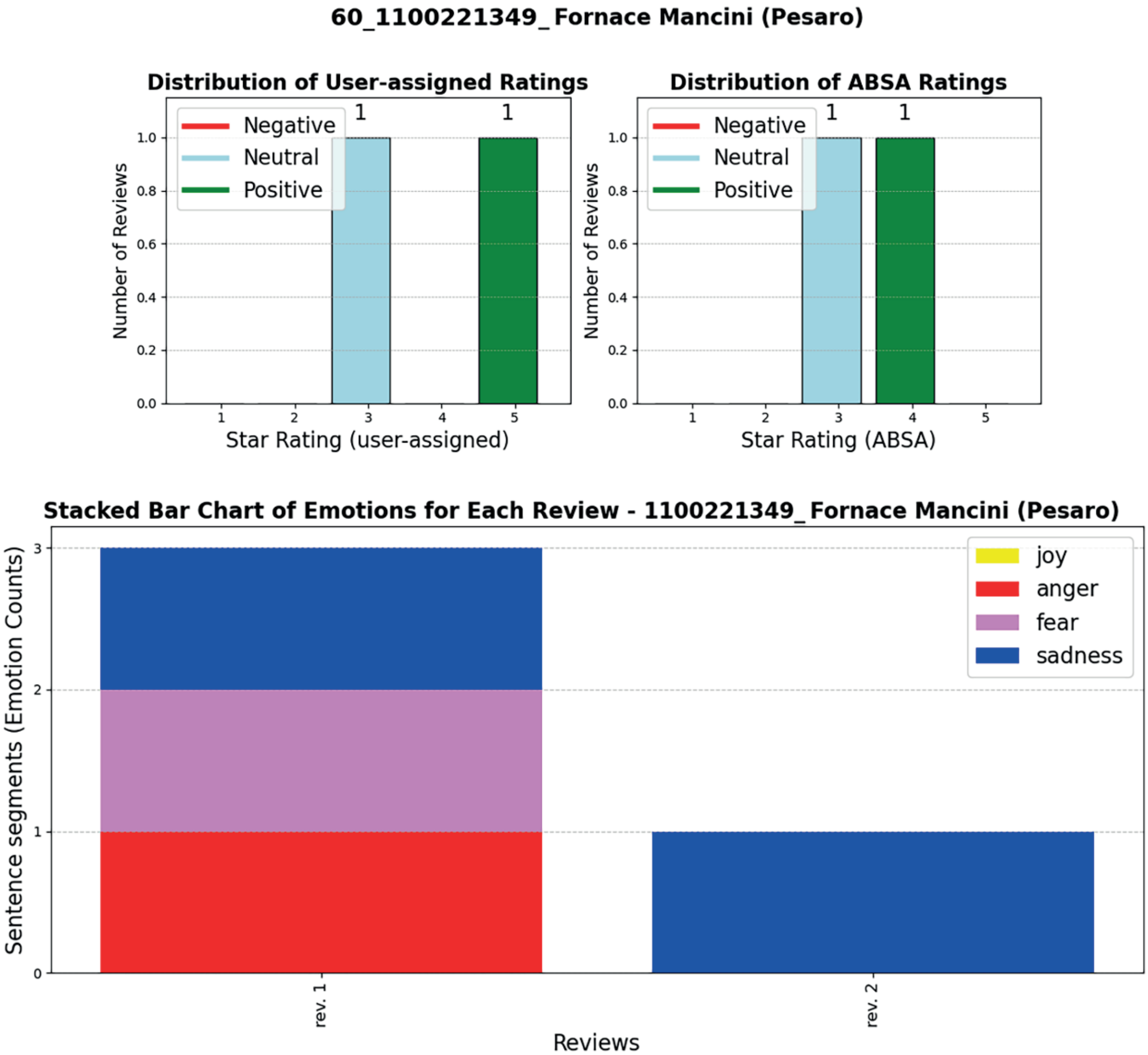

Figure 5. Top: Histograms representing the distribution of ratings directly assigned by users (left) and of resulting scores of the ABSA (right) for the former Mancini furnace in Pesaro; Bottom: Representation of the emotions associated with each of the analyzed reviews' sentence segments for the former Mancini furnace. © 2025, D'Orazio et al.

Table 4. Classification of conservation state terms from ICCD sheets. © 2025, D'Orazio et al.

Sentiment polarity	ICCD state of conservation	ABSA score
Positive	Excellent; Good	5 4
Neutral	Discrete; Absence of damage; Work in progress; Under renovation	3
Negative	Minor damage; Moderate damage; Medium damage; Damage of moderate level; Mediocre; Bad; Very bad; Severe damage; Very severe damage; Partly collapsed; Ruin; Collapse; Collapsed	2 1

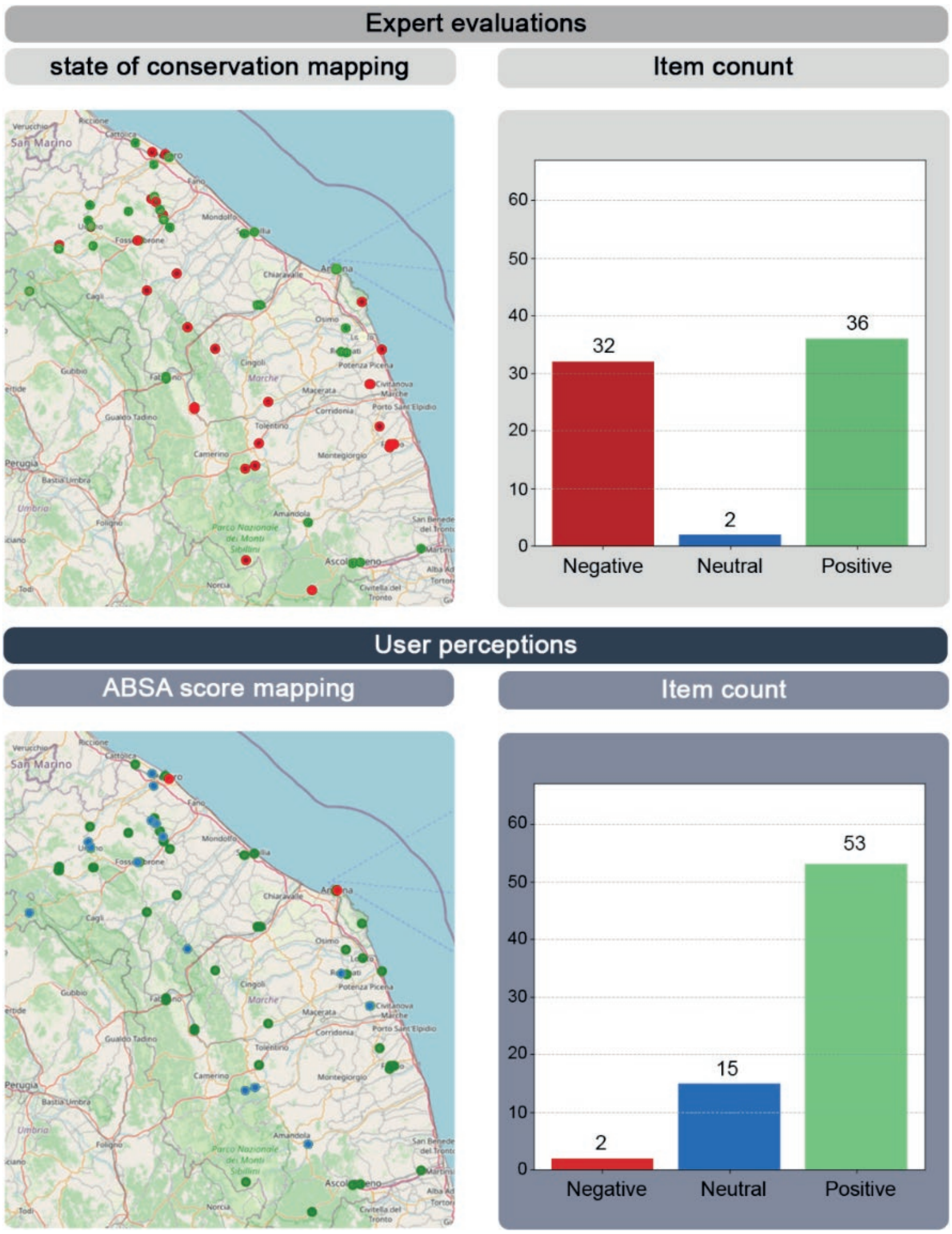

Figure 6. Mapping of expert and user data, respectively, concerning the evaluations on the state of conservation of heritage architectures and ABSA scores resulting from the proposed methodology. © 2025, D'Orazio et al.

Table 5. Example of reviews for the San Decenzio cemetery in Pesaro, reporting decay and damage to the structure. It is noteworthy that ABEA correctly interprets the use of the capital letters as a means of expressing anger. © 2025, D'Orazio et al.

Heritage Architecture	Unique national ID	Selected tokens	User	User-assigned rating	ABSA score	Example of review – English translation	ABEA emotions
San Decenzio Cemetery	1100221395	Part; cemetery; need; sinks; money; signs; night; exit; enters; pavilion; compressed	User_01	1/5	2/5	Cemetery in a pitiful condition, the new part needs constant work due to infiltrations, not to mention the old one taken by storm by pigeons that defecate on so many tombstones, in addition to the poor maintenance (see sinks always clogged)	sadness
						cemetery in a pitiful condition	sadness
						the new part needs constant work due to infiltration	sadness
						in addition to the poor maintenance (see sinks always clogged)	sadness
			User_02	1/5	2/5	IT IS IN INDECENT CONDITION: ESPECIALLY THE FLOWER PAVILION, THE LAST ONE BUILT, WHERE IT STILL RAINS INSIDE: they are the mirror of those who govern us, incapable of spending public money: all the last works have been resolved with compressed chipboard panels and painted with water-repellent paints that are already showing clear signs of subsidence but according to our politicians it is usable and well maintained	Sadness, fear, anger
						ESPECIALLY THE FLOWER PAVILION	anger
						incapable of spending public money	anger
						all the last works have been resolved with compressed chipboard panels	fear
						painted with water-repellent paints that are already showing clear signs of subsidence	sadness

timely actions and routine maintenance can prevent costly, delayed restoration efforts that may compromise assets or overlook key issues.

To support up-to-date and comprehensive monitoring protocols, a novel methodology was proposed to integrate user perceptions from social media platforms with official heritage conservation catalogues. This approach leverages SA and EA to process user-generated reviews from Google Maps, employing NLP techniques to isolate heritage-related topics from other aspects discussed in comments.

ABSA returned an overall positive perception of the heritage sites located in the Italian region of Marche, selected as a case study. With regard to the directly user-assigned 5-star ratings, results tended toward less *extreme* values, with fewer 1- and 5-star scores. Deeper examination of specific items yielded additional insights, such as the appeal of abandoned structures.

Comparing user perceptions with expert evaluations exposed outdated catalogue records, with notable discrepancies in resulting user perceptions. Some sites marked positively by experts met with user criticism over maintenance issues, alongside the conveyance of anger and sadness-related emotions; these catalogue entries dated back 20 years. Conversely, buildings damaged by the 2016 earthquake and marked negatively by experts received positive feedback from users, reflecting restoration efforts unrecorded in official documents.

This study presents a new methodology for ABSA and ABEA in heritage monitoring and identifies critical issues in current protocols. Future research may refine this model, developing automated matching procedures between official and user-generated datasets, a process currently hindered by issues related to naming conventions and coordinates. At present, this matching is done manually, making it time-consuming. Automating the selection of heritage tokens would also represent a significant improvement. By constructing and linking a heritage-related thesaurus, the selection of relevant tokens could form the foundation for a fully automated process. Once these issues are addressed and the model refined, the methodology could be applied to even larger datasets, such as at the national scale. Other potential implementations could involve exploring and complementing additional social media platforms, which could significantly enrich the insights derived from users' feedback and provide further validation.

This work lays the foundation for real-time monitoring platforms driven by user data, enhancing resource allocation and fostering participatory approaches by engaging the public, whose role currently remains underutilized in heritage management.

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7. AUTHOR CONTRIBUTIONS

Marco D'Orazio: Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project Administration. *Elisa Di Giuseppe:* Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project Administration. *Maria Francesca Muccioli:* Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review and editing, Visualisation.

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Artificial Intelligence for Detecting Surface Alteration Phenomena in Stone-Built Heritage: The Case of the 'Unfinished Church' of Venosa

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Abstract. Point clouds and 3D models have become essential not only for the digitisation process but also for the non-invasive assessment of deterioration and potential decay mapping in Cultural Heritage, particularly in the built environment and architectural landmarks. These resources facilitate precise digital inspections and enable a comprehensive analysis of the morphological and material properties of heritage assets, in strict alignment with conservation principles. Recent advancements in Artificial Intelligence have further refined 3D data and image processing, introducing sophisticated techniques for segmentation and classification through both supervised and unsupervised learning paradigms. Building upon these breakthroughs, this study explores the semi-automatic identification of surface alterations in the stone masonry of the south-east façade of the 'Unfinished Church', which is part of the Most Holy Trinity Complex in Venosa (Southern Italy). The mapping process started with the photogrammetric point cloud, employing RGB colour-detection techniques, followed by the implementation of two Machine Learning algorithms (Fast Random Forest and K-Nearest Neighbours) to examine the UV texture of the polygonal model. Comparative analyses, both quantitative and qualitative, were conducted to assess the effectiveness of these methods in identifying and classifying alterations, highlighting their potential to support preservation efforts and guide future maintenance strategies.

Keywords: Artificial Intelligence, Built Heritage, Image Processing, Point Cloud, Surface Alteration

1. INTRODUCTION

Cultural Heritage (CH) encompasses the tangible and intangible expressions of human history, including traditions, artworks, documents, and archaeological sites. Among its tangible aspects, Built Heritage (BH) holds a crucial role, comprising historic buildings, monuments, and architectural structures that reflect the achievements, identities, and narratives of past societies [1-2]. The preservation of BH has become a critical global priority, particularly in light of the accelerating impacts of climate change, environmental degradation, natural disasters, and human activity [3-4].

In response to these challenges, advancements in digital technologies have revolutionised CH documentation and analysis, with 3D point clouds – generated through photogrammetry or LiDAR – emerging as essential tools [5-6]. These datasets, composed of millions of spatially referenced points enriched with radiometric attributes such as RGB colour and reflectance intensity, enable highly detailed geometric reconstructions and material properties. When integrated with textured 3D models, point clouds not only advance the digitisation of heritage but also serve as powerful non-invasive tools for diagnosing surface and structural degradation and informing conservation strategies.

Concurrently, the application of Artificial Intelligence (AI) has catalysed substantial progress in the analysis of CH datasets [7], harnessing state-of-the-art techniques in image and point cloud processing [8, 9]. These AI-driven methodologies have demonstrated exceptional efficacy in the automatic recognition of colour and texture patterns, enabling the detection of surface alteration and degradation phenomena. Machine Learning (ML) algorithms – such as Random Forest (RF), K-Nearest Neighbours (K-NN), Support Vector Machines (SVM), and more – along with advanced Deep Learning (DL) techniques – like PointNet, Dynamic Graph Convolutional Networks (DGCNN), or the recently introduced Segment Anything Model (SAM) – have become integral to these tasks [10-11].

By leveraging feature extraction techniques, these methods effectively segment and classify data based on chromatic anomalies, reflectance patterns, and geometric inconsistencies, enhancing the accuracy and precision of analysis [12-13]. The integration of colour-based approaches, which assign distinct RGB colours to regions of interest within the point cloud, enables the rapid detection of altered areas and deterioration patterns. This methodology is particularly powerful when combined with texture-based techniques, such as orthophotos or UV maps [14-15], for the semi-automatic identification of cracks, erosion, and other forms of material degradation, such as in stone, thus providing a comprehensive and reliable evaluation of both surface and structural conditions [16-17].

Moreover, AI has made considerable strides in the automatic recognition and differentiation of architectural elements, such as columns, arches, and façades, within point clouds. This ability to segment and classify architectural features contributes significantly to our understanding of the complex geometry of historic buildings [18, 19]. These methodologies enhance the accuracy of segmentation and classification of point clouds, even when datasets are incomplete or only partially annotated. This is particularly significant for advancing the Scan-to-BIM process, which involves the semi-automatic conversion of semantic point clouds into Building Information Models (BIM) [20], with the model also incorporating data derived from degradation analysis [21].

Although AI presents significant opportunities for conservation in the built environment, its application raises ethical challenges, including data bias and the marginalisation of human expertise. To uphold authenticity and ethical integrity, AI should complement, rather than replace, human judgment [22-23].

1.1 Aims of the Research

Following the insights of a previous study [15], this research represents a significant advancement in the development of semi-automatic methodologies for mapping surface alterations on Stone-Built Heritage. Focusing on the south-east façade of the Unfinished Church, part of the Most Holy Trinity Complex in Venosa (Italy), the investigation examines degradation phenomena across a 60 m^2 stone masonry area.

Diverse colour-detection techniques were initially applied to the photogrammetric point cloud and subsequently to the corresponding polygonal model. These methodologies are rigorously assessed through both analytical and visual comparisons, providing a comprehensive evaluation of their effectiveness, reliability, and accuracy in detecting decay patterns, ultimately offering innovative solutions for the preservation and monitoring of heritage assets.

1.2 Overview of the Case Study

The Most Holy Trinity Complex, located in the ancient Latin colony of Venosa within the Basilicata region of Southern Italy, is an important historical site with an architectural evolution spanning from the Roman period (3rd century BC) to the Baroque era (17th-18th century) [24]. The entire site features the ancient church, which features a Paleo-Christian design with a central nave, side aisles, and a unique corridor crypt. Adjacent to it is a guesthouse, while behind the church stands the 'Unfinished' church, a grand but incomplete structure (Figure 1).

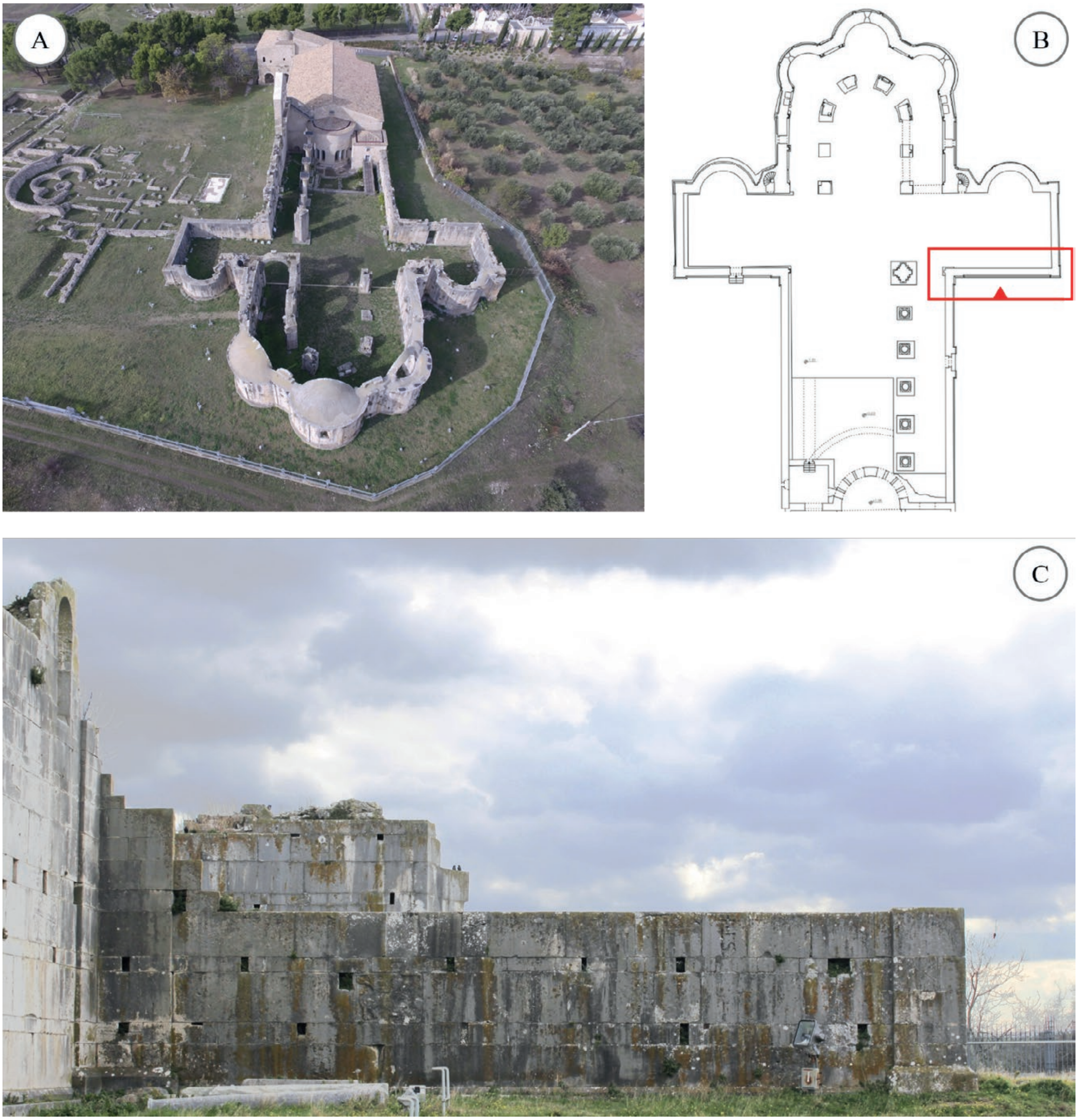

Figure 1. Complex of the Most Holy Trinity in Venosa (Southern Italy): A) Aerial view of the abbey site; B) Unfinished Church floor plan and identification of the case study; C) Case study: Southwest façade of the Unfinished Church. (Source: elaboration by the authors).

The ancient church underwent significant modifications, influenced by the Lombards in the 10th century and the Normans in the 11th and 13th centuries. In 1059, Pope Nicholas II consecrated the abbey, establishing it as a shrine for the Hauteville family at Robert Guiscard's request. By 1297, the Order of Malta took custodianship of the complex, though the construction of the new church was never completed. Today, the complex remains an exceptional example of medieval architecture, offering a valuable insight into the construction techniques and cultural influences that shaped the region over centuries [25].

2. METHODOLOGY

The workflow, as shown in Figure 2 begins with the generation of a point cloud representing the wall face of the unfinished church, derived from high-resolution photographic images, with a particular focus on its classification using Agisoft Metashape Pro 1.5.0 software. The methodology utilises RGB data to identify and delineate regions exhibiting surface alterations accurately. These phenomena, represented as point clouds, are subsequently converted into polygonal meshes to facilitate the calculation of degradation surfaces – an analysis that would not be feasible using point clouds alone.

Next, automatic degradation recognition is conducted through the analysis of the UV texture, extrapolated from the polygonal mesh generated from the complete RGB point cloud. This process employs two AI algorithms: Fast Random Forest (FRF), implemented via the open-source software FIJI 1.52r, and K-NN, customised within the MATLAB environment. The three degradation analysis methods – one based on colour detection from the point cloud and two on texture analysis – are then compared to assess their effectiveness.

2.1 Building the Point Cloud and the Polygonal Model

The first step involved the construction of the 3D point cloud of the southwest façade of the Unfinished Church using photogrammetric techniques. A Canon EOS 1200D DSLR camera and a Phantom DJI 3 Professional drone captured 269 images for model reconstruction, with a maximum distance of 10 metres from the surface and an 80% overlap between adjacent shots in both directions. The images were preprocessed using Adobe Photoshop's Camera Raw plugin to optimise exposure, contrast, saturation, sharpness, and white and black balance. The images were then imported into Agisoft Metashape Pro for digital processing and 3D spatial data generation. Initial image alignment was performed automatically by the software through the detection of tie points. In cases of misalignment, additional tie points were manually added.

To verify the alignment accuracy, both automated and manual methods were employed, generating a sparse point cloud. Once the alignment was refined, a dense point cloud of approximately 64 million points was generated, later reduced to 40 million by removing irrelevant sections. The point cloud was scaled to real-world dimensions based on on-site measurements. A textured polygonal mesh consisting of approximately 8 million faces was then created, and an 8192×8192 pixel UV map was extracted, which was subsequently downscaled to 1024×1024 pixels for surface alteration analysis.

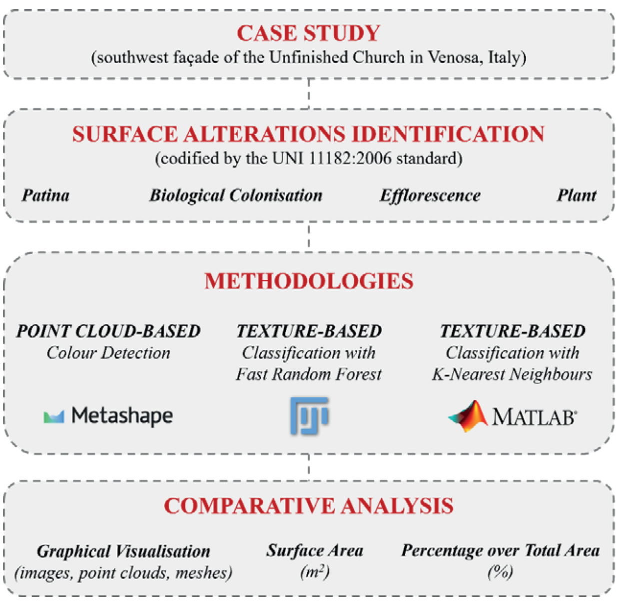

Figure 2. Methodological Workflow. (Source: elaboration by the authors).

2.2 Colour-Detection on the Point Cloud

Starting from the reconstruction of the dense point cloud, Metashape software was used to identify and extract point sets based on uniform chromatic features, aiming to create a degradation map. During the analysis, four types of surface alteration phenomena were detected, as defined by the UNI 11182:2006 standard 'Cultural Heritage - Natural and Artificial Stone - Description of the Alteration - Terminology and Definition' [26] and the Illustrated Glossary on Stone Deterioration Patterns [27]:

i. Patina: 'Chromatic modification of the material, generally resulting from natural or artificial ageing and not involving in most cases visible surface deterioration';
ii. Biological Colonisation (or Biological Patina): 'Colonisation of the stone by plants and micro-organisms such as bacteria, cyanobacteria, algae, fungi and lichen (symbioses of the latter three). Biological colonisation also includes influences by other organisms such as animals nesting on and in stone';
iii. Efflorescence: 'Generally whitish, powdery or whisker-like crystals on the surface. Efflorescences are generally poorly cohesive and commonly made of soluble salt crystals';
iv. Plant (or Vegetation): 'Vegetal living being, having, when complete, root, stem, and leaves, though con-

sisting sometimes only of a single leafy expansion (e.g. Tree, fern, herb)'.

The software enabled the classification of degradation types within the point cloud by detecting representative points based on RGB values (red, green, and blue), which were used to map surface alterations. Subsequently, the algorithm was trained to segment the point cloud automatically, using conditional statements to identify points based on defined colour criteria. Specifically, the procedure for tie point selection based on colour intensities involved several key steps.

First, the script accessed the active document and chunk in Metashape, importing the necessary libraries and retrieving the point cloud and track data. Colour parameters ('r', 'g', 'b') and a tolerance value were defined to set the range for selecting points based on their colour. The script then iterated through the point cloud, selecting points whose colours fell within the specified range, considering the tolerance. Once the points were selected, the Metashape interface was updated to reflect the changes, completing the point identification process.

For the manual selection, ten groups of representative points were annotated for each degradation type, which facilitated the definition of a tolerance range for automated segmentation and the extraction of semantic point cloud classes. Finally, polygonal meshes were generated from these surface alteration classes. These continuous three-dimensional models, composed of networks of flat surfaces oriented in space, enabled the calculation of areas affected by various degradation patterns, while turning off mesh interpolation to prevent the artificial insertion of data into areas that are effectively voids or gaps (Figure 3).

2.3 Texture-based Classification on the Polygonal Model with Fast Random Forest Algorithm

To assess the effectiveness of various automated methods for identifying superficial alterations on stone surfaces, image processing techniques were applied to the 3D model of the church, focusing on texture features associated with degradation. A textured polygonal mesh

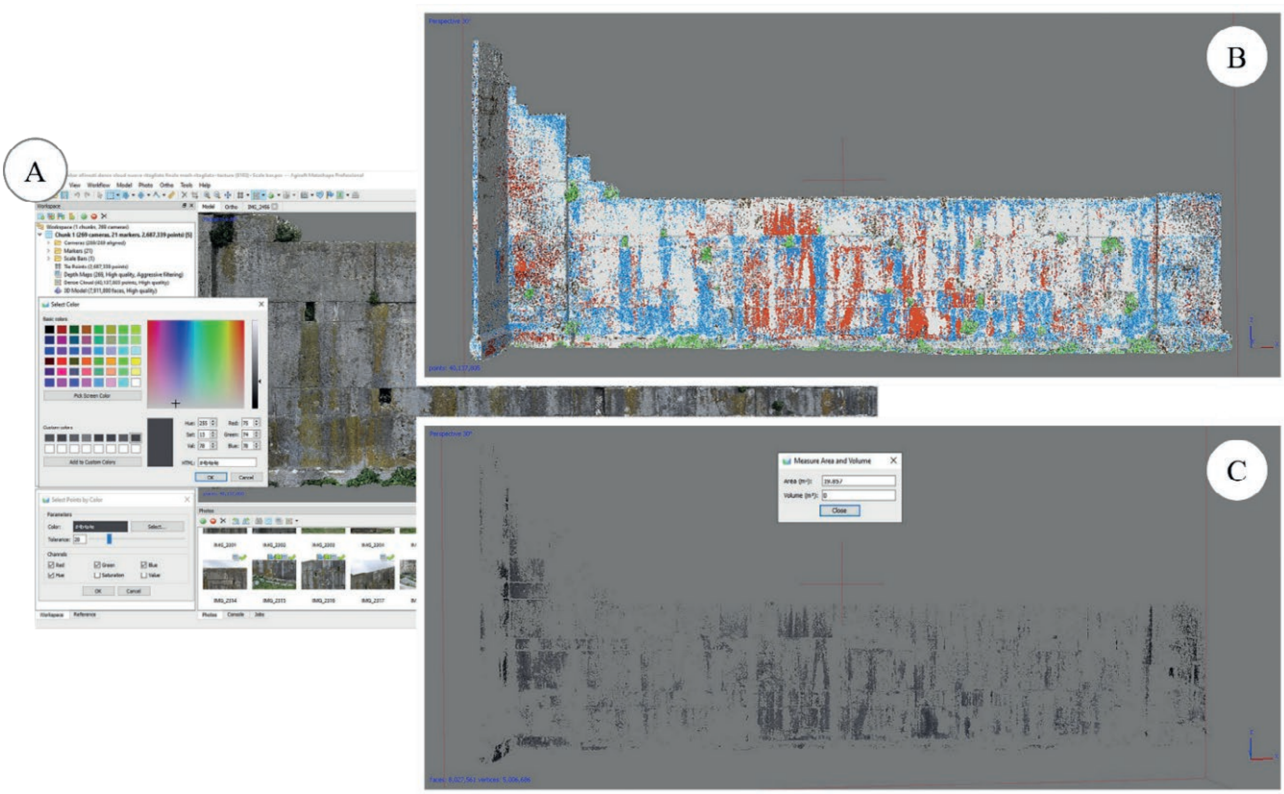

Figure 3. Point cloud colour-detection for surface alteration phenomena within the Metashape environment: A) Manual selection of representative points in the RGB scale for each alteration; B) Semantic point cloud with alteration classes ('patina' in red, 'biological colonisation' in blue; 'efflorescence' in brown, 'plant' in green; C) Example of extracting surface measurements from the 'patina' mesh. (Source: elaboration by the authors)

of the façade was created using Metashape Pro software, followed by the extraction of a UV map. UV mapping transforms the 3D model, defined by points with x-y-z coordinates, into a 2D surface represented by u-v coordinates. This facilitates the arrangement of the model's polygons on a 2D plane for analysis.

The UV map of the façade was then imported into FIJI®, an open-source image processing software based on the Java programming language. To ensure accurate classification, a reference scale was established by inputting measured distances between targets on the Metashape-processed model, correlating pixel-based measurements with the actual physical dimensions. The software automatically converted the 1024×1024 pixel RGB image into a metric scale of 10.68×10.68 metres. The FRF algorithm, a variant of the RF framework, was used for texture-based classification via the Trainable WEKA Segmentation plugin [28]. FRF optimises the traditional RF method by reducing training time while maintaining high predictive accuracy, making it computationally efficient for large datasets.

Specifically, FRF constructs an ensemble of decision trees, where each tree is built from a random subset of the training data. Key aspects of the algorithm include:

- Decision Trees: Each tree splits the data recursively based on impurity measures like Gini impurity or information gain, aiming to reduce uncertainty at each node.
- Random Feature Selection: For computational efficiency, only a random subset of features is evaluated at each split, which helps to reduce the complexity of the model without sacrificing accuracy.
- Ensemble Learning: The classification is determined by majority voting across the trees in the ensemble, improving generalisation and robustness.
- Statistical Foundation: The algorithm seeks to minimise impurity at each split, with the goal of creating nodes that are as homogeneous as possible, thereby increasing the purity of the resulting subsets.
- Final Prediction: The output class for a given input is the one that receives the most votes from all decision trees.

In this study, the classifier was configured with 200 trees and two random features per node, balancing computational efficiency and classification accuracy.

During classification, regions of interest (ROI) were manually selected for each texture type, including 'Patina', 'Biological Colonisation', 'Efflorescence', 'Plant', 'No Pathology', and 'Background'. Each texture class was represented by ten training regions. The classification process yielded a 32-bit UV map, which was subsequently converted to an 8-bit image for more efficient manipulation. Probability maps, highlighting areas of degradation in red, were then generated. A black and white binary conversion process was applied to separate objects from the background, with threshold values calculated iteratively until they surpassed the mean pixel value.

The surface areas of the identified degradation features were calculated by defining pixel area ranges (in m^2) and excluding irrelevant areas of the image using circularity values, which quantify the shape of the objects, where a value of 1.0 corresponds to a perfect circle, and values approaching 0.0 indicate more elongated or irregular shapes. Figure 4 shows the entire texture-based process.

2.4 Texture-based Classification on the Polygonal Model with K-Nearest Neighbours Algorithm

In addition to the FRF method, an exploratory study was conducted using the K-NN algorithm, implemented within the MATLAB environment, to classify UV textures extracted from the 3D model of the church. The K-NN algorithm works by calculating the Euclidean distance in an n-dimensional space between the target pixel and the training data points, where n corresponds to the number of attributes used in the classification. Unlike traditional nearest-neighbour methods, K-NN classifies a target based on the majority vote of the k-nearest neighbours, thus improving robustness to outliers and noise within the dataset.

The classification process (Figure 5) involved several key steps:

- Image Preprocessing: The source RGB image is first visualised, and its pixel dimensions, as well as its real-world size in metres, are defined. This enables a direct link between the image's spatial resolution and actual object dimensions.
- Selection of Regions of Interest (ROIs): For each class, the user manually selects at least 10 example regions directly from the image. These regions are stored in the 'sample_regions' cell array, marking the positions of selected regions that represent each class. This step is essential for capturing the class features, particularly when they are difficult to model mathematically.
- Colour Space Conversion: The RGB image is converted to the L*a*b* (CIELAB) colour space. This transformation separates the chromatic components ('a*' and 'b*') from the brightness ('L*') component, thus improving the algorithm's ability to capture colour variations while reducing the influence of lighting conditions.
- Classification Using K-NN: For each pixel, the Euclidean distance to the mean values of each class

Figure 4. Texture-based classification process using Fast Random Forest within the FIJI environment: A) Training and pre-classification stages in the 32-bit UV map; B) Final classification results in the 8-bit UV map ('patina' in red, 'biological colonisation' in blue, 'efflorescence' in pink, 'plant' in green, 'no pathology' in yellow, 'background' in purple); C) Generation of probability maps; D) Particle analysis for calculating the area of alterations based on circularity. (Source: elaboration by the authors)

in the 'a*' and 'b*' colour channels is computed. The pixel is then assigned to the class of its k-nearest neighbours, with *k=3*. This choice of k balances local sensitivity *(k=1)* and robustness to noise *(k>1)*, making it ideal for accurately classifying the image's local features.

– Visualisation of the Classified Image: Once classified, a colour-coded image is generated, with each class represented by a specific colour. This coloured representation provides a clear visual interpretation of the classified results.
– Scatter Plot in the 'ab' Colour Space: A scatter plot is created to visualise the distribution of classified pixels in the 'a*' and 'b*' colour channels. This plot reveals the separability of the classes and aids in identifying any overlaps or clear distinctions in the data.
– Calculation and Visualisation of Percentage Areas: The number of pixels and the corresponding area (in square metres) for each class are calculated. These values are then converted into percentage areas relative to the total surface area, providing a quantitative measure of the spatial distribution of the various degradation types.

3. RESULTS

The outcomes of the degradation mapping are presented through graphical representations, surface area measurements, and percentage values relative to the total examined area. A comparative analysis is conducted across three proposed classification methodologies: Point Cloud (PC) Colour-based, Texture-Based with FRF, and Texture-Based with K-NN. The results include both the classified point cloud and the polygonal meshes onto which the UV textures classified by the two texture-based methods were reprojected (Figure 6 and Figure 7). To enhance the clarity and consistency of visual interpretation, uniform colours were assigned to each class across all methodologies: 'Patina' (pure red), 'Biological Colonisation' (cyan), 'Efflorescence' (magenta), 'Plant' (pure green), and 'No Pathology' (pure grey).

From a visual quality perspective, significant progress has been achieved in identifying patterns corresponding to different degradation phenomena, leveraging classifications derived from the dense point cloud. However, it is important to acknowledge that classification, while robust, is not entirely unequivocal. Lower accuracy or a reduced dataset can introduce errors, leading to the representation of a segmented region under multiple labelled classes. The texture-based approach,

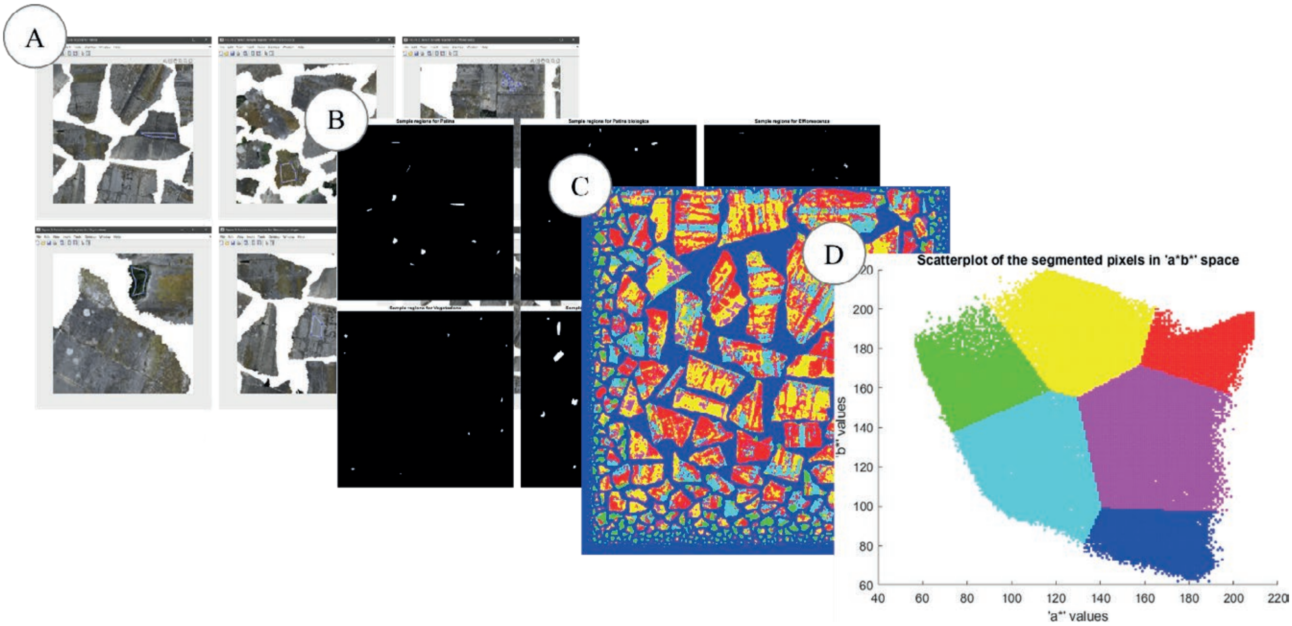

Figure 5. Texture-based classification process using K-Nearest Neighbours within the MATLAB environment: A) Examples of region of interest (ROI) for each class; B) Sample regions for each class; C) Classified image in the RGB colour space ('patina' in pure red [255 0 0], 'biological colonisation' in cyan [0 255 255], 'efflorescence' in magenta [255 0 255], 'plant' in pure green [0 255 0], 'no pathology' in yellow [255 255 0], 'background' in pure blue [0 0 255]); D) Scatter plot of the segmented pixels in the a*b* space and visualisation in the RGB space (with the same colour conventions). (Source: elaboration by the authors).

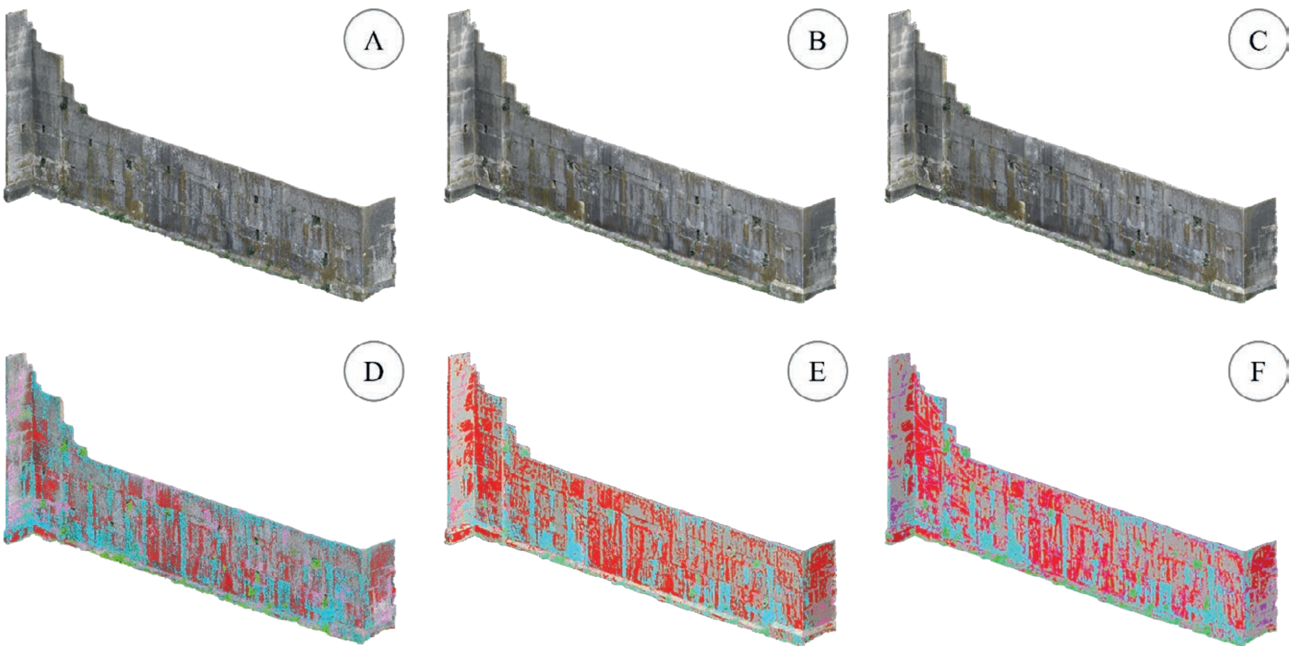

Figure 6. Visual representation of the initial data (point cloud or mesh) alongside the final classified results: A) Point cloud; B-C) Polygonal mesh; D) Classified point cloud; E) Classified mesh with FRF; F) Classified mesh with K-NN. (Source: elaboration by the authors)

implemented using both FRF and K-NN, aligns visually with the point cloud colour-based method but encounters specific challenges, particularly in accurately identifying the Efflorescence phenomenon. A slight misclassifi-

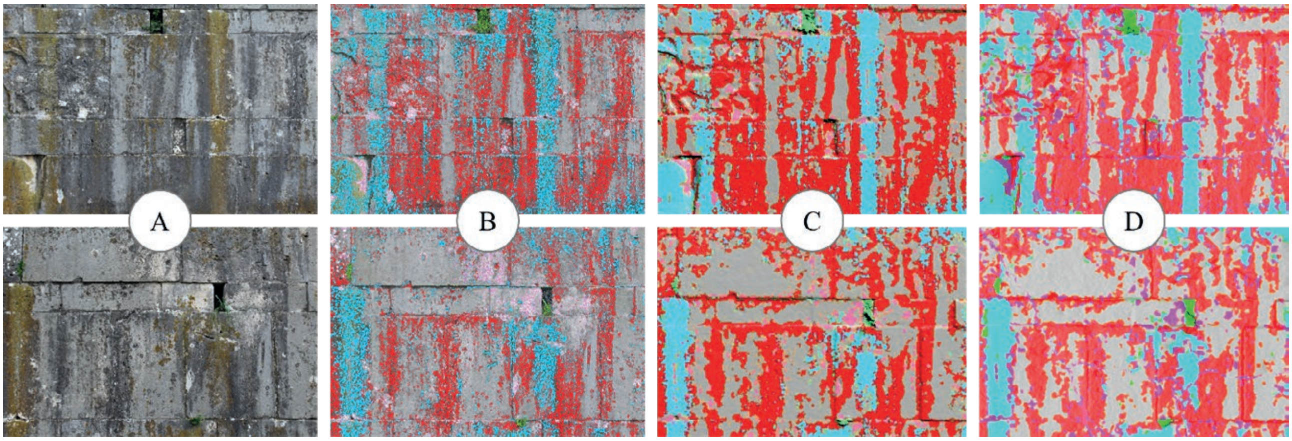

Figure 7. Detailed visual representation: A) Original image; B) Classified point cloud; C) Classified mesh with FRF; D) Classified mesh with K-NN. (Source: elaboration by the authors),

Table 1. Results of the degradation mapping with the three approaches: Point cloud colour-detection (PC), Texture-based classification with Fast Random Forest (FRF), and Texture-based classification with K-Nearest Neighbours (K-NN).

Type of Degradation	Surface Area (m^2)			Percentage over Total Area (%)		
	PC	FRF	K-NN	PC	FRF	K-NN
Patina	19.86	20.02	18.10	33.03	33.33	30.15
Biological Colonisation	10.02	10.26	12.21	16.67	17.08	20.33
Efflorescence	5.36	5.56	4.45	8.92	9.27	7.42
Plant	5.59	5.75	5.22	9.30	9.58	8.68
No Pathology	19.29	18.47	20.07	32.09	32.75	33.42

cation is observed due to potential confusion with plant-origin substances secreted by lichens within the Biological Colonisation category. However, the Patina and Plant phenomena are more precisely recognised, especially when employing the FRF method.

A quantitative evaluation of the three mapping approaches reveals significant variations in the estimated areas of degradation categories (Table 1).

In the point cloud colour-based method, 'Patina' emerges as the most prominent category, covering 33.03% of the total surface, closely followed by 'No Pathology' at 32.09%. Other categories exhibit a balanced distribution, with 'Biological Colonisation' and 'Efflorescence' accounting for 16.67% and 8.92%, respectively, while 'plant' covers 9.30% of the area. The FRF Texture-based approach maintains 'Patina' as the dominant category at 33.33% but introduces a notable redistribution of the remaining categories. 'Biological Colonisation' increases slightly to 17.08%, while 'Efflorescence' and 'Plant' show increments to 9.27% and 9.58%, respectively. 'No Pathology' experiences a minor decline to 32.75%. The K-NN Texture-based approach exhibits substantial variations, with 'Biological Colonisation' emerging as the dominant category at 20.33%, surpassing 'Patina' (30.15%). 'Efflorescence' significantly decreases to 7.42%, while 'Plant' and 'No Pathology' maintain stable proportions at 8.68% and 33.42%, respectively.

A comparative analysis (Figure 8) highlights that the point cloud colour-based approach results in a relatively balanced distribution among degradation categories, with 'Patina' and 'No pathology' in near equilibrium. The FRF approach indicates an increased estimation of 'Plant' and a redistribution of other categories compared to the colour-based method. In contrast, the K-NN approach exhibits a significant shift, with 'Biological Colonisation' taking precedence and notable fluctuations in other surface estimations.

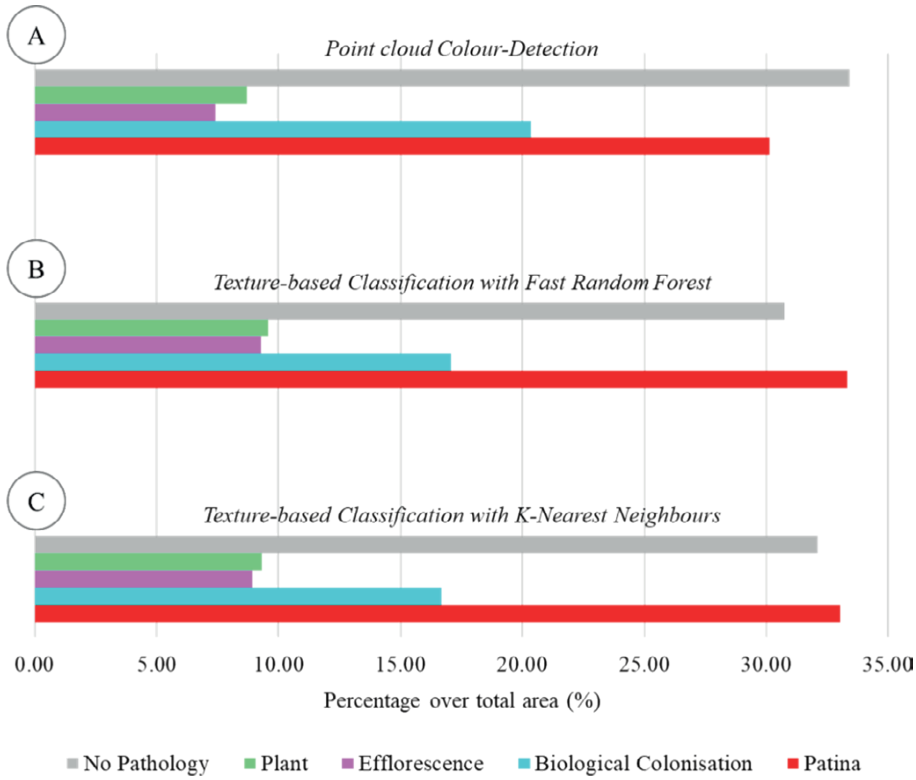

Figure 8. Comparative analysis of three classification approaches based on the percentage of surface area occupied across the stone masonry. (Source: elaboration by the authors)

4. LIMITATIONS OF THE RESEARCH

This study has demonstrated the potential of integrating AI into Built Heritage, particularly through semi-automated processes for extracting chromatic properties from point clouds and photorealistic 3D models. However, several limitations must be acknowledged.

One of the key limitations was the lack of a universally accepted objective criterion for classification assessment, as no absolute ground truth was used in the comparative analysis. Furthermore, point cloud classification, while providing valuable insights, often requires case-by-case evaluation during the interpolation of polygonal meshes to ensure accurate surface calculation and prevent errors such as missing areas or distortions in the final output.

The methodologies employed also exhibit varying levels of accessibility. Open-source tools like FIJI perform exceptionally well despite being free, offering a high degree of functionality and flexibility for many applications, especially when compared to proprietary software like Metashape, which, although more expensive, tends to be more limiting in this case. Moreover, using dedicated programming languages allows for high customisation, but this requires advanced technical expertise and a significant initial investment in algorithm development.

Another important consideration is the inherent variability of the data during the training process, as human supervision remains essential, particularly in the initial stages of data selection and annotation, to ensure that the colour and textural characteristics employed are accurate and meaningful.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The integration of semi-automated processes for extracting chromatic properties from point clouds and 3D models represents a significant advancement in automation and efficiency. Nonetheless, while this study has primarily focused on the final classification outcomes, future research will emphasise the adoption of standardised and robust criteria to ensure a more objective and precise assessment of model performance.

Moving forward, further advancements are anticipated in the integration of semantic data within Scan-to-BIM modelling platforms. Point clouds capturing the spatial extent of degradation or textures representing surface conditions will be effectively incorporated into BIM models. These semantic data layers will be mapped to specific building elements, such as walls, providing a more precise and contextualised representation of deterioration.

By associating these degradation markers with relevant material properties, historical data, and construction techniques within IFC-compatible digital formats, BIM will facilitate more informed decision-making for conservation and restoration efforts while ensuring seamless interoperability with advanced analytical tools. This integration will further strengthen heritage monitoring and conservation, enhancing the ability to preserve historic buildings more effectively.

Moreover, future research will greatly benefit from the integration of cutting-edge technologies, including SAM, Generative Adversarial Networks (GANs), and advanced DL frameworks. These innovations are expected to enhance both the accuracy and automation of degradation diagnostics, ultimately enabling more data-driven and efficient heritage preservation strategies.

6. AUTHORS CONTRIBUTIONS

Michele Buldo: Conceptualisation, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – original draft preparation, Writing – review and editing, Visualisation, Project Administration, Funding Acquisition. Fabio Fatiguso: Conceptualisation, Methodology, Investigation, Resources, Writing – review and editing, Visualisation, Supervision, Project Administration, Funding Acquisition. Elena Cabrera-Revuelta: Conceptualisation, Methodology, Investigation, Resources, Writing – review and editing, Visualisation, Supervision, Project Administration, Funding Acquisition. Cesare Verdoscia: Conceptualisation, Methodology, Investigation, Resources, Writing – review and editing, Visualisation, Supervision, Project Administration, Funding Acquisition.

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Tabarca Building Renovation Project: A Historical Perspective in Genoa's Port

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Abstract. The revitalization of long-disused sites with a focus on production activities is a critical endeavor for the preservation and integration of such sites into the urban fabric, a challenge that Italy also faces. Buildings once deemed "modern" are now key markers of local historical and economic evolution, yet the process of their revitalization demands both careful study and practical solutions. Any effort to adapt these structures must balance conservation with modern functionality, ultimately hinging on the broader theme of restoration and reuse. The Tabarca Building in Genoa serves as a paradigmatic case in point, given its profound cultural significance for both the city and the nation. It was the inaugural facility in Italy to incorporate refrigeration technology for the preservation of goods, a groundbreaking innovation in the early 20th century that profoundly reshaped global commerce and gave rise to new architectural forms. Despite its notable legacy, the full potential of the Tabarca Building remains largely underappreciated. This paper demonstrates that restoration and repurposing work on this historic warehouse highlights the importance of forward-looking interventions, ensuring heritage buildings remain both relevant and respectful of their unique characteristics and surrounding context.

Keywords: Architectural Engineering, Adaptive Reuse Strategies, Maritime Architectural Heritage, Integrated Multidisciplinary Approach, Traditional Building Techniques.

1. INTRODUCTION

The transformation of decommissioned industrial areas into spaces integrated within the modern urban fabric represents one of the most complex and stimulating challenges for contemporary architecture. The process of repurposing such areas is particularly critical in port zones, which retain significant historical and industrial heritage. With the advent of the post-industrial era, many of these spaces have undergone a gradual decline, raising urgent questions about their redevelopment and reactivation. In Italy, as in the rest of Europe, the renewal of these areas not only addresses the challenges of urban decline but also presents an unprecedented opportunity to reimagine the use of built heritage and promote more sustainable and inclusive territorial planning [1].

In Europe, cities such as London, Liverpool, and Hamburg serve as emblematic examples of port area transformation. In London, Canary Wharf stands as a significant example of profound territorial renewal: while some historic buildings were preserved for museum purposes, most pre-existing structures were demolished to make way for a new financial district. The process of urban regeneration radically transformed the area, leaving only the docks as remnants of the original conurbation. The connection between the industrial past and the new financial district is therefore primarily intangible, marked by the continuation of the area's production vocation [2]. In stark contrast, other cities have opted for a more conservation-focused approach to regenerating their port areas. Liverpool's Albert Dock and Hamburg's Speicherstadt are excellent examples of how historical memory can be preserved through targeted repurposing interventions that respect the existing urban fabric. These sites, listed as UNESCO World Heritage Sites, effectively demonstrate how industrial heritage can be valued and integrated into the contemporary urban landscape [3, 4].

In Italy, the transformation of decommissioned port spaces poses a critical challenge for urban planning in major coastal cities. Genoa, the second-largest Italian port by cargo traffic [5], offers a striking example. Historically, the Port of Genoa has always been the city's beating heart, significantly influencing its urban development. The first major urban reconversion and port space reuse initiative materialized with the project coordinated by architect Renzo Piano for the Old Port (Porto Antico) during the 1992 Expo, held to celebrate the 500th anniversary of the discovery of America. This intervention transformed the Old Port area into a vibrant urban center, combining new constructions such as the Piazza delle Feste and the Genoa Aquarium with the restoration of monumental structures such as Porta Siberia and the Palazzine del Porto Franco, as well as the repurposing of abandoned warehouses like the Cotton Warehouses (Magazzini del Cotone) and the Millo Building [6].

The successful transformation of the Old Port inspired, in subsequent years, the redevelopment of the Darsena, a previously decommissioned port area whose urban recovery process is still ongoing. Originally developed at the end of the 19th century, the modern Darsena functioned for decades as a vital logistics hub for goods arriving at the Port of Genoa, yet it remained isolated from the surrounding urban context despite its central location within Genoa's historic center. Despite numerous proposed redevelopment projects, many of which were never realized [7], the area's revival began only in 1995 with the opening of the Faculty of Economics and Commerce in the Scio District, designed by architects Aldo Pino and Aldo Luigi Rizzo. This intervention emulated the success of the Faculty of Architecture redevelopment by Ignazio Gardella, which had already initiated a virtuous regeneration process in Genoa's historic center. The area subsequently benefited from further interventions, such as the transformation of the Galata District into the Museum of the Sea and Navigation in 2004, designed by Guillermo Vázquez Consuegra, and the conversion of the Cembalo District into residential spaces in 2005, executed by Enrico Bona. Despite these developments, some structures remain abandoned, highlighting the persistent challenges in urban redevelopment processes [8]. Among these, the Tabarca District, built at the end of the 19th century as the site of Italy's first refrigerated warehouse, is an example of significant historical value awaiting adequate recovery. A historical and typological analysis is essential to appreciate not only the building's history but also its potential for transformation within the current urban context.

This study aims to examine the Tabarca building using a methodological approach that integrates multiple scales and disciplines, exploring its topographical context and historical, economic, and functional aspects. The objective is to provide a comprehensive overview of the building by analyzing its location within Genoa's urban fabric, its historical-functional context, its current state, and the ongoing repurposing project. This investigation aims to highlight the historical legacy of the Tabarca District and offer a model for the recovery of similar structures in Italian and European port cities.

2. METHODOLOGY

The conservation of historic buildings always requires following a precise interdisciplinary approach, which means following a method. The concept of a "methodological approach" means following specific phases in sequence and interacting with each other, then allowing an intervention on the building without creating information gaps that could then compromise the result. It is a fundamental theme that cannot be avoided in the knowledge, intervention, and valorization of buildings.

The object of this study, the Industrial complex of Tabarca, presents itself simultaneously as a single element and as part of a contextual complex (the Darsena), which must be understood in all its aspects: historical, functional, geometric, and topographical. Without this framework, it would also be difficult to implement an authentic restoration project and, above all, enhance the property's characteristics. In line with this aim, a team of specialists examined the various aspects of the property in an integrated manner. This approach involved integrating multiple surveys, each conducted with its own precise methods.

Firstly, the contextual and topographical framework was defined, since, as mentioned, the building cannot be understood as a "white elephant" but as part of an essential historical economic system, such as the Genoese Darsena. Then, an analysis of the historical features was carried out, as the Tabarca building is a fundamental emblem for the history of cold storage; the analyses concerned a targeted study on the functional system that was crucial also to compare with other similar structures to deduce their origins and models; this research has mainly acted through bibliographic and archival funds. Lastly, the work included an analysis of the current state, involving a technical construction assessment of the structural condition, the state of conservation, and a geometric survey.

3. DISCUSSION AND RESULTS

3.1 Historical Development of the Darsena Area

The industrial archaeology building that is the subject of this study does not represent an isolated architectural element separated from its context; on the contrary, it is part of an important organic system of multi-layered buildings born in response to common and connected policies. The context in question is the Genoese port of Darsena (Figure 1).

The maps and historical documents were fundamental for this purpose. The area was used as a port from the end of the 13th century. From this moment, its history and growth officially started [9-11].

During the 15th and 16th centuries, the layout of the area was planned in a more specific way by the Consuls of the Municipality of Genoa: on the north-west side there is the arsenal, in the central area there is the "Darsena delle Galere" and on the south-east side the "Darsena del Vino", the latter is separated from the previous part thanks to a north-south pier. This moment coincides with a period of great prosperity for the maritime Republic of Genoa.

In the 17th century, a slight modification was documented in the area between the Arsenale and the Darsena delle Galere. In this part, a large structure characterized by a series of arches was inserted, probably used as warehouses and workshops (Figure 2).

Military use was the primary vocation of the place, and as a consequence, the arsenal and the military services were the key points for the area. The context maintained its characteristics unchanged until the end of the 18th century. The area continued to be divided into the Carenaggio Darsena, the Galee Darsena, where galleys for both military and commercial uses were moored and the Arsenale, where the galleys were equipped for war [12].

In 1870, the municipality of Genoa obtained the transfer of the Darsena, which brought about a radical transformation. In fact, in 1873, the area was converted to commercial use and definitively lost its military value. This event is responsible for the subsequent construction of the Tabarca building, the subject of this study, and

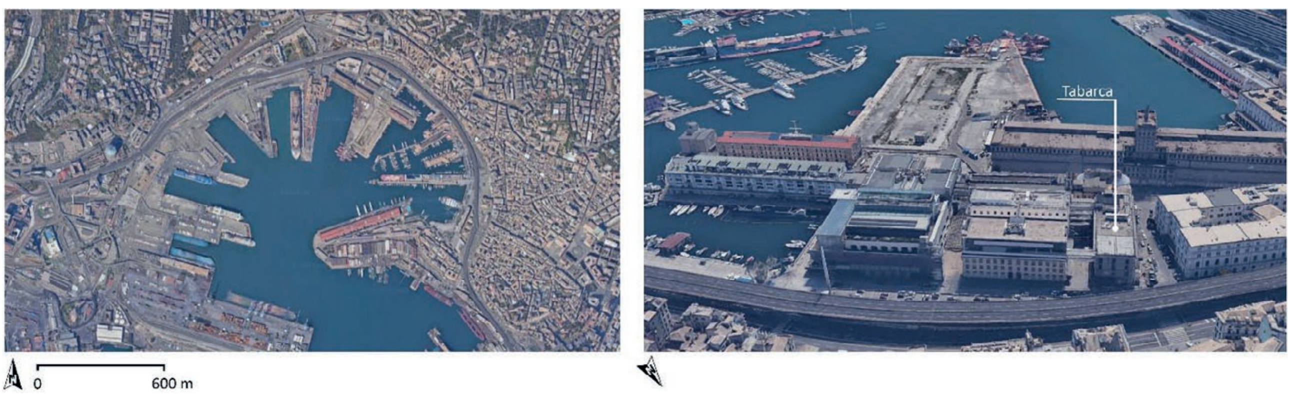

Figure 1. Satellite image of the Porto Antico area of Genoa (on the left); general view of the Darsena area with indication of the Tabarca building (on the right). (Source: Google Earth, elaboration of the Authors).

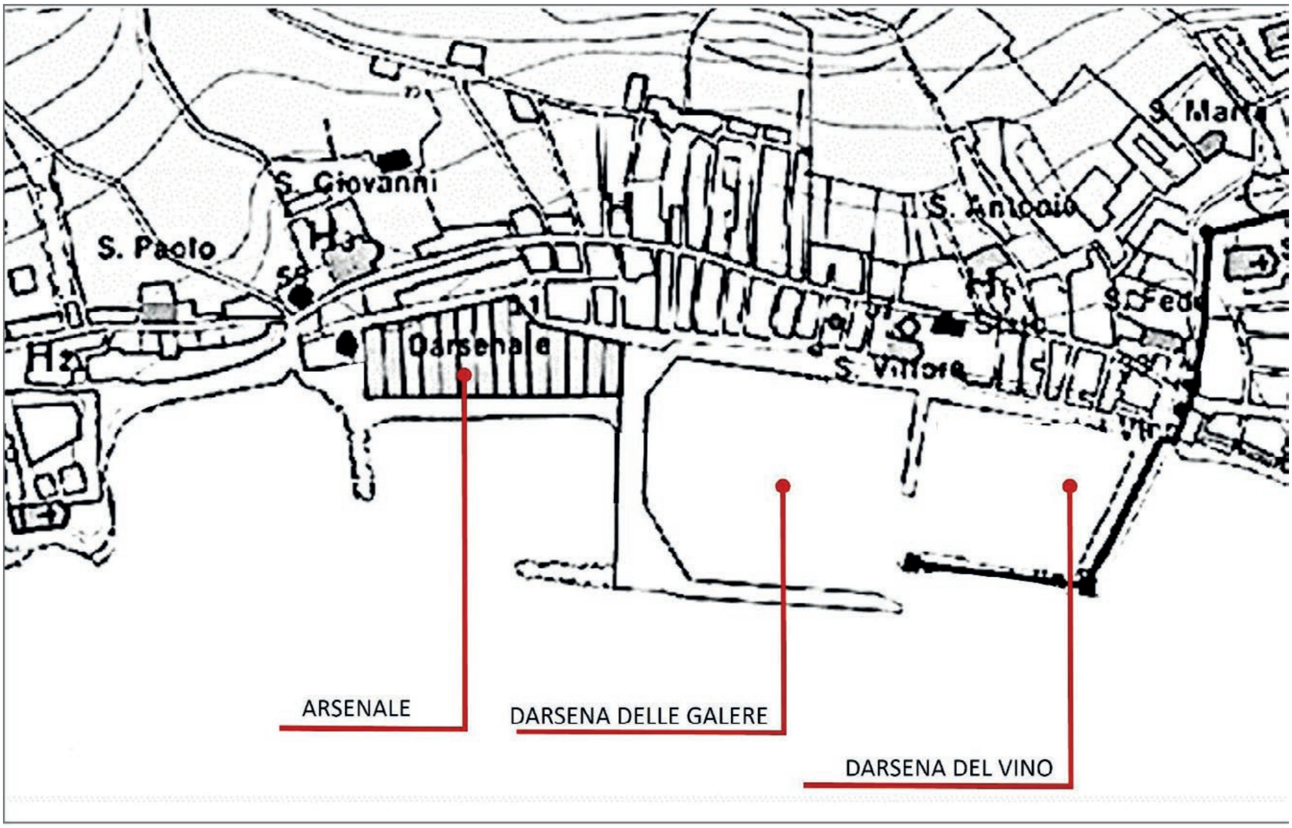

Figure 2. Darsena area in the 15th century. (Source: Elaboration by the Authors).

many other transformations in the area. In 1889, a comprehensive project to arrange the area was approved. The Tabarca, which is part of this scheme, was built between 1895 and 1898 [13].

In addition to this building, warehouses, and neighborhoods were built that took their names from the Genoese colonies: Cembalo, Scio, Galata, Metelino, Caffa, and Farmagosta (destroyed to make way for the Sopraelevata). The modifications continued after the First World War, when there was a need for more space. To facilitate this, the series of works to raise the buildings began in 1921.

An important moment for the Tabarca building came in 1923 when the Municipality of Genoa signed an agreement with the Società dei Magazzini Frigoriferi Genovesi for the raising of the Scio district and the installation of a new Frigorifero to replace the one in the Tabarca district. From this moment on, the structure took on the main connotation that would characterize it until the present day and that also connects it to the other structures, all of which were designed to fulfil the same purposes and destinations [14].

In conclusion, examining the history of the single building and the entire context (Figure 3), as briefly described, two important phases can be summarized: the first, of a military nature; the second, of an economic nature. The building subject to this study falls within this second phase, which should be seen not only as a single structure but also as part of an organic system. This system has made the Genoese Darsena unique in terms of its characteristics, history, and composition [15].

3.2 Historical Framework of the Building Typology

At the start of the 20th century, the Quartiere Tabarca assumed a distinct role within the Genoese port as the site of Italy's first refrigerated warehouse dedicated to food storage [16]. Examining the state of the refrigeration industry during this period is crucial to understanding how engineering disciplines tackled the challenges presented by this innovative building typology. Such an analysis sheds light on the structural and technical features of the Quartiere Tabarca.

Interest in industrial refrigeration began in the 19th century, particularly in its latter half, with the invention and mass production of early refrigeration systems. These systems relied on cooling achieved through

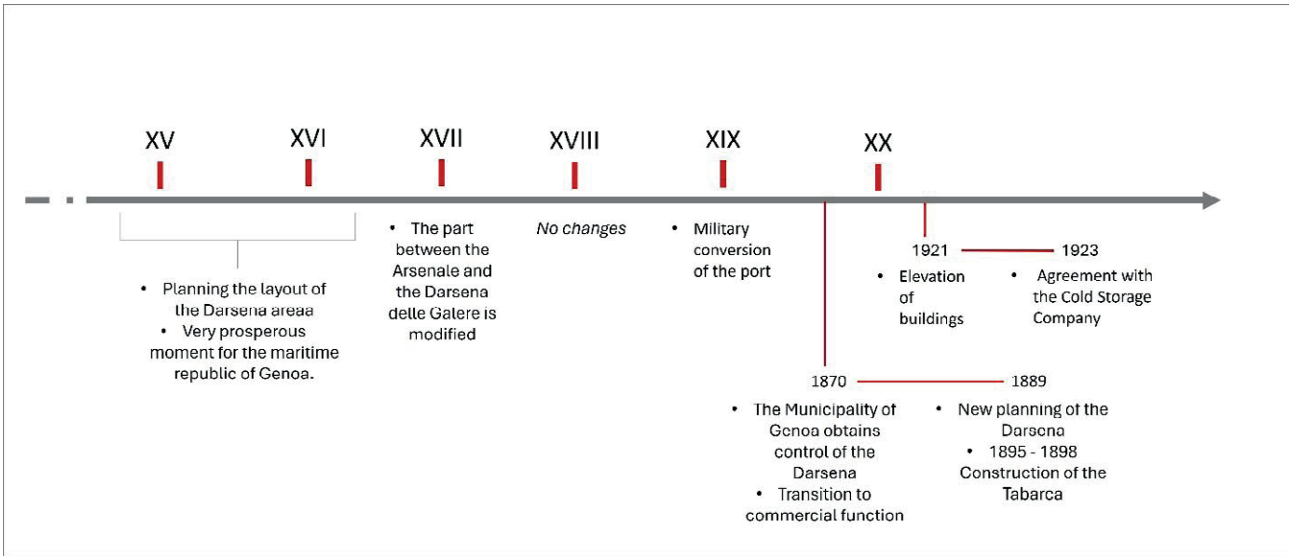

Figure 3. Timeline of the main events that characterize the historical evolution of the Darsena and the building known as the Tabarca. (Source: Elaboration by the Authors).

the compression and expansion of specific refrigerants. Initial technologies used ammonia and sulfur dioxide due to their ability to liquefy under pressure. However, ammonia was gradually phased out because of its corrosive properties and health risks. Alternatives such as carbon dioxide and methyl chloride, though safer for humans, introduced technical challenges due to the high operating pressures required [17].

Various methods were employed to cool storage rooms. One involved piping refrigerant gases directly into the storage areas, offering high efficiency but posing risks of gas leakage that could harm both stored goods and personnel. Another approach utilized refrigerants to cool a non-freezing liquid circulated through coils along the ceilings of storage rooms. This method required forced ventilation to prevent frost accumulation, which could disrupt optimal environmental conditions for food preservation [18]. A third technique used brine solutions to cool air circulated into storage rooms through wooden ducts. This method capitalized on convective airflows driven by density differences between hot and cold air [19].

The construction of refrigerated warehouses necessitated the adoption of novel building techniques to achieve unprecedented performance levels. Insulation materials became critical, selected for properties such as resistance to moisture, non-flammability, and resistance to pests. Early methods involved creating air gaps between cold storage rooms and exterior walls using lightweight bricks known as "voids" (Figure 4a). Subsequently, cork elements, particularly corkboard, were used to fill wall cavities, though this approach proved costly and difficult to implement (Figure 4b) [18]. This challenge led to the development of compressed cork panels patented by Grunzweig and Hartmann of Ludwigshafen. Marketed under the brand "Reform," these panels were praised for their ease of installation and mechanical reliability, making them suitable for insulating floors and roofs. Alternative materials included pumice, peat, vegetable or mineral charcoal, often used in loose form as fillers for vaulted ceilings. Advances in insulation materials also enabled lightweight construction of cold rooms using timber frames combined with insulation layers and external claddings [20].

Flooring materials in cold rooms were selected for durability, waterproofing, and ease of cleaning. Asphalt was initially used but was later replaced by cement-based screeds, offering higher mechanical performance. Linoleum, patented in the 19th century, provided another option, offering ease of maintenance, though it remained more expensive than cement-based alternatives [18]. Roofs in masonry cold stores typically consisted of metal I-beams supporting solid brick vaults, topped with a lightweight concrete layer mixed with cork or peat for improved thermal performance. The interiors of cold rooms were finished with washable cement plaster or enamel coatings, with enamel more common in English-speaking regions.

Doors and windows in cold storage facilities were designed for airtight sealing, with wooden doors large enough to accommodate foodstuffs. Lighting solutions varied between European and American contexts. French, British, and American cold stores lacked natu-

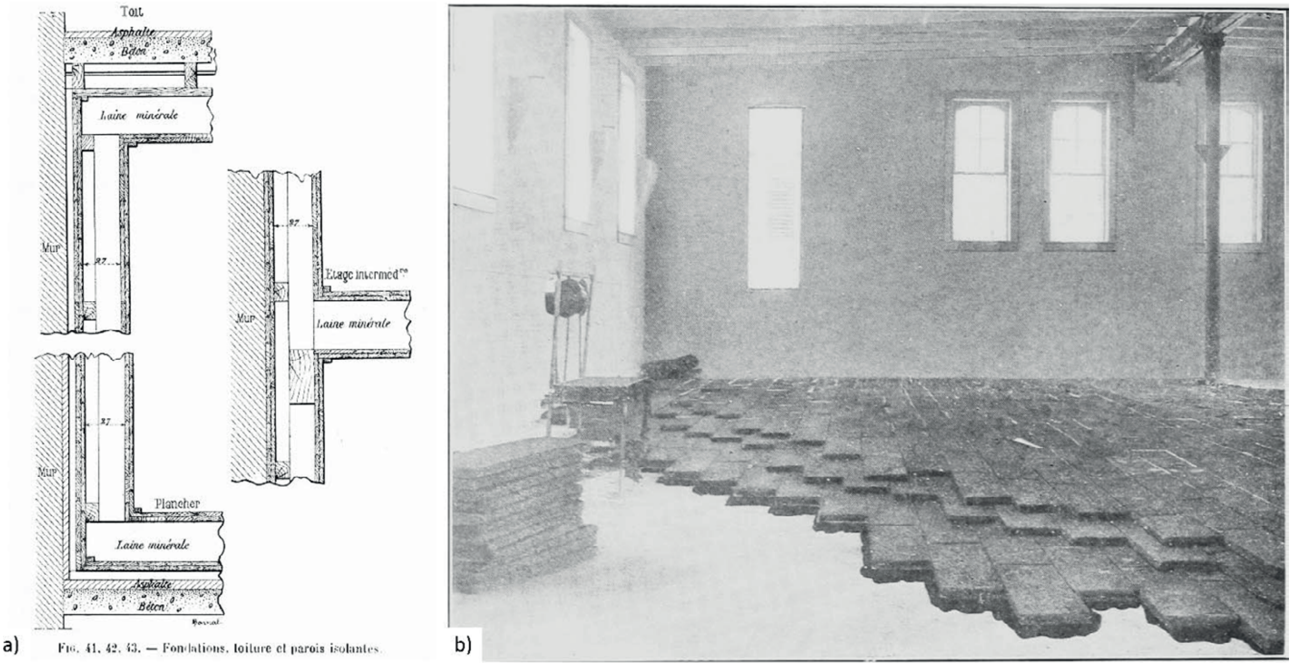

Figure 4. Technical solutions for the construction of cold rooms: a) Schematic section of a masonry cold room; b) Construction of a cold room with a cork-based insulation system. (Source: Figure 4a from [18]; Figure 4b from [21]).

ral lighting (e.g., Lyon Cold Storage, Villette Factory), whereas German facilities incorporated natural light to meet hygiene standards. Well-lit environments facilitated thorough cleaning, which was challenging under artificial lighting at the time due to the limitations and maintenance costs associated with incandescent bulbs. Alternatives like oil or gas lamps were unsuitable as they altered internal climatic conditions. Natural lighting in German facilities was achieved using reinforced glass panes with metal meshes to enhance mechanical strength – a technique that gained popularity in early 20th-century Central Europe [19].

Ventilation was another critical aspect in cold store design, essential for preventing food spoilage, condensation, and mold during periods of system inactivity. To address these issues, the "Schwarz device" was introduced. This device comprised a metal cylinder with threaded plugs, including an insulated outer plug. Natural rubber gaskets ensured airtight sealing, while a metal grille prevented insect or unauthorized entry [21].

To contextualize the techniques used in constructing cold stores, it is essential to examine the development of the refrigeration industry in Europe and Italy. At the beginning of the 20th century, the global evolution of refrigeration was marked by significant heterogeneity. The United Kingdom played a leading role, establishing itself as a pioneer in constructing refrigerated port warehouses and developing one of the first commercial fleets equipped with refrigerated environments [21]. In the UK, the growth of manufacturing industries facilitated the commercialization of ammonia-based and, later, carbon dioxide-based refrigeration systems. These advancements enabled applications ranging from transporting frozen meat to early scientific research in laboratory settings. One notable example was the Baerselman Cold Storage facility on London's Southbank, one of Europe's first large-scale cold stores [22].

Notably, the Genoa cold store, located in the Quartiere Tabarca, was Italy's first refrigerated warehouse. Established in 1901 by the Società Anonima dei Magazzini Frigoriferi Genovesi, the facility became operational in April 1902 and underwent significant expansion in 1906 [16].

The Genoese cold-storage depot featured rooms distributed across four levels, interconnected via an internal staircase and an electric lift system. A single corridor illuminated by windows facilitated access to the cold rooms. These windows were located exclusively at the junctions, as the cold rooms themselves lacked natural light. Instead, visibility within the storage areas relied entirely on electric lighting. Insulation materials included cork, applied as loose fill for the roofs and as panels for the floors and perimeter walls. In cold rooms requiring lower temperatures (-6 °C), additional insulation was achieved using mineral wool, then commercially known as Cotton Silicate [23].

The facility's refrigeration system, manufactured in England by F&Hall of Dartford (UK), utilized carbon dioxide technology with a total capacity of 45,000 refrigeration units per hour [18]. This system supported 32 cold rooms, designed to store various foodstuffs with a total volume of 6,500 cubic meters, maintaining temperatures between -7 °C and 2 °C [24].

In 1926, in response to growing demand for refrigerated storage, the Quartiere Scio, also located near the docks, was repurposed for this purpose, effectively replacing the Quartiere Tabarca. As a result, the refrigerated facilities in the Quartiere Tabarca were gradually dismantled, and the area was repurposed for general storage without specific temperature requirements [24].

3.3 Existing Conditions

The Quartiere Tabarca exhibits structural and functional features typical of late 19th-century industrial buildings. The structure rises four stories, with each level internally divided into six sections (Figure 5a), separated by masonry load-bearing walls. The façades present a regular arrangement of openings, creating a consistent visual rhythm (Figure 5b). The southeastern and northwestern elevations are currently plastered and painted, whereas the northeastern façade remains unfinished.

At present, all extensions facing Via Lercari and part of Via Rubattino have been demolished, though some remnants of surface finishes can still be found on the northwest elevation. Meanwhile, the southeastern façade retains a steel canopy that has suffered significant deterioration due to oxidation of its metal components and the complete lack of maintenance throughout the 20th century.

The flat roof has been repurposed to accommodate shared technical installations serving both the building itself and adjacent structures. Internally, most ground-floor units have independent access from the exterior, and some feature internal mezzanines. These are composed of hybrid timber-steel trusses, which are directly anchored to the building's structural masonry. Vertical circulation is provided by staircases made from a combination of timber, steel, and reinforced concrete, which have undergone significant degradation, as evidenced by the pronounced warping of the supporting beams.

On the upper floors, access is provided by a stairwell and an elevator, both located at the southernmost section of the last bay. The horizontal circulation on each level is organized around a central corridor running along the eastern side, from which individual rooms are reached (Figure 5c).

The former layout of the cold storage areas is now challenging to discern. Still, their former presence is

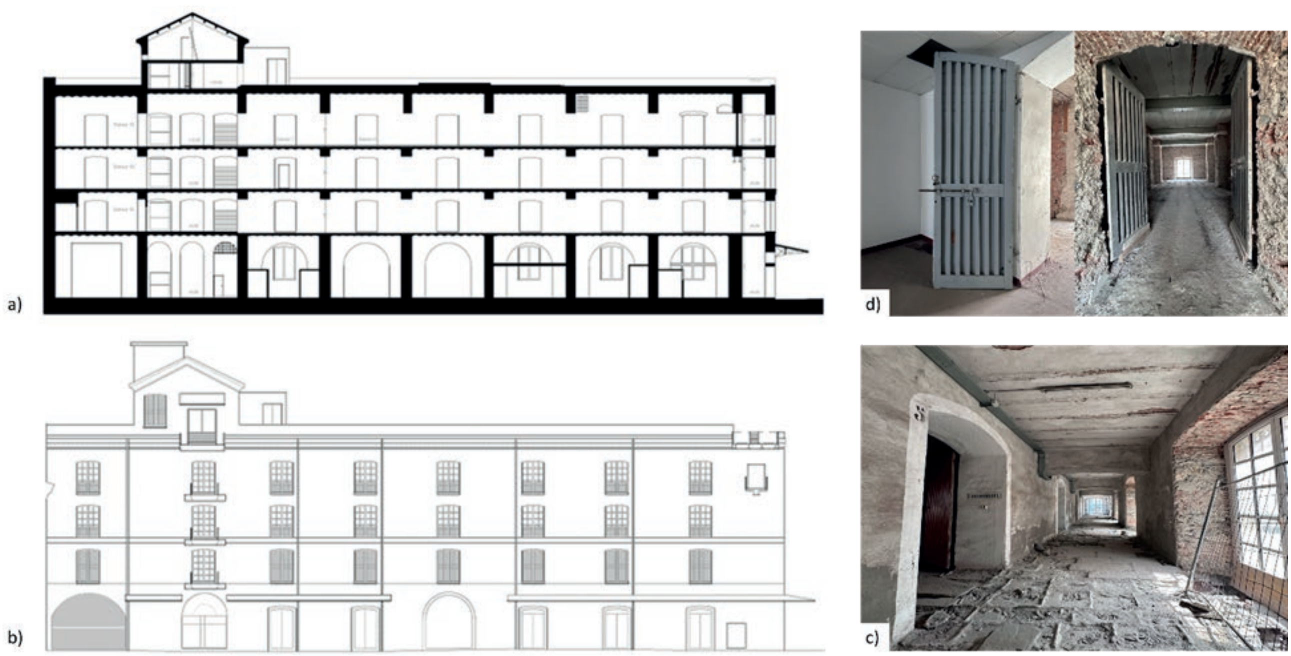

Figure 5. From top left to right counterclockwise: a) longitudinal section of the building; b) south-east view from Via Lercari; c) corridor on the east side of the building; d) interior wooden doors. (Source: Authors).

indicated by several large, hermetically sealed wooden doors that once connected these spaces to adjacent rooms (Figure 5d).

Inside, the upper floors remain unfinished, revealing the load-bearing masonry. The masonry follows a striped construction technique, consisting of horizontal layers of solid bricks alternated with squared stone courses measuring approximately 85 cm in height (Figure 6a). The stone material, known as Promontorio stone, was widely employed in Genoese architecture and quarried in the Sampierdarena area [25]. Like the primary metal beams, the walls incorporate granite stiffening elements, enhancing their connection with the horizontal structural framework.

At the surface level, the walls exhibit widespread deterioration, with clear evidence of multiple modifications over time. The presence of replastering, inconsistencies in surface finishes, and areas of renewed, restored, or removed coatings reflect the numerous interventions carried out on the building during the 20th century, none of which resulted in a comprehensive restoration. Additionally, window frames have been partially replaced.

Beyond the absence of plaster and unfinished surfaces across much of the upper two floors, other visible signs of masonry deterioration include flaking, discoloration, peeling, and cracks in the plasterwork. The cracks, particularly concentrated on the ground floor, are likely due to settlement in the masonry structure.

The load-bearing masonry is supported by intermediate floors composed of metal girders, upon which brick vaults are constructed (Figure 6b). The area above the vaults was originally filled with a lightweight cast mixture based on lime and pozzolanic aggregates. A 3–5 cm thick lime screed was then applied over this layer, followed by the final flooring. The building features a variety of floor types, differing in materials and structural patterns, each contributing to its historical significance. Notably, some sections of what is believed to be the original flooring remain intact within the Tabarca factory, consisting of 8 cm thick stone tiles (Figure 6c).

3.4 Reuse and conversion design project

The proposed reuse project for the Tabarca building is designed to address the client's functional needs while integrating contemporary architectural, technological, and infrastructural innovations. The intervention seeks to enhance energy efficiency, seismic safety, and social functionality, ensuring cost-effective management and maintenance while prioritizing the historical preservation of the structure.

The building will be repurposed as an Advanced Maritime Training Center for students of the Italian Merchant Marine Academy. The restoration project was executed using Building Information Modeling (BIM) in full compliance with current regulations (Figure 7a).

The ground, first, and second floors will be dedicated to academic and training activities, while the third floor will accommodate student residences designed according to current regulations, with multifunctional spaces balancing educational and residential needs. The distribution of spaces is based on the need to preserve the material and spatial integrity of the historical structure while implementing necessary functional adaptations. The architectural approach respects the original layout of Tabarca, minimizing demolition while optimizing spatial organization. The

Figure 6. From left to right: a) masonry with courses of brick and Promontorio stone with the granite padstone where the floor beam ends; b) vaulted ceiling with metal joists; c) floor made with limestone elements. (Source: Authors).

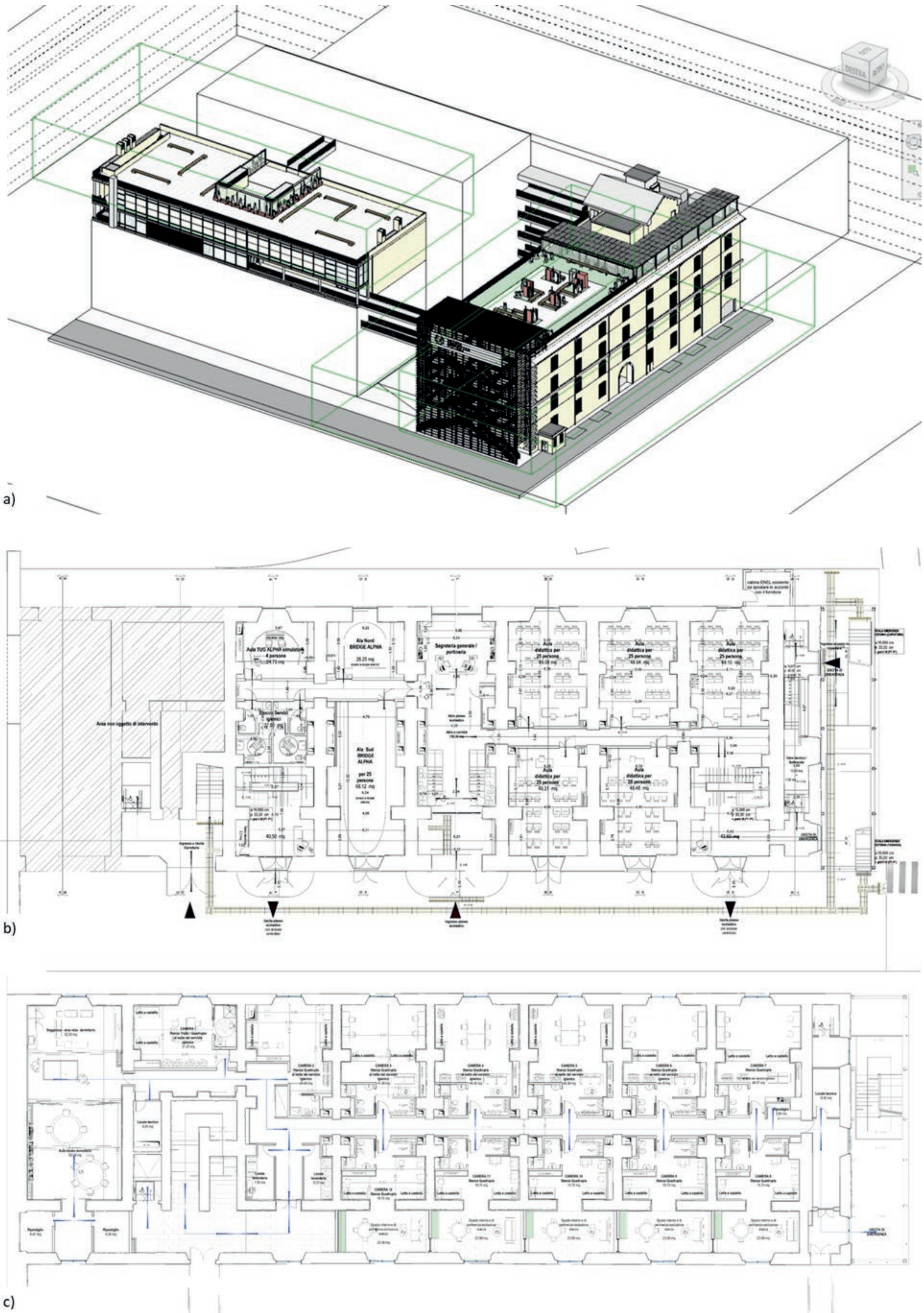

Figure 7. Restoration project of the Tabarca building: a) BIM model of the proposed design; b) ground floor plan of the proposed design; c) first floor plan of the proposed design. (Source: Authors).

circulation layout is designed for clarity, accessibility, and spatial continuity.

At the ground floor, navigation simulators will be installed in dedicated classrooms. These high-tech systems replicate ship operations, enabling trainees to simulate real-world conditions, including port entries and exits in digitized maritime environments (Figure 7b). To enhance teaching effectiveness, mezzanine levels have been introduced in the simulation classrooms, allowing instructors to observe training activities from an elevated perspective.

The adaptive reuse strategy considers the spacious warehouse layouts at different levels. The upper floors are reorganized to accommodate student residences, maintaining the original structural configuration while optimizing the distribution of living spaces (Figure 7c).

The middle floors are designated for academic activities, respecting the building's historical geometry while introducing modern educational infrastructure. To comply with safety regulations, a new vertical circulation system has been implemented, separating residential and academic functions through the installation of independent stairwells and elevators.

The design of the interventions was driven by the intent to respect the historical building and enhance its original structure. New partitions constructed using drywall systems are fully reversible, thereby preserving the integrity of the building's original spatial configuration. Particular attention was devoted to the conservation and enhancement of the original masonry arches along the corridor, achieved by inserting lightweight partitions designed to emphasize these features through the integration of seating elements and transparent panels (Figure 8a). This approach not only safeguards the existing architectural components but also reinterprets them with new functions and renewed significance. Similarly, new internal claddings were introduced where required to accommodate technical systems; these were conceived with the same guiding principle, contributing to a balanced dialogue between preservation and innovation (Figure 8b). An additional reversible intervention, in line with the building's conservation constraints, involved the use of non-invasive partition walls limited to a height of 2.70 meters (Figure 8c). These elements integrate building services while enabling flexible layouts for furnishings and equipment, all without compromising the original masonry.

The flooring follows a continuous system, blending with existing historical surfaces and enabling spatial reconfiguration through the repositioning of lightweight partitions. For the slab, a conservation-based approach is adopted. This involves cleaning vaulted surfaces and steel beams to remove deteriorated materials while preserving the structural integrity of the brick vaults. If necessary, mechanical removal techniques will expose the original structural components, restoring their aesthetic and functional integrity (Figure 8d).

The functional reconfiguration of the Tabarca building culminates in the adaptive reuse of the rooftop. This area will be accessible to the public and will feature a green roof and photovoltaic panels, underscoring the project's commitment to environmental sustainability (Figure 9a). The design sought to reconcile the goal of creating a usable space with the need to accommodate both existing and newly installed building systems. To this end, specific mitigation strategies were implemented, including the shielding of air handling units (AHUs) and drainage columns through corten steel cladding and steel framing systems (Figure 9b). This approach aims to reestablish the material dialogue that characterizes the structural reinforcement interventions on the lower floors.

The intervention meets key regulatory requirements for seismic and fire safety. The seismic strategy preserves the building's spatial layout by reinforcing foundations, strengthening existing structural openings, and upgrading localized slabs. For fire safety, a major issue was ensuring proper evacuation routes, resolved by adding a transparent glass enclosure on the north façade containing an independent steel-framed emergency stairwell. The addition improves safety while remaining reversible and architecturally integrated.

4. CONCLUSION

The study has highlighted the historical and technological significance of refrigerated warehouses, a rare yet highly relevant typology in the evolution of industrial architecture between the late 19th and early 20th centuries. These buildings exemplify the integration of mechanical systems with architectural design, incorporating innovative construction solutions to ensure high thermal insulation performance and compliance with hygienic and sanitary requirements. Within this framework, the Tabarca building emerges as a particularly significant case, not only as the first refrigerated warehouse built in Italy but also for its strategic location within the Darsena of the Port of Genoa.

The original spatial configuration of the building has facilitated its adaptive reuse as an Advanced Maritime Training Center for the Italian Merchant Marine Academy. The generous interior spaces have allowed for the integration of student accommodations and dedicated areas for high-tech navigation simulators, ensuring

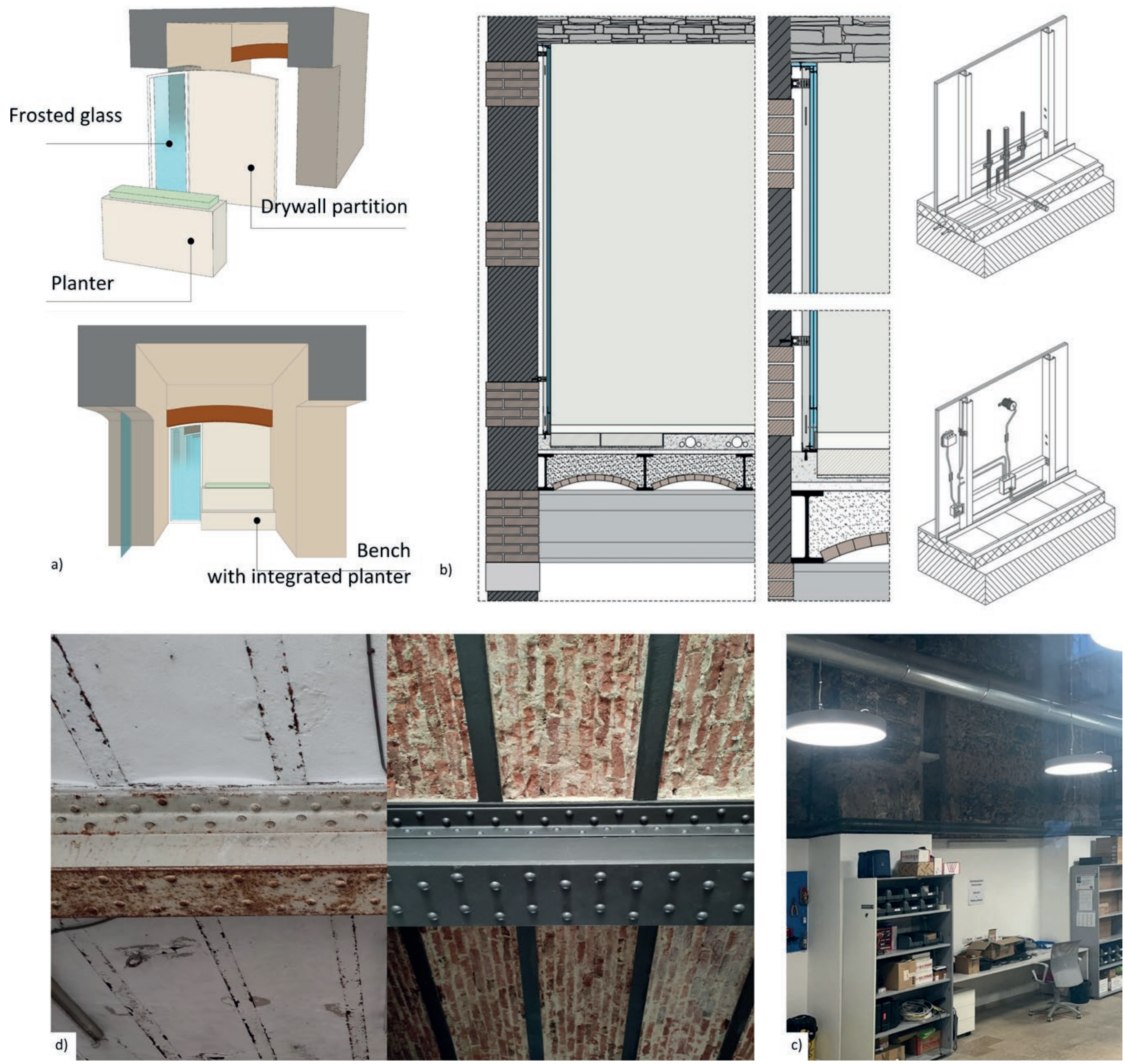

Figure 8. Clockwise from top left: a) exploded axonometric view and detail of the lightweight partition system positioned beneath the original arches; b) internal cladding system for the routing of electrical, plumbing, and HVAC services; c) low partition wall for service line passage; d) conservative restoration of banded masonry and floor system with brick vaults and steel beams, shown in a before-and-after comparison. (Source: Authors).

that the new function aligns seamlessly with the building's maritime heritage.

The Tabarca reuse project serves as a model for sustainable repurposing of industrial heritage, contributing to the revitalization of an area already characterized by academic institutions. The intervention demonstrates the feasibility of a rehabilitation strategy that effectively balances technological innovation with heritage conservation, offering a replicable approach for the adaptive reuse of historical structures in port and industrial settings.

5. ACKNOWLEDGMENTS

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Figure 9. From left to right: a) roof plan: on the right, the accessible area highlighted in color; on the left, the service zone dedicated to mechanical systems; b) mitigation system for drainage columns and internal ventilation units, along with the roof assembly and stratigraphy. (Source: Authors).

torate of the Municipality of Genoa, as well as the Temporary Consortium of Professionals (RTP) responsible for drafting the Executive Refunctionalization Project commissioned by the Municipality of Genoa and analyzed in this study.

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6. AUTHORS CONTRIBUTIONS

Although the research conducted and presented in this contribution is unified, the Authors individually assume editorial responsibility for the text, as follows: Salvatore Polverino for paragraphs 1 and 3.2; Lucrezia Longhitano for paragraph 2 and 3.1; Giuliana Sciacca for paragraph 3.3; Santi Maria Cascone for paragraph 4; and paragraphs 3.4 jointly by Santi Maria Cascone and Giuliana Sciacca.

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First Results Using Digital Image Correlation for Deformation Field Measurements in Laboratory Tests on Textile Reinforced Mortar (TRM)-strengthened Masonry Panels

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Abstract. The Digital Image Correlation (DIC) technique is a non-contact, full-field optical method and a non-destructive evaluation approach that enables the measurement of displacements and strain fields across an entire surface during experimental tests. This technique provides high-resolution data, enabling the measurement of global strain, the detection of localized strain concentrations and crack initiation, and monitoring the evolution of dominant damage mechanisms. DIC's ability to capture both in-plane and out-of-plane displacements makes it a powerful tool for detailed structural assessment. This paper presents preliminary results on the application of the DIC technique during diagonal compression tests of $1.2 \times 1.2 \times 0.25$ m^3 unreinforced and strengthened clay brick masonry panels. The strengthening system consists of two Textile Reinforced Mortar (TRM) layers applied on both wall sides and connected by helical stainless-steel connectors. Glass fiber bidirectional fabrics are used as TRM reinforcing meshes, embedded in a 30 mm thick lime-based mortar. A couple of CMOS cameras were used to apply the stereo-DIC algorithm and record the three-dimensional displacement field during test execution. The displacement field obtained through DIC has been compared and validated with that obtained through the more common analog Linear Variable Differential Transformers (LVDT). The comparison highlighted the benefits and weaknesses of the DIC technique.

Keywords: DIC, TRM, masonry, laboratory test, diagonal compression test, shear modulus.

1. INTRODUCTION

In recent decades, the topic of strengthening existing structures has been one of the most extensively investigated by researchers in the field. This interest encompasses both performance under static loads and resistance to seismic actions. Particular attention has been directed toward the reinforcement of masonry structures, both due to their widespread use and because they often involve buildings of significant architectural heritage [1-3]. This growing interest within the scientific community has driven the advancement of innovative strengthening techniques [4-7], particularly those leveraging composite materials. Composite materials are increasingly employed in structural repair and retrofitting due to their exceptional strength-to-weight ratio, minimal impact on structural mass, ease of application, and versatility. These systems typically consist of high-strength textiles, which may be unidirectional or multidirectional, and are fabricated from materials such as aramid, basalt, carbon, glass, PBO, steel, or natural fibers like flax, hemp, and jute. The textiles adhere to structural surfaces using organic matrices, such as epoxy, polyester, polyurethane resins, or inorganic matrices, including cement or lime mortars. Organic matrix systems are classified as Fibre/Steel Reinforced Polymers (FRP/SRP) when epoxy resins are utilized [8], or Fibre/Steel Reinforced Polyurethanes (FRPU/SRPU) when polyurethane matrices with high deformability are employed. In contrast, mortar-based systems are known as Fabric Reinforced Cementitious Matrix (FRCM), Textile Reinforced Mortar (TRM) [9], or Steel Reinforced Grout (SRG) when steel textiles are used.

The validation and performance assessment of reinforcement systems utilizing these materials, as well as the engineering and optimization of detailed aspects (e.g., compatibility between reinforcement and matrix), necessitate experimental campaigns, often involving full-scale specimens. Such tests are essential for obtaining reliable results that can support the development of analytical models used by designers in the sector. To accurately understand the mechanical behavior of specimens subjected to such tests, it is essential to record both the loads applied to the tested specimens and their corresponding deformations.

Standard test methods for determining mechanical properties of masonry assembly generally prescribe the use of Linear Variable Differential Transformers (LVDTs) to monitor displacements during tests. If properly used, these instruments have a virtually infinite life cycle, but they can incur damage if adopted in destructive tests, causing high repair or replacement costs. Some standards recognize this problem, allowing the removal of the LVDT instrumentation before reaching the specimen collapse, ASTM E519-22 [10].

Moreover, in these cases, crack formation or non-uniform load distribution may affect the results without being properly detected, especially when matrix damage may disrupt the reading of the measurement devices, making displacement data unavailable, unreliable, or not representative of the global behavior.

In addition, the use of traditional sensors can, in some cases, complicate the experimental setup preparation for various reasons: their size can be problematic (particularly with small specimens), they often require initial calibration, and they need to be mechanically fixed to the specimen (typically through adhesive bonding, although mechanical fastening is required when the substrate does not permit adhesion). Finally, these sensors are sensitive to voltage fluctuations and provide data limited to the specific portion of the specimen where they are applied.

To overcome these drawbacks, in the last few years, several full-field contactless optical measurement techniques have been developed for measuring displacements during experimental tests in place of more common LVDTs [11-13]. Among others, the Digital Image Correlation (DIC) technique has become one of the most promising measurement methods, obtaining significant information on the strain state of the material/structure with a complete reconstruction of the crack pattern [14]. For this reason, it has been widely used in several fields, reaching a relatively advanced knowledge of testing setups and data processing [15-20]. The accuracy of such a technique is undoubtedly growing as the resolution of the optical recording instruments increases.

DIC is a contactless full-field optical technique for measuring displacements during experimental tests that can be potentially used in place of LVDT instrumentation to avoid damaging instrumentation during tests of full-scale walls. However, despite DIC being successfully used in several fields, such as for the characterization of building materials [21-22], its potential application in testing full-scale walls has not yet been thoroughly investigated [23].

For this reason, this paper presents the preliminary results of an experimental campaign to evaluate the potential of the DIC technique for monitoring the displacement of masonry walls during experimental tests. In particular, the results of diagonal compression tests on two unreinforced and two strengthened masonry walls with dimensions of $1.2 \times 1.2 \times 0.25$ m^3 are reported. The adopted strengthening system consists of two layers of TRM, which is a promising alternative to fiber-reinforced polymer (FRP) composites or the shear and out-of-plane strengthening of existing masonry structures due to their higher compatibility with historic masonry substrates, higher vapor permeability, reversibility, and resistance to UV radiation and high temperatures [24-26].

A stereo-DIC technique was used to record the three-dimensional displacement field during diagonal compression tests. A comparison between DIC results and those obtained through the more common analog LVDTs is reported. Finally, the nominal tangential elastic moduli obtained from the two measurement systems are computed and compared.

2. MATERIALS AND METHODS

2.1. Materials

Four masonry walls with dimensions of 1.2 × 1.2 × 0.25 m^3 were built using fired clay bricks measuring 250 × 120 × 55 mm^3 (with an average compressive strength of 30 MPa) and commercially available lime mortar in 10 mm thick joints. Two of these walls (M1, M2) were left unreinforced, while the other two (MR1, MR2) were reinforced using a Textile Reinforced Mortar (TRM) system applied to both sides of the walls.

The TRM reinforcement system consisted of a bidirectional alkali-resistant (AR) glass fiber grid (density 280 g/m^2) coated with a polyvinyl alcohol layer (Fig. 1). This grid was embedded in a 30 mm thick layer of a fiber-reinforced, hydraulic lime-based matrix. To enhance the connection between the TRM layers and the wall, stainless-steel helical connectors with a nominal diameter of 8 mm and a tensile strength of 830 MPa (as provided by the manufacturer) were installed (Fig. 1). These connectors were bent over the glass fiber grid for a length of approximately 100 mm, ensuring a robust mechanical bond. A similar TRM reinforcing approach was tested and described in detail in [27].

Table 1. Geometrical and mechanical properties of the glass fiber yarns of the fabric: equivalent thickness (s), tensile strength (f_{ft}), ultimate deformation (ε_f), and elastic modulus (E_f), according to the technical sheets provided by the manufacturer.

Material	s [mm]	f_{ft} [MPa]	ε_f [%]	E_f [GPa]
Warp yarn	0.0339-	1600	1.7	58
Weft yarn	0.0339-	1570	1.7	61

Table 2. Mechanical properties of the mortars: compressive strength (f_{Mc}), flexural strength (f_{Mb}), and elastic modulus (E_d).

Material	f_{Mc} [MPa] / COV (%)	f_{Mb} [MPa] / COV (%)	E_d [GPa] / COV (%)
Masonry mortar	4.78 / 4.73	1.78 / 0.91	9.25 / 1.30
TRM matrix	8.35 / 2.86	3.56 / 3.89	12.32 / 1.10

The geometrical and mechanical properties of the glass fiber yarn of the fabric are provided in Table 1, while the mechanical characteristics of the inorganic mortar, evaluated following EN 1015-11 [28] and EN 12504-4 [29], are 100 summarized in Table 2.

2.2 Methods

The tests were carried out according to the standard ASTM E519-22 [10]. A monotonic force-controlled diagonal load with a loading rate of about 1 kN/s was applied

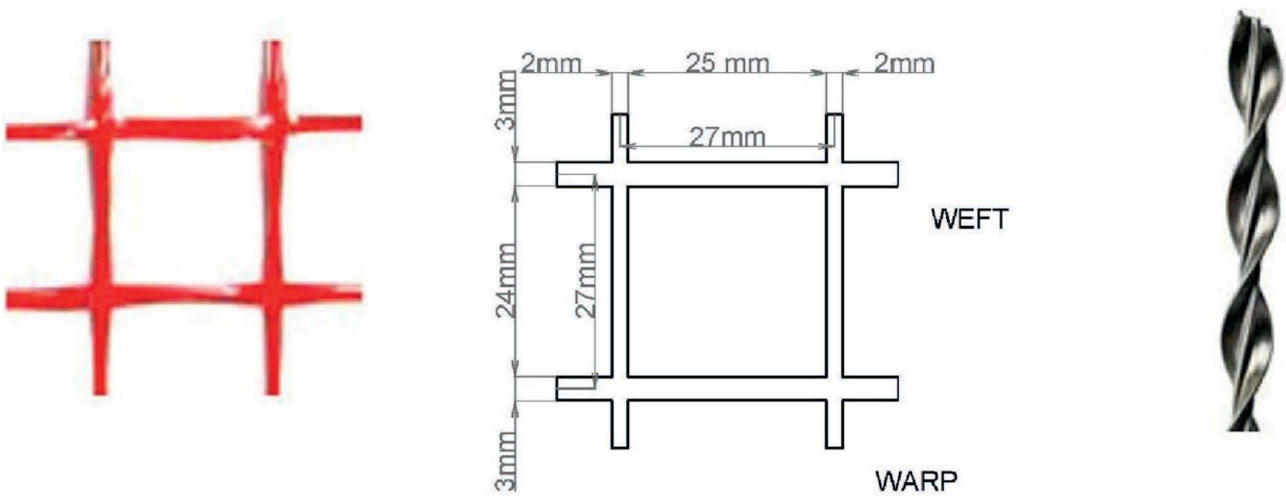

Figure 1. Geometrical characteristics of the glass fiber fabric and stainless steel helical bar adopted in this study. Dimensions in millimeters.

on the bottom corner of the specimens using six hydraulic jacks with a total compression capacity of 3000 kN, similar to the ones used in [30-32]. The experimental setup is reported in Fig. 2.

To minimize friction, ensure uniform load distribution, and avoid directly loading the two TRM reinforcement layers, neoprene pads were placed at the loaded corners of the masonry walls. To monitor displacements during the tests, four Linear Variable Differential Transformers (LVDTs) were installed on the wall surfaces, with two sensors on each side (see Fig. 2).

The data from the LVDTs were recorded using a Spider8 data acquisition system running Catman software, operating at a sampling frequency of 2 Hz. Among the LVDTs, sensors LVDT 1 and LVDT 3, positioned on the wall face monitored by the Digital Image Correlation (DIC) system, were employed to measure horizontal and vertical displacements, respectively, for comparison with the results obtained through the DIC technique.

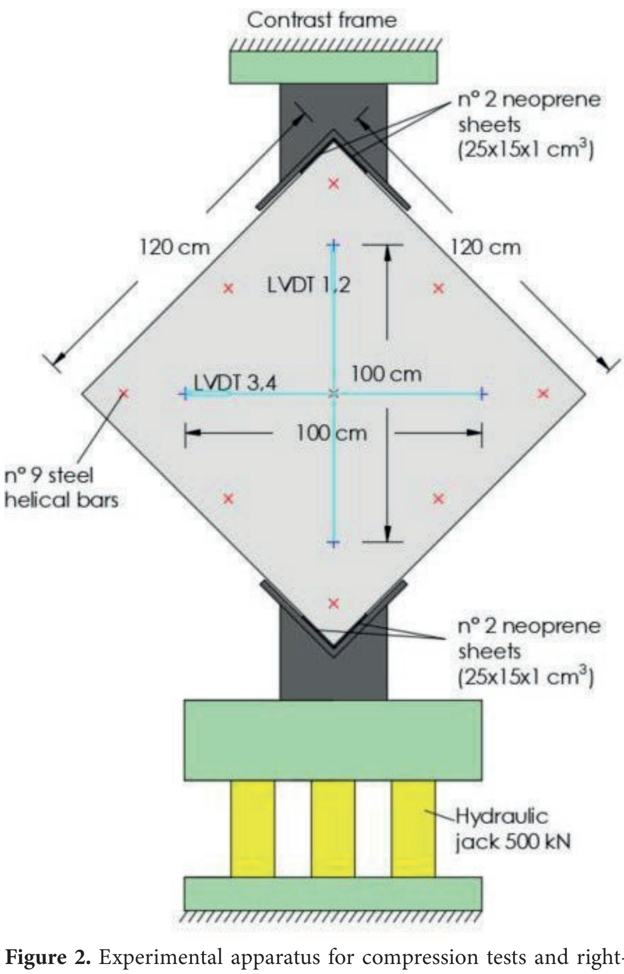

Figure 2. Experimental apparatus for compression tests and right-handed 3D-DIC coordinate system.

For the strengthened masonry panels, the LVDTs were mounted directly onto the surface of the TRM layers (see Fig. 2), ensuring that the displacement measurements accounted for the behavior of the reinforced assembly. This setup enabled an accurate evaluation of the consistency between traditional point-based measurement techniques and the DIC method, providing insights into the reliability and applicability of DIC for tracking displacement fields in both unreinforced and reinforced configurations. As an example, Fig. 3 shows the images of an unreinforced and a reinforced specimen before the execution of the diagonal compression test.

For the scope of this work, the nominal stresses were computed by referring to the masonry section only, i.e., without considering the thickness of the two TRM layers. Future studies will verify the accuracy of this assumption to determine the actual mechanical properties of the strengthened masonry walls. Then, the nominal shear stress was computed as $\tau = 0.707\ P/A_n$ according to ASTM E519-22 [10], where P and A_n are the applied load and the net cross-sectional area of the unreinforced masonry wall, respectively. The shear strain was obtained through LVDT measurements as $\gamma = \varepsilon_v + \varepsilon_h$, where ε_v and ε_h are the average strains, in absolute value, along the compressive and tensile diagonals of the panels. Then, the shear stiffness modulus of the wall (G) was computed by linear regression of the τ-γ experimental curve between 10 and 40% of the maximum strength.

2.3. Digital Image Correlation

The displacements and the strains of the wall surface were measured by using a 3D-DIC technique, which consists of the acquisition, during tests, of digital pictures of the frontal surface of the specimen, previously painted with a speckle pattern with black and white dots (or with black dots only in the strengthened case due to the light gray surface) and illuminated by a halogen lamp. In this work, two complementary (CMOS) digital cameras (model Pixelink® B371F) were used. The main characteristics of the cameras are given in Table 3.

The cameras were calibrated in a common global system by means of the Matlab Calibration Toolbox. Calibrating a stereo vision sensor is required for determining the intrinsic parameters of each camera and the relative position and orientation, and then to compute, by stereo-triangulation, the 3-D coordinates of a point corresponding to matched pixels on the two images. In this work, the calibration procedure involved repeated acquisitions of a regular target (consisting of a 10×10 dots grid, 100 mm pitch, and 40 mm of dot diameter), moved in different positions within the working vol-

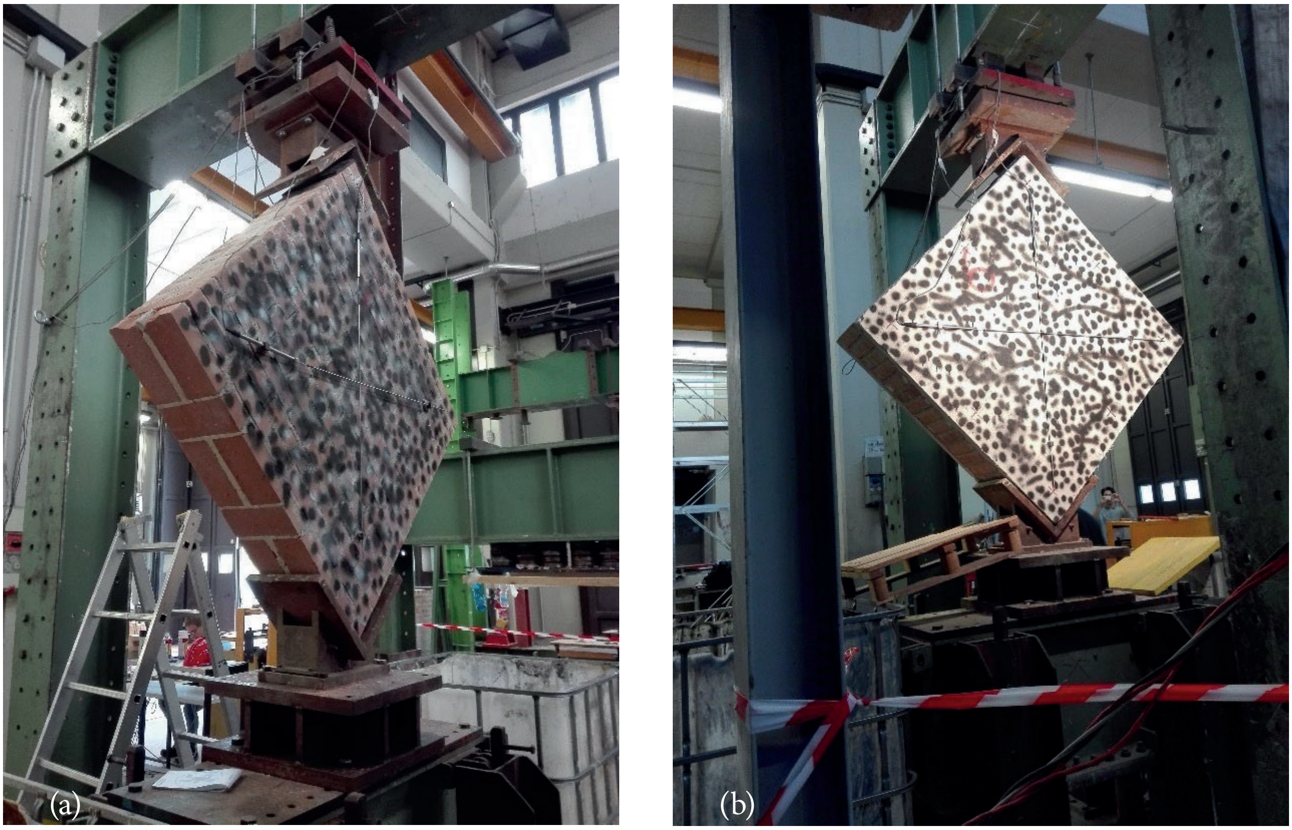

Figure 3. Unreinforced specimen (a) and a reinforced specimen (b) prior to the diagonal compression test.

ume. Calibration data are presented in Table 3, which also reports the quantitative calibration errors, expressed as the standard deviations of the displacement measurements and the resulting strains. These values were obtained by acquiring a series of stationary images prior to specimen testing. This procedure was employed to evaluate the performance of the correlation technique and the accuracy of the strain measurements. No systematic bias was detected, as the average strain values show small random fluctuations around zero. The standard deviations are approximately constant and are on the order of 100 microstrain.

Fig. 4a shows a typical picture recorded by one camera with an overlaid measurement grid. The subsets discretization used for the DIC analysis was 20×20 pixels, with a measurement point every 30 mm. The subset size of 20 × 20 pixels was selected as a compromise between spatial resolution and correlation robustness, in accordance with previous studies [13] Fig. 4b shows the 3D grid calculated by stereo triangulation with the schematic position of the two frontal cameras.

After testing, the digital images acquired were post-processed by an in-house developed 3D-DIC software. The grid of the elements is initially defined on the undeformed image of camera 1. To determine the corresponding grid on the undeformed image of camera 2, the epipolar constraint given by the fundamental equation of Longuet-Higgins (1) is used:

$$\left[\widetilde{m}'\right] \bullet [F]_{3\times3} \bullet [\widetilde{m}] = 0 \tag{1}$$

where $\widetilde{m}'$ and $\widetilde{m}$ are the corresponding points of the two cameras, and *F* is the essential matrix depending on the calibration parameters of the cameras. Based on global DIC, the correlation method between the deformed images incorporates the same epipolar constraint and the assembling approach of the Finite Element Method. The displacements of all grid measuring points were obtained by minimizing the correlation error computed all over the current frame with respect to the reference frame [33] calculated with the following expression:

$$e = \sqrt{\sum_i \left\| s_{id}(X_{d)}) - s_{iu}(X_{u)}) \right\|} \tag{2}$$

where X_d and X_u indicate the coordinates of the deformed and undeformed grid nodes, respectively,

Table 3. Optical setup and calibration parameters of the adopted cameras: f_x and f_y are the focal length in pixels, c_x and c_y are the principal point coordinates, T_x, T_y, T_z are the translation vector, and α_x, α_y, α_z are the rotation vector.

		Camera 1	Camera 2
Sensor	[Type]	CMOS	CMOS
Sensor pixel size	[μm]	6.8 × 6.8	6.8 × 6.8
Sensor resolution	[pixel]	1280 × 1024	1280 × 1024
Frame rate	[fps]	2	2
Lens	[Type, mm]	C mount, 25	C mount, 25
Working distance	[mm]	2500	2500
Sensor noise	[gray level, dB]	0.94, −19	0.94, −19
Subset size	[pixel, mm]	20, 30	20, 30
Displ. accuracy (st. dev)	[pixel, mm]	±[0.02, 0.05]	±[0.02, 0.05]
Strain accuracy (st. dev)	[mm/mm]	±0.0001	±0.0001
Calibration data			
$f_x - f_y$	[pixel]	1830 - 1828	1815 - 1809
cx − cy	[pixel]	716 - 480	583 - 488
$T_x - T_y - T_z$	[mm]	450 – 593 – 2874	
$\alpha_x - \alpha_y - \alpha_z$	[rad]	0.3491 – 0.0557 – 0.8327	

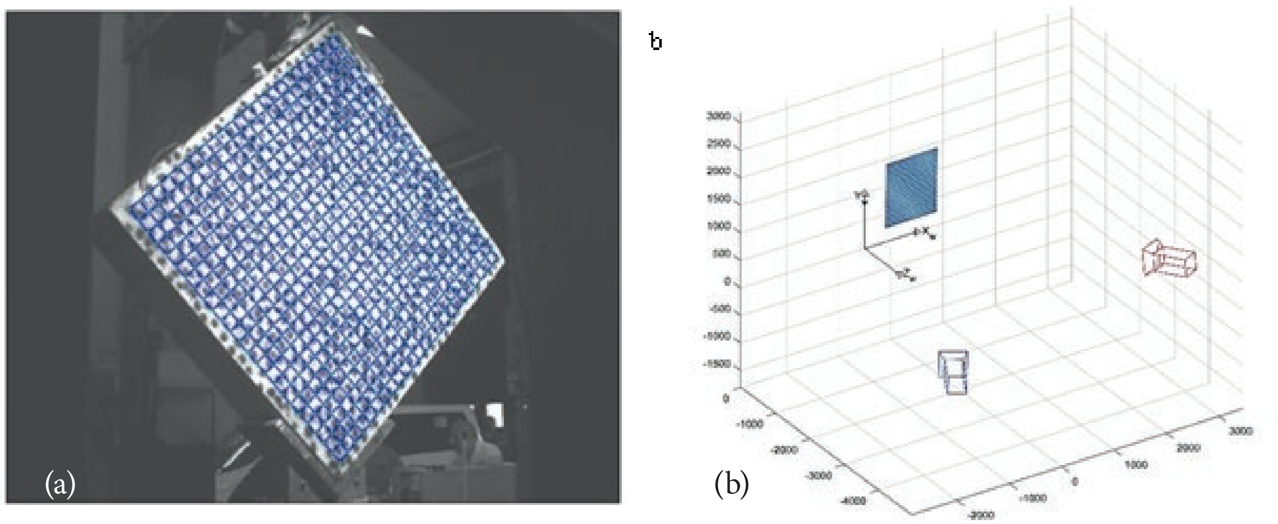

Figure 4. (a) Picture with overlaid grid, (b) 3D grid point and calibration reference frame.

while S_{id} and S_{iu} indicate the sub-images associated with the i-th element on the deformed and undeformed image.

The zero-mean sum of square difference (ZSSD) criterion was adopted to avoid the effects of lighting offset and inhomogeneity. Outputs were obtained by referring to the right-handed coordinate system shown in Fig. 4. Strains (ε_x, ε_y, and γ) were computed using the Cauchy-Green theory, starting from the 3D node displacements.

3. RESULTS

In Fig. 5, the results of the diagonal compression tests in terms of nominal τ-γ curves are reported. The unreinforced walls were characterized by quite a linear behavior until reaching the maximum shear stress (about 0.9 MPa), after which the sudden collapse of the specimen occurred due to the reaching of the principal tensile strength of the masonry near the wall center. As expected, a slightly stiffer (and stronger) behavior is obtained for the strengthened panels, characterized by a first linear part of the curve until the crack of the TRM layers (at about 1.3 MPa), also reaching a higher deformation value. No detachment at the TRM matrix-to-substrate interface was observed during the test, indicating a good bond of the inorganic mortar with the masonry substrate.

Fig. 6 and Fig. 7 show horizontal, vertical, and out-of-plane displacements (dx, dy, and dz, respectively) obtained from DIC measurements for two representative walls (M1 and MR2, respectively). In particular, the displacements related to 3 different moments during the test are plotted (t_1, $t_{2,}$ and t_3, see Fig. 5). Specifically, for the strengthened masonry wall, t_1 corresponds to the moment when the initial cracking occurred t_3 marks the end of the test, and t_2 represents an intermediate point in time between t_1 and t_3. For the unreinforced masonry wall, t_3 corresponds to the instant at which the specimen failed; t_1 refers to the moment when the applied load reached half of the peak (failure) load; and t_2 represents the intermediate time instant between t_1 and t_3.

From the d_x and d_y displacement maps, it is possible to observe that, during the test, the masonry walls were not subject to a uniform upward displacement, but they had a slight rotation with respect to the normal axis of the masonry wall surface. Moreover, d_z allowed verifying the occurrence of out-of-plane rigid rotations of the walls. This behavior cannot be observed if a bidimensional DIC algorithm is adopted. Comparing the maps, it can be observed that the unreinforced wall has a brittle behavior, while the strengthened one has a ductile behavior. In fact, at the maximum load of the strengthened panel (t_2), multiple cracks propagated through the TRM layer until the panel collapses (t_3).

From the 3D node displacements, strain values before collapse were calculated. Fig. 8 shows the maps of the shear strain γ for unreinforced masonry walls (M1) and for strengthened masonry walls (MR2). The strain maps, shear and Von Mises strain, were used to evaluate the evolution of specimen cracking during the test: in the maps of Fig. 8, red concentrations of shear strain indicate the areas where specimens cracked.

Finally, Fig. 9 shows the τ-γ curve for one unreinforced and one strengthened wall calculated with the values measured with the LVDTs according to the standard ASTM E 519-22 [10] and the curve obtained with the results of the DIC. The DIC shear stress-strain curves showed similar trends to those obtained with LVDT. The shear deformation γ obtained with the DIC was calculated as the average of the values of the whole surface of the wall. The oscillations of the curve obtained with the DIC technique depend on the cameras' non-optimal positioning. In particular, due to the large support frame, the cameras were placed with too large an angle between the optical axes and a consequent non-optimal illumination. Despite this, a similar trend is obtained in the first part of the two curves, from which the shear modulus G is computed. In particular, the deviations occurring at 0.8 MPa for the strengthened wall depend on the out-of-plane deflection of the wall and the consequent parallax error between the two cameras, due to the presence of the LVDTs.

This issue highlights the need for improved integration of the experimental setup. Future configurations should consider the use of an increased number of cameras (e.g., 4–5) to achieve a more accurate reconstruction of the surface geometry and to reduce occlusions and parallax effects in areas where physical sensors are present. Additional strategies include the adoption of optical markers in place of physical sensors near critical regions and the implementation of pretest alignment and calibration protocols to minimize misalignment errors and enhance system compatibility.

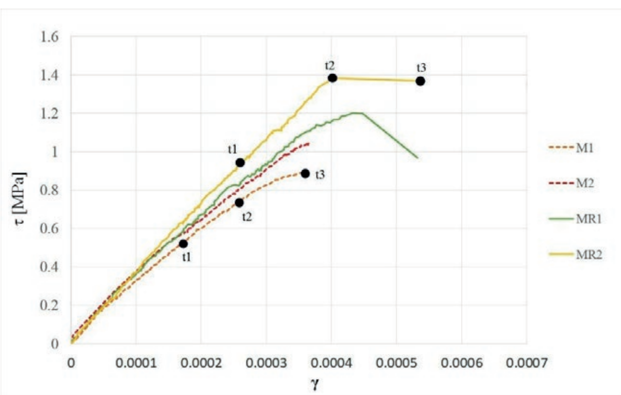

Figure 5. Stress-strain curves τ-γ obtained from LVDT for unreinforced masonry walls (M1 – M2) and strengthened (MR1 – MR2).

4. CONCLUSION

This study explores the potential of Digital Image Correlation (DIC) as an advanced and versatile tool for assessing the mechanical behavior of masonry walls during diagonal compression tests. By comparing DIC measurements with those obtained from traditional Linear Variable Differential Transformers (LVDTs), the research highlights the ability of DIC to provide detailed, full-field displacement and strain data. This capability is particularly valuable for capturing complex structural responses, including in-plane and out-of-plane deformations, as well as the evolution of crack patterns and damage mechanisms.

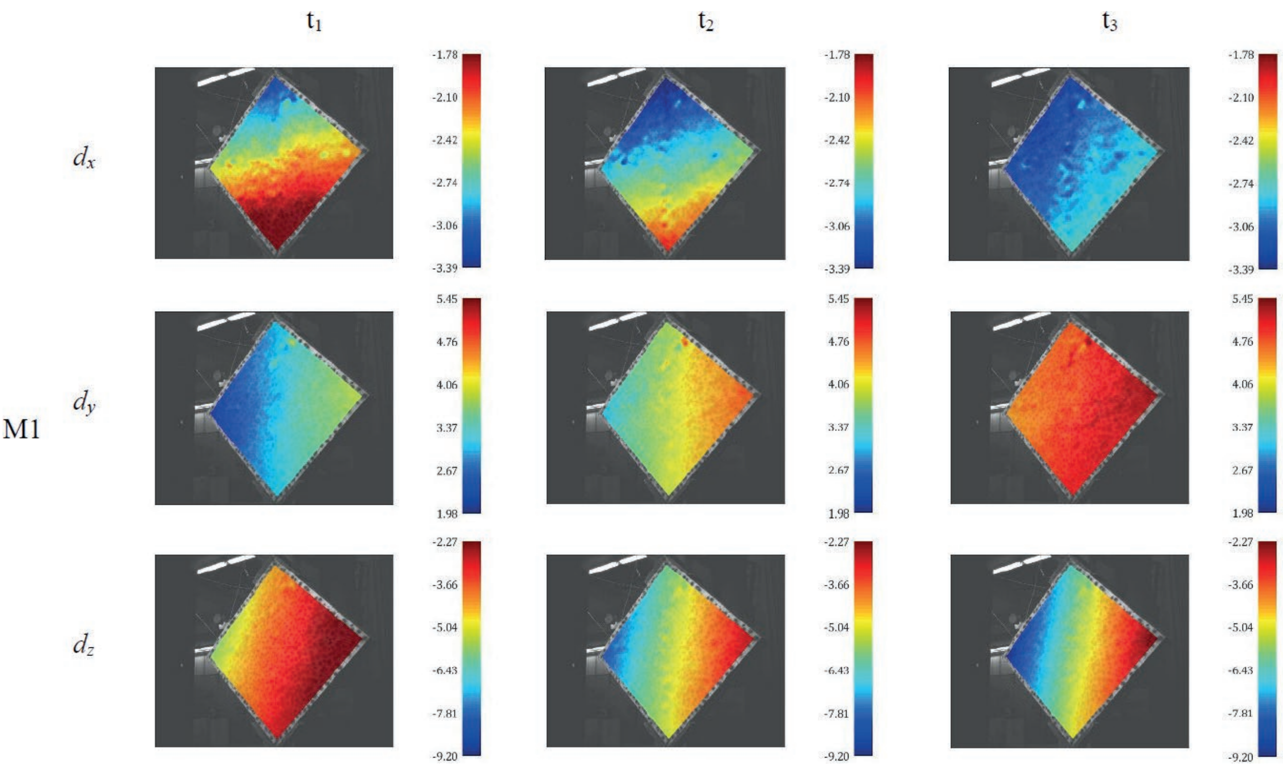

Figure 6. Displacements (mm) maps obtained from DIC for unstrengthened unreinforced masonry walls (M1).

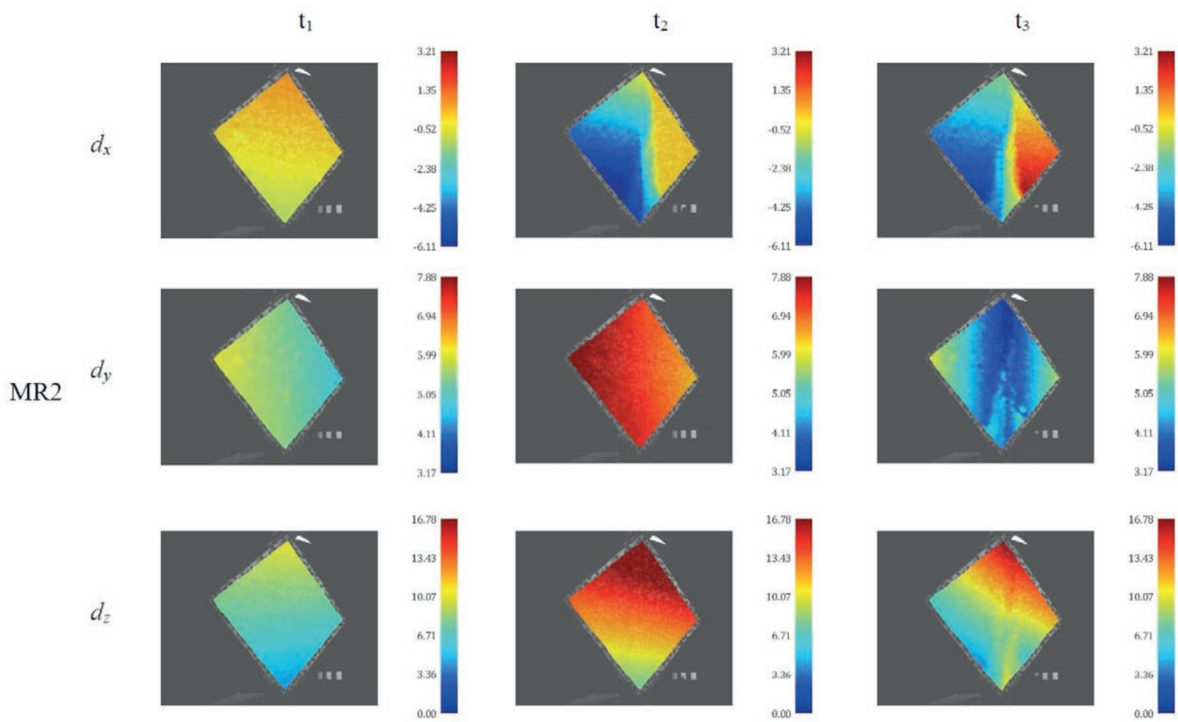

Figure 7. Displacements (mm) maps obtained from DIC for strengthened masonry walls (MR2).

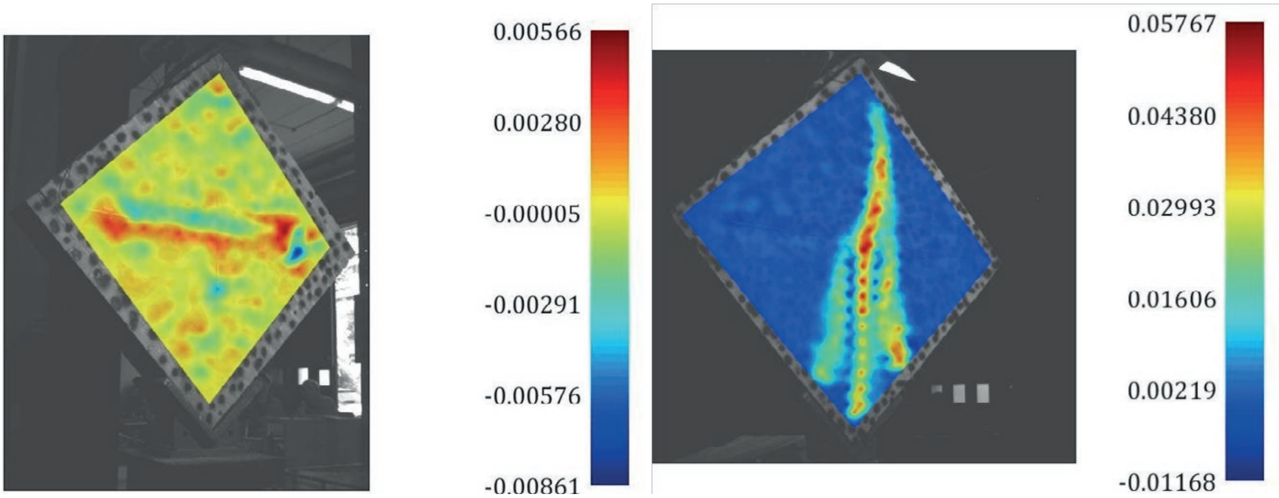

Figure 8. Maps of shear strain γ obtained from DIC for unreinforced masonry walls (M1) and for strengthened masonry walls (MR2).

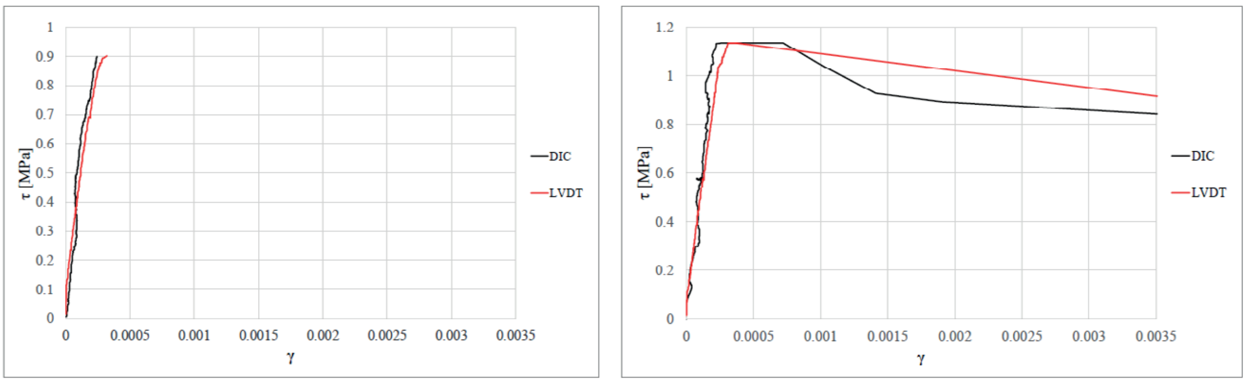

Figure 9. Stress-strain τ-γ curves obtained from LVDTs and DIC for a representative unreinforced and strengthened masonry wall.

The results demonstrate that the strengthened masonry walls, reinforced with a Textile Reinforced Mortar (TRM) system, exhibit significantly enhanced mechanical performance compared to unreinforced walls. Specifically, the TRM layers improved stiffness, increased peak load capacity, and delayed the crack propagation, leading to a more ductile failure mode. These findings underscore the effectiveness of TRM as a strengthening technique, especially for applications involving historic masonry structures where compatibility, reversibility, and durability are critical considerations.

The study also underscores the unique advantages of DIC over conventional point-based measurement systems. While LVDTs are limited to discrete measurement points, DIC offers a comprehensive view of the deformation behavior across the entire specimen surface. This feature is particularly advantageous in capturing non-uniform deformation patterns, such as localized rotations or out-of-plane displacements, which might otherwise go undetected. Despite some technical challenges, such as suboptimal camera positioning and illumination, the DIC technique provided results that closely aligned with those from LVDTs, particularly in the linear portion of the load-displacement curves.

However, some discrepancies in the later stages of loading were observed, primarily attributed to parallax errors and the influence of LVDT hardware on DIC measurements. Future studies should focus on refining the experimental setup to address these limitations. Improvements in camera alignment, lighting conditions, and the minimization of interference from traditional measurement devices will enhance the accuracy and reliability of DIC data.

Moreover, this research demonstrates the potential for DIC to serve as a complementary or alternative tool to traditional methods in experimental campaigns involving full-scale specimens. By providing high-resolution, three-dimensional data, DIC enables a more nuanced understanding of structural performance, paving the way for improved modeling and analysis techniques. Integrating DIC into experimental workflows can facilitate the development and validation of innovative strengthening solutions, particularly for masonry structures subject to complex loading scenarios.

In conclusion, the findings of this study confirm the utility of DIC as a robust and reliable method for structural assessment. Its ability to capture detailed displacement fields, coupled with its non-invasive and versatile nature, makes it a valuable tool for future research and practical applications. Although the present study was conducted under controlled laboratory conditions, the proposed method shows potential for scalability to on-site applications. However, further investigation is needed to address practical challenges such as lighting, surface texture, and environmental variability. Continued exploration of DIC's capabilities will further enhance its role in advancing the field of structural engineering, particularly in the development of sustainable and effective reinforcement strategies for existing structures.

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7. AUTHOR CONTRIBUTIONS

Conceptualization: E.Q., S.L., J.D., G.M.; Funding acquisition: E.Q., S.L., J.D., G.M.; Project Administration: E.Q., J.D., G.M.; Investigation: G.C., G.M., J.D.; Methodology: G.C., G.M., J.D., E.Q.; Validation: G.M., G.C., J.D., E.Q., S.L., V.C., F.M.; Visualization, Writing and Editing, G.M., G.C., J.D., F.M.

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A Philological Digital Platform to Experimental Preservation: Upcycling the Prefabricated School Buildings Heritage

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Abstract. In Europe, the increasing demand for public education between the 1950s and 1960s prompted extensive school-building programs. The design of these new schools was supported by updated pedagogical theories, which inspired a rethinking of building layouts. From a technological point of view, intensive experimentation with prefabricated construction systems was carried out to meet emerging design concepts for school buildings, as well as to accelerate construction and reduce costs. Nowadays, late 20th-century school buildings have emerged as fragile architectural heritage, characterized by experimental technological solutions that require the development of customized preservation approaches. This contribution presents a philological digital platform to document and analyze exemplary late 20th-century school buildings: this platform aims to support the conception of a novel preservation strategy driven by the principles of the circular economy. The analysis is framed within the broader scenario of participatory practices for the experimental preservation of late 20th-century public building heritage.

Keywords: BIM, GIS, Archival research, Selective dismantling, Reuse.

1. INTRODUCTION

In Europe, between the 1950s and 1960s, the increasing demand for public education prompted extensive school-building programs [1]. In Italy, a special program of 'experimental school buildings' was launched in 1961 and coordinated by the "*Centro Studi per l'Edilizia Scolastica*" of the Ministry of Public Education (Ministero della Pubblica Istruzione) [2]. The program supported the construction of a significant number of school buildings between 1961 and 1980. These schools featured prefabricated construction systems to speed up building and minimize expenses. At the same time, new pedagogical theories inspired a rethinking of school layouts, which became based on the modularity and flexibility of school spaces. This pushed the experimentation of easy-to-assemble and disassemble construction systems, mostly based on light prefabrication [3]. Over time, late 20th-century prefabricated school buildings have faced a generalized lack of acceptance from user communities. They have also aged poorly, requiring significant maintenance and upgrade interventions, and have emerged as a fragile and extensive building stock that urgently requires the development of customized preservation approaches [4].

According to the European Union Cohesion Policy (EUPC), improving school buildings is an opportunity to strengthen both the Integrated Territorial Investment (ITI) and the Community Led Local Development (CLLD) strategies in relation to the urban and social role of school buildings [5]. Within this framework, since the school system is increasingly perceived as a common good, the lack of acceptance of prefabricated school buildings by user communities represents a significant issue that often favors demolition over conservation. The implementation of participatory practices – involving end-users in the upgrade process of the school buildings – can be effectively exploited to broaden the field of their preservation, including through experimental approaches [6].

In this context, Construction History studies, based on the analysis of documentary sources, play a crucial role in increasing awareness within communities about the tangible and intangible values of the prefabricated school building heritage. This supports the classification of a specific cluster of 20th-century cultural and technological heritage. Digital approaches in Construction History – especially those related to philological BIM [7-10] – facilitate the extraction and organization of historical and technical data to be used in actual maintenance and preservation scenarios. This is achieved through the production of structured digital archives and data-analysis tools related to the history and technology of the buildings [11]. The current literature proposes a significant reference framework related to the use of BIM as a documentation tool to support the knowledge, preservation, and valorization of contemporary building heritage [12-14]. Nevertheless, the use of BIM for organizing archival document-based knowledge is still an emerging topic [15,16] that requires further insights.

Under these premises, on the one hand, the article presents the construction of a philological digital platform to document and analyse exemplary prefabricated school buildings of the late 20th Century, serving further as a data-analysis tool to support preservation strategies based on circular economy-driven practices within the recent literature and regulatory framework related to the application of the Minimum Environmental Criteria (CAM) [17-18]. On the other hand, the article presents the application of the digital platform to an Italian case study, testing the tools to support a specific preservation approach based on 'selective dismantling' and the reuse of building components. In this latter sense, the article aims to provide evidence for the use of the philological digital platform as a decision-making tool to broaden the practice of selective dismantling and the reuse of building elements within Italian professional communities.

The paper is structured as follows: Section 2 presents the methodology adopted for the construction of the philological digital platform, relying on the BIM approach; Section 3 presents the application of the digital platform considering a case study of 15 school buildings, functioning as kindergartens, which feature the patented 'Benini' construction system composed of precast concrete elements; Section 4 presents the results of four workshop experiences related to the participative implementation and testing of the philological digital platform with different users-clusters and stakeholders. Conclusions and future research perspectives are presented in Section 5.

2. THE CONSTRUCTION OF THE PHILOLOGICAL 3D INFORMATIVE MODEL

The proposed methodology –as shown in Figure 1– relies on the extended use of a BIM-based web platform, designed and developed to meet the following key functionalities: i) digital archive of the historical and technical documents related to the design, construction and operational life of the single building; ii) information management tool for the organisation and the representation of the historical and technical data derived from the documentary analyses; iii) analytical tools to interrogate data related to the building, supporting the simulation of scenarios related to the potential disassembly and reuse of the building components; iv) production of interoperable dataset in user-friendly tabular format and integration of informative data in a webGIS platform.

The construction of the BIM model develops into subsequent phases, leveraging a philological approach: 1) comparative analyses of the historical documents, overlapping and intersecting data derived from the different sources, and preparation of the model source data; 2) definition of the structure of the model and the naming scheme of the digital objects and related documentary sources; 3) geometric modelling and information enrichment of the model; 4) definition of a specific set of parameter dedicated to the assessment of the poten-

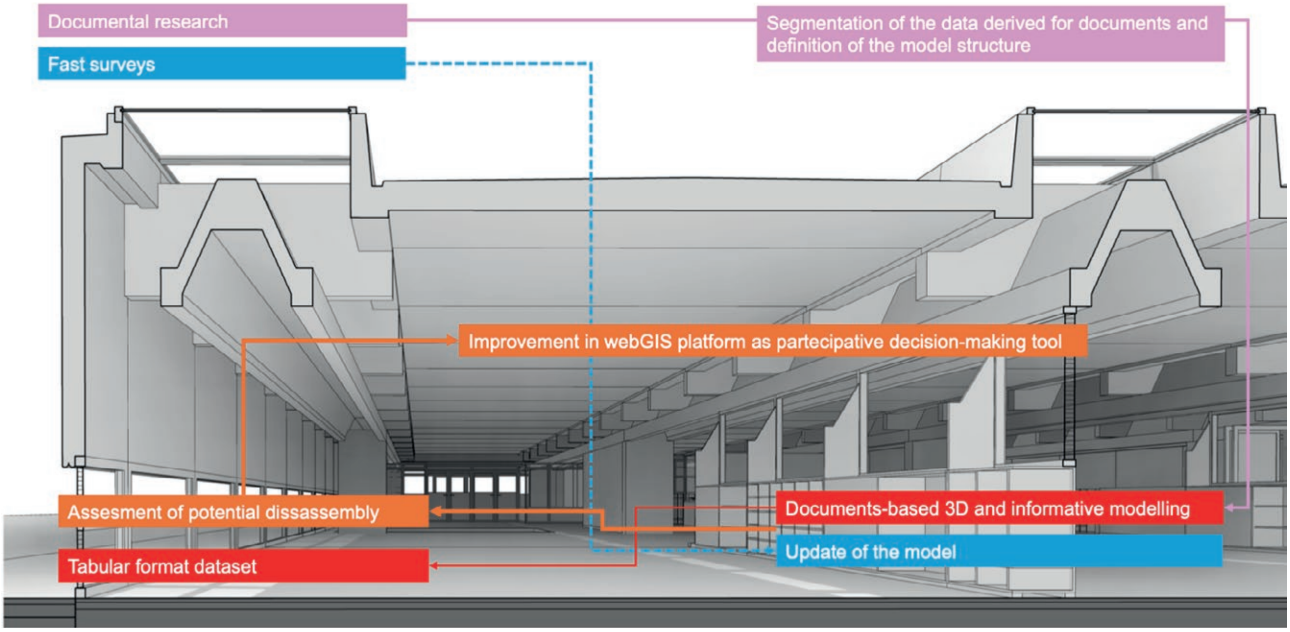


Figure 1. Workflow adopted for the construction of the philological digital model (© the authors, 2025).

tial disassembly of the building elements; 5) production of interoperable dataset in tabular format and automatic generation of informative field, related to the single building, in GIS format.

To meet the design functionalities, the model refers to the "Level of Information Need" (LOIN) concept [19-20]. According to the purpose of the BIM and the limited dimensions of the school buildings, both the geometry and the informative parameters concern the single construction components. The granularity of the information supports the in-depth study of the connection, regarding both the structural and non-structural components of the buildings, to assess the disassembly potential of each building component. From the interoperability protocols, the methodology relies on the definitions defined by the Industry Foundation Standard (IFC) and on the use of datasets, using tabular data standards CSV. The Revit platform is utilised for geometric and informative modelling, leveraging the software's native functionality to extract data in a tabular format. The webGIS platform's informative enrichment, based on a tabular data frame, utilises a basic Python code executed on the QGIS console.

3. THE CASE STUDY

In 1971, the Italian Ministry of Education launched a tender for the design and construction of 15 single-storey prefabricated buildings for kindergartens in various municipalities across north-central Italy [21].

The Benini company was awarded the contract for 15 buildings, containing 3 or 6 classrooms each. They utilised a proprietary construction system, patented by Celestino Benini in 1975 (Italian patent n. 1036570), developed in collaboration with architect Luigi Pellegrin. This system comprises five prefabricated reinforced concrete elements: columns, beams, wall panels, and roof panels, which can be assembled in various configurations. Based on the 'Gaburri-Structurapid' system [22], the columns are hollow elements requiring on-site concrete casting. Patented in 1975, the system is adaptable to both single-storey and multi-story buildings. It relies on the assembly of precast elements, varying in shape according to three configurations (A, B, and C) detailed in the 1975 patent. For the kindergarten project, configuration C was selected; the first two configurations were used for two different types of multistorey school buildings, designed by Pellegrin between 1970 and 1975 [2, pp. 110-123]

The system allows the creation of modular spaces with custom-designed furnishings. The building plan is organised around a 7.20 × 14.40 m modular grid, resulting in overall dimensions of 27 × 25 m. An off-centre entrance hall leads to an open space featuring a lowered central area for everyday pedagogical activities. The three classrooms, each with expansive ribbon windows, are situated on the opposite side. The construction involves the straightforward assembly of the five

Table 1. Pellegrin-Benini School Buildings in Italy (data from the Italian Ministry portal "Scuola in chiaro" and Google Maps, 2024).

Municipality	Location	Geographic Coordinates	Current Function
Alba	Strada Rorine	44°41'24.6'N 8°01'24.13E	Primary school
Chivasso	Via Paleologi	45011331.5" N7053'03 93E	Primary school
Rivoli	Via Antica Rivoli	45°04'44.7'N 7030'53.3" E	Primary school
Lodi	Via Lago di Como	45°18'40.2N 9030'42 1" E	Primary school
Morbegno	Via Prati Grassi	46°08'19 3" N9034'04.7°E	Primary school
Spinea	Via Donizetti	45°29'14.2'N 12°09' 48 4" E	abandoned building
Arezzo	Via Carlo Pisacane	43027'46 4'N 11°51" 35 9" 5	Primary school
Prato	Via Galcianese	43052'47.4'N 11°04'54.0'E	Primary school
Civita Castellana	Via Salvator Allende	42°17'55.9'N 12°24'26.2E	Primary school
Lucca	Via Vecchi Pardini	43050'47.7N 10028'51.0" E	Primary school
Latina	Via Milazzo	45026'45.0'N 9°05'47.4" E	abandoned building
Cesano Boscone	Via XXV Aprile	45026'45.0'N 9°05'47.4"E	Primary school

structural elements, starting from the ground up. Columns are positioned at the modular grid intersections, supporting inverted V-shaped beams. Shaped wall panels, spaced 1.20 m apart, are then erected on the beams. Floor slabs rest on these panels, forming skylights where they align with the beams. The perimeter walls have a specialised design to accommodate the hanging of external wall panels, secured by mechanical joints.

Today, the 15 buildings are in different states of maintenance, ranging from fully functional to abandoned (Table 1). Those that are still in use suffer from significant issues with rainwater drainage and have been heavily modified by the addition of roofing structures or poorly executed maintenance interventions on the window systems, both of which disregard the original design constraints and technological solutions.

3.1 The application of the philological 3D information model in selective dismantling and reuse scenarios

Following the proposed philological BIM methodology, a model of the 15 'Pellegrin-Benini' prefabricated school building was developed utilizing the Revit platform and relying on interoperability protocols based on the combined use of IFC standards and tabular data standards CSV. The CSV data frame is used for the automatic informative enrichment of the Shape file via the QGIS Python console, facilitating subsequent webGIS integration.

The modelling process is divided into three main phases: 1) modelling of the 'protype-building': this involves creating a detailed digital model of a typical building based on the original design documents; 2) model update: updating the 15 individual building models to reflect their current state, based on fast surveys; 3) data export: extracting geometric and informative data using interoperability standards, such as IFC and CSV; 4) georeferencing of data: provide simplified and geolocalised 3D representation of the building featured by key informative field, automatically enriched from the parse of the CSV dataset.

The elaboration of the source data (Figure 2) of the 'protype-building' model develops via the iterative cross-reference information from three sets of key documents: technical and calculation reports submitted within the tender launched by the Ministry of Education, accompanied by executive drawings of the structural elements (conserved by Ministry of Education Archive, Experimental School Founds, Italian Central State Archive); the patent drawings for the Benini construction system (conserved by Italian Patent and Trademark Office Archive, Italian Central State Archive); and construction site photographs taken by the architect (conserved by Luigi Pellegrin Archive, CSAC Parma).

Geometric and informative data were extracted from these key documents, which were subsequently ordered and classified using unique alphanumeric codes (IDs) assigned accordingly to the defined relational structure of the digital model. In this specific case, the hierarchy of the elements composing the construction system – pillars, beams, walls, and the two types of panels – was translated into a definition of categories of the digital object composing the model, related through a three-level hierarchical structure. Within the relational scheme of the digital model, the category of beams (B), the one of the walls (W), and the one of the pillars (P) represent the first hierarchical level; the two types of panels (p), the second level, while the architectural elements such as the façade and the roof windows, the third. According to this hierarchical scheme, the nomenclature of all

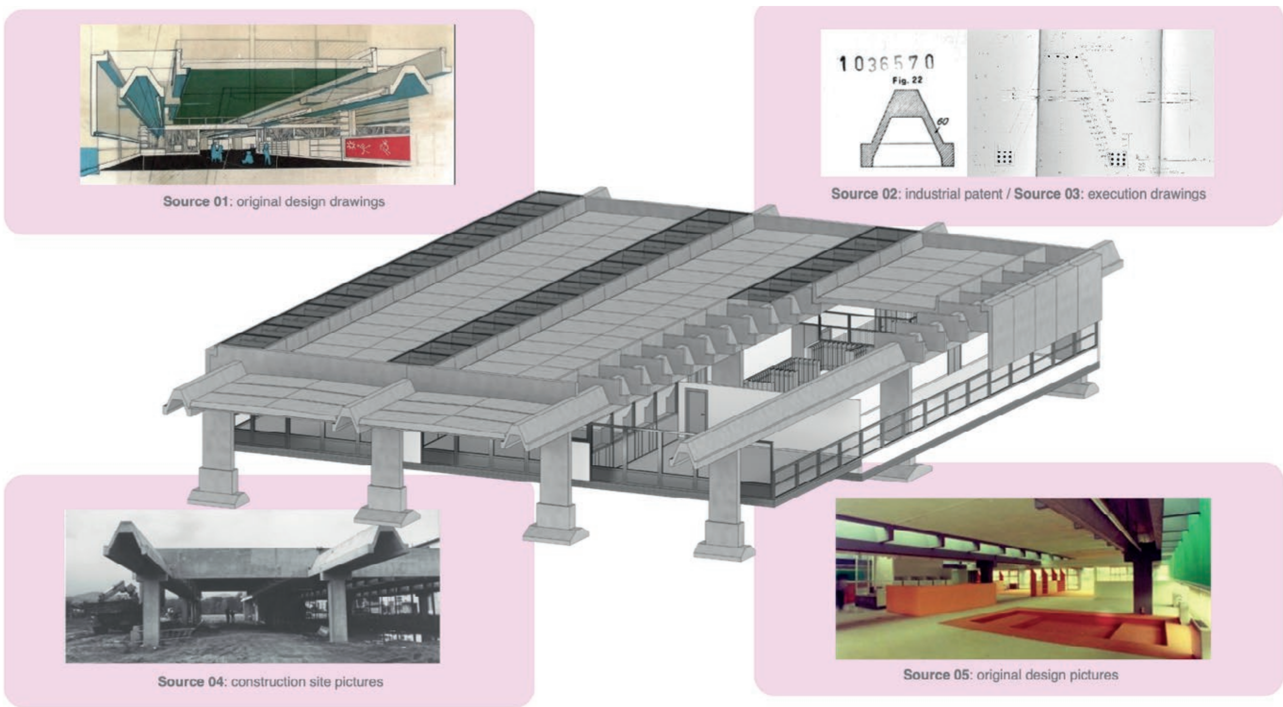


Figure 2. Table of the source data of the "prototype-building" model (© the authors, 2025).

the digital objects of the model featured the assignment of IDs, ensuring the correlation between the individual digital object and the represented building component. Furthermore, the ID that identifies the single building component is assigned to the related set of documents, thereby ensuring a bilateral informative flow between the documentary sources related to the model and each digital object representing the building components.

The geometric model was developed through the segmentation into nested objects, with increasing levels of detail. For instance, the digital objects representing the reinforcement of beams, pillars, and walls were developed, based on data from the original execution drawings and calculation reports, as "local models" correctly nested within the 'B', 'P', and 'W' general categories.

In this sense, each category of elements presents a detailed dataset regarding general geometric features, the data related to the history of the building, and the characteristics of the building material. Furthermore, the local models are exploited as an internal source to generalise and expand the related informative set to all the components of the building, exploiting standardisation. This procedure assures, on the one hand, the embedding of specific detailed information, guaranteeing, on the other hand, the fast usability of the model without informative data loss (Figure 3).

The "model update" phase focuses on the integration of the actual state of the 15 buildings, starting from the 'Type-Building' philological model. In particular, the update focuses on integrating novel geometries of roofing window systems, derived from fast photographic analyses or the analysis of documents concerning maintenance interventions stored in the technical office of individual school buildings. In this sense, the case of the school buildings of the Chivasso Municipality stood out for the construction of a superimposing steel structure without any relation to the original design of the school.

The "data extraction" phase relies on the creation of an interoperable data frame based on a standard tabular format (CSV). More specifically, by leveraging the IDs of the individual digital objects, the information content of the model can be easily represented in tabular format, without losing the semantic association with the related building components. Each element of the model, identified by its ID, corresponds to a comprehensive dataset, organised at multiple levels concerning history, geometry, construction details, material characteristics, and actual state. The datasets are extended to the documentary sources, integrating hyperlinks to the key documents, previously labelled by the corresponding IDs.

The final step of the workflow supports the management of the 15 school buildings at the territorial scale, processing data related to the single building in the urban

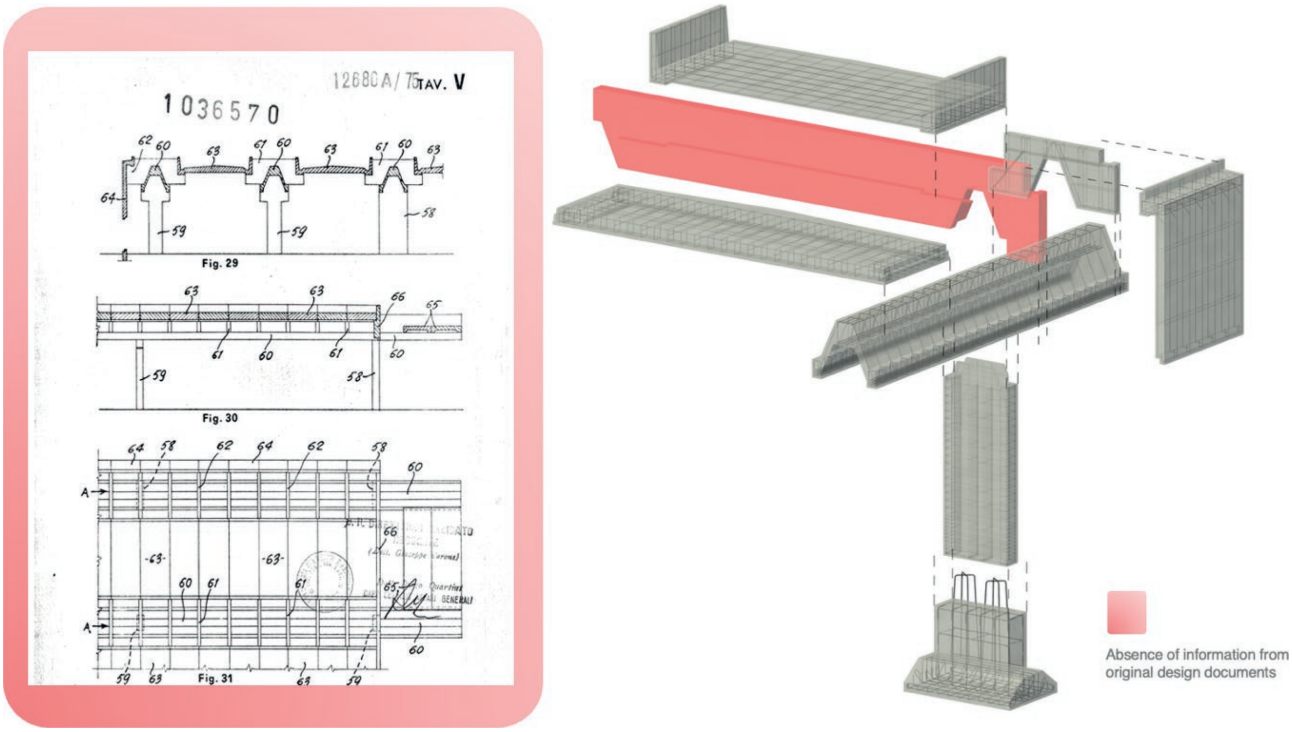


Figure 3. View of the philological 3D and informative model of the structural elements of the 'Type-building' and related industrial patent exploited as a documentary source for the modelling process (© the authors, 2025)

context. The informative data extracted from the model in tabular format are processed to automatically enrich a webGIS platform, based on an SQL spatial database and directly connected to a web viewer. The 15 schools are localised and associated to simplified representation, embedding a set of informative parameters directly derived from the BIM – exploiting the Phyton code-based parse of the data frame in table format run by the QGIS console – including the set of main quantitative and qualitative data concerning each building components (ID, age, number, weight, state of decay, disassembly index).

The actual state of the 15 school buildings requires the development of specific strategies to manage their next future conditions, including experimental preservation actions. In this sense, discussing the future of the 15 school buildings in the broad framework of the optimisation of the resources in the construction sector, a possible path can be the assessment of the potential disassembly of the school building according to the selective dismantling procedures, traced by the regulatory framework of the Minimum Environmental Criteria (CAM) and the most affirmed manifestos on circularity in construction based on the threefold principle of "share knowledge"; "gathering data"; "valorise the existing building stock" [23-25].

In this sense, a specific set of 'disassembly parameters' was used to qualitatively assess all aspects related to the possibility of disassembling structural and non-structural components of the analysed buildings. As reported in the following Table 2, such parameters reflect the main principles of Design for Disassembly and the actual practices of 'selective dismantling', according to the actual regulatory framework (ISO 20887:2020) [26]. The main set comprises six parameters – Ease of access, Independence, Reversible connection, Weight, Obsolescence, Standardisation, named accordingly to the general principle of Design for Disassembly required by the ISO 20887:2020 [24]. The values of each parameter are classified in three base classes – low, medium, and high – and are assigned based on document-based knowledge, supported by on-site visual inspection. Each class of values – low, medium, high – corresponds, respectively, to a numerical score ranging from 0 to 2. The main set of 7 parameters is applied to each building element to assess its potential disassembly, evaluated through a numerical value, ranging from 0 to 12, considering the sum of the values assigned to each parameter. Furthermore, a corrective parameter is considered for the overall evaluation of the potential' Disassembly Index'. As shown in Table 3, this param-

Table 2. Set of parameters considered to assess the "Disassembly index".

Name of the parameter	Description	Value of the parameter		
		Low (0)	Medium (1)	High (2)
01_Ease of access	Ease of access to building components with minimal damage to and impact on them and adjacent assemblies (ISO20887)	exposed and accessible on one side	exposed and accessible on two sides	exposed and accessible on all sides
02_Independence	Quality of the components to be removed without affecting the performance of connected or adjacent systems (ISO20887)	exposed and not accessible from the top	exposed and partially accessible from the top	exposed and accessible from the top
03_Reversible connection	Connection that can be disconnected or disassembled (ISO20887)	Passing iron rebars	Concrete infill	geometric connection
04_Weight	Weight of the structural component for construction site disassembly activities	>50 kg	20-50 kg	<20 kg
05_Obsolence	Express the % damage area/ total area of the element, considering visible damage.	>60%	20-60%	0-20%
06_Standardization	Possibility to standardize the disassembly process using efficient and repetitive techniques measured via the % value expressing the quantity of the element/total of the structural elements (ISO20887)	0-20%	20-60%	>60%

Table 3. Corrective parameter considered to assess the "Disassembly index".

Name of the parameter	Description	Value of the parameter		
		Low (0)	Medium (1)	High (2)
Safety of disassembly	Proven knowledge about the construction materials, identifying potential hazardous substances (ISO20887)	proven existence of hazardous substances (documentary basis)	assessment of hazardous substances (visual inspection)	proven absence of hazardous substances (documentary basis)

Table 4. Subset of parameters considered to assess the "Shared Heritage".

Name of the parameter	Description	Value of the parameter		
		Low (0)	Medium (1)	High (2)
Age of construction	Age of the building, referring to the construction period, considering cut-off of cultural heritage constraints (d. lgs. 22 gennaio 2004, n. 42)	<70	70	>70
Documentary heritage	Presence of documents proving links with historical and technological background (d. lgs. 22 gennaio 2004, n. 42)	authorial design proven by original drawings	authorial design proven by original drawings, literature of the time	authorial design proven by original drawings, literature of the time, and industrial patents
Consistency of the original design principle with the DfD framework	Proven knowledge about the original design choice in terms of ease of access, independence, and reversible connections	visual assessment of construction details	knowledge about the historical-technical context (literature)	proven knowledge about the original design choice (documentary basis)

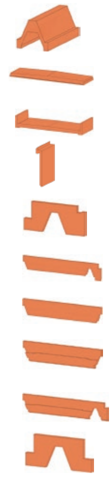
NAME	VOLUME	ease of access	independence	reversible connection	weight	obsolence	standardization	safety of disassembly	**disassembly index**	FIGURES
STR-BEAM-SHAPED-CA	7.59 m³	2	1	2	1	2	2	2	**11**	
STR-PAN-PORCH-RC	2.55m³	2	2	2	0	2	2	1	**12**	
STR-PAN-ROOF-RC	2.89m³	1	2	2	1	2	2	1	**12**	
STR-PAN-WALL-RC	variable	2	2	2	0	2	2	1	**12**	
STR-PART-EXT-RC	0.24m³	2	1	2	0	2	2	1	**11**	
STR-PART-EXT-RC	2.47m³	2	2	2	0	2	2	1	**12**	
STR-PART-FINAL-C	2.18m³	2	2	2	0	2	2	1	**12**	
STR-PART-FINAL-D	3.06m³	2	2	2	0	2	2	1	**12**	
STR-PART-FINAL-E	3.15m³	2	2	2	0	2	2	1	**12**	
STR-PART-INT-RC	0.22 m³	2	1	2	0	2	2	1	**11**	

Figure 4. Results of the assessment of the Disassembly Index for the main set of the building horizontal elements of the Benini systems (© the authors, 2025)

eter, named Safety of disassembly is evaluated, according the same classes of values – low, medium, high –, on documental basis and visual inspections: as it assesses the presence of potential hazardous substances, the low score (0) nullified the value of the potential 'Disassembly Index' obtained by the sum of the previous six parameters; the medium score (1) confirms the value of the potential 'Disassembly Index' requiring further on-site survey to confirm the values; the high score (2), confirms the value of the potential 'Disassembly Index'.

According to the study of the historical and technological knowledge of the analysed building, previously obtained through the documentary sources, a further specific cluster of parameters is, thus, dedicated to the assessment of the 'inherited identity' [23] of each building element. As is shown in Table 4, this latter cluster includes the following three parameters: 'Age of construction', 'Documental heritage', and 'Consistency of original design principle to DfD'. The latter three parameters are evaluated considering three base classes – low, medium, and high – corresponding to the numerical score ranging from 0 to 2, based on document-based information. 'Age of construction' refers, in this specific case, to the 70-year cut-off from construction date that, according to the constraints introduced by the Italian Law on Cultural Heritage, excludes selective dismantling from the possible scenarios. 'Documental heritage' refers to the cultural values of the building, inherited from the historical and technological background, that could be assessed on a documentary basis. Similarly, the 'Consistency original design principle to DfD' refers to the original design choice in terms of ease of access, independence, and reversible connections, according to documentary evidence. In this case, the latter two variables include, indeed, a tentative evaluation of the historical and technological value of the building, or better, of its construction system, supported by the documentary evidence of the original design drawings by Luigi Pellegrin, the literature of the time concerning the school building design, and the industrial patent describing the construction system.

Combining the analytical definition of the 'Disassembly index' with the structured dataframe provided by the informative model of the building, a comprehensive measurement of the potential disassembly of each building component can be produced, supported by effective three-dimensional representations. Figure 4 shows the axonometric views of the school building, showing the graphic results of the value of the 'Disassembly index' assigned to each building component. In orange and red, the values of the 'Disassembly index' are shown for the structural and architectural elements of the type-building; in blue, the values of the same parameters are shown for the structural elements of the renewed roof of the specific case of the school building in Chivasso.

The list of values of the 'Disassembly index' corresponding to each building element is, thus, combined in

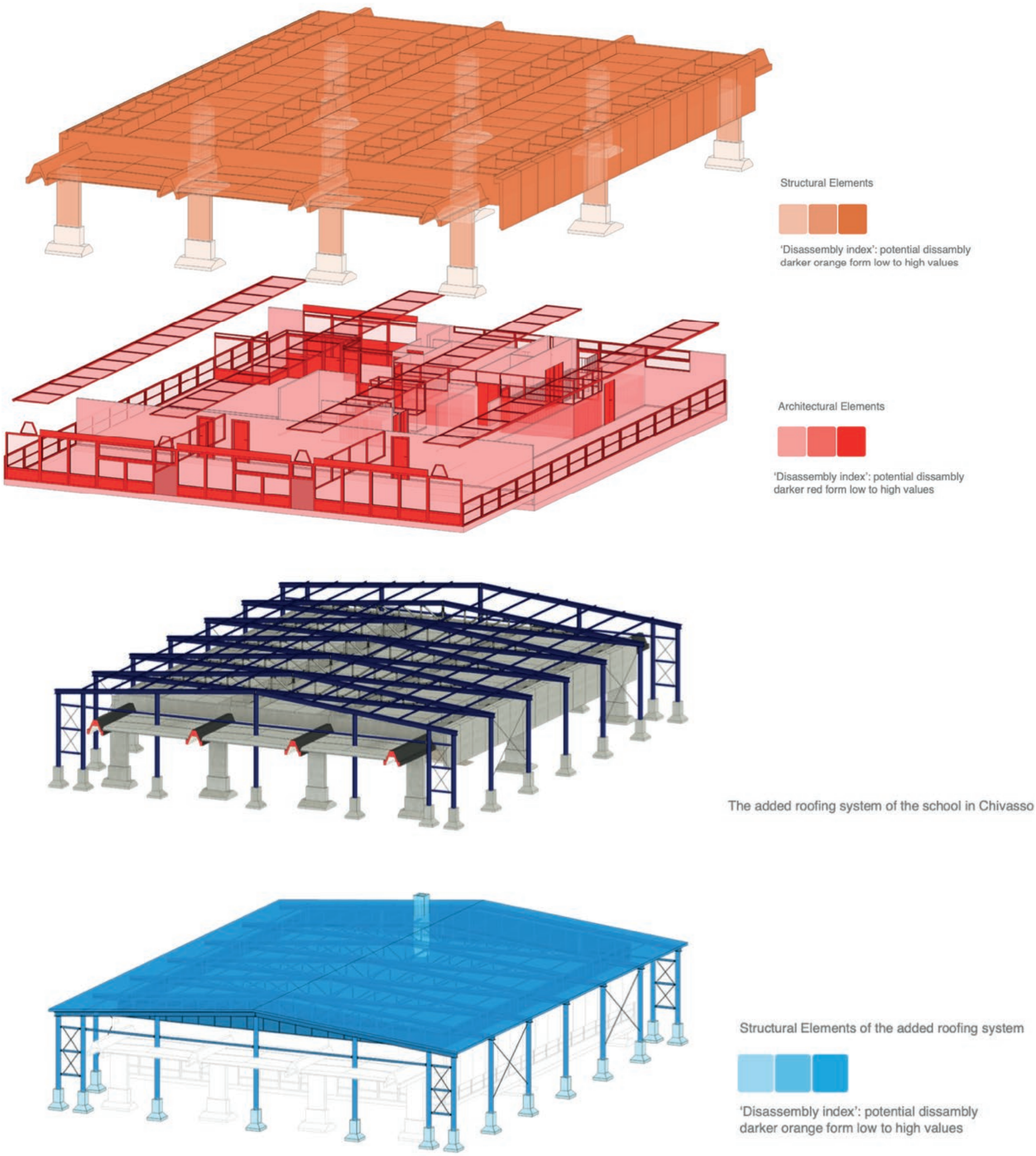


Figure 5. Results of the assessment of the Disassembly Index for the 'type-building', in orange and red, and for the specific case of the school building in Chivasso, in blue (© the authors, 2025).

a 'Disassembly index' at the building scale, corresponding to an average value, providing valuable data to support the decision-making process of the stakeholders involved in the school building maintenance and preservation.

4. ABOUT PARTICIPATORY PRACTICES TO DESIGN AND TEST THE PHILOLOGICAL DIGITAL PLATFORM

According to the application of participatory methods following what has been defined as the "shift from local government to local governance" [27], the use of integrated digital tools allows the construction of organised special database for the collection of information relating to the history of the building and its components, providing, at the same time, an easy-to-use tool to simulate the preservation scenarios, including the alternatives of selective dismantling and reuse. The possibility of collecting, connecting and display the historical and technical data allows to reconstruct the history of the building, from the project to the construction, to the subsequent interventions, contextualising it in the cultural and social horizon that led to the use of industrialised solutions and prefabrication in school buildings: this allows to bring the local communities closer to the material knowledge of the buildings, sharing the cultural values of the technological and the architectural solutions of the original design. Furthermore, the simulation of selective dismantling and reuse scenarios, supported by the virtual reconstructions, on the one hand, increases the awareness of the environmental criteria linked to the actual management of the existing buildings, and, on the other hand, can provide a useful tool to apply participative methods to the reuse design process.

A direct experience of the usefulness of the proposed digital-platform-aided participatory approach for the preservation of the 20th-century school buildings and the refinement of the methodology was investigated through four design workshops that were organised in different contexts. Three workshops were organised within the framework of the ESF project "SchoolNET. Innovative tools for the sustainable and inclusive refurbishment of school buildings and the management of urban mobility" [28], and they mainly focused on participatory consultation and discussion among different actors. At the same time, a fourth one, part of the PRIN 2022 PNRR "Upcycling Architecture in Italy" [29], was dedicated to exploring the methodology of DfD-Design for Disassembly and upcycling applied to a paradigmatic example of a prefabricated school building of the 1960s [4].

The first workshop "Science for All. *Raggiungi, crea e costruisci la tua scuola ideale*!" was organised in Padova with the participation of eight primary schools, organised in group work focusing on mobility – how

Figure 6. Activities dedicated to the public engagement within the Workshop "Non-Formal Spaces of Education", University of Thessaly (© picture by the authors, 2024).

they get to school -, structures – how they perceive the building where they are – and inclusion – provoking reaction of affection or disagreement of school places. The second one in Volos during the Erasmus+ Blended Intensive Program "Non-Formal Spaces of Education. Reclaiming the School as a Space of Commons" sought to investigate the possibility of creating new educational spaces in existing schools through the adaptation and transformation of an existing building and its surrounding space [30]. Both workshops had engaged teachers, students, and pupils in a participatory design using the tool of collage to inquire about expectations, desires, and daily practices of the pupils (Figure 6). The goal was to provide concrete indications for rethinking educational spaces, informing the development of the webGIS SchoolNET platform by shifting the point of view from developers to future users. The experiences highlighted how digital tools designed to facilitate decision-making processes for the transformation of the environment and school spaces should necessarily pass through a participatory process, respecting the value of social capital and cultural heritage represented by the school. The high social value of the school system and the possible repercussions on the urban communities of reference of the redevelopment and transformation actions require a precise participation activity with the users of the school network.

The third workshop, titled "Awareness on Schools" refurbishment and sustainable management, brought together assignees, corporate and network partners, professionals from the construction and plant engineering sector, and those involved in renewable energy production. It took place at the Fenice Academy in Venice. The focus was on raising awareness of the digitalisation and virtuous management of school buildings, and the design of systemic interventions at the building and urban scale. The intervention was a moment of confrontation between professionals from the fields of construction and plant engineering, renewable energy production, and public administration. In particular, the round table discussion focused on the use of BIM as a tool to guide the redevelopment and management of school buildings. On the one hand, the need to implement simplified and agile models, understood as databases with three-dimensional visualisation possibilities, was highlighted. In fact, this approach allows for easier data collection within the model and its use by managers (public administrations and municipal technical offices) of school buildings. On the other hand, the importance of a complete digital modelling leading to the implementation of a digital twin was emphasised, where the fidelity of the representation and computerisation of the data allows for greater efficiency in the management of the model and the building, despite requiring greater knowledge and commitment on the part of the managers (public administrations and municipal technical offices) of school buildings.

Eventually, an attempt to test the methodology, within a pedagogical approach for PhD students, has been investigated during a research-by-design workshop that was organised in June 2024 at Sapienza University of Rome, which involved 13 PhD students, from 5 different Italian universities, in the framework of the PRIN 2022 PNRR "Upcycling Architecture in Italy" [29]. In this case, the construction of the philological BIM, according to the presented methodology, focused on the experimental preservation of a prefabricated school building to explore 'selective dismantling' and potential reuse, and upcycling of its building elements. The model was tested involving the community of local stakeholders charged with the current maintenance of the school building, providing key data to develop the conception and the functioning of the digital platform: in particular, the need to provide easy-to-use viewers of the 3D-informative models, supported by an analytical dashboard for the assessment of the economic-financial impact of the selective dismantling processes, emerges. Furthermore, the heritage assessment issue was underlined, providing key data for the development of the digital platform as a 'living archive' [31] dedicated to preservation actions, exploiting the organisation of the historical and technical documentary framework.

5. CONCLUSIONS

The present paper addresses the construction and the use of an integrated digital platform to support knowledge and experimental preservation of the late 20th-century school building heritage. The methodology includes philological tridimensional and informative modelling approaches, exploiting documentary sources, and participatory practices in the development and testing phase of the digital platform. The study presents a twofold outcome: assessing the effectiveness of the proposed methodology for the construction of integrated digital platform dedicated to the actual actions of preservation of the late 20th Century school buildings, with specific reference to prefabricated school buildings and experimental preservation actions, including 'selective dismantling' and 'reuse'; opening a further discussion on participatory practices for the actual preservation of the school buildings within the current socio-technical scenarios.

Regarding the first point, the study validates the proposed philological modelling approach, based on documentary sources, to provide a structured data frame concerning the history and the technological solutions of the buildings. In this sense, the proposed modelling approach allows the exploitation of a technical and data framework to produce an analytical tool to support the assessment of potential 'disassembly' and, then, reuse of the building elements, providing an easy-to-use interoperable data frame exploiting table style sheets and special representation of data. The procedure – based on the combined use of a philological BIM with the evaluation of the potential disassembly according to the current regulatory framework on DfD – is conceived as modular and replicable to different building typologies, particularly featured by the use of prefabricated systems. In this sense, the method can be considered effective to support decision-making within the challenging preservation of the broader prefabricated building heritage of the late 20th Century [32].

Regarding the second point, the study stresses the role of participatory design for the preservation and reuse of 20th-century school buildings using a digital tool to facilitate interaction among different stakeholders. To inform the construction of the digital tool, preliminary participatory design workshops engaging different potential stakeholders (pupils, professionals, researchers, and university students) may offer helpful information about how to transfer an easy-to-use interoperable data frame into a friendly and straightforward interface. Accordingly to the outcome of these workshops, the use of digital tools, may help to facilitate the employment of actual practices of Design for Disassembly to expand the potential reusability of the building components and transformative actions allowing to retrace and share the material history, through the documents of the original design and the construction process and share intangible values of the schools building provide by the action of 'documenting'.

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7. AUTHORS CONTRIBUTIONS

The Individual contributions of the authors are as follows. Ilaria Giannetti: Conceptualization, Data analysis, Writing of the original draft, Visualization, Editing and Supervision; Angelo Bertolazzi: Conceptualization, Data analysis, Writing of the original draft, Visualization, Editing and Supervision; Fabiano Micocci: Conceptualization, Writing of paragrah 4, Supervision. The authors would like to thank Eng. Cristian Tolù for his contributions to the Figures of this article.

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Multi-Objective Optimization of Facade Retrofit Solutions for Italian Residential Precast Concrete Buildings

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Abstract. The current European policies aim to obtain a significant reduction in CO_2 emissions, targeting a carbon-free economy by 2050, and propose an extensive renovation plan for the residential building heritage. The majority of Italian residential buildings predates energy-saving regulations and are currently affected by several environmental issues. This paper proposes retrofitting measures for the external walls of an existing residential precast building dating back to the 1980s, located in the Province of Florence. Two different technological solutions have been evaluated for the redevelopment of facades, featuring recladding with a Vêture system and a rainscreen solution. The methodology of the research implements a BIM-based approach: the building was modelled in the Revit environment, while optimized facade layouts were generated using an algorithm developed in Grasshopper, considering various design parameters. As for the Vêture solution, the chosen configuration reduces the total number of panels installed, minimizing at the same time the use of special components. A similar approach has been adopted in the case of the rainscreen solution, but resorting to an optimization procedure through genetic algorithms. The solutions of interest have been hence selected in the Pareto front, considering the type and number of panels. The retrofit interventions explored improved the building's energy label from F to E, also enhancing its aesthetic quality.

Keywords: Residential building stock, precast structure, energy retrofit, optimization, BIM.

1. INTRODUCTION

The challenging environmental strategy set by the European Union to achieve a carbon-free economy makes redevelopment interventions addressing the existing building heritage extremely urgent. In Italy, the existing residential building stock accounts for about 12.5 million facilities, 60% of which was built before 1970 when national standards for energy saving were still lacking [1]. As a consequence, 71% of the Italian residential building stock currently belongs to low standards considering the energy labelling classification (E, F and G), being characterised by an average energy performance index equal to 185.4 kWh/m^{2}y. As previously introduced, the age of public residential structures is a detrimental factor that heavily affects the energy performance, as well as the architectural and aesthetic quality, of social housing buildings.

Between the 1960s and 1980s, precast systems were adopted in Tuscany to meet the increasing demand for housing facilities, particularly in Florence, Sesto Fiorentino and Prato. The recourse to prefabricated, standardized solutions, replicable in different contexts, was highly promising at that time to reduce costs and to speed up construction processes, but resulted in several issues over time. Nowadays, these buildings are characterised by inadequate structural behaviour, rigid structural and architectural schemes, and a lack of aesthetic refinements. Moreover, the technological solutions adopted, combined with the low quality of the materials used, have determined poor thermal insulation, inadequate internal comfort conditions and high annual energy demand. In this context, retrofitting interventions are necessary but can sometimes be complex and challenging due to structural and technological limits, as reported by some authors in the literature. Ciulla et al. [2] remark on the difficulty of selecting the proper redevelopment solutions for facades, while Ballarini et al. [3], following a cost-optimal evaluation, recommended acting on heat generators as the most cost-effective intervention for the same building stock, also analysed by Corrado et al. [4]. Other studies deal with specific retrofit solutions, both at the building scale [5] and urban level [6-7].

The widespread diffusion of new digital and computational tools has been reshaping scientific research trends over the last decades. Several researchers propose BIM-based methodologies applied to the existing building heritage [8-9] for its energy and structural retrofit [10] and its management over the life cycle [11-12]. The advantages of BIM-based approaches also rely on interoperability with tools for structural, energy, and environmental simulations or Life Cycle Assessment analysis [13]. Recently, some authors have proposed the integration of emerging artificial intelligence (AI) into BIM modelling and parametric design using the Visual Programming Language (VPL) tool [14-16]. The research on the energy retrofit of existing building facades using innovative design tools mainly deals with dynamic solar shading systems and adaptive facades, without considering traditional solutions well-established in the market.

This paper aims to demonstrate the potential of using VPL (Visual Programming Language) tools in parametric design procedures to highlight how optimization techniques can support decision-making, particularly in the assessment phase of technological and economic feasibility.

The research focuses on the design of potential retrofit interventions for an existing precast multi-storey residential building chosen as a case study. Acting on the facades was prioritized given the greater dispersing surface, the currently low thermal resistance and the poor aesthetic quality. In this regard, Vêture and rainscreen facades were foreseen in the research to include two distinct technological solutions that are commercially available and commonly used in current practice. The study was carried out implementing digital tools within a BIM-based approach. At first, the building was modelled in the BIM environment through Revit software starting from the original architectural and structural project documents. The modelling phase was useful to organize, systemize and manage all the retrieved building data as well as to provide a reference digital twin for the subsequent analyses. A Grasshopper script was developed to explore different layouts for facade recladding panels and to optimize their arrangement through two different approaches.

2. METHODOLOGY

The research was developed by applying the methodological steps detailed below and illustrated in Figure 1:

- Historical archival research. This phase is based on previous research conducted by the authors that resulted in the classification of the different precast concrete systems used within the 1970s and 1980s to build social and public housing in the Florentine area. An exhaustive document acquisition campaign from *Casa Spa* Archive was held at the time, investigating original design projects, the correspondence during the construction phase, patents, bills of quantities and cost inventories. The original documents were scanned to obtain digitalized materials, and in the meantime, a photographic on-field survey was conducted to assess discrepancies with real conditions.
- Case study building selection. Following a careful examination of the available material, a 5-storey linear building sited in the Municipality of Sesto Fiorentino, and built between 1981 and 1985 using the CA-AB system, was chosen as the reference case. This choice was based on the documentary coverage of the building, the widespread adoption of the same construction system during that period, and on its peculiarities, which make the results of this study extendable to other kinds of building types.

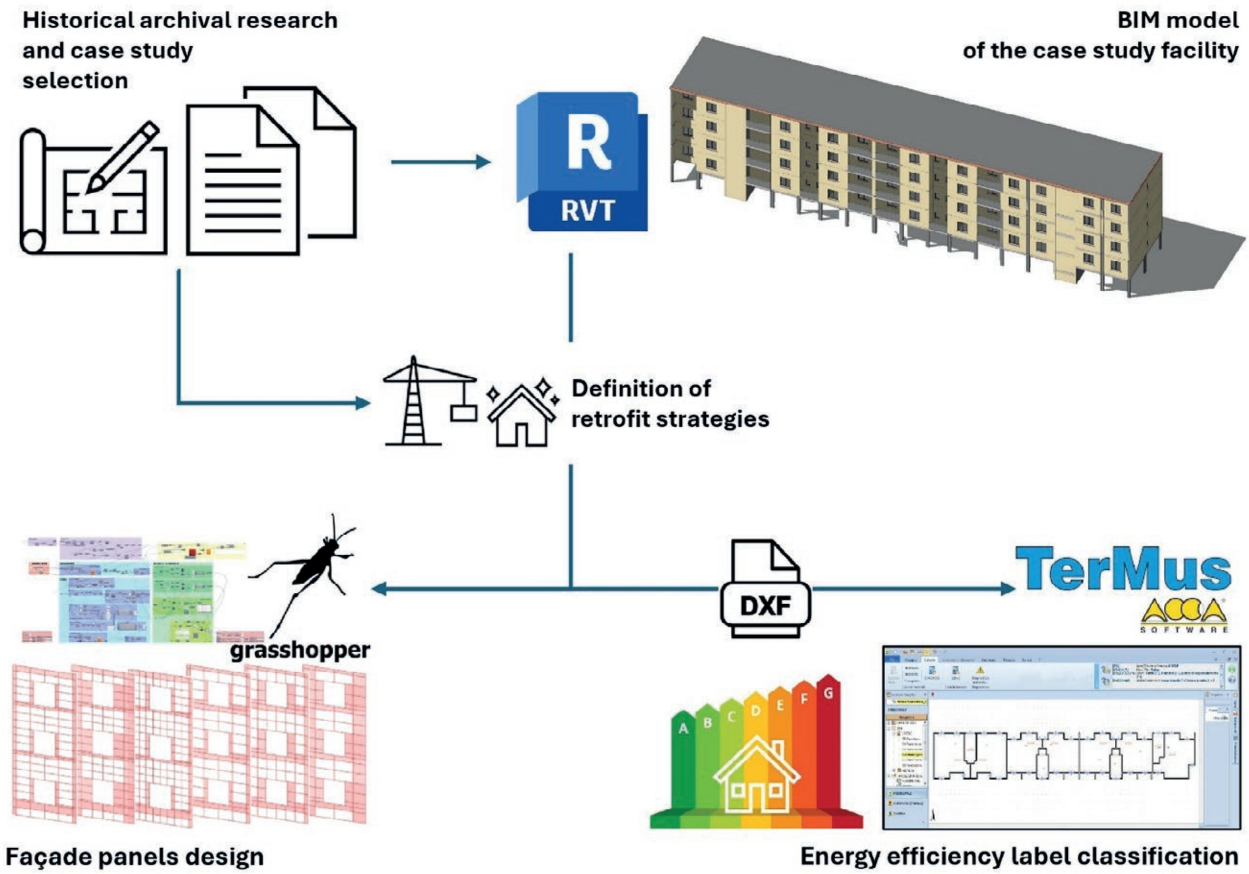

Figure 1. Methodological workflow of the research. © 2025, Authors.

– BIM-modelling phase. The case study was modelled in a BIM environment using Revit software, following the architectural, structural, and technological details retrieved in the specifications of the original design documents and considering the photographic documentation acquired. The incongruences assessed between the various design documents available were also solved to produce a reliable as-it-is condition model.
– Definition of retrofit strategies. Two different technological solutions among those available on the market were considered for the architectural and energy redevelopment of existing facades. Both configurations were designed to achieve the same thermal resistance and convey equivalent energy savings for heating demand. The first one is a Vêture recladding system, composed of a horizontal metal substructure and a panel (6.6 cm thick, U=0.54 W/m^{2}K) made of fibre-reinforced composite mortar finishing and a thermal insulation layer (EPS additivated with graphite) with open joints. The second alternative is a traditional rainscreen cladding system with a metal substructure, a thermal insulation layer (wood fiber - 6 cm thick, λ = 0.038 W/m^{2}K), and completed with low-thickness (3.5-20.5 mm) ceramic tiles as external finishing.
– Facade panels design in the Grasshopper environment. The building's geometry was directly imported from Revit into the Rhinoceros environment, via Grasshopper plug-ins, referring to a portion of the external facade. A series of VPL scripts was developed to define the geometry of the facade recladding panels for both the retrofit solutions, including optimization and design optioneering algorithms.
– Energy efficiency label classification. To quantify the effectiveness of the energy retrofit proposed, the building geometry was imported in TerMus software to evaluate both pre and post redevelopment state following the current Italian energy standards [17-18]. A gas condensing boiler (efficiency equal to 0.7) was selected as heat source and the setpoint temperature during winter was set equal to 20°C to

reflect the residential intended use. Natural ventilation for minimum air change rate and the domestic hot water demand have been included in the energy balance. However, some simplified assumptions were made: apartments were modelled as homogeneous zones given the uniform operation conditions, and lighting loads were not accounted for, as well as the internal heat gains.

2.1 The Case Study

The case study (Figure 2) is a 5-storey linear building located in the municipality of Sesto Fiorentino (Florence). This building was commissioned by the IACP (*Istituto Autonomo Case Popolari*) of the Province of Florence in 1981 and completed on 1st July 1985.

The building, oriented along the NE-SW direction, has a rectangular shape with main dimensions equal to 63.10 × 11 m and a gross floor area of about 700 m^2. It is composed of two different structural units with seismic joints at 27.50 m along the prevailing axis. The ground floor (2.40 m high) hosts private cellars, technical rooms and collective open spaces with *pilotis*, while the other four upper levels (2.70 m high) comprise a total of 30 apartments of different sizes (Table 1). Vertical connections are ensured by four lifts and stair blocks.

Considering the elevation, the openings are aligned and present the same dimensions. In the main fronts: 1.40 × 1.40 m for windows and 0.90 × 2.40 m for balcony glazing doors. On secondary fronts, only smaller openings (0.80 × 0.90 m) can be found.

As far as the structure is concerned, it was built adopting the CA-AB system [19]. This patent foresees a precast reinforced concrete frame structure with single-story columns and beams in slab thickness (24 cm), with structural joints made by additional concrete casting. The beams have a trapezoidal cross-section with extrados longitudinal reinforcement bars. The floor slabs are partially prefabricated and lightened with polystyrene blocks. The external walls feature the following stratigraphy (total thickness 19.5 cm) from the internal to the external side: plasterboard panel (1 cm thick), polystyrene thermal insulation (5 cm), hollow bricks (12 cm) and external plaster (1.5 cm). These facades are characterised by the following thermal properties: thermal transmittance U=0.544 W/m^{2}K, surface mass M_s=96 W/m^{2}K, and periodic thermal transmittance Y_{IE}=0.4 W/m^{2}K. The roof slab is completed with a polystyrene thermal insulation (5 cm thick) and a bituminous waterproof sheet as a finishing layer (1.5 cm). For the calculation of the thermal properties, UNI 10351 was considered [20]. As for the internal walls, they were realized recurring to dry-wall partitions.

2.2 Facade panels design

Figure 3 provides a general overview of the VPL Grasshopper script, briefly described in this paragraph to highlight its crucial components and the decision-making approaches followed for selecting the most suitable design alternative.

The script can be divided into three different macro-sections: a block of instructions is initially meant to select and import the portion of the facade under consideration directly from the BIM model, while the two others are dedicated to the definition of the panels' layout and selection of the most suitable configuration for both the Vêture and rainscreen alternatives. The latter sections are made up by using the same logic and procedural steps. Going into detail and referring to the numbering proposed in Figure 3:

a) Segmentation of the facade: this operation is meant to subdivide the geometry of the current facade state into homogeneous portions. This preliminary operation is crucial to defining the arrangement of the facade cladding panels in the subsequent steps.
b) Definition of panels' size: through a numeric slider, the width and height of each panel can be set, with different values allowed according to the technological solution chosen:
   - Vêture system: dimensions derived from commercially available products. The standard height of the panel can be either 0.45 m or 0.60 m, while the width associated with each varies

Table 1. Internal layout of the apartments.

Flat	Area [m^2]	Floor	Users	Living room with kitchenette	Bathroom	Double bedroom	Single bedroom	Balcony
A	45	1	2	X	X	X		X
C	60	2,3,4,	3	X	X	X	X	X(2)
D	70	1	4	X	X	X(2)		X

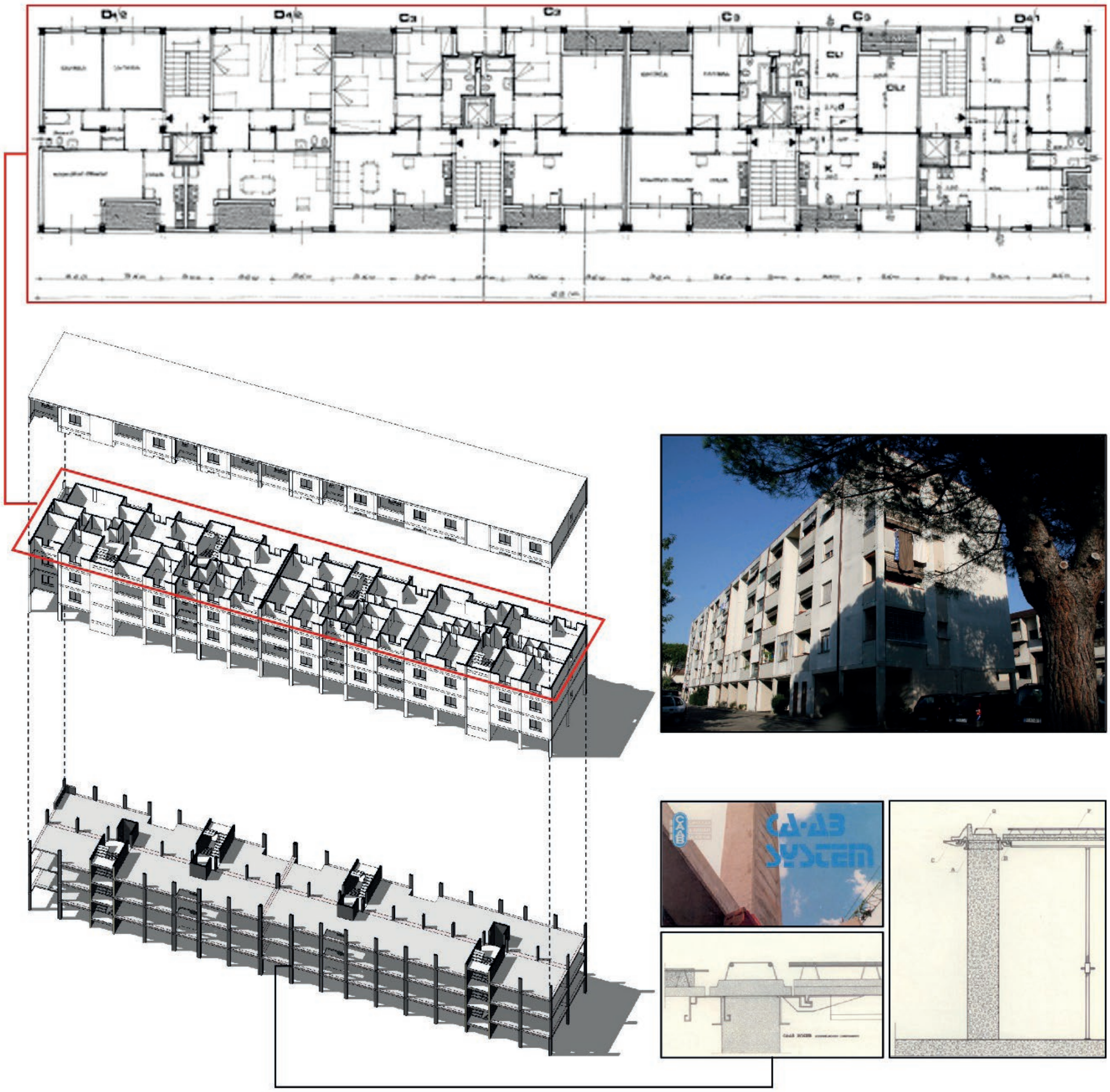

Figure 2. Case study building. Type floor plan, photographic evidence, patent details. © 2025, Authors.

from 0.45 to 0.90 m in the first case and from 0.60 to 1.20 m in the latter.

– Rainscreen facade: as previously introduced, the solution featuring low-thickness ceramic cladding tiles allows for a wider range of geometries; in this case, both width and height were assumed to vary between 0.10 m and 1.10 m with increments of 0.10 m.

c) Definition of panels' layout: following the previously introduced facade segmentation and adopting the dimensions set in the b) section, the layout of panels was generated. The following assumptions have been introduced when defining the constraints for tiles' arrangement:

– Vêture system: given the peculiarities of this technology, horizontal bands between windows were addressed as the reference sections. In these areas, rows of cladding panels were assumed to begin from the bottom side and to be arranged symmetrically with respect to the

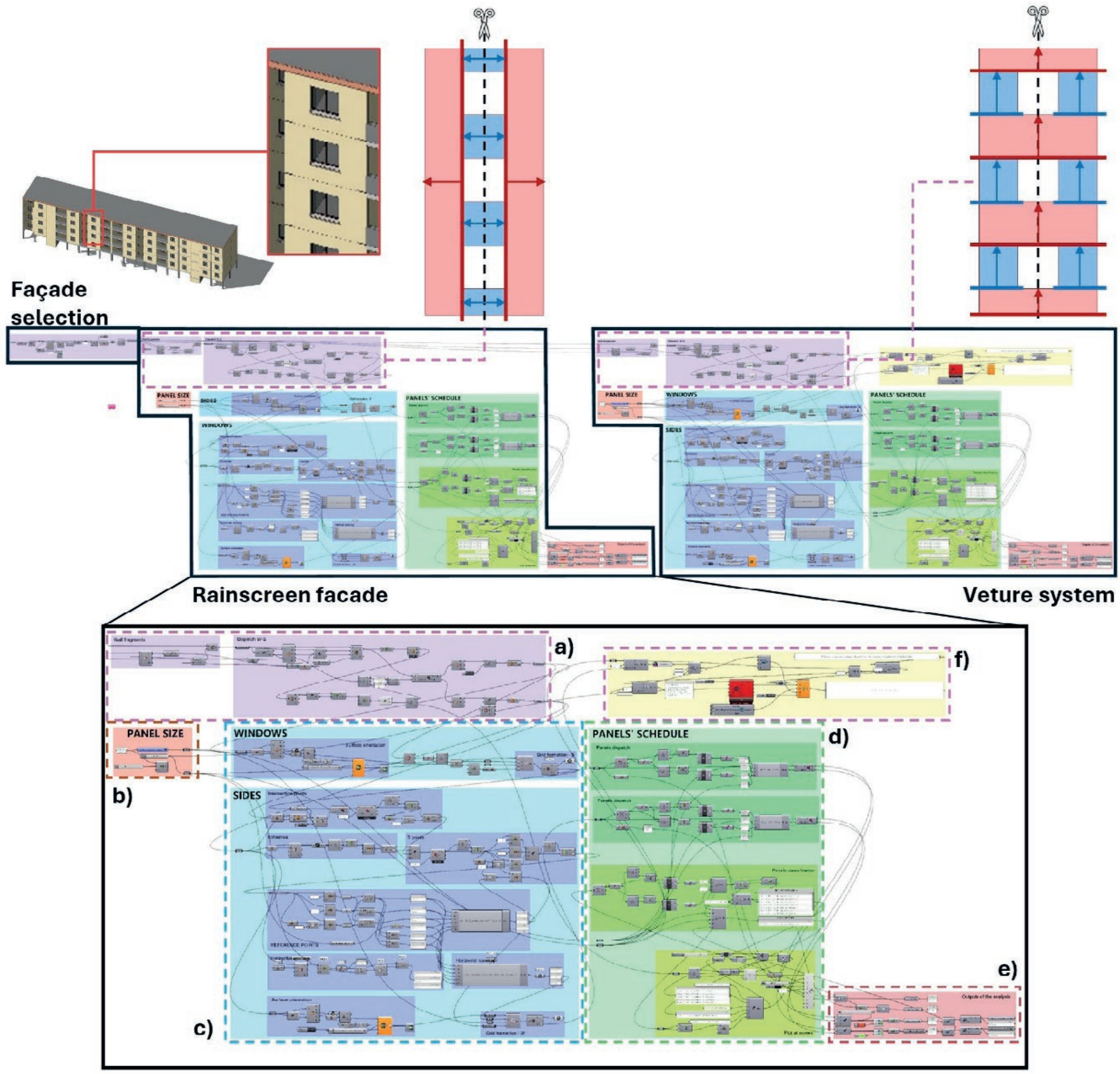

Figure 3. Details about the Grasshopper VPL script. © 2025, Authors.

whole facade. Sections adjacent to the windows were subsequently clad following the same logic.

– Rainscreen facade: to exploit the variability of panels' shape and size ensured by this solution, the vertical sections located at the sides of the windows were primarily addressed in this case. In the smaller vertical sections between windows, the cladding panels were consequently aligned with the ones in the main sections. To respect the vertical symmetry of the facade, the width of the panels in these portions was obtained through an approximation based on this formula: $W_2=L/[round(L/W_1)]$, where W_1 represents the width of panels in the main sections and W_2 the one to be determined, and L stands for the total length of the same section.

The portions of the facade chosen as mainly influencing in both configurations are highlighted in red in Figure 3. The layout in the blue sections is hence derived from the arrangement of tiles in the former. In the same schemes, the thick colored lines point out the starting alignment for the creation of the panelling grid and the arrows express its direction of development.

d) Creation of the panels' schedule: the main relevant information about each alternative layout is collected and plotted on the screen. A different color was associated to each panel type generated, providing immediate visual feedback. The report includes the following parameters:
   - Number of standard panels, accounting for all the tiles whose dimensions are exactly the ones set in advance;
   - Number of non-standard panels, accounting for all the tiles differing from the standard ones to fit the remaining portions of the facades. For each type of panel, the width, height, and number of elements are provided;
   - Dimension of the shortest element serves as a parameter to evaluate the feasibility of the solution and consequently to avoid configurations with excessively small components.

e) Output of the analysis: the main outcomes of the analysis are collected to be later used as evaluation criteria:
   - Vêture system: the total number of panels and the area covered by non-standard panels;
   - Rainscreen facade: the total number of panels, the number of panels' typologies, and the number of non-standard tiles.

f) Evaluation of feasible alternative configurations: both design optioneering and optimization procedures were set to select the preferred layout among those generated, acting on the variables related to the size and geometry of the cladding panels. In particular, the former was applied in the case of the Vêture solution because of the limited number of configurations to be evaluated. The TT Colibri and DesignExplorer components [21-22] have been included in the algorithm for this purpose. On the other hand, a multi-objective optimization was conducted for the rainscreen recladding through the Octopus component, featuring a genetic algorithm. The height and width of the panels represent the variable parameters to act on, while the optimization was set to minimize the total number of panels used and the number of non-standard ones. The total number of panels and the area covered by non-standard panels were specified as evaluators in the design optioneering analysis. However, in this case, the selection of the most suitable solution is carried out directly by the designer, rather than relying on the autonomous computational capability of the chosen genetic algorithm. The selection of these evaluation parameters stems from considerations on design for manufacturing and assembly: as recognized in the literature, minimizing non-standard panels can enhance economic feasibility by reducing fabrication and manufacturing costs, can support environmental sustainability by preventing material waste, and can speed up the construction process acting on the on-site labor complexity [23-24].

3. RESULTS AND DISCUSSION

For a better comprehension of the results, this section has been divided into different sub-paragraphs addressing the various topics covered in the study. At first, results about facade layout design will be presented, in distinct sections for the Vêture and rainscreen configuration, while the energy label classification will be introduced later.

3.1 Vêture system

In the case of the Vêture recladding, the combination of possible height and width values available on the market led to six different solutions. Figure 4 presents them, numbered A-F, according to the visualization scheme proposed by DesignExplorer. The interactive interface of this tool allowed for the filtering and selection of the configurations by imposing restrictions on the input variables or outcomes of interest in each vertical column. As previously introduced, reducing non-standard panels was assumed to be particularly relevant for the final selection, along with limiting the total number of panels, which was meant to simplify installation procedures. In the graphical representations of the different layouts included in Figure 4, the non-standard tiles are highlighted in red.

The different configurations obtained will be synthetically described in the following, along with some general considerations about the results obtained in this case:

- Solution A (0.45 × 0.45 m): it foresees 216 panels, the highest value among the possible alternatives produced given the smallest size of the tiles, but significantly reduces the number of non-standard elements (9.66 m^2);
- Solution B (0.45 × 0.675 m): it reduces the number of panels to 120, but it is affected by a considerable area covered by non-standard units (20.19 m2), making it the least efficient option;
- Solution C (0.45 × 0.9 m): it requires 144 panels but maintains the same non-standard area as Solution A, offering improved efficiency;

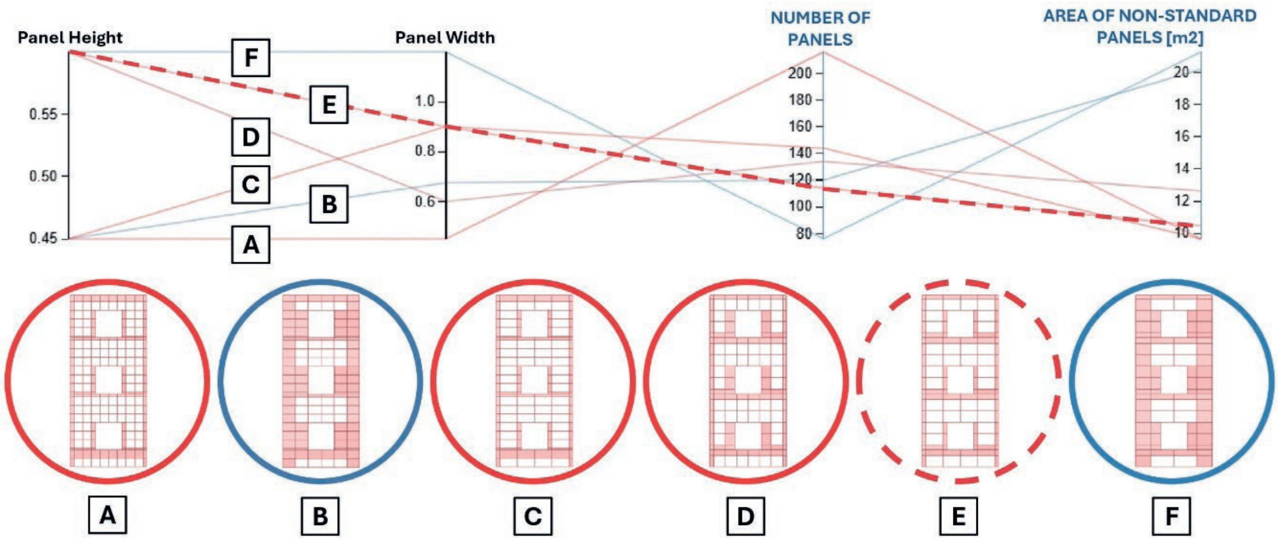

Figure 4. Analysis of facade layouts when adopting the Vêture system. © 2025, Authors.

- Solution D (0.6 × 0.6 m): it involves 134 panels, even if with a slightly higher amount of non-standard units (12.63 m^2); for this reason, despite being less efficient than other options, it may work as an acceptable compromise solution;
- Solution E (0.6 × 0.9 m): reduces the total number to 114 modules and lowers the non-standard area to 10.47 m^2 units, offering an optimal balance between modularity and waste reduction;
- Solution F (0.6 × 1.2 m): with only 76 panels, it features the lowest amount of panels used given the large dimensions of the cladding elements. However, this affects the number of non-standard pieces, which is sensibly higher than that of other solutions (21.27 m^2).

Configurations B and F, highlighted in blue in Figure 4, proved to be severely penalized by a higher number of non-standard components, as both show an area covered by irregular tiles approximately double with respect to the other solutions. However, it must be remarked that layout F is characterised by the absolute lowest number of elements, allowing for a significant speedup in installation processes by using large-format panels, which could be a crucial factor in some cases. All the other configurations present similar performance in terms of non-standard panels, but present a total number of panels ranging in a wide interval, ranging from 216 in solution A to 114 in solution E. The latter, outlined with a dashed red line in Figure 4, was identified as the most promising solution: it minimizes the use of special components while also reducing the total number of panels, thanks to the implementation of large tiles (0.6 × 0.9 m).

3.2 Rainscreen system

The optimization of the panels' arrangement for the rainscreen facade recladding was performed using the Octopus plug-in in the Grasshopper environment. A total of 60 generations, each with a maximum of 75 individuals, were autonomously produced during the optimization process, and the results are illustrated in Figure 5. The different alternatives are represented as boxes and plotted in a 3D space (XYZ), where each axis expresses one of the evaluation parameters: types of panels, total number of panels, and number of non-standard panels. The configurations highlighted in red belong to the so-called "Pareto front", which includes all of the "non-dominated" solutions. This means that no single solution in this set can be improved in one objective without causing a degradation in at least one other. Within the context of facade retrofitting, this implies that each layout on the Pareto front reflects a specific compromise among the relevant competing performance indicators. For the optimization carried out in this research, three distinct solutions emerged as the most promising under the given boundary conditions. All the layouts considered features panels 0.90 m high but differ in terms of width:

- Solution A: despite having the lowest number of panel types, it requires the highest number of cladding tiles due to their limited width (0.10 m);
- Solution B: this represents a balanced compromise between the extremes, involving a limited number of both total panels and non-standard ones;
- Solution C: large-size panels enable to reduce their number, even if nine different formats are needed.

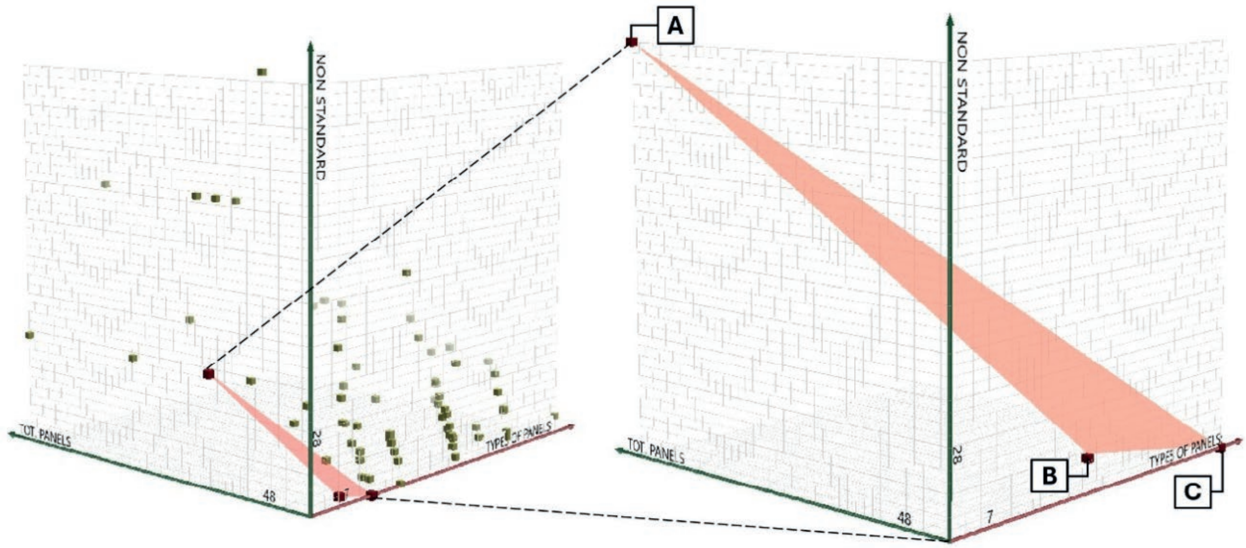

Figure 5. Pareto Front of possible layout solutions for the rainscreen façade. © 2025, Authors.

Table 2. Details about the Pareto front solutions.

Solution	Height [m]	Width [m]	Types of Panels	Total number of panels	Non standard panels
A	0.9	0.10	7	372	84
B	0.9	0.70	8	56	32
C	0.9	1.10	9	48	28

Moreover, it must be remarked that enlarging the panel size may result in undesired complexity of the substructure.

Table 2 summarizes the key properties of each solution, while Figure 6 illustrates their final visual appearance along with the panel schedule generated by the Grasshopper script.

To support informed decision-making, a structured interpretative framework can be adopted. Project stakeholders should first establish the relative importance of the objectives based on project-specific constraints. Prioritizing selection criteria can lead to the exclusion of undesired solutions from the very beginning of the decision-making process. For instance, if minimizing labour time is considered mandatory, solutions with fewer total panels may be addressed. Later, for a comparative trade-off analysis, each solution on the Pareto front should be evaluated, looking for the one that balances both quantitative and qualitative factors. Finally, external factors not initially considered, such as the market availability of non-standard components, initial investment cost, and architectural or aesthetic preferences, should be incorporated. These considerations often lead to preferring one solution over others, even when purely technical trade-offs are balanced.

Remarkably, in the study presented, all non-dominated solutions belonging to the Pareto front are eligible layouts for retrofitting, considering the rainscreen facade technological solution. The final selection among these alternatives should be informed by the project's priorities – whether cost minimization, architectural uniformity, or ease of execution is paramount. Additionally, the availability of suppliers for non-standard components and the client's aesthetic preferences play a decisive role.

In the Vêture system, layouts are imposed through precise values of design parameters (such as panels' width). In contrast, the rainscreen system offers a higher level of freedom in design selection, ensured by specific cladding materials, which may lead to a preference for other configurations over the optimized ones. Moreover, the recourse to rainscreen solution can allow to satisfy higher quality standards in terms of materials used, aesthetic finishing and cladding panels layout, and effects on more aspects of building performance (e.g. moisture

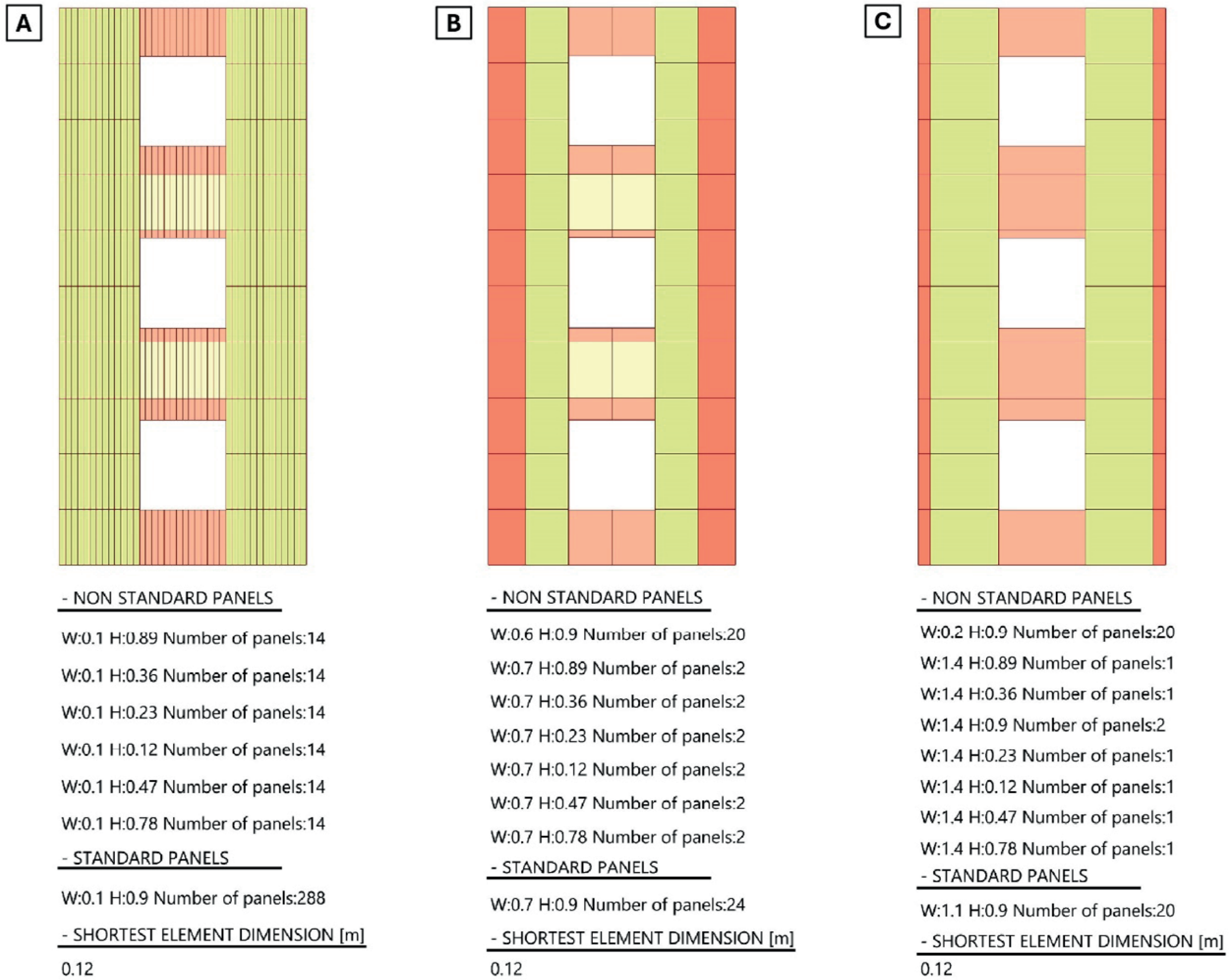

Figure 6. Graphical representation of the Pareto front solutions and related panels' schedule. Green elements are the standard ones, while the red ones are those that do not match the preset dimensions. © 2025, Authors.

removal, micro-ventilation in air gaps). In both facade technologies, it has to be remarked that the use of large-size panels should be carefully evaluated also in relation to constructability limitations associated with site accessibility, scaffolding size, or the need for dedicated installation equipment (e.g. platforms, lifting cranes).

3.3 Energy label

The energy efficiency classification of the existing building highlights several issues related to the external envelope's performance, particularly during the winter season, as shown in Figure 7. The thermal transmittance of both the external walls and the roof slab do not meet the minimum required thermal transmittance for climate zone D. This results in a Global Average heat transfer coefficient for transmission (H'_T) equal to 0.756 W/m^2 and the heat losses through the external envelope ($Q_{h,TR}$) equal to 71% of the total losses. As regards the calculation of the design peak load, the energy losses for transmission were calculated to be 67 kW, while the primary energy demand for heating is over 500 kWh. The presence of about 270 m^2 of glazing dispersing surface, characterised by window frames without thermal breaks and single glazing panes, is an additional detrimental factor for the building's performance during the winter season. In conclusion, the global non-renewable energy performance index ($EP_{gl,nren}$) is equal to 115.77 kWh/m^2/y (energy label F), indicating a low performance of the external envelope for the winter season. This evidence justifies the urgency of intervening on the external wall

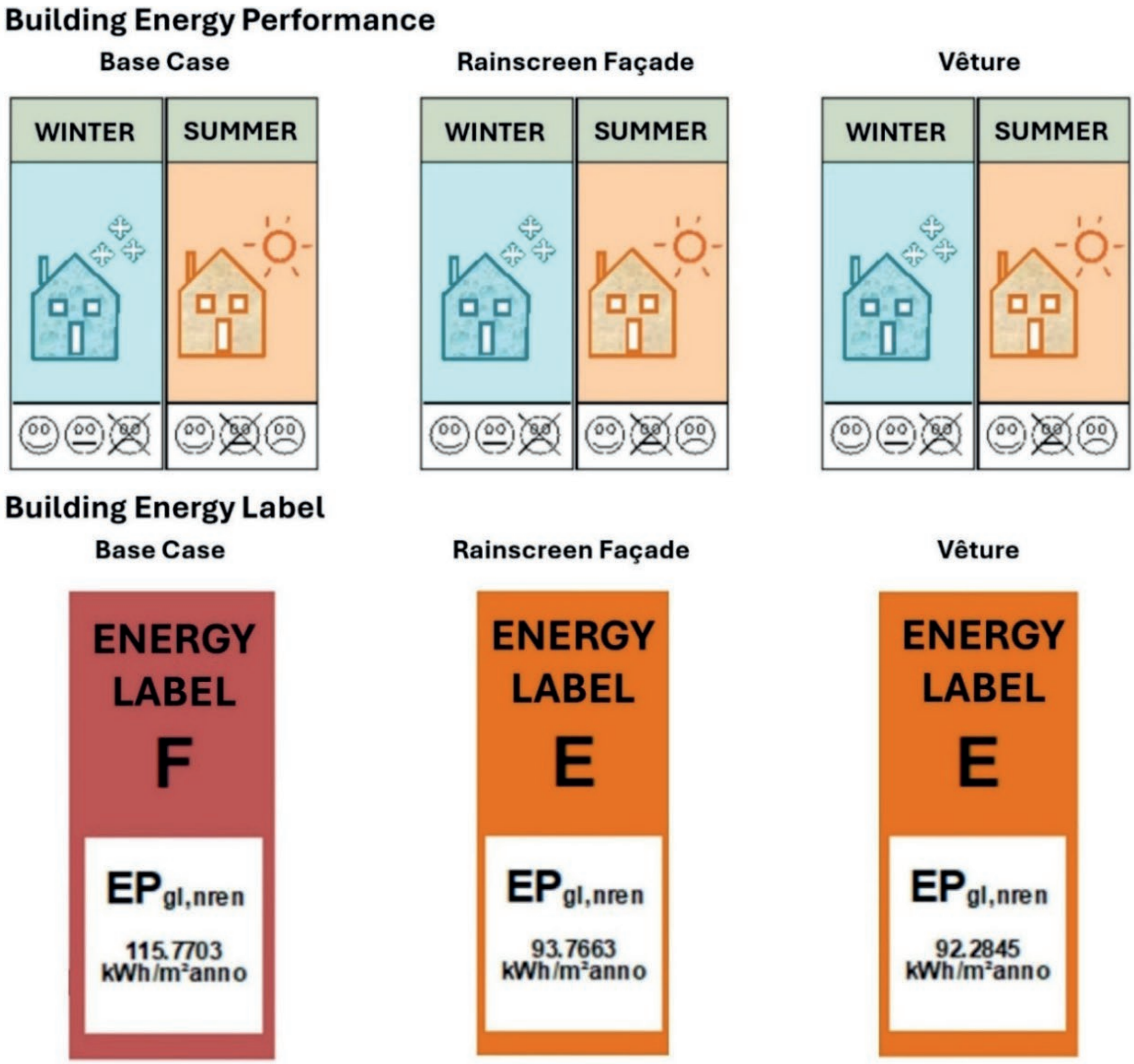

Figure 7. Building energy performance and Energy Label of the base case and the two retrofitting configurations. © 2025, Authors.

stratigraphy of these types of buildings to improve their energy performance, indoor thermal conditions for the occupants, and their visual and aesthetic appeal. Both redevelopment measures foreseen for the external walls result in an improvement of energy performance with a consequent upgrade in the energy label. At first, an enhancement of the thermal properties of the external walls can be achieved: the solution with the rainscreen system is characterised by a thermal transmittance equal to 0.29 W/m^{2}K while the Vêture cladding system reaches a value of 0.27 W/m^{2}K. On the other hand, the surface mass is affected to a lesser extent compared to the base case (133 kg/m^2), given the lightweight nature of the recladding applied. For both redevelopment measures considered, a decrease in energy losses through the external envelope equal to 5% and a reduction in the primary energy demand of about 90 kWh occur. In conclusion, for the Vêture solution, an energy label E is obtained with $EP_{gl,nren}$ = 93.77 kWh/m^{2}y; the same energy label E is ensured by the rainscreen recladding, even if with a slightly lower $EP_{gl,nren}$ (92.28 kWh/m^{2}y).

4. CONCLUSIONS

The research discussed in the paper demonstrates the integration of digital tools, such as Grasshopper and Octopus, to systematically explore facade recladding configurations that balance energy efficiency, material optimization, and aesthetic considerations.

Within the study workflow, the BIM modeling phase played a crucial role, allowing for the digital reconstruction of the case study building based on the currently available design documents, ensuring the development of a reliable as-is model, essential for subsequent analyses and optimization. However, some inconsistencies were identified in the original documentation, indicating the potential need for further on-site verification to enhance data accuracy and address any unresolved discrepancies.

A key contribution of this work is the application of multi-objective optimization in defining panel layouts for two facade retrofit solutions. By employing parametric modeling and genetic algorithms, the methodology minimizes the use of non-standard components, optimizes panels distribution, and reduces installation complexity. The computational analysis enabled the identification of Pareto-optimal solutions, providing a set of trade-offs between conflicting design criteria.

The energy models produced highlighted the effectiveness of energy retrofitting of existing residential building stock: improving building thermal performance results in a reduction of energy losses and an upgrade from energy label F to E. Large-scale applications of these interventions can substantially benefit from the application of data-driven digital workflows to speed up and optimize design procedures by informed decision making on a wide set of facilities.

At this stage, the study is currently affected by some limitations. Structural verification and substructure system design are essential to ensure safety and compliance, but the analysis carried out at this stage of the research was simply preliminary and meant to ensure the feasibility of the interventions proposed. These aspects must be hence taken into account at later stages of design with a detailed assessment. Moreover, the energy performance of the facility, currently assessed by performing simple energy labelling, should be refined through detailed energy modelling simulations.

Future research should expand upon these findings by including additional evaluation criteria, such as energy efficiency, LCA evaluations, or load-bearing implications (to account for the effects on yearly demand, environmental impact, and to consider limitations related to different construction typologies and load-bearing capacity). Integrating artificial intelligence-driven generative design could be another enhancing factor to both speed up decision-making and ameliorate the overall quality of the alternatives investigated.

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Leveraging Digital Elevation Models for Data-driven Assessment of Evolutionary Damage in Built Heritage

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Abstract. The paper aims to illustrate how implementing a digital elevation model enables an extensive comprehension of the current deformation crisis state of overturning masonry in the context of a case study. The approach explores the interoperability challenges and details in scan-to-HBIM processes, thereby elucidating how HBIM models can support operations that are intended to maintain and preserve extant historic assets despite the persistent challenges. This illustrative investigation underscores the effectiveness of applying digital technologies to advance the conservation and management practices of built cultural heritage, particularly in addressing structural concerns associated with historic masonry. The information should involve meticulous knowledge, anamnesis, visual inspection, and instrumental measures, as dataset accuracy is crucial in architectural heritage, where surveyed objects exhibit complex geometries and significant deformation. It is a deliberate, synthetic operation that develops a structural model for assessment. A key finding of the present paper is that the precision and detail of the model determine the accuracy of structural analysis results, emphasising the importance of accuracy consideration to achieve meaningful and reliable results. As a consequence, the building assessment demonstrated which parts of the building's façades were overturning while identifying the thorough kinematic phenomena progressively acting.

Keywords: Built heritage conservation, Damage assessment, Kinematic phenomena, Out-of-plane overturning mechanism, Scan-to-HBIM.

1. INTRODUCTION

Structural analyses of buildings often rely on simplified geometric models to expedite numerical computations, minimise processing demands, and streamline workflows. While this simplification can be both valid and practical, it is critical to ensure that such reductions do not compromise the reliability of the analysis results. The fidelity of the model plays a pivotal role in achieving accurate outcomes, particularly when capturing the essential physical behaviours and structural responses of the system under study. This requirement becomes even more pronounced when dealing with historic buildings of cultural significance, which present unique challenges due to their historical and architectural value. In the context of cultural heritage, the structure's geometry is rarely straightforward. These buildings frequently exhibit complex forms, asymmetries, irregularities, and accumulated damage resulting from ageing, environmental exposure, and historical modifications. These factors must be carefully considered when developing a geometric model, as over-simplification can lead to significant inaccuracies in interpreting structural behaviour or assessing vulnerabilities. For instance, a detailed model may be necessary to capture the nuanced effects of cracks, deformations, or missing elements that could influence load paths or stress distributions.

To address these complexities, modern geometric modelling methods have emerged, leveraging advances in digital technology and remote sensing. High-resolution techniques such as laser scanning and photogrammetry can produce highly detailed and accurate representations of a building's surface. These tools provide very useful data for reconstructing external geometry with unprecedented precision. However, they primarily capture visible surfaces and external morphology, and often lack critical information about interior structural features, subsurface defects, or concealed construction details [1]. Understanding the full structural behaviour of a historical building requires more than surface-level data. Comprehensive investigations that integrate both advanced technology and traditional diagnostic methods are essential. This holistic approach involves anamnesis, a thorough study of the building's phenomenological history, construction techniques, and prior interventions. Instrumental measurements such as ground-penetrating radar, infrared thermography, ultrasonic testing, and micro-drilling can reveal internal anomalies, material properties, and hidden damage. These methods are further complemented by detailed visual inspections conducted by experienced conservation professionals. Such experts can identify patterns of deterioration, assess material conditions, and evaluate the effectiveness of previous repair work

Additionally, integrating these diagnostic results into the geometric model transforms it into a more complete and functional representation. The enriched model becomes a powerful tool for simulation, enabling analysts to account for specific material heterogeneities, localised weaknesses, and the interactions between damaged and intact elements. For example, in seismic analysis, the accurate representation of cracks and voids can significantly influence the predicted dynamic response of a structure. This, in turn, provides critical insights for risk mitigation and retrofitting strategies. In the field of cultural heritage preservation, the goal of structural analysis is not solely to ensure stability. It also aims to maintain authenticity and minimise interventions. Achieving this goal requires a delicate balance between technological precision and an informed appreciation of the building's historical context. Each model thus becomes a bridge between the past and future. It preserves the memory embedded within the structure while equipping engineers and conservators with the data needed to protect it for generations to come.

1.1 The pilot site

The monastery of St. Catherine is located within the dense urban fabric near the Estense Castle, positioned behind the ancient urban axis of Via degli Angeli, now known as Corso Ercole I d'Este [2]. This area also includes the former Church of Santa Maria degli Angeli and the Palazzo dei Diamanti. The distinctiveness of the site stems from the initial absence of comprehensive geometric data and its complex planimetric configuration. Specific planovolumetric transformations were identified through meticulous inspections and direct observation of this extensive complex. However, it is important to emphasise that the current descriptions still require substantial documentary evidence to understand the nature and extent of these transformations fully

The lack of detailed geometric data at the outset of the project highlights the critical role of on-site inspections in uncovering key planovolumetric features of the building. Consequently, the initial investigations focused primarily on the structure's chronological stratification. Archival documents were examined to shed light on its original layout, formal characteristics, and geometric configuration, particularly those aspects that have been altered over time. A meticulous review of numerous indirect historical sources housed in the Ferrarese Diocesan Archive revealed several original rooms that had been lost due to substantial architectural transformations. This process enabled the identification of historically significant spaces that had been obscured by the passage of time and successive modifications. To document the current condition of the monastery, data were collected through a comprehensive survey methodology tailored to the site's distinctive typological and geometric complexity, ensuring increased precision in capturing both the material stratification and the spatial articulation of the architectural organism [3-4]. The primary goal of this documentation strategy was to leverage state-of-the-art technologies and tools, accounting for the site's specific challenges, while ensuring high accuracy in the survey and data processing phases.

Figure 1. (left) Ferrara, aerial view from the south. At the image centre, the Dominican monastery of St. Catherine. (right) The monastery of St. Catherine in the urban fabric of the Ferrara Herculean addition.

1.2 Research background: TLSs and UASs dataset fusion

The continuous advancement of technologies such as terrestrial laser scanners (TLSs) and unmanned aerial systems (UASs) has significantly facilitated data acquisition processes. The Leica P40 TLS survey campaign was carried out in two phases: planning and acquisition. More than 200 laser scanner station points were pre-estimated. In situ scans were optimised by room size and complexity. Acquired data were processed in Leica Cyclone r2020.1®, aligned with <4 mm tolerance, and exported after registration into a unified 3D point cloud database. A single three-dimensional coordinate system was then established, with the origin point (Figure 2) located at the centre of the cloister. The point cloud was subsequently decimated and exported in .pts format. To support this operation, due to the large file size and processing demands, the building was divided into four segments: the west wing, the east wing, the south wing, and the former church (Figure 3).

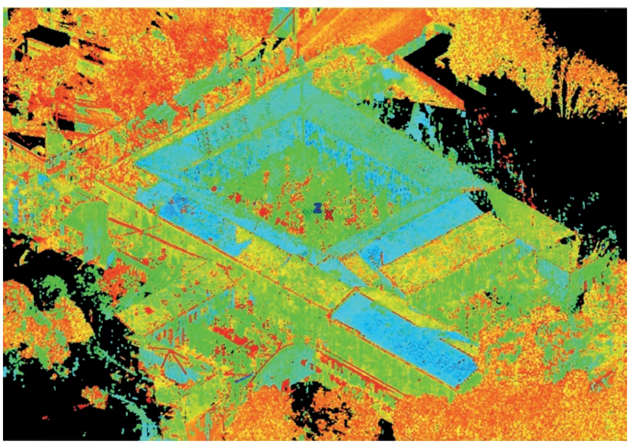

Figure 2. Perspective view of the registered 3D point cloud processed in Leica Cyclone r2020.1®, registered within a single coordinate system centered on the cloister.

The UAS photogrammetric acquisition was performed using a DJI Mavic 3 Enterprise, with mission planning optimized to achieve a ground sample distance of 4 mm/pixel, suitable for 1:20 scale documentation. Flights were conducted approximately at 20 m altitude for nadir mapping and at distances of 10 m for façade capture, ensuring proper image overlap (≥80%) and minimal angular distortion. Images were processed in Agisoft Metashape Professional r2.0.10, enabling the generation of high-resolution orthomosaics, adaptive textures, and 3D meshes for characterizing the damaged state of the masonries (Figure 4). These datasets were subsequently processed to generate precise and accurate 3D models of detailed objects. However, no single sensor can provide a comprehensive understanding of a large structure, even when multiple scans are conducted [5]. To overcome this limitation, the integration and interaction of both technologies were employed. By geometri-

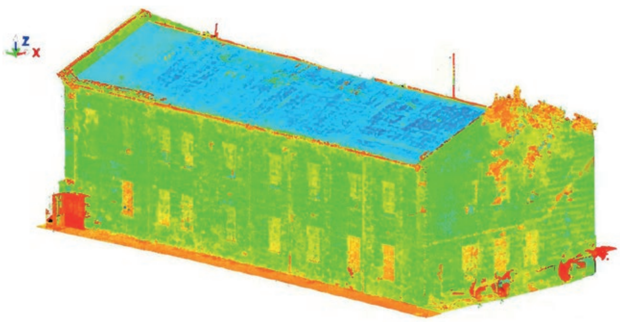

Figure 3. A detailed axonometric view of the TLS point cloud processed in Leica Cyclone r2020.1® True Space mode, showcasing the former church of St. Catherine.

Figure 4. The orthomosaic of the south-facing elevation along Via Roversella, generated in Agisoft Metashape Professional r2.0.10®. On the right, the eastern wing reveals substantial structural transformations of the former church's liturgical hall, resulting from its 20th-century conversion into a vocational high school.

cally aligning the two datasets, this approach supported the development of a variety of assessment processes [6].

A practical framework that combines UAS photogrammetry and TLS for 3D mapping and monitoring of complex heritage assets has been developed. This methodology integrates ground-based survey techniques and aerial photogrammetry through the CloudCompare v2.12.4 platform, reinforcing its pivotal role in the analysis and interpretation of built cultural heritage [7]. The integration of both methods results in maps, orthophotos, and 3D models. Data fusion enhances the accuracy of 3D representations by combining information from multiple sensors. This process is particularly important for advanced tasks of visualization, typological classification, and quantitative assessment in heritage studies. The choice of data acquisition method depends on factors such as the object's geometry, surface morphology, required accuracy, and the logistical constraints and financial sustainability of the operation. While various approaches exist, each comes with inherent limitations and operational trade-offs. Terrestrial Laser Scanning (TLS), for example, is restricted by its line-of-sight, which reduces its effectiveness in occluded or confined areas, such as narrow courtyards or interiors with complex partitions. Its performance can also be affected by reflective or absorptive materials, surface moisture, and ambient lighting conditions. Unmanned Aerial Systems (UASs) offer a cost-effective and efficient means of surveying, particularly for capturing high-resolution images of inaccessible zones, such as rooftops, upper cornices, or structures at risk of collapse. However, UAS-derived 3D models can suffer from indistinct textures, radiometric inconsistencies, and a general lack of geometric density in shadowed or reflective areas, reducing their reliability for detail-critical applications. Ground-based digital cameras represent another low-cost solution for 3D modelling. Yet, like TLS, they are constrained by line-of-sight issues and require careful control of camera calibration parameters and network geometry to avoid reconstruction errors.

Given the strengths and weaknesses of each technique, a multi-source and multi-scale integration of data becomes not only advantageous but necessary for generating accurate and semantically rich 3D digital twins. The proposed multi-sensor data fusion method employs a wavelet-based decomposition and reconstruction algorithm to create a refined 3D building model by integrating TLS and UAS datasets. This hybrid approach enhances spatial continuity and surface detail, ensuring both metric reliability and visual fidelity. The TLS dataset was also used to validate the model [8-9], which demonstrated an accuracy of 2.3 mm higher than the TLS-only model, confirming the effectiveness of the fusion strategy in improving both geometric precision and interpretative potential.

2. DAMAGE MECHANISMS ASSESSMENT IN LOAD-BEARING STRUCTURES

2.1 Built heritage modelling in HBIM environment

The advancement of information technology offers a significant opportunity to transform conventional practices in built cultural heritage conservation and the construction sector. Such an approach is particularly relevant for activities concerning the monitoring and management of existing architectural heritage, where accurate data acquisition and interpretation are essential to support informed conservation strategies and long-term maintenance planning. In this context, the proposed methodology relies on an integrated 3D metric survey as the basis for generating Digital Elevation Model (DEMs), further supported by the development of a Historic Building Information Model (HBIM) [10-12]. This model plays a key role in identifying the most appropriate interventions to improve the structural behaviour of brick masonry elements [13]. Photogrammetric processing, when compared to the geometric database derived from TLS-based point cloud data, proved to be highly effective. It provided accurate working material that enabled a reliable representation of the external surfaces, fully consistent with the building's actual 3D configuration [14]. The use of as-built BIM techniques in heritage modelling aims to reinforce the relationship between geometric modelling and information management. Among the key attributes considered are temporal evolution, spatial constraints, and damage documentation, all of which contribute to a comprehensive understanding of the building's lifecycle and inform targeted conservation actions. [15]. In particular, HBIM is well-suited for reconstructing built heritage based on available descriptive data, including historical records, bibliographic sources, archival photographs, and drawings. Analysing the evolutionary and transformative phases of lost architectural elements proves especially valuable, as these aspects directly influence the structural assessment of load-bearing systems, providing critical insights into original construction logic, material discontinuities, and potential weaknesses within the historic fabric. [16]. The monastery is not merely a virtual model. It serves as a critical component of the conservation project, where the various parts of the Dominican cloister complex are transformed into intelligent parametric objects. These elements contain structured relational data as well as detailed quantitative and qualitative attributes. Ultimately, the HBIM model functions as a parametric design environment, capable of storing, updating, and linking information in a coherent and dynamic framework [17].

2.2 Digital elevation modelling

Digital Elevation Models represent the elevation distribution of a terrain or a specific surface in archaeological contexts. They are exported in raster format, allowing each image pixel to be associated with elevation values expressed through a predefined colour scale [18]. In this study, DEMs were employed as analytical tools derived from an indirect survey of the pilot site, which proved to be particularly complex due to its stratigraphic configuration. Unlike their more established application in archaeological excavation analysis, DEMs are still rarely used for studying building façades and even less so in structural assessments [19]. This represents an underexplored field of research.

In contrast to horizontal ground strata, the elevations of the masonry walls were visualised through false-colour textures mapped onto vertical planes, offering a detailed representation of their current condition. At the level of architectural interpretation, it became possible to systematise conventional stratigraphic evidence based on materials and construction techniques. Damage patterns affecting the walls were also considered, particularly when they revealed stratigraphic discontinuities that would otherwise be difficult to detect. More importantly, these patterns served as indicators of active structural damage mechanisms. The analysis focused on the southern sector of the monastery, along Via Roversella. Here, a strong correlation emerged between the current condition of the structural elements and the architectural stratification gathered over time.

This approach proved especially significant for the analysis of macroelement kinematics within the broader conservation project. The front elevation was analysed by projecting it onto an ideal reference plane. This surface was defined as perfectly orthogonal and aligned through the midpoint of the masonry thickness, allowing a normalised reading of the façade. The method revealed multiple phases of transformation, namely the opening of new windows, the closure of others, and the insertion of intermediate floors associated with changes in use, which were graphically represented and subsequently interrogated from a structural standpoint. In particular, a zone of high concern was identified where an incipient out-of-plane rotation appears to localise, plausibly activated by the thrust transmitted by the roof struts (Figure 5). The evidence from TLS point cloud processing, including systematic slices at 1 m pitch, supports this interpretation and indicates areas of potential concern. To support this preliminary kinematic interpretation, the TLS point cloud was processed through a systematic sequence of horizontal and vertical slices extracted at a constant 1 m pitch, thereby generating a modular grid and the corresponding wireframe representation of the façade. This slicing-based modelling enabled a first-order verification of geometric continuity between the interior and exterior faces, providing evidence compatible with predominantly monolithic behaviour within the wall plane and, conversely, not supporting the presence of non-integrated facing leaves whose differential deformation could promote peak-load-induced local instability. Although the deformation is not readily appreciable along the longitudinal development of the slender masonry walls, the bottom-right overlay of the extracted slices against ideal horizontal and vertical reference lines documents, albeit in a barely perceptible manner, the onset of the rotation mechanism. A more explicit and metrically controlled representation of this phenomenon is provided later in the paper through DEM-based processing, which allows the deformation field to be visualised and quantified with

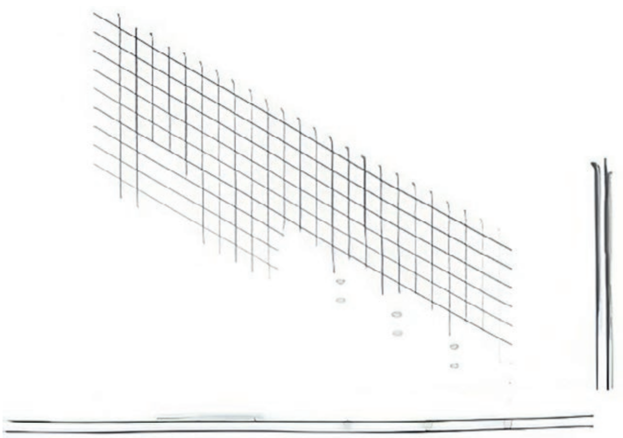

Figure 5. Front elevation along via Roversella, TLS-derived horizontal and vertical slices extracted at 1 m pitch and assembled as a modular grid/wireframe for preliminary screening of out-of-plane rotation; the inset overlay against ideal axes suggests.

higher sensitivity. The point of most significant structural instability corresponds to two distinct stratigraphic units.

These units reflect a shift in the roofing technique, which also marks the spatial division between the liturgical hall used by cloistered nuns and that intended for laypeople. This architectural modification induced a progressive superficial depression, which became more pronounced over time, ultimately resulting in the current generalised deformation of the façade. The deformation later extended to the entire central section. The case study, the former liturgical hall of the Dominican monastery, is morphologically defined as an assembly space enclosed by structural macroelements: lateral walls, façade, apse, timber trusses, and reinforced concrete floors added during its later adaptation for educational use. These macroelements, collectively, constitute the structural system of the building. Through evolutionary damage analysis, the study identified both unique and recurring collapse mechanisms for each macroelement, many of which are widely documented in the literature. This was achieved using the limit equilibrium method, specifically following a kinematic approach to structural analysis.

The analysis of potential in-plane and out-of-plane damage mechanisms in brick masonry walls has led to notable and insightful results. These analyses are particularly significant, as they aim to evaluate the forces that activate these mechanisms in relation to wall geometry and the dimensional relationships among structural elements [20-21]. The collapse mechanism of a masonry macroelement is typically characterised by the formation of zones with concentrated deformation. These zones separate the macroelement into quasi-rigid blocks that behave kinematically, leading to collapse when subjected to perturbing forces. The initial singularities most likely to generate disaggregation are found at the connection points between macroelements, where the load-bearing structure is most vulnerable. In such zones, relative roto-translations may develop between adjacent elements.

To support the identification of the most appropriate safety interventions, the contribution of DEMs in the evolutionary damage analysis of macroelements is highlighted here. One particularly hazardous behaviour observed is the horizontal flexural deformation of the brick wall, as clearly illustrated by the DEM. In this condition, the masonry wall is joined to perpendicular walls, but its top edge is unrestrained. When subjected to seismic action orthogonal to its plane, the wall exhibits a horizontal arching effect (Figure 6). Specifically, the horizontal thrust from the roof is transferred to the wall. At the orthogonal intersections, this thrust splits into two components: one orthogonal to the wall, which is absorbed by the tie rods of the roof trusses; and one parallel to the wall itself. In the limit equilibrium condition, three hinges typically form, one near the centre of the wall and two at the intersections with the truss ends, where tensile stresses are highest.

The three-hinged isostatic arch becomes unstable when its hinges align. If the wall fails to engage contrasting elements that provide an equal and opposite reaction, the collapse kinematics will be activated. This is the precise condition found in the case under analysis. The wall is held by tie rods but is stressed by the anomalous pushing action of a strut and by the hammering forces of the large roof framing elements. Moreover, the tensile strength of the masonry is reduced, increasing the risk that the material forming the wall's outer face may detach. This detachment is caused by tensile stresses that develop within the masonry core as part of the kinematic deformation. Additional factors contribute to the onset of horizontal bending mechanisms. These include the presence of aligned openings just beneath the roof band and the quality of the masonry itself, which affects the height of the detachment wedge.

The identification of horizontal bending mechanisms is significantly supported by the DEM, which provides essential information on existing and potentially active macroelements, even in cases where visible damage is minimal. When cracking is not yet present, potential out-of-plane collapse mechanisms may still develop, involving varying extents of the wall surface [23]. However, it remains impossible to determine in advance which kinematic mechanism is most likely to occur. To define the most unfavourable scenario, it will be necessary to assess multiple collapse conditions, each assuming different geometries of the masonry areas involved in

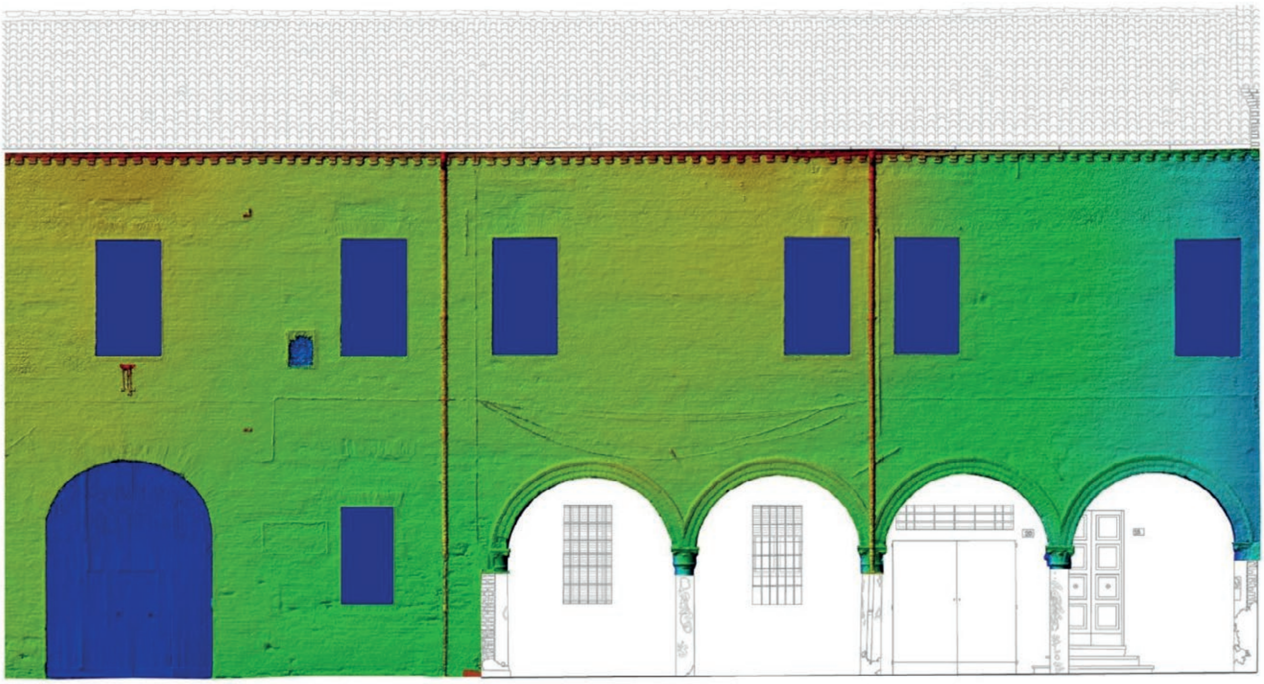

Figure 6. Front elevation along via Roversella, digital elevation mode processed in Leica Cyclone r2020.1®. The false-colour DEM highlights deformation patterns that are not detectable through direct visual inspection. In particular, at the junction between the gutter pipe and the right-hand downpipe, the red hue representative of the wall surface indicates a strain distribution consistent with the activation of an out-of-plane overturning mechanism. This condition has then been attributed to the deterioration of the timber truss bearing support, which has led to a structural transition from isostatic to thrusting behaviour.

the kinematic process [24]. To determine the most unfavourable condition, it will be necessary to assess various collapse factors assuming varying geometries of the masonry regions influenced by the kinematics [25].

3. RESULT AND DISCUSSION

The integration of photogrammetric and TLS data through a multi-sensor approach enabled the generation of a high-resolution digital elevation model, which proved to be a critical tool for identifying early signs of deformation in the historic masonry structures of the Dominican nuns' compound. Assessing the behaviour of load-bearing structures in built heritage contexts requires both precise 3D geometric modelling and advanced information management systems. These are typically realised through digital twins generated via photogrammetry and laser scanning, alongside semantic knowledge integration using geographic information systems and ontology-based tools [26]. The latest developments in building information modelling (BIM) incorporate both 3D modelling and structured information management [27]. By leveraging the dense spatial granularity of the DEM, the study captured early displacements and strain patterns across the south elevation, which could not be discerned through conventional visual inspection. This finding highlights the diagnostic potential of DEMs in capturing the premonitory deformations that precede the onset of out-of-plane failure mechanisms in historic walls and the development of an explicit crack pattern.

In the specific case of the via Roversella façade, the methodology implemented integrates laser scanning, computer science, Geographic Information System (GIS), and particularly BIM as its foundational components [28]. The false-colour rendering of the elevation data, mapped onto orthogonal projection planes, revealed a subtle yet coherent horizontal flexure extending across the upper third of the masonry surface. This deformation, although imperceptible through traditional surveying techniques, is consistent with the hypothesis of an evolving macroelemental mechanism involving horizontal bending and rotation around the truss anchorage zones. The localised strain concentrations, represented in red and yellow hues in the DEM visualisation, coincide with zones of structural discontinuity historically associated with spatial transitions within the *endonartece* hall, such as the demarcation between the cloistered and lay areas. This correlation confirms the DEM's capacity to interpret architectural transformations as potential precursors to mechanical instability. The chronological stratification of the façade, reconstructed through archival analysis and architectural interpretation, provided a more nuanced understanding of its structural behaviour. The area exhibiting the highest deformation was also the segment most affected by 20th-century interventions, including the insertion of reinforced concrete floors and alterations to the original roofing system. These modifications induced eccentric load distributions and altered the thrust paths transmitted by the timber trusses, thereby amplifying the flexural demands on the slender masonry panels. The DEM, in this context, became a medium through which these hidden effects could be quantified and localised with high precision. Notably, the DEM allowed for the anticipation of collapse kinematics by identifying deformation modes before the complete crack pattern associated with the masonry's settling response manifested. This pre-diagnostic function is particularly significant in heritage contexts, where preventive conservation strategies often need to operate in the absence of overt structural symptoms. The identification of stress trajectories and micro-deformational anomalies supports a predictive understanding of macroelement behaviour, particularly when integrated with knowledge of mechanical discontinuities, construction techniques, and load-bearing hierarchies. In this regard, the study demonstrated that the DEM could simulate an intermediate condition between the as-is configuration and the limit equilibrium state, effectively capturing a transitional phase in the structural lifecycle. This capability is especially relevant for walls exhibiting three-hinged arch behaviour, where the incipient collapse mode is governed by the alignment of hinges and the degeneration of in-plane restraints. The current case study revealed that the pushing action of the roof queen-post timber truss system, compounded by the absence of adequate counter-thrust mechanisms in the longitudinal direction, promoted a partial and localised overturning mechanism in the affected masonry (Figure 7). The DEM detected this deformation as a differentiated surface deflection, offering a direct false-colour visualisation of the deformation gradient along the affected wall surface.

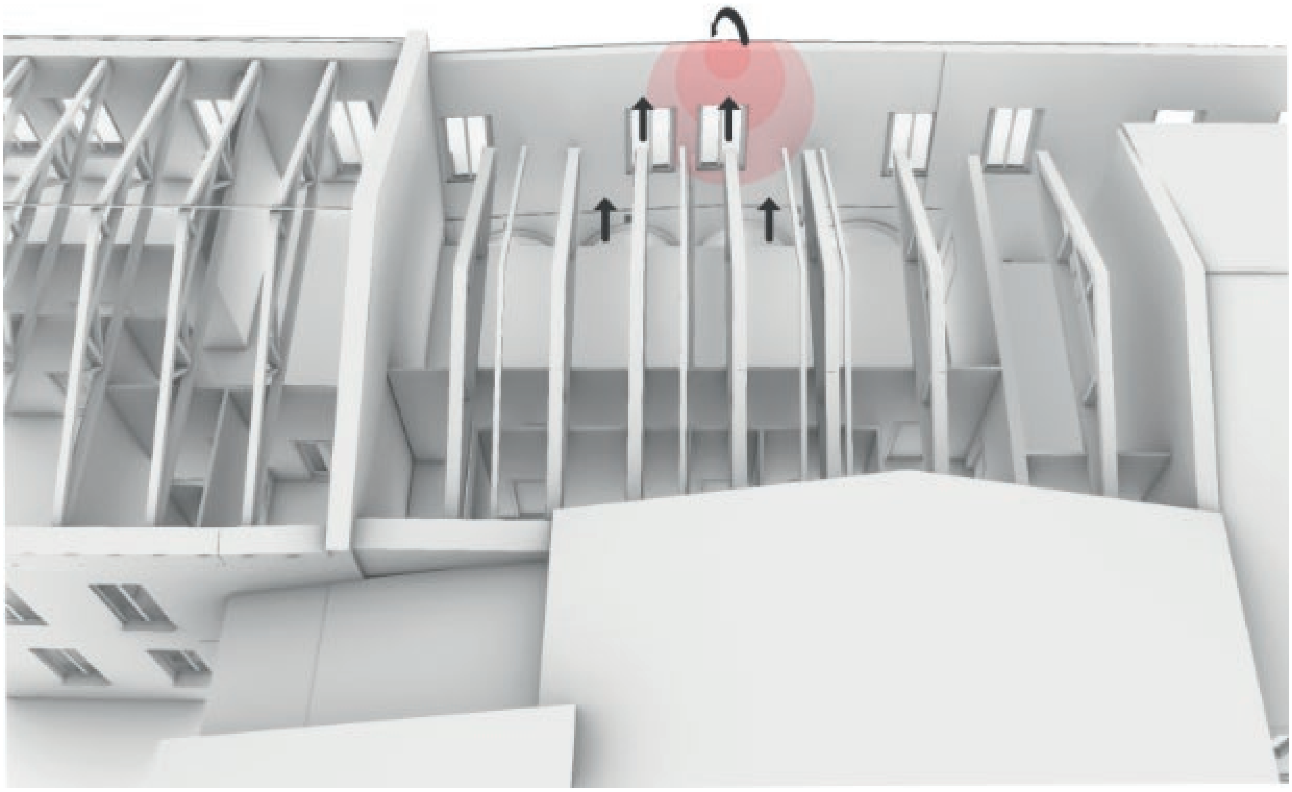

Figure 7. Former church of St. Catherine, south elevation, macroelement collapse mechanism. The representative three-dimensional model of the collapse mechanism is developed using Graphisoft Archicad 27®, providing a more straightforward interpretation of the triggering cause linked to the degradation of the roof queen-post timber truss system lying behind the masonry wall.

The integration of the DEM into the structural interpretive framework thus represents a methodological advancement that enriches the traditional visual and analytical toolset available to heritage engineers. The use of advanced geometric modelling technologies within HBIM environments enhances the capacity to assess the condition of complex building envelopes. By encoding deformation signals within a continuous digital surface, the DEM bridges the gap between metric data acquisition and structural interpretation, providing an early warning system that aligns with the principles of non-destructive, reversible, and minimally invasive conservation. The approach adopted in this study demonstrates the value of employing DEM analysis not as a post-event mapping technique but as a proactive monitoring strategy capable of influencing decision-making processes in structural conservation.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

The outcomes of the present investigation illustrate the potential of DEM integration into HBIM workflows as a decisive step forward in the structural diagnosis of built heritage. The ability to capture micro-deformations before the emergence of visible damage redefines the role of elevation models within conservation practice, elevating them from mere representational devices to analytical instruments that can inform structural assessments. This evolution aligns with the overarching aim of preventive conservation: to detect, interpret, and mitigate vulnerabilities before irreversible failure occurs.

A critical implication of the proposed methodology lies in its capacity to embed the DEM as a structured information layer within the broader HBIM environment. This interoperability transforms the DEM from a static visual product into a dynamic data component capable of dialoguing with other informational strata, such as historical documentation, material diagnostics, and performance simulations. In this sense, the DEM becomes a semantic and geometric medium, linking the morphological reality of the building with the predictive logic of structural analysis. The case study has demonstrated that a DEM-enhanced HBIM model can effectively support the identification of stress concentrations, the recognition of stratigraphic discontinuities, and the modelling of localised instability scenarios. By spatialising these phenomena within the digital model, the HBIM environment transcends its original descriptive function and assumes a prescriptive role in defining conservation priorities. The integration of DEM data facilitates this transition by offering a high-resolution understanding of deformations, thereby allowing the simulation of mechanical responses under various boundary conditions and anticipating potential collapse mechanisms.

Future research directions should focus on expanding the use of DEM as a permanent layer in HBIM platforms, moving beyond episodic applications toward systematic integration within digital twins of heritage structures. Such integration requires the development of standardised protocols for DEM generation, classification, and updating, as well as the definition of metadata schemes that preserve the interpretative value of the elevation data over time. The implementation of interoperable data pipelines will be crucial to ensure consistency across software environments and analytical domains. Moreover, the increasing use of IoT-enabled monitoring systems and AI-based anomaly detection tools opens new opportunities for real-time updating of the DEM layer. This dynamic linkage would allow HBIM models to evolve from static repositories of past and present conditions into predictive environments that continuously assess the stability of architectural macroelements. In this context, the DEM could act as a sentinel system capable of issuing alerts when deformation thresholds are exceeded, thus triggering preventive interventions. From a methodological standpoint, the recognition of the DEM as a structural information layer repositions HBIM as a tool not only for documentation and management but also for real-time structural decision-making. The integration of this layer into the HBIM paradigm responds to the growing need for models that are both historically accurate and structurally insightful. This dual capacity enhances the utility of digital models in supporting conservation strategies grounded in material authenticity, structural integrity, and long-term sustainability.

In conclusion, the interoperability between DEM and HBIM systems represents a key vector for innovation in heritage conservation. The ability to integrate elevation-based deformation data within a comprehensive digital model transforms the HBIM into a multifunctional tool that supports design, analysis, and monitoring. This convergence marks a shift toward a more smart and responsive approach to preserving built heritage, one in which structural understanding, digital representation, and conservation action converge within a unified methodological framework.

5. FUNDING

This contribution aligns with the author's research focus on deploying advanced digital technologies for the critical assessment of built cultural heritage, particularly

in interpreting the successive transformative phases that define long-term historical sedimentation processes. The study adheres to a preventive, risk-informed perspective, emphasising the early detection of latent vulnerabilities and subtle indicators of emerging instability as crucial to mitigation. The research received no external financial support.

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Resilience and Operability in Post-Disaster Scenarios: Case Study of a Defined Set of Churches after the L'Aquila Earthquake

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Abstract. The digitization of built heritage is essential for safeguarding cultural and historical assets, particularly in the face of disruptive events. In this context, this paper assesses the resilience and operability of existing churches, supported by a comprehensive digitization workflow and a large dataset of data. Specifically, the work focuses on 26 churches of the Sulmona-Valva Diocese damaged during the 2009 L'Aquila earthquake. The proposed workflow integrates systematic data collection, the development of empirical and theoretical resilience curves, and the calculation of a Global Resilience Index. Unlike traditional methodologies, this study incorporates restoration funds as a weighting factor in resilience assessments, reflecting the cultural and historical importance of each structure. Additionally, the integration of data into a flexible digital platform enables real-time analysis and resilience planning, supporting informed decision-making for urban planning and resource allocation. These digital platforms significantly enhance the resilience assessment of cultural heritage by enabling the storage and processing of large datasets, thereby revolutionizing both academic research and operational practices. The findings highlight the potential of a data-driven framework to enhance the protection and conservation of heritage buildings in seismic-prone areas.

Keywords: Architectural engineering, Built heritage, Resilience, Earthquake, Church.

1. INTRODUCTION

The word "resilience", as defined by contemporary dictionaries, refers to the ability of a system to return to its original state after being disturbed. Resilience is a multidisciplinary concept that applies to various fields, including ecology, social sciences, engineering, and economics. In seismic engineering, resilience is defined as the capacity of a system to absorb, manage, and adapt to seismic events. This concept is particularly crucial as it allows for the development of economic and political strategies aimed at reducing the impact of disruptive events. This study adopts an engineering-oriented approach to resilience assessment, integrating empirical and theoretical methods to quantify the ability of heritage churches to recover functionality after an earthquake.

In recent years, numerous authors have explored the concept of resilience from the engineering perspective, seeking ways to evaluate the resilience of specific or generic systems. The literature review conducted by Hosseini et al. [1] categorizes resilience evaluation methods into two primary types: 1) qualitative assessment approaches and 2) quantitative assessment procedures. Qualitative approaches include methods without specific mathematical formulations. Quantitative assessment procedures, on the other hand, offer measurable metrics that can be applied broadly or adapted to specific fields.

One of the first quantitative measures of resilience was proposed by Bruneau et al. [2-3] as the area under the functionality curve *Q(t)* of the system analyzed between the initial time of the extreme event t_0 and the time corresponding to the end of the recovery process T_R. When the extreme event is an earthquake *E*, these measures were named t_{0E} and T_{RE}, respectively. The approach proposed by Bruneau et al. [2-3] implements a general quantitative procedure independent of the type of the considered system (transport, buildings, infrastructure, hospitals, etc.) and is considered as the starting point of this work.

Over the past 15 years, many scientific publications have proposed new methods and approaches for quantitatively measuring resilience [4]. However, despite their number, these approaches can be classified into two macro-categories: a) probabilistic approaches and b) deterministic approaches, based on the presence or absence of a systematic evaluation of the uncertainties inherent to the extreme event and the capacity of the system, respectively. According to the probabilistic approach (a), the system's functionality must be measured using a loss estimation method that considers uncertainties regarding future extreme events [5-10]. Chang and Shinozuka [5] introduced a probabilistic approach for assessing resilience, measured with two elements: (i) loss of performance and (ii) length of recovery. Resilience is defined as the probability that the initial performance loss of the system after an outage is less than the maximum acceptable performance loss and that the full recovery time is less than the maximum acceptable outage time. Youn et al. [6] define resilience as the sum of the passive survival rate (reliability) and proactive survival rate (restoration) following a disruption. Ayyub [7] measures resilience as a combination of "robustness" (how well a system resists problems) and "resourcefulness" (how quickly a system recovers). Using advanced probabilistic formulations, Ayyub's [7] method considers both how to prevent problems (reliability) and how to handle them when they occur (recovery speed). Franchin and Cavalieri [8] developed a methodology to quantify the resilience of infrastructure networks following seismic events. Their approach evaluates network efficiency based on connectivity and accessibility, where closer node connections enhance overall performance. The proposed resilience index integrates multiple factors, including the number of displaced individuals, pre-earthquake network performance, and post-disaster recovery speed, with uncertainties addressed through a probabilistic approach. According to Cimellaro et al. [9-10], "resilience" is defined as a function indicating the capability to sustain a level of functionality. It is calculated as the area under the functionality curve, normalized to the control time, where the functionality is obtained from a probability function taking into account direct and indirect losses.

Other studies on resilience [11-13] determine the functionality of lifeline systems using deterministic approaches (b), based on time-dependent restoration curves calculated after specific earthquakes. Dueñas-Osorio et al. [11] developed a practical time-series approach to quantify lifeline system resilience. Using restoration data from power, potable water, and telecommunication systems following the 2010 Mw 8.8 Offshore Maule, Chile, earthquake, they constructed restoration curves that depict the fraction of subscribers with service over time, illustrating the recovery process. Cimellaro et al. [12-13] expanded upon the time-series approach to resilience assessment by introducing a method that quantifies the interdependency between critical infrastructure systems. They developed an equation based on the cross-correlation function between two restoration curves, allowing them to calculate an interdependency index. This index provides a numerical value that helps identify the systems that contribute most significantly to overall recovery challenges. By quantifying these interdependencies, the method enables more targeted allocation of resources, focusing on the systems that have the greatest impact on overall resilience. The deterministic nature of this approach facilitates statistical analysis of time series data, enabling an accurate resilience assessment of the asset under consideration. For this reason, it was selected as the reference method of this study. However, its implementation may present limitations due to data scarcity. Nevertheless, in the case analyzed in this study, the availability of previously inaccessible datasets – released over the years following the 2009 L'Aquila earthquake – has mitigated this limitation. Although deterministic approaches have been widely applied to assess the resilience of critical infrastructures and urban systems, their application to historical buildings remains limited. In particular, the resilience of heritage churches – complex architectural and structural typologies of essential cultural significance – has not been systematically addressed. This study aims to bridge this gap by adapting deterministic resilience assessment methods to cultural heritage.

Seismic resilience can be assessed at various levels, depending on the intended objective. At the individual structure level, seismic resilience is evaluated by measuring a building's or infrastructure's capacity to absorb seismic forces and recover its lost performance. However, resilience can also be evaluated on a broader scale by considering multiple structures or infrastructures belonging to the same system, such as an urban community, a diocese, or a local healthcare system. Resilience of a community is specifically defined in a framework formulated by Renschler et al. [14] and Cimellaro et al. [15]. It subdivides resilience into seven dimensions according to the acronym PEOPLES: Population and demographics, Environmental/ecosystem, Organized governmental services, Physical infrastructure, Lifestyle and community competence, Economic development, and Social-cultural capital. According to the PEOPLES framework, physical infrastructures can be divided into two major groups: facilities and lifelines. The first group includes residential, commercial, and cultural facilities, while the second consists of communications, healthcare, food supply, utilities, and transportation. However, this classification neglects two basic types of facilities and lifelines: critical physical infrastructures and heritage buildings. Critical infrastructures provide essential support for economic and social well-being, public safety, and the functioning of key government responsibilities. Historical buildings are a testament to our past and key elements of our cultural heritage. It is crucial to establish appropriate methods and procedures to assess their resilience to protect and preserve them for future generations. In view of these considerations, the analysis of the seismic resilience of the churches is particularly relevant, as most of them are national architectural and historical heritage. Additionally, as churches can contain significant numbers of people during celebrations, they can also be classified as critical physical infrastructures. This study builds upon previous works by adapting existing resilience assessment frameworks to the context of heritage churches and integrating digitalization processes to enhance resilience monitoring and management.

Beyond resilience assessment, digitalization has become increasingly relevant in heritage management. Digital tools facilitate the systematic collection, storage, and analysis of post-disaster recovery data, supporting informed decision-making for both structural interventions and conservation planning. Several studies [16-17] have demonstrated that integrating seismic vulnerability and risk assessments into digital platforms enhances monitoring capabilities and long-term heritage management. However, the application of such methodologies to quantitative resilience modeling remains limited. This research addresses this gap by developing a digitization workflow specifically tailored for engineering resilience assessments, incorporating a structured data management framework to optimize resource allocation and post-disaster intervention strategies.

This work presents a new path for the large-scale evaluation of the seismic resilience of heritage buildings. Using recent earthquake data, this approach adapts current theories on empirical and theoretical resilience curves to the built heritage to calculate a global resilience index. Additionally, it introduces and constructs a framework for digitizing the resilience of the built environment to support urban planning and resource allocation. The innovation is twofold: for the first time, data from different churches are used to obtain a global resilience index; furthermore, this work proposes guidelines for implementing this process in an integrated platform designed to enhance the digitization of the management of the built environment.

To this end, the seismic resilience of 26 churches in the Sulmona-Valva Diocese (Abruzzi, Italy) following the 2009 L'Aquila earthquake is assessed using both empirical and theoretical approaches. Initially, resilience is estimated through an empirical, quantitative analysis of observed damage after the earthquake, with a damage index assigned to each church. Subsequently, theoretical resilience curves are calibrated based on empirical data, allowing for the estimation of resilience even when detailed data is unavailable. This calibration adapts methods commonly used for lifeline systems to the specific context of heritage structures, thus creating a replicable model for resilience assessment. The evaluation of resilience is performed assuming that the complete recovery of structural functionality corresponds to the completion of the works and the reopening of the churches. Finally, the procedure for integrating the churches' data into a dynamic and flexible platform is implemented, as well as the definition of the logic tree for the automation of the entire procedure.

2. METHODOLOGICAL APPROACH

2.1 Operational Framework

The proposed methodological approach consists of four detailed steps that define the resilience curves for heritage buildings. Each step is systematically described, highlighting both the methodological framework and the key innovations compared to the existing state of the art. To ensure clarity, this section presents the methodological aspects independently from the case study results, including appropriate references to support the methodological framework and clearly distinguishing it from the empirical findings.

1. *Data Collection*: The first step involves collecting data for the 26 churches considered in the analysis. This includes gathering values for the damage index of each church, which is calculated based on observed damage mechanisms affecting the primary structural elements. Additionally, data on the allocation of restoration funds and the progress of reconstruction works are systematically collected. The monitoring of restoration progress is conducted on a bimonthly basis, allowing for a detailed temporal assessment of the recovery process. Although this step aligns with the deterministic approach to resilience assessment [11-13], it introduces key innovations: (1) the collected data refer to the built heritage rather than critical infrastructure or lifeline systems, (2) the damage index is used as an indicator of functionality loss rather than a direct measure of functional disruption, and (3) the gradual restoration of the monument's functionality is assessed based on the progress of the restoration works. Specifically, the damage index is progressively reduced as a function of the percentage of allocated funds effectively spent on restoring functionality.
2. *Empirical Resilience Evaluation*: In the second step, empirical resilience curves are derived for each church, following a deterministic approach to quantitatively assess engineering resilience [11-13]. However, this study introduces two pivotal novelties. First, the functionality loss after the earthquake is calculated by using the damage index id, providing an innovative metric for assessing post-earthquake degradation. Second, the recovery function is modelled based on financial investment, where the restoration progress is quantified according to the percentage of funds spent relative to the total allocated for the considered heritage building. This approach enables a more dynamic and resource-sensitive evaluation of resilience, distinguishing it from traditional methodologies.
3. *Theoretical Resilience Evaluation*: Since constructing detailed empirical resilience curves requires acquiring a substantial amount of data, which is not always available, the empirical data were used to calibrate and adapt theoretical formulations from the literature [10], which are generally applied to lifeline systems, to the context of Italian built heritage.
4. *Calculation of the Global Resilience Index*: For each analyzed heritage building, the average functionality over time is calculated, following the approach suggested by Bruneau et al. [2-3]. As an innovative contribution, this study introduces a Global Resilience Index, which quantifies the overall seismic resilience of the entire church system. Unlike traditional approaches, this index is computed by weighting the resilience contribution of each church in proportion to the percentage of funds allocated to its restoration, relative to the total funds assigned to the entire church system. This methodology provides a more representative measure of systemic resilience, highlighting the role of financial investment in post-disaster recovery at a network scale.

2.2 Comparison with Existing Approaches

Although previous studies have developed deterministic approaches to assess the resilience of lifeline systems and critical infrastructure [2-3, 11-13], these methods cannot be directly applied to buildings, particularly to the built heritage. This study overcomes this limitation by introducing the following innovative aspects compared to existing methodologies:

- Traditional approaches typically assess direct functional disruption, whereas this study models functional loss using the damage index i_d, offering an assessment of functionality directly related to the effects of the earthquake on the building.
- Existing models often assume standardized recovery functions, while the proposed methodology incorporates financial investment as a key driver of recovery, using the percentage of funds spent as a dynamic indicator of resilience.
- Previous applications of resilience indices do not consider heritage networks, whereas this study introduces a Global Resilience Index that quantifies systemic resilience across multiple heritage buildings, weighting each contribution based on allocated restoration funds.

3. DEFINITION OF THE RESILIENCE CURVES

3.1 Data Collection

The first step in defining global resilience in a territorial context is a) to identify and locate the building systems to be analyzed and b) to assess the damage sustained by each building through the determination of a comprehensive damage index. In this work, a system of churches belonging to the Sulmona-Valva Diocese was analyzed. This diocese is located in the ecclesiastical province of L'Aquila (Italy) and includes 251 churches distributed across 49 different municipalities. The seismic damage sustained by masonry churches in the Sulmona-Valva Diocese after the 2009 L'Aquila earthquake was extensively analyzed by De Matteis et al. [18]. Their analysis focused specifically on three-nave churches, which represent 14% (26 buildings) of the total number of churches in the diocese. The selection of these churches was motivated by the substantial homogeneity found in terms of materials, geometric ratios, and architectural typology.

After examining the damage caused by the 2009 earthquake, De Matteis et al. [18] identified 28 damage mechanisms affecting the primary macro-elements of the analyzed churches (such as façade, colonnade, vaults, apse, transept, dome, and bell tower), in accordance with the Italian Code for the reduction of seismic risk of cultural heritage [19]. These mechanisms provide a comprehensive understanding of the vulnerabilities exhibited by various parts of the church structures during seismic events. De Matteis et al. [18] also defined six possible levels of damage, denoted as d_k, ranging from 0 to 5. A level of $d_k = 0$ indicates that no damage has occurred to the macro-element, or that the macro-element is not present, while $d_k = 5$ represents a complete collapse of the macro-element. To provide an overall assessment, a global damage index i_d is assigned to each church analyzed, using the following equation, as suggested by [19]:

$$\mathrm{i_d} = \frac{1}{5} \cdot \frac{\sum_{k=1}^{28} \rho_{k,i} \cdot d_{k,i}}{\sum_{k=1}^{28} \rho_{k,i}} \quad (1)$$

where ($\rho_{k,i}$) is a weight score, ranging from 0 to 1, based on the influence that the mechanism i has on the global structure stability. Table 1 identifies location, foundation period, acronym and damage index of each of the 26 churches of the Sulmona-Valva diocese examined by De Matteis et al. [18] and used in this work for the calculation of the resilience of the ecclesiastic system.

In order to obtain resilience curves for the individual churches, all information regarding public funding allocated by authorities for post-earthquake reconstruction was collected, including the start and completion dates of the works as well as the progress of the works at bimonthly intervals. The data were obtained by considering the reports of the funds allocated by the MiC (*Ministero della cultura* - Ministry of Culture) and work assignment decrees for the period before the year 2012 and, the bimonthly monitoring reports from the USRA (*Ufficio Speciale Per la Ricostruzione dell'Aquila* - Special Office for the Reconstruction of L'Aquila), for the period from 31/10/2013 to 30/06/2024 [20]. The USRA monitoring reports provide, for each funded intervention, the type of intervention, the cost, the first disbursement of funds, the estimated completion date, the implementation status (design, execution, testing, or completed intervention), and the percentage estimate of work progress. Where not specifically indicated, the initial fund disbursement has been considered as coinciding with the start of work.

Table 2 summarizes the information gathered for the churches listed in Table 1. Note that information on the funds received and the corresponding start date of work was available for only 16 of them. According to the information gathered in this study, other churches have not undergone any type of post-earthquake intervention, and for this reason, their resilience was not analyzed in this study. Specifically, Table 2 includes the project description along with the corresponding funding, the total cost of the intervention, the date of the initial funding, the completion date, and the estimated percentage of work completed for some of the monitored periods. This analysis revealed that some churches, such as San Francesco (SFR) in Castelvecchio Subequo Santa Maria Assunta (SMS) in Castel di Ieri, San Pelino (SPE) in Corfinio or San Pietro Celestino (SPC) in Pratola Peligna, were restored shortly before the earthquake, and no further consolidation interventions were planned. For other churches, again located in the province of L'Aquila, such as San Marco Evangelista (SME) in Castel del Monte or San Martino (SMA) in Gagliano Aterno, the restoration interventions have only recently begun, and the completion date remains unknown.

Table 2 also highlights that the allocated funds are not always proportional to the damage indices assessed after the 2009 L'Aquila earthquake. This discrepancy is shown in Figure 1, where, for each analyzed church, both the amount of allocated funds and the damage index following the 2009 earthquake are reported. It should be noted that the amount of funds allocated may depend more on the church's historical and artistic value rather than solely on the damage index, reflecting specific choices in funding allocation.

3.2 Empirical Resilience

The resilience of a community, a system of buildings, or a single structure to a disastrous event can be represented through a curve. On the x-axis, there is the

Table 1. Location, foundation period, and damage indices of the three-nave churches belonging to the Sulmona-Valva Diocese analyzed by De Matteis et al. [18] and used in this work for the calculation of the resilience of the entire ecclesiastical system. Dataset of Damage Index is derived from De Matteis et al. [18] and is here presented in a new tabular format. © 2025, Authors.

ID	Church	Municipality	Acronym	Construction century	Damage Index
1	San Marco Evangelista	Castel del Monte	SME	XV	0.277
2	Santa Maria Della Pace	Capestrano	SMP	XVII	0.296
3	San Martino	Gagliano Aterno	SMA	XIV	0.360
4	San Francesco	Castelvecchio Subequo	SFR	XIII	0.197
5	San Benedetto Abate	San Benedetto in Perillis	SBA	VIII	0.072
6	San Giovanni Battista ed Evangelista	Castelvecchio Subequo	SGE	XVIII	0.203
7	San Pietro ad Oratorium	Capestrano	SPO	VIII	0.096
8	Santa Maria Assunta	Castel di Ieri	SMS	XV	0.352
9	Santa Gemma	Goriano Sicoli	SGM	XVI	0.637
10	Santa Maria Nova	Goriano Sicoli	SMN	XVI	0.451
11	Santa Maria Del Borgo	Vittorito	SMB	XVI	0.048
12	Santa Maria Maggiore	Raiano	SMM	XV	0.128
13	Basilica di San Pelino	Corfinio	SPE	XI	0.027
14	San Michele Arcangelo	Roccacasale	SMI	XIII	0.083
15	Madonna Della Libera	Pratola Peligna	MDL	XVI	0.080
16	San Pietro Celestino	Pratola Peligna	SPC	XV	0.064
17	Santa Maria Delle Grazie	Anversa degli Abruzzi	SGR	XVI	0.232
18	Santissima Annunziata	Sulmona	SSA	XIV	0.067
19	San Panfilo	Sulmona	SPA	XI	0.112
20	San Domenico	Sulmona	SDO	XIII	0.216
21	Santa Maria Della Tomba	Sulmona	SMT	XIII	0.016
22	Santa Maria Maggiore	Pacentro	SMR	XVI	0.080
23	Santa Maria Della Valle	Scanno	SMV	XII	0.027
24	San Salvatore	Cansano	SSL	XII	0.152
25	San Nicola	Cansano	SNB	XIII	0.152
26	Santa Maria del Carmelo	Villa Scontrone	SMC	XVIII	0.000

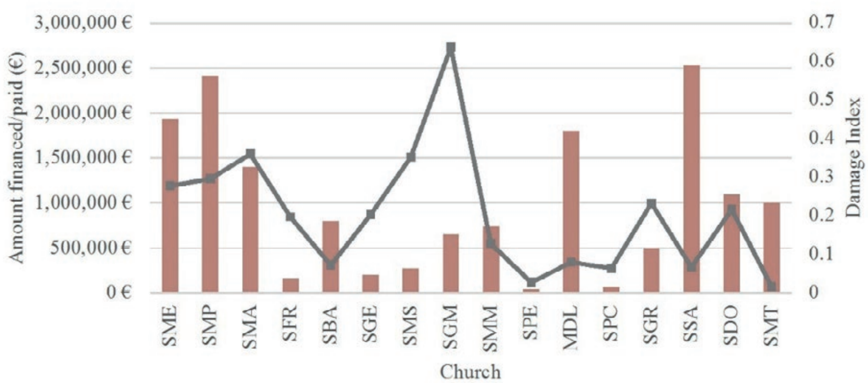

Figure 1. Funds allocated for each analyzed church that received funding compared with the corresponding damage index assessed after the 2009 earthquake. © 2025, Authors.

time *t*, starting from the catastrophic event (or immediately before), up to the period when the system has fully regained its original functionality. The y-axis represents the system functionality Q(*t*). Before the event, functionality is at 100%. When the event occurs, functionality drops sharply, followed by a recovery phase. The speed of recovery depends on the community's recovery capacity, political choices, and availability of funds.

Table 2. For each of the analyzed churches: project description, total cost of the intervention, date of initial funding, completion date, and estimated percentage of work completion across several monitored periods. © 2025, Authors.

ID	Acr.	Image	Project Description	Total Cost (€)	First Payment Date	Work Complet. Date	Estimate percentage of completion works (%) 31/12/2011	31/08/2014	31/12/2014	30/04/2015	31/12/2015	31/12/2016	31/12/2017	30/04/2018	31/12/2018	30/06/2019	31/12/2019	31/08/2020	31/12/2020	30/06/2021	31/12/2022	30/04/2023	31/08/2023	30/04/2024	30/06/2024
1	SME		Safety Works for the Bell Tower	431,500	27/03/2020	05/11/2021	0	0	0	0	0	0	0	0	0	0	0	4	70	70	100	100	100	100	100
			CIPE 135 Seismic Retrofitting	1,500,000	17/05/2023	31/12/2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	10	10	10
2	SMP		Securing a section of the Church	8,245	06/03/2014	30/04/2014	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
			CIPE 112 Recovery Restoration Works	2,400,000	-	30/12/2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	SMA		CIPE135 San Martino	900,000	19/05/2020	30/06/2025	0	0	0	0	0	0	0	0	0	0	0	0	4	4	6	6	6	6	6
			CIPE 52/2021 Consolidation and Restoration	500,000	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	SFR		OPCM 3820 Phase II Urgent Works for the Restoration of Habitability	164,523	25/10/2010	06/07/2011	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	SBA		CIPE 77 Consolidation and Restoration Works	800,000	30/04/2023	31/12/2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	50	70	98
6	SGE		CIPE 52 Assignment of Design Services	200,000	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	SMS		OPCM 3820 Phase II Structural Restoration Project	273,369	20/09/2010	04/07/2011	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	SGM		Consolidation and Restoration works	650,000	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	SMM		OPCM 3820 Phase II Urgent Safety Works	438,430	18/03/2011	25/01/2012	92*	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
			OPCM 3820 Phase III Urgent Safety Works	260,000	26/09/2011	14/02/2012	68*	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
			OPCM 3820 Phase II Urgent Works. Painting Works	40,000	29/02/2012	11/07/2013	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
10	SPE		OPCM 3820 Phase I Definitive Safety Intervention	41,370	16/11/2009	22/10/2010	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
11	MDL		CIPE 52/2021 Consolidation and Restoration Works	1,000,000	-	31/12/2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			CIPE 77 Consolidation and Restoration Works	800,000	29/05/2018	30/06/2020	0	0	0	0	0	0	0	0	49	49	100	100	100	100	98	95	98	98	98
12	SPC		OPCM 3820 Phase I Definitive Safety Works	72,110	15/09/2009	15/12/2010	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
13	SGR		CIPE 77 Consolidation and Restoration Works	500,000	31/10/2019	30/06/2025	0	0	0	0	0	0	0	0	0	0	0.5	2	5	5	5	25	25	25	25
14	SSA		CIPE 112 Consolidation Works	1,500,000	16/11/2023	30/12/2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
			CIPE 135 Consolidation Works	1,000,000	26/11/2013	30/12/2015	0	3	7	70	96	97	100	100	100	100	100	100	100	100	100	100	100	100	100
			Urgent Safety Works	31,900	16/11/2009	30/11/2010	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
15	SDO		CIPE 135 Consolidation and Restoration Works	1,100,000	16/12/2014	31/12/2015	0	0	1	6	6	51	68	68	70	70	71	71	71	71	71	71	71	71	71
16	SMT		CIPE 135 Conservative Consolidation Works	1,000,000	10/12/2013	04/10/2014	0	5	33	51	86	87	87	87	87	87	100	100	100	100	100	100	100	100	100

The data collected on the 16 churches analyzed and shown in Table 2 allowed for the plotting of their empirical resilience curves, characterized by data directly observed on-site (Figure 2). In this case, the date of the disastrous event corresponds to April 6, 2009, the date of the L'Aquila earthquake, and the points on the x-axis correspond to the dates when the progress of the works was monitored. The points on the y-axis, corresponding to the restoration of functionality, were derived based on the damage index i_d and the percentage of work completion. Specifically, at each time t_i, i_d was scaled as a function of the corresponding percentage of work completion. In the case of churches undergoing multiple interventions, the damage index was scaled based on the cost of each intervention and its completion status. Subsequently, the functionality $Q(t_i)$ was calculated as indicated in Eq. 2. In this way, a null damage index $i_{d,ti}$ corresponds to a functionality $Q(t_i)$ of 100%, while, for example, $i_{d,ti} = 0.2$ corresponds to $Q(t_i) = 80\%$.

$$Q(t_i) = 1 - i_{d,t_i} \qquad (2)$$

where $Q(t_i)$ is the functionality of the considered church at the time t_i and $i_{d,ti}$ is the corresponding damage index.

Figure 2 shows the empirical resilience curves for some of the churches listed in Table 2. These curves exhibit substantial and significant differences compared to the restoration curves found in the literature, which focus on different types of lifeline systems [11-13]. Specifically, in this case, there is a long period t between the occurrence of the event and the start of recovery and consolidation works, which can vary from a few years to over ten years. There are, in fact, churches that, more than 15 years after the event, have just started or have yet to begin restoration and consolidation works (SMA, SGE, SGM), despite the funds having been allocated long ago.

Generally, there is a minimum level of functionality below which structural recovery is no longer cost-effective, as the physical structure of the building has been damaged to such an extent that its original functionality can no longer be restored with an efficient cost-benefit ratio. In such cases, the structure is typically replaced with a new building serving the same functions as the original one. From a resilience perspective, this concept can be expressed as the presence of a Minimum Functionality (MF) Level, below which the structure is unable to recover its original function. Heritage buildings are characterized by very low or null MF coefficients, as their recovery is not determined by an optimal cost-benefit ratio but by the goal of preserving and passing cultural and historical heritage to future generations. In this study, none of the analyzed churches reached their MF coefficient, as the maximum observed damage after the 2009 L'Aquila earthquake was 0.637, according to [18].

3.3 Theoretical Resilience

Constructing detailed empirical resilience curves often demands a substantial volume of data, which may not be readily available for all contexts. To address this limitation, empirical data were leveraged to calibrate and adapt theoretical formulations commonly applied to lifeline systems to the unique characteristics of Italian built heritage. The use of a limited dataset calibrated with real data enables the estimation and comparison of resilience across various built heritage systems. This approach also supports the digitalization and automation of resilience assessment processes for entire systems, offering a replicable methodology.

The works of Cimellaro et al. [9-10], as well as studies using their method [e.g., 21-26] state that the recovery of a system can follow three different theoretical curves f_{rec}: (a) linear, (b) exponential [26] and (c) trigonometric [6]. The most basic approach is a linear recovery function (a), typically applied when no information is available on preparedness, resource availability, or societal response. An exponential recovery function (b) may be suitable when an initial influx of resources is present, with the recovery rate gradually slowing as the process nears completion. A trigonometric recovery function (c) can be used when societal response and recovery are limited by a lack of organization and/or resources

$$\begin{aligned} &(a) \quad f_{rec} = 1 - Q(t) = a\left(\frac{t - t_{0E}}{T_{RE}}\right) + b \\ &(b) \quad f_{rec} = 1 - Q(t) = 1 - a\,exp\left[\frac{-b(t - t_{0E})}{T_{RE}}\right] \\ &(c) \quad f_{rec} = 1 - Q(t) = 1 - \frac{a}{2}\left\{1 + cos\left[\frac{\pi b(t - t_{0E})}{T_{RE}}\right]\right\} \end{aligned} \qquad (3)$$

where f_{rec} is the recovery function, which is the complement of $Q(t)$, a is the global damage index of the considered church after the earthquake, b is a constant value calculated using curve fitting to available data sources, t_{0E} is the instant of time when the earthquakes occur, and T_{RE} is the recovery time necessary to go back to pre-disaster condition evaluated starting from t_{0E}.

The type of recovery curve is influenced not only by the specific characteristics of the system but also, and more importantly, by the level of damage caused by the earthquake. When a structure experiences minimal damage, its recovery is typically rapid and follows an exponential curve over a short period of time. Con-

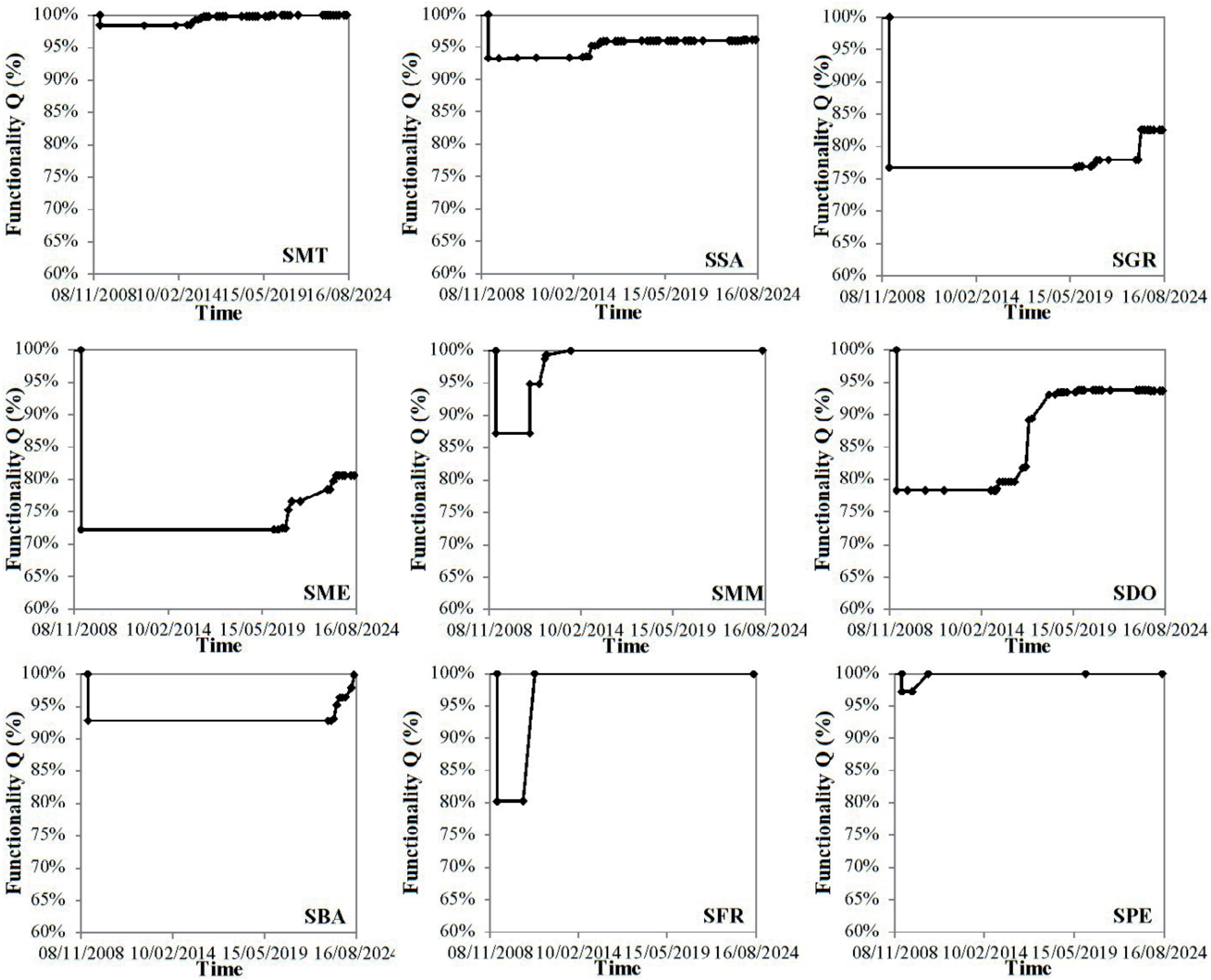

Figure 2. Empirical resilience curves of the three-nave churches of the Sulmona-Valva Diocese after the 2009 L'Aquila earthquake. © 2025, Authors.

versely, when a structure suffers extensive or moderate damage, the recovery of its original functionality is likely to be slow and follows a trigonometric curve. Figure 3 shows the recovery curves as a function of the damage level caused by the seismic event, as well as the minimum functionality level below which the original system is generally not restored.

The empirical resilience curves shown in Figure 2 were compared with the theoretical resilience curves. This comparison was adapted to the Italian context by adjusting the theoretical approach presented in Figure 3. Typically, a disruptive event is immediately followed by the reconstruction process; however, in the case of the three-nave churches in the Sulmona-Valva Diocese, there is an extended delay between the L'Aquila earthquake and the start of recovery efforts. Consequently, Equations 3a, 3b and 3c were applied by setting t_{0E} to the date when securing, consolidation, or restoration work began on the churches, rather than the instant when the earthquake occurred. For instance, Figure 4 displays comparisons between the empirical and theoretical resilience curves for some of the analyzed churches. It is observed that this adjustment to t_{0E} enables the empirical resilience curves to align with the theoretical ones. This alignment suggests that, even without continuous monitoring of the reconstruction progress, a resilience curve can be hypothesized based on the known end of the works and the period between the destructive event and the start of reconstruction, allowing for the derivation of the corresponding resilience index, which is equal to the area under the curve.

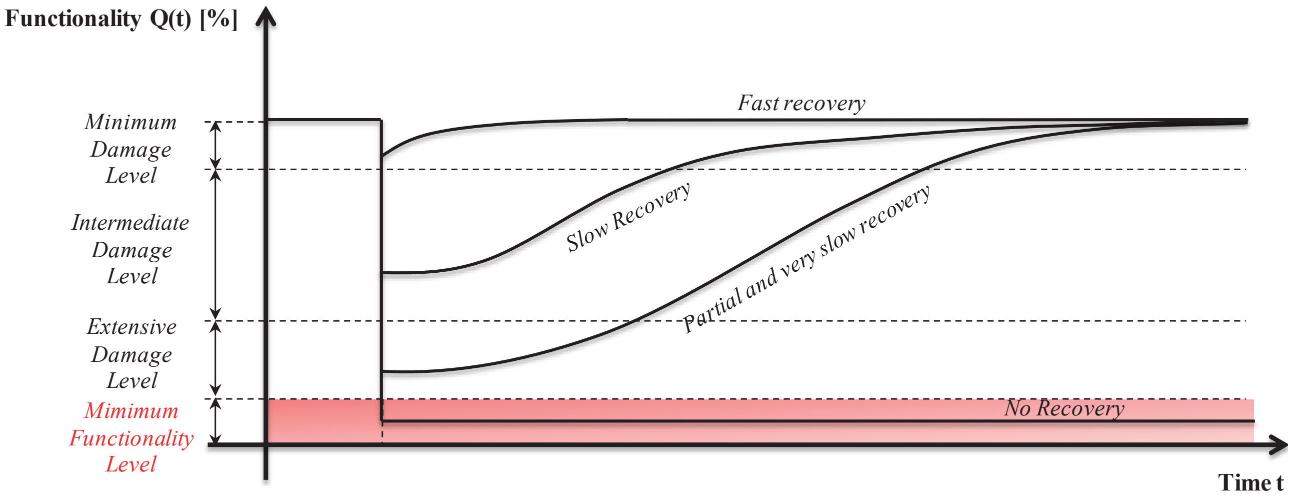

Figure 3. Recovery curves as a function of the damage level generated from a seismic event and the minimum functionality level below which the original system is not generally restored (in red). © 2025, Authors.

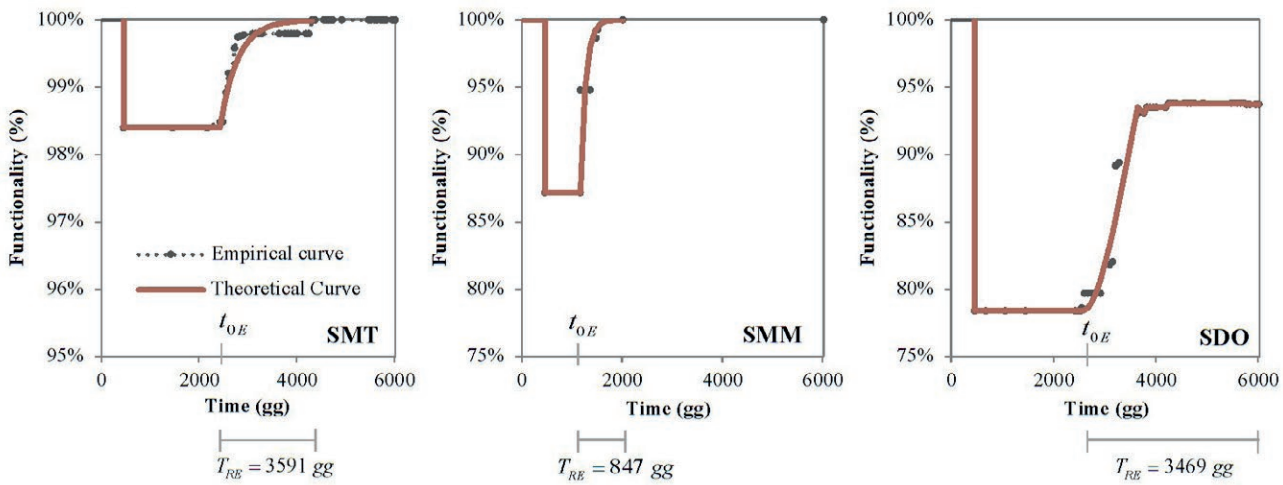

Figure 4. Comparison between empirical (in black) and theoretical (in antique rose) resilience curves for the SMT, SMM and SDO churches. © 2025, Authors.

3.4 Global Resilience Index

To develop a global resilience index, it is first essential to determine the average functionality over time for each church. Each church's resilience curve represents its functionality $Q(t)$ as a function of time t. By calculating the average functionality over the observation period (i.e. the area under the functionality curve), a representative measure of each church's resilience is obtained:

$$Q_i = \frac{1}{T}\int_{t_0}^{T} Q_i(t)dt \quad (4)$$

where $Q_i(t)$ denotes the functionality of church i at time t, and T represents the total observation period (from the earthquake occurrence to the completion of restoration).

The resilience of the single heritage building is calculated as a percentage. A resilience of 100% indicates that the heritage structure did not sustain damage from the disruptive event, or that no damage occurred. Conversely, a resilience of 0% indicates a total collapse of the historical building, with no intent or possibility of restoring the lost functionality. For example, a resilience of 50% may correspond to a damage index of 1, while higher resilience values correspond to progressively lower damage indices. Resilience is calculated as the area under the curve, normalized over the observation period *T*. Therefore, for the same disruptive event, if the restoration start, recovery function, and damage index remain unchanged, the resilience value is the same whether *T* is 10 or 20 years. When the start date of restoration does not coincide with the disruptive event, the recovery curve does not begin immediately after the event but at the start of the restoration work. Nevertheless, resilience is always calculated as the area under the *Q(t)* curve between the disruptive event and the completion of work. Where there is no completion date, the reference point is the date of the last monitoring.

In developing a Global Resilience Index that reflects the overall seismic resilience of the church system, this study introduces a novel approach: weighing the resilience contributions of individual churches based on the funds allocated for their restoration. This methodology leverages the assumption that higher restoration funding correlates with greater historical, cultural, or social importance, offering an indirect but pragmatic indicator of priority. In existing literature, resilience indices often rely on factors such as structural vulnerability, geographic location, or specific damage assessments as primary criteria for weighing resilience elements (see, for instance, methodologies by Cimellaro et al. [14-15] in the PEOPLES framework apply a resilience-based design in urban settings). However, this approach does not account for the significance of cultural heritage in resilience, nor does it directly incorporate financial considerations as a reflection of priority.

For each church i, a weight W_i proportional to the allocated restoration funds F_i was assigned:

$$\mathrm{w_i} = \frac{\mathrm{F_i}}{\sum_i \mathrm{F_i}} \tag{5}$$

where the sum of weights equals 1. This weighted approach provides a Global Resilience Index (R_{global}) calculated in percentage terms as:

$$\mathrm{R_{global}}\,(\%) = \sum_i \mathrm{w_i} \cdot \mathrm{Q_i} \tag{6}$$

where Q_i represents the average functionality over time for each church, expressed as a percentage. By adopting restoration funding as a weighting factor, this study aligns resilience calculations with practical, real-world considerations, enhancing the representation of both recovery dynamics and cultural importance. This approach also supports resource allocation strategies that align with both structural resilience and heritage conservation.

3.5 The Global Resilience Index Application

The Global Resilience Index for the three-nave masonry churches in the Sulmona-Valva area was calculated using theoretical resilience curves for 12 churches from a dataset of 26 with sufficient data. As previously mentioned, in the absence of sufficient data, it is possible to calculate theoretical resilience. To demonstrate the potential of this approach, the theoretical model was validated by assuming the absence of certain data and then compared with the empirical calculation. The calculated resilience, weighted according to the allocated restoration funds, resulted in a value of 88.5%, reflecting a generally high resilience of Abruzzo's churches to seismic events.

The procedure was repeated by constructing theoretical resilience curves without accounting for the time between the destructive event and the start of restoration, while maintaining the same completion date, percentage of work completed, and resilience function. This approach allowed for the calculation of an ideal resilience index of 90.8%. It should be noted that in this case, the same completion date was maintained. If, instead, the duration of the consolidation works is kept constant by eliminating the delay between the destructive event and the start of works – thus moving the completion date earlier – the resilience became equal to 94.2%. These results emphasize the impact of timely resource allocation by public authorities, illustrating how more immediate interventions can substantially enhance the resilience of cultural heritage.

4. DIGITIZATION OF RESILIENCE CURVES

4.1 Digitization workflow

The digitization workflow for assessing the seismic resilience of heritage buildings follows a systematic approach that integrates data collection, analysis, dynamic visualization and strategic planning into a coherent framework. This workflow focuses on an automated data management system tailored to resilience assessment. It is designed to guide the entire process, from gathering initial damage data to implementing a dynamic digital platform for ongoing management and resilience planning. The goal is to provide a scalable and adaptable tool for monitoring restoration progress, quantifying resilience indices, and supporting decision-making for conservation strategies.

The workflow is divided into five main stages, from raw data collection to digital representation and resilience assessment:

- *Data Collection and Organization*. A georeferenced Innovative Technology (IT) platform is constructed using a system based on Geographic Information System (GIS) to spatially organize and visualize resilience data. This platform allows for the precise localization of each heritage building and the collection of relevant information, including post-earthquake damage indices, allocated restoration funds and restoration progress tracking, conducted on specific time intervals for precise monitoring.
- *Implementation of a Structured Database*. Data is structured in a relational database, where each church identification (ID) serves as a unique reference, enabling continuous monitoring of the building's resilience evolution. To ensure real-time updates, the system is designed to interface directly with public databases that publish information on allocated restoration funds (e.g. [20]). This integration allows for automated retrieval of funding data, ensuring that resilience calculations remain dynamically updated as new funding rounds are approved or disbursed.
- *Development of Resilience Curves*. Empirical resilience curves are constructed based on the percentage of completed restoration work. In cases where data is not available, theoretical resilience curves are developed using average data from similar churches, with the potential application of machine learning algorithms to enhance predictive accuracy. At this stage, analyses are conducted at the building scale, and algorithms are implemented within the platform to dynamically plot resilience curves, ensuring real-time assessment.
- *Identification of a Global Resilience Index*. The R_{global} index is calculated as a weighted average based on the resilience of individual buildings and the funds allocated for their restoration, reflecting the overall system's resilience. In this case, a territorial scale is used to provide the resilience dynamics of the overall heritage system, which are displayed in a graphical real-time interface.
- *Planning of Safety Measures for the Heritage System*. Based on the resilience analysis, this final stage focuses on identifying buildings with lower resilience so that policymakers and stakeholders can adequately and reasonably plan the allocation of funds, safety measures, or restoration interventions needed. To assist this process, the system can provide recommendations for prioritizing funds, security measures, and interventions upon request, ensuring optimal heritage preservation strategies.

Figure 5 provides a visual representation of the digitization workflow, highlighting each stage and illustrating how data flows from collection to analysis and implementation. Each step is interconnected, and each piece of information is essential to the next step, supporting an efficient resilience strategy for heritage buildings.

4.2 Limitations and future directions

From an operational perspective, the web-based platform and digitization workflow can vary in complexity. For instance, the algorithm for identifying resilience can be implemented on a basic platform, working as an Excel sheet, where specific details for each church ID are recorded.

On the other hand, a more advanced platform, which could be developed through future research, would significantly enhance functionality. The proposed georeferenced computing platform and GIS-based system outlined in this study represent a conceptual framework for future implementation, aimed at improving data integration, automation, and visualization capabilities. Once fully developed, this system would enable automated calculations, real-time data retrieval from public databases, and dynamic visualization of resilience metrics, providing a scalable and adaptive tool for heritage conservation strategies.

5. CONCLUSIONS

This paper presents a comprehensive approach to assessing the resilience and operability of heritage churches impacted by the 2009 L'Aquila earthquake. The proposed workflow integrates systematic data collection, empirical and theoretical resilience curve development, and a global resilience index calculation to support informed decision-making and enhance resilience planning.

The key aspects covered in this paper and the innovative contributions include:

(a) The quantitative calculation of resilience for cultural heritage, addressing the gap in the existing scientific literature related to quantitative resilience studies, which have primarily focused on lifeline systems and, more recently, on schools.
(b) The development of empirical resilience curves based on restoration funding allocation and the monitoring of work progress, offering a novel perspective on how financial resources impact resilience.
(c) The comparison and calibration of empirical and theoretical resilience curves, including the adap-

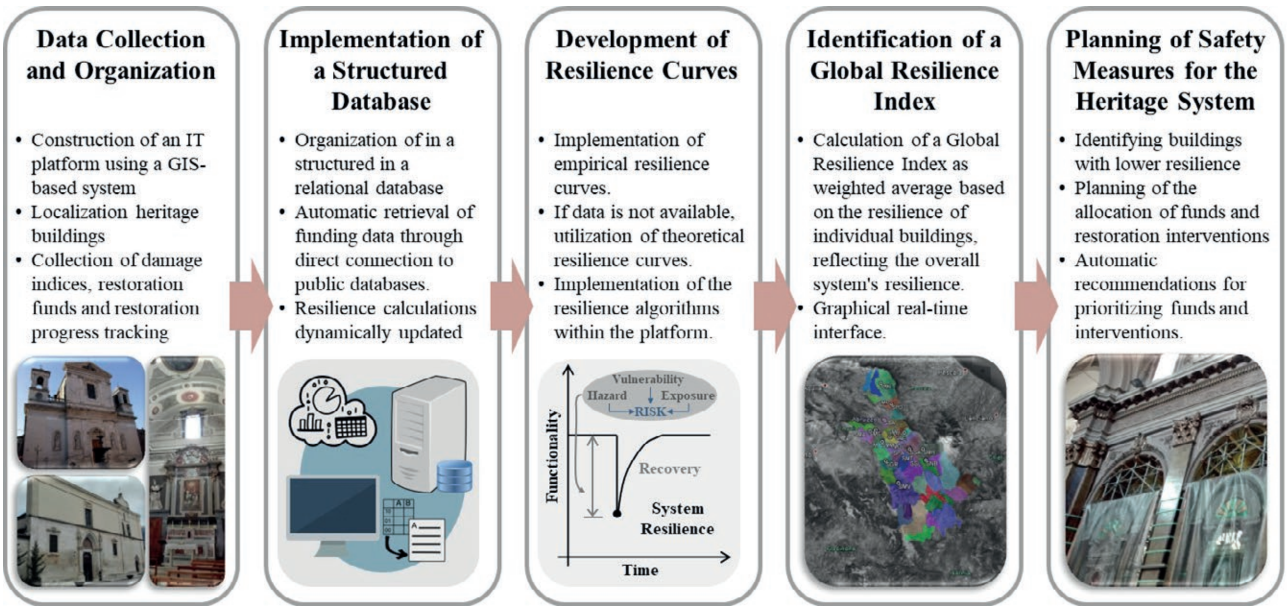

Figure 5. Digitization Workflow for Seismic Resilience of Heritage Buildings. © 2025, Authors

tation of theoretical models to cultural heritage cases. Constructing detailed empirical resilience curves often requires substantial data, which may not always be available. To address this, empirical data were used to calibrate theoretical resilience functions, adapted from lifeline systems to the unique characteristics of Italian built heritage. This approach enables the estimation and comparison of resilience across heritage systems, supports the digitization and automation of resilience assessments, and provides a replicable methodology.

(d) The calculation of a global resilience index, which aggregates the resilience of individual churches, weighted by the allocated restoration funds, reflecting both their physical resilience and their cultural and historical significance. These results highlight the critical role of timely resource allocation by public authorities, demonstrating how prompt interventions can significantly enhance the resilience of cultural heritage.

(e) The creation of a digitization workflow designed to facilitate easy resource allocation and intervention planning, ultimately improving the resilience of built heritage and preparing it for potential disruptive events.

Overall, the findings demonstrate that the proposed framework not only advances current methodologies for resilience assessment but also provides a practical tool for enhancing the preparedness of heritage buildings for disruptive events. Future research could integrate this approach with advanced predictive technologies, such as machine learning, to further enhance resilience modeling and improve accuracy.

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– INTERCONNECTING: Data, Analysis, and Digital Immersive Models for Sustainable Conservation of the Built Heritage: risk assessment and proactive strategies. PNRR-Next Generation EU—1.3 Extended partnerships—CHANGES Spoke 7—Protection and conservation of cultural heritage against climate changes, natural and anthropic risks. Leader: University of Florence CUP B53C22004010006. Topic: *Data processing and digital modeling*.
– MULTI-TWIN: Intelligenza artificiale a supporto di analisi Multi-rischio mediante digital-Twin. PNRR-Next Generation EU—1.4 National Centers. Mission 4, "Education and Research"—Component 2, "From Research to Enterprise"— Investment Line 1.4, Project 'National Centre for HPC, Big Data and Quantum Computing—HPC' CUP H93C22000450007. Topic: *Application of AI, data analysis and virtual reality for monitoring and management of infrastructure and resources as well as multi-hazard analysis at a regional scale with a focus on historic centers, critical buildings and environments* (i.e., forests).

The opinions and conclusions presented by the authors do not necessarily reflect those of the funding agencies.

8. AUTHOR CONTRIBUTIONS

Cristina Cantagallo: Conceptualization (lead), Data Curation, Formal Analysis, Methodology (lead), Software (supporting), Validation (lead), Visualization, Writing – Original Draft Preparation (lead), Writing – Review & Editing (equal). Valentino Sangiorgio: Conceptualization (supporting), Software (lead), Methodology (supporting), Supervision, Validation (supporting), Writing – Original Draft Preparation (supporting), Writing – review and editing (equal).

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New Approaches to Manage and Enhance 20th-Century Architectural Heritage Through Digital Archives

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Abstract. This paper presents the initial findings of a research program funded by the EU Recovery Plan, which includes a doctoral project focused on promoting knowledge and enhancing contemporary architectural heritage through the creation of a digital archive dedicated to public works built in Genoa from 1945 to the present. Conducted in collaboration with national and international institutions, the research focuses on 20th-century architecture, a form of heritage often undervalued and in need of maintenance or refurbishment. In agreement with the Municipality of Genoa, the study begins with post-war museums, recognized for their national and international significance. These works are now facing the phase of renovation, and it is crucial to understand if and how their conservation and valorization can be combined with the adaptation needs. The project, based on the analysis of unpublished archival documents, aims to preserve materials otherwise at risk of deterioration and to support the development of a public documentation center. The archive enables the reconstruction of the museums' complex histories, shedding light on design integrity, authorship, and transformation causes - key information for planned interventions. The critical selection, digitization, and dissemination of these materials will create a resource accessible to both scholars and the general public, fostering broader awareness of contemporary architectural heritage and its values.

Keywords: Contemporary architecture, Heritage, Museums, Enhancement, Digital archive.

1. INTRODUCTION

The construction and architectural production of the 20th century, which was quantitatively very significant compared to previous epochs, has attracted increasing attention from the cultural and scientific world in recent decades, for various reasons. On the one hand, we have witnessed a gradual and pervasive process of "patrimonialization" [1], which has extended the concept of "heritage" from individual objects of recognized historical and artistic value to broader episodes and contexts that recount the social and productive history of communities, including intangible and built landscapes. On the other hand, we are faced with a large amount of built heritage, often in a precarious state of conservation, for which there is no widespread public appreciation. It is therefore necessary to reflect on the reasons and criteria that could support the selection and valorization of works that are so diverse in terms of architecture, context, and construction.

For the last two decades, the Ministry of Culture (MiC) has also been dedicating resources to this area of research, launching an extensive national campaign for the selection of architectural works from the second half of the 20th century and the beginning of the new millennium, with a view to their potential protection, enhancement and dissemination to a wider audience. In October 2022, MiC's Directorate-General for Contemporary Creativity (DGCC) and Fondazione Scuola Beni Attività Culturali organized two study days entitled "Inheriting the Present", during which the new platform of the Census of Italian Architecture from 1945 to the Present [2] was presented. This mapping project has involved the collaboration of several Italian universities, including the University of Genoa (UniGe) since 2009 (under the scientific responsibility of Stefano F. Musso and Giovanna Franco).

Indeed, the many architectural heritages of the 20th century are part of a modern and contemporary history whose historical sense is not yet fully established, nor its value widely recognized. This historiographical and value indeterminacy constitutes a critical and methodological challenge, even before a technical one [3]. The approach to modern and contemporary architectural and urban heritage - whether through efforts to experience, preserve, and assimilate it, or, conversely, to deny and destroy it - is shaped by complex and still unsettled processes of selection.

2. STATE OF THE ART

A first look at this heritage cannot ignore historiographic approaches aimed at identifying meanings and values beyond everyday use. The more recent the heritage, the more we perceive it as embedded in a condition of processuality and simultaneity, which makes attributing shared values difficult. This requires both temporal distance and a respectful attitude in terms of conservation and enhancement. The 20th century has brought a level of complexity in which individual and collective actions, as well as economic, political, social, cultural, and technical values, are intertwined. These works are «the repository of attempted institutional, bureaucratic, technical and artistic rationalities; they bear witness to the layering of constantly renewed policies and social imaginaries» [4]. This complexity, together with a dimension of simultaneity or synchronicity (one of the fundamental implications or possible declinations of the term "contemporary") [5], inevitably influences the way we perceive built artifacts. Time is a fundamental key in the processes of "signification": it transforms the built material, determining new aesthetic canons and evolutions in taste.

The legacy of the recent past plays a crucial role in shaping both individual and collective memory [6]. It is therefore legitimate and necessary to ask whether a "cultural memory" of 20th-century architecture exists and whether this memory constitutes a basis for its recognition as heritage. Addressing these questions requires interpreting the idea of testimony or trace [7] and reflecting on the possibility that places can transmit values strong enough to justify protection, preservation, and appropriation by the communities that inhabit them. However, a close examination of the 20th-century production is not limited to the historiographical theme alone. Studying this topic provides an opportunity to reflect on possible interpretations of controversial yet unavoidable history [8-9].

The research project presented here is situated within this broader context and aims to document, study, digitize, and disseminate a cultural heritage emerging from historically significant episodes that remain only partially understood and therefore potentially neglected. The idea of a digital archive stems from the national census campaign on contemporary architecture initiated by the former Directorate General for Contemporary Art and Architecture (now DGCC), in collaboration with the then Regional Directorates and local Superintendencies. In Liguria, this campaign was carried out by the Department of Architecture and Design at the University of Genoa and resulted in the publication of "*Architetture in Liguria dopo il 1945*" (Figure 1) [10].

A key methodological challenge of the census, published in 2016 (Figure 1), was to define criteria for identifying works of «relevant historical-artistic interest» (according to the Cultural Heritage Code). These criteria sought to assess each work's critical significance within its historical period from diverse disciplinary, cultural, and technical perspectives. Evaluations focused on:

- The importance of the author, regardless of the critical fate of each work.
- The building types and uses, also considering some particular innovations in the relation between the creation of space and its perception.
- The relevance and significance of the work for the social community of reference (industrial architec-

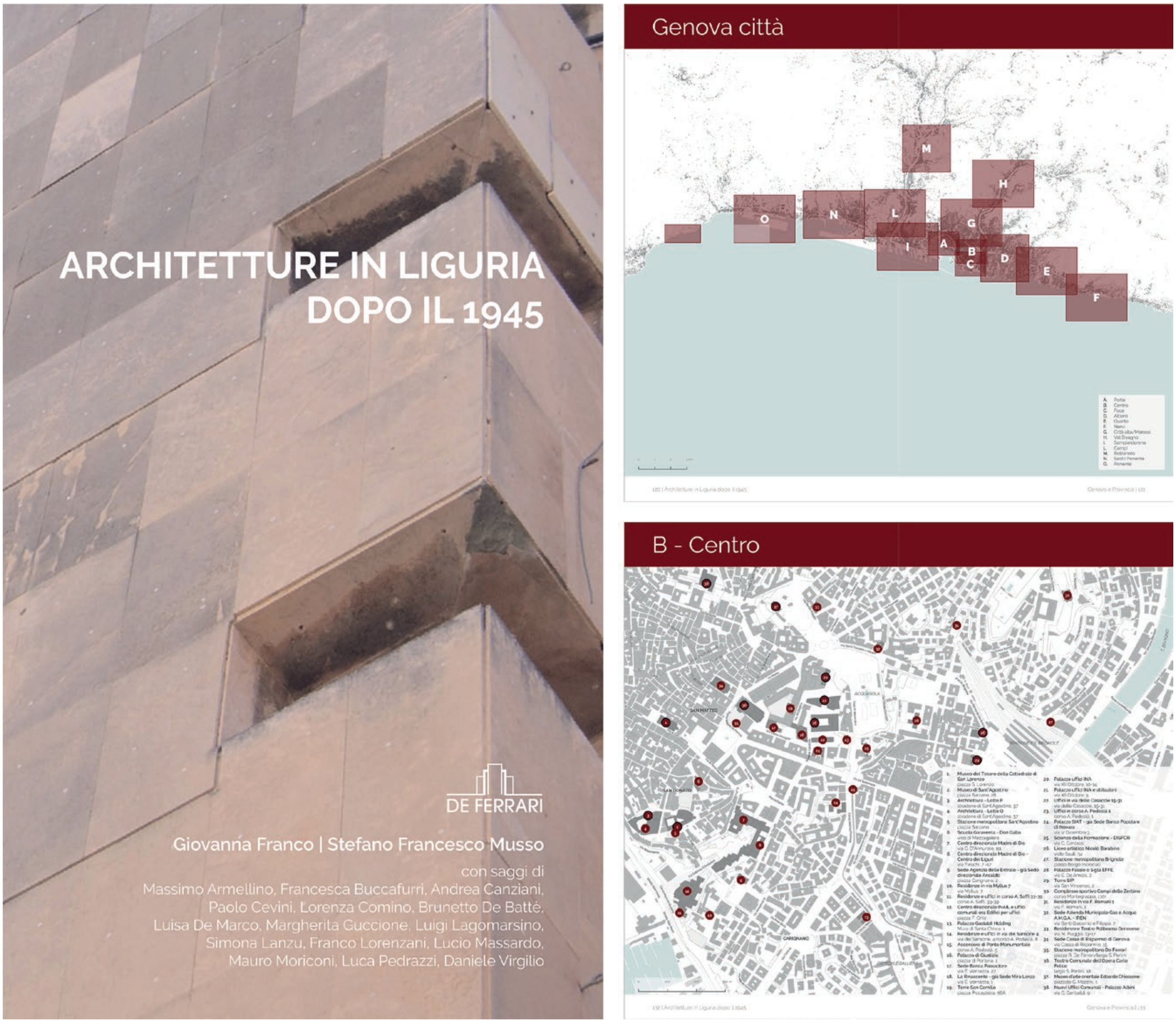

Figure 1. "*Architetture in Liguria dopo il 1945*", volume edited by Giovanna Franco and Stefano Francesco Musso. The book represents the scientific and informative basis for the research presented in this article. Image composition by the authors.

tures, maritime colonies) or in the Italian and international cultural debate.

- The relationship with the urban or landscape and environmental context, particularly important in the complex, fragile, and delicate Ligurian territory, where construction is traditionally based on terracing.
- The evolution of the construction logic and principles, along with the use of materials that were innovative for the period.

This effort led to a census of approximately 600 works spread across the regional territory. For each, descriptive records were created based on ICCD (Central Institute for Cataloguing and Documentation) cataloguing standards (Sheet A), then uploaded to the MiC portal and the geoportals of the Liguria Region [11] and the Municipality of Genoa [12] (Figure 2). This large amount of data forms the basis of the research presented here.

An additional outcome was the development of LigurArch900 (Figure 3), a mobile application offering dynamic, keyword-driven, and thematic itineraries. While the printed volume presented a curated selection, the broader aim of the census was to promote the widespread dissemination of its results. This has opened new research directions, particularly the creation of a digital archive to organize and provide access to the extensive

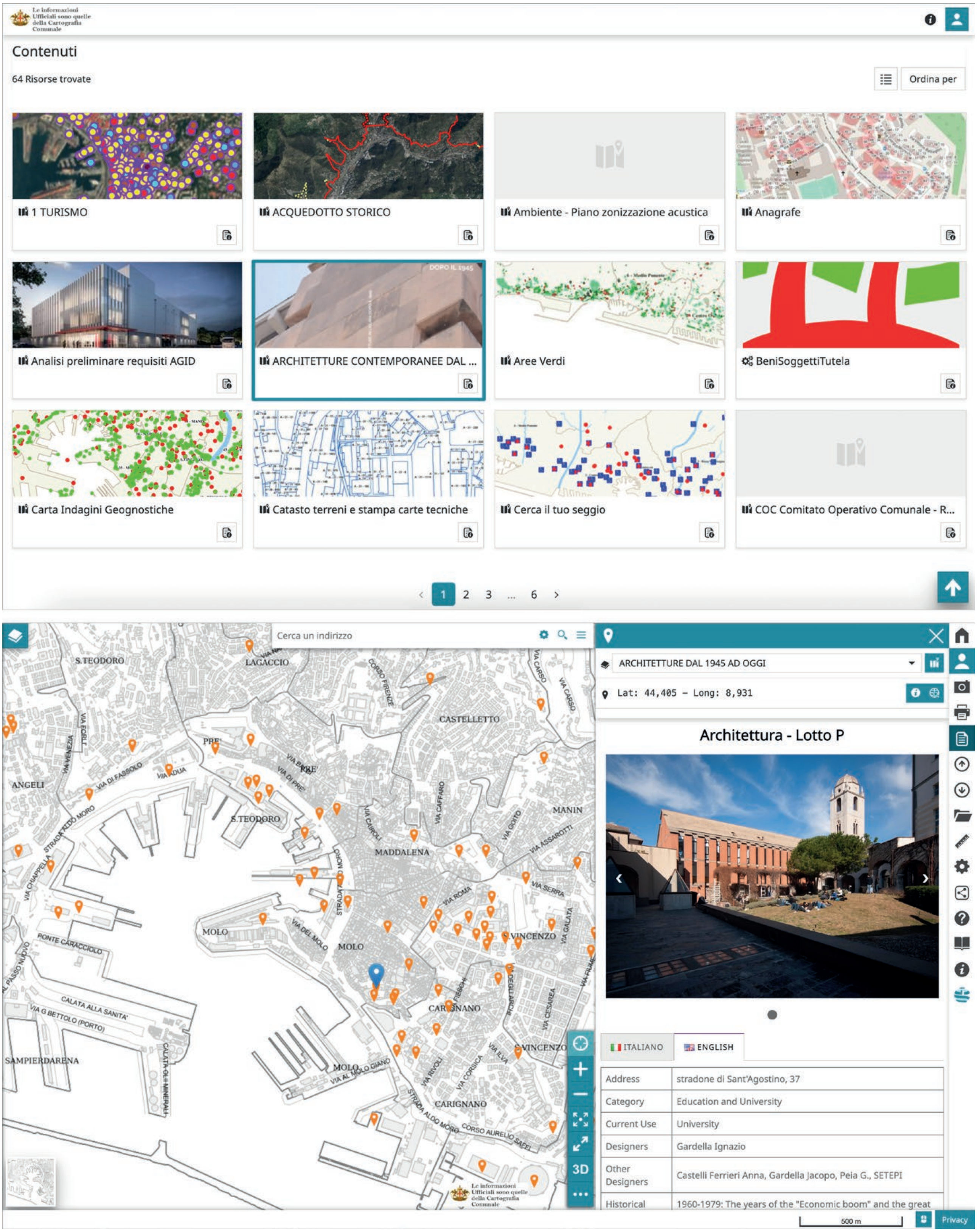

Figure 2. "*Architetture dal 1945 ad oggi*", section of the geoportal of the Municipality of Genoa that collects the outcomes of the census carried out by the university and published in 2016. Image composition by the authors.

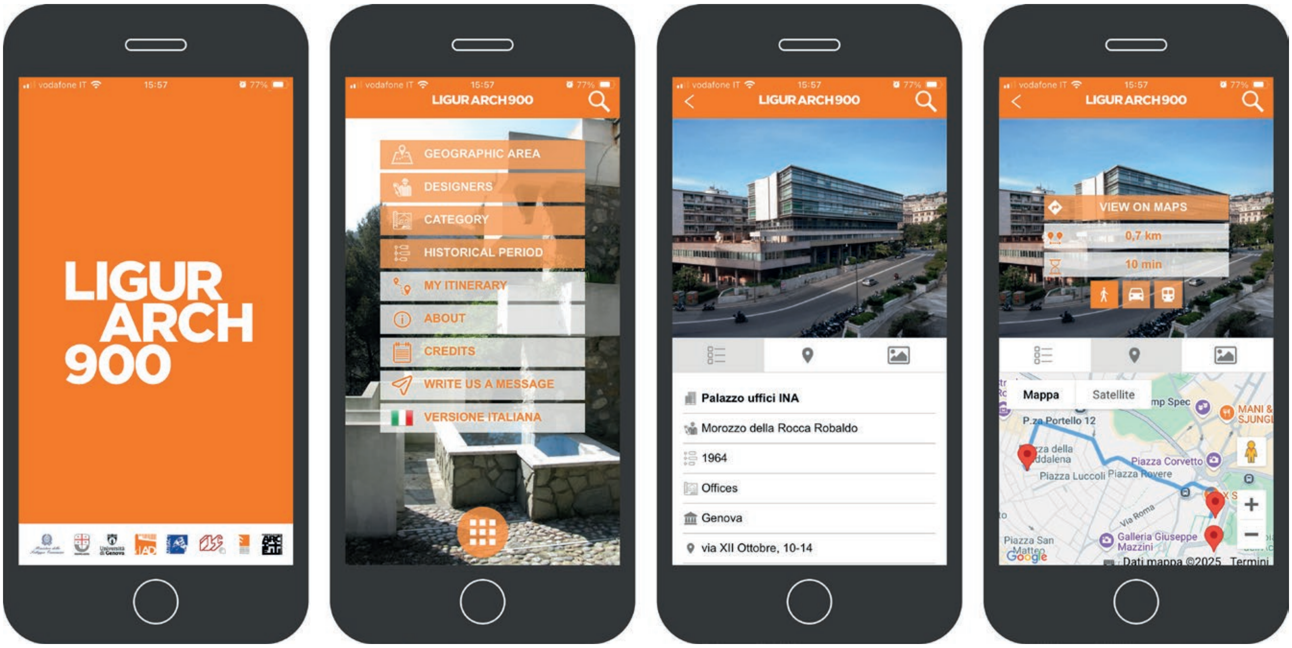

Figure 3. LigurArch900, a digital application for smartphones and tablets, represents another outcome of the 2016 census. Image composition by the authors.

iconographic, bibliographic, and documentary materials collected during the campaign. Such a resource would help overcome the current fragmentation and dispersal of documentary materials, scattered among various public and private institutions, and serve as a critical infrastructure for preserving, studying, and disseminating recent architectural heritage.

This initiative also aligns with ongoing trends in the digital transformation of architectural archives, which have accelerated the digitization of analog collections and increasingly deal with born-digital records. Additionally, it builds on a growing ecosystem of digital archives and catalogues dedicated to contemporary architecture, both nationally and internationally. In Italy, notable examples include the Archivio degli Architetti portal of the National Archival System (SAN), the platforms of MAXXI's Architecture Archive Center, IUAV's Archivio Progetti, the CSAC of the University of Parma, and the Carlo Scarpa Archive in Castelvecchio. International references, such as the DOCOMOMO Virtual Exhibition (MoMove), the Collection Platform of Het Nieuwe Instituut, and the Getty Research Institute's Architecture & Design Collection, exemplify how public engagement is promoted through the adoption of narrative approaches, interactive tools, and user-friendly interfaces. These cases highlight how architectural archives are evolving from static repositories into active instruments of cultural dissemination, capable of shaping collective memory and reaching audiences beyond the academic sphere. In line with this perspective, the Genoese project seeks to position itself within this international network, experimenting with open-access models and interpretative approaches that engage both specialists and the general public.

However, despite the proliferation of such digital repositories, the consistent and coordinated adoption of international archival description standards, such as ISAD(G) and ISAAR(CPF), and metadata standards, such as METS and Dublin Core, remains uneven. Initiatives like the International Image Interoperability Framework (IIIF) aim to promote further standardization and interoperability, fostering the shared use and cross-institutional circulation of digital content. Growing attention to accessibility, openness, and collaboration is reshaping archival practices, with the broader goal of democratizing access to knowledge and promoting a more inclusive cultural memory.

3. OBJECTIVES OF THE RESEARCH

The main outcome of the research is the design of a digital archive that will collect the most significant public architectures built in Genoa from the second half of the 20th century to the present, creating an irreplaceable knowledge base for the proper management, preservation, and enhancement of this heritage, rightly considered more fragile than the historical one.

The digital archive, initially developed through collaboration between the University of Genoa (which already hosts its own Archivio di Architettura) and the Municipality, may be enriched with private acquisitions, following the example of other major Italian architectural archives and in agreement with other local institutions (Fondazione Ordine Architetti, Fondazione Palazzo Ducale, Archivio Wolfsonian, Archivio Fondazione Renzo Piano). A specific agreement has been signed between the Department of Architecture and Design (UniGe) and the Directorate of Public Property and Heritage (Municipality), which is responsible for coordinating with other municipal offices to provide access to their respective archives, currently only paper-based and fragmented. The research may also involve the Territorial Information Systems Office (Municipality), whose GeoPortale already includes the results from the University-led census of key architectural works.

This project is intended to foster connections among public institutions, such as the Municipality, the Metropolitan City, the University, and peripheral bodies of the MiC, and to join a national and international network of contemporary architecture archives and research centers. Although the archive prototype is being developed within the scope of doctoral research, its structure has been conceived for future scalability, with the long-term goal of establishing a replicable and adaptable model to support local authorities, cultural organizations, and academic research at multiple levels. This approach seeks to address the knowledge gaps critical for future interventions and to promote greater awareness and sensitivity toward contemporary architecture, a form of heritage whose values are not yet fully consolidated or unanimously recognized.

The research also aims to expand the current specialized and sector-specific knowledge on the subject, while promoting the development of accessible itineraries for a broader, more diverse audience. Its interdisciplinary approach compares the fields of Information and Communication Technologies and Archival Science with those of Cultural Heritage, intending to contribute to the digital transition process already underway in other sectors. The project aligns with the objectives of Mission 1 "Digitalization, Innovation, Competitiveness, Culture, and Tourism" of the National Recovery and Resilience Plan (NRRP), ensuring that its horizontal principles are met, particularly with the themes of Open Data, tourism, and innovative mapping tools for cultural heritage.

4. MATERIALS AND METHODS

4.1 Digital Archives of Architecture: Methods of Creation and Management

After conducting a preliminary reconnaissance of the front ends of major architectural archive web platforms, the first phase of the research involves analyzing their creation and management methods. The objective is to identify and study models of preservation and use of digital documentary heritage, particularly regarding access, dissemination, licensing, and copyright.

The survey began with the drafting of a questionnaire, created using Microsoft Forms, to gather information from institutions on the administrative and organizational structure of their archives. It addressed several key aspects: the origin of the archive; the quantity and types of materials held; agreements with public and private fonds owners and possible loan arrangements; inventory and metadata standards; file formats resulting from digitization; software used for archival inventory and digital libraries; and information and services made freely available for users.

The questionnaire has been distributed in Italian to the members of the National Association of Archives of Contemporary Architecture (AAA/Italia) and in English to institutions affiliated with DOCOMOMO International, to reach the most important modern and contemporary architecture archives worldwide. Although the data collected so far are partial, as additional responses are still being received, they already reveal a widespread lack of homogeneity in the methodologies and standards applied, which in some cases align more with bibliographic or cataloging domains than with archival practice. Nevertheless, promising examples have emerged, especially in the integration of user access strategies, digital storytelling tools, and participatory features.

These initial findings underscore the urgency of adopting shared methodological frameworks and validate the relevance of the Guidelines of the National Plan for the Digitalisation of Cultural Heritage (NPD), issued by the Central Institute for the Digitalisation of Cultural Heritage (MiC) [13]. The NPD offers practical solutions to the observed inconsistencies: it establishes technical parameters for digitization, metadata standards, file formats, and licensing policies, thereby promoting alignment among institutions. Framing and comparing the questionnaire results within this regulatory context, the research outlines a roadmap for the methodological structuring of the new archive.

4.2 Consistency Check and Selection of Documentation of Interest

Following the agreement reached, an archival investigation has been conducted on the documentary material deposited in various offices of the Municipality of Genoa. After consulting these archives and reviewing the available documents, the research was directed toward Genoa's post-war museums (Figure 4): the exhibition designs of Palazzo Bianco (Franco Albini, 1950) and Palazzo Rosso (Franco Albini, 1952-62), the Museo d'arte orientale Edoardo Chiossone (Mario Labò, Cesare Fera, and Luciano Grossi Bianchi, 1949-71), the Museo del Tesoro della Cattedrale di San Lorenzo (Franco Albini, 1952-56), and the Museo di Sant'Agostino (Franco Albini and Franca Helg, 1962–85).

These architectures, recognized nationally and internationally as exemplary works, have recently undergone, or are currently undergoing, the phase of renovation, and it is crucial to understand if and how their preservation and enhancement can be combined with the current adaptation needs. These interventions are driven by increasing visitor numbers, safety and energy-saving regulations, more innovative lighting solutions, and new ways of conserving and communicating the exhibits [14].

The maintenance, conservation, restoration, enhancement, and renovation of these museums raise fundamental questions relating to the concepts of "original" and "authentic".

- How much of the original projects by the masters of museography has been preserved, or can still be traced?
- What is the authorship of these works, and how much is the result of later interventions?
- What were the main reasons for their alterations and modifications?

The research aims to address these questions through the study and critical analysis of archival documentation, comparing it with existing literature and verifying the current state of the works. This in-depth investigation may yield new interpretative keys and insights into the various phases that have shaped their history, informing future design decisions. In this context, the digital archive plays a central role: by organizing and linking materials that are fragmented across multiple institutions and often at risk of deterioration, it enables a more comprehensive reconstruction of each museum's evolution. Unlike conventional archival consultation, it provides structured access, cross-referencing, and thematic exploration, supporting both critical inquiry and practical planning.

The archival investigation involves a critical selection of documents related to these museums, which are now scattered among various municipal offices, and are collected to form the prototype of the new digital archive of contemporary Genoese architecture. Given the interdisciplinary nature of museum design and the recurring issues these buildings face, this selection methodology may serve as a model for documenting other major public works constructed in Genoa since 1945.

As with other notable examples from the Italian museum season, these projects have undergone modi-

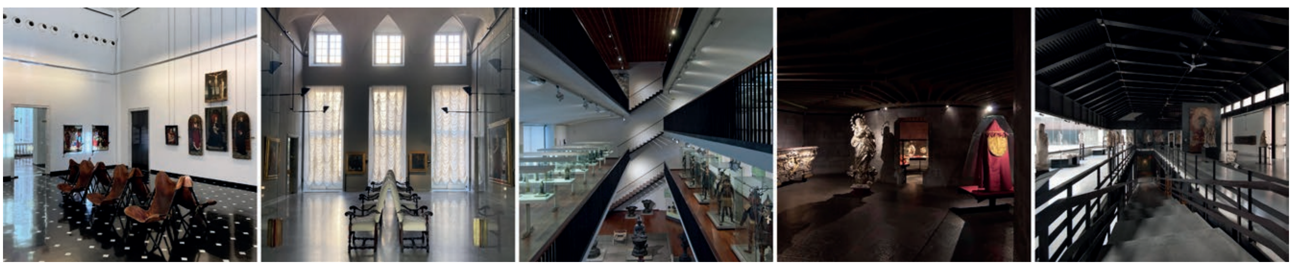

Figure 4. From left to right: exhibition designs of Palazzo Bianco and Palazzo Rosso (photos by Elena Geria), Museo d'Arte Orientale Edoardo Chiossone, Museo del Tesoro della Cattedrale di San Lorenzo, and Museo di Sant'Agostino (photos by Luca Pedrazzi). Major renovations at Palazzo Bianco began in 2004 (Genoa's year as European Capital of Culture), including the expansion of exhibition spaces into the adjacent Palazzo Tursi (City Hall), the replacement of the former Albini-designed connection with a new linking volume, the addition of a rear glass structure housing a new staircase, and upgrades to technical and lighting systems. Palazzo Rosso has undergone several interventions since 1998, including restoration of its historic rooms and updates to exhibition routes, accessibility, and visitor facilities; the most recent works (2020-22) focused on technological upgrades and building systems compliance. The Museo d'Arte Orientale Edoardo Chiossone, closed for nearly two years, reopened in June 2023 after structural and plant system upgrades. The renovation included improved accessibility, the recovery of the panoramic terrace, and a renewed yet historically faithful permanent exhibition. The Museo del Tesoro della Cattedrale di San Lorenzo underwent renovation works between 2009 and 2011, funded by the Ministry of Culture, focusing on the conservation of the displayed works, upgrading of the lighting system, restoration of the glass-concrete skylights, and reorganization of the exhibition layout. Finally, the Museo di Sant'Agostino, closed since 2019 following the collapse of a large window on the main façade, is currently awaiting major renovations. Aside from the partial reopening of the triangular cloister and the church in May 2024, planned works include the restoration of all internal and external glass panes, overall upgrading of building systems, improved accessibility, new visitor facilities, and a renewed exhibition layout.

fications and rethinking during both the design and construction phases, often resulting in outcomes that diverge from original intentions. Additional interventions have followed over time, driven by regulatory requirements, exhibition needs, or changes in taste. Therefore, the selection of documentary material intended to reconstruct and preserve the full history of these architectures will have to bear witness not only to their authors' original ideas, but also to the stages of realization and the various transformations, «silent» [15] and otherwise, that have taken place to date.

The research also implies a comparison with the experiences developed in other «Musei dei Maestri», such as the Museo di Castelvecchio in Verona (Scarpa), the Sale dei Primitivi at the Uffizi (Michelucci, Scarpa, Gardella, Morozzi), and the Musei Civici in Padua (Albini, Helg), to name but a few, which have faced similar problems and proposed different answers and solutions to the challenges related to the preservation of documentation and the renewal of architectural works [16].

4.3 The Process of Inventorying and Digitization following the NPD

To facilitate the inventory and digitization of the material of interest identified during the second phase of the research, a relational database was set up to organize the various documentary items and associate them with the folders, binders, fonds, and archives in which they are held, as well as with the architectural works they document. The database, divided into tables (Table 1), was created using the pgAdmin 4 application of the open-source PostgreSQL 16 software. This structure ensures rapid data retrieval and continuous updating, and it is already configured for future online consultation through the development of a public, read-only APIs that will enable structured web access. Its standardized design also facilitates integration into digital library platforms.

The selection of fields within the tables aligns with the core descriptive elements outlined in the General International Standard Archival Description (ISAD(G)) [17], developed by the International Council on Archives. This framework has been widely adopted to ensure consistency and interoperability in archival descriptions across institutions. ISAD(G) is included in Italian national standards published by the Istituto Centrale per gli Archivi (ICAR) and is also referenced by the NPD [18] for the generation of descriptive metadata in the archival domain.

Beyond the mandatory ISAD(G) elements - Reference Code, Title, Date(s), Level of Description, Extent and Medium, and Name of Creator(s) - the database incorporates additional attributes tailored to architectural documentation, reflecting practices observed in major national and international digital archives of architecture. These include specific details for drawings (such as scale, technique, and support) and photographs (includ-

Table 1. Relational database, list of fields selected for each table (PK: unique primary key; FK: foreign key; MTM: many-to-many relationship).

BUILDINGS	BIBLIOGRAPHY	ARCHIVES	FONDS	BINDERS	FOLDERS	DOCUMENTS	DRAWINGS	PHOTOS
building_code [PK]	biblio_code [PK]	archive_code [PK]	fond_code [PK]	binder_code [PK]	folder_code [PK]	document_code [PK]	drawing_code [PK]	photo_code [PK]
name	author	name	archive_code [FK]	fond_code [FK]	binder_code [FK]	folder_code [FK]	folder_code [FK]	folder_code [FK]
municipality	title	adress	name	existing_code	title	title	title	other_source
address	editor	owner	notes	title	header	protocol	number	date
cadastre_data	magazine/volume	notes		first_date	first_date	date	date	author
latitude	series			last_date	last_date	author/sender	review_date	size
longitude	number			description_level	description_level	receiver	author	tecnique
current_owner	publisher			extent	extent	extent	size	medium
typology	place			description	description	document_type	tecnique	outdoor/indoor
original_use	year			notes	file_name	description	medium	description
current_use	pages			building_code [MTM]	notes	partial_transcript	scale	annex_to [FK]
designer	notes					annexed_doc [FK]	drawing_type	file_name
other_designers	building_code [MTM]					annexed_draw [FK]	description	notes
design_start						annexed_photo [FK]	annex_to [FK]	tags
design_end						annexed_to [FK]	file_name	
construction_start						file_name	notes	
construction_end						notes	tags	
period						tags		
description								
notes								
biblio_code [MTM]								
binder_code [MTM]								

ing interior or exterior views and source information), thereby extending the descriptive capacity to meet the nuanced requirements of architectural records.

Genoa's post-war museums serve as pilot cases for the future expansion of the new digital archive, which will eventually include all the city's major contemporary public works. Using the census of contemporary Ligurian architecture carried out by the Department of Architecture and Design as a starting point, the methodology for selecting buildings will follow the quality criteria defined by the MiC for the Census of Italian Architecture from 1945 to the Present [19]. In preparation for this expansion, the data tables have been linked to QGIS software, into which the shapefile derived from *"Architetture in Liguria dopo il 1945"*, freely downloadable from the Municipality's GeoPortale, has been imported. The shapefile uses georeferenced points to locate the surveyed architectures in the city area, along with their corresponding descriptive data, from which the *building* table is derived.

The research has also included an update of bibliographic sources for each building already featured in the volume, through consultation of online library catalogs. These additions are reflected in the *bibliography* table. Ultimately, this database model was designed to support a comprehensive inventory system, facilitating effective search and analysis of the collected iconographic, bibliographic, and documentary materials, and explicitly linking them to the architectural works they reference.

In agreement with the holding institutions, the documentation selected during the second phase will be digitized according to the NPD Guidelines. As for the image files resulting from the scans of the documentary material, «the output master file consists of a package of files including:

- the uncompressed 16- or 48-bit (grayscale* or RGB) TIFF 6.0 file, depending on the chromaticity of the item
- the uncompressed RAW file, with the XMP collateral file attached» [20].

Also necessary for the digitization process is the description of the digital objects through appropriate metadata, including descriptive metadata, administrative and management metadata (divided into technical and intellectual property components), structural metadata, and preservation metadata. The Guidelines recommend the use of METS (Metadata Encoding and Transmission Standard), a standard widely used internationally and serving as the exchange language between afferent systems and the MiC's Digital Library at the national level [21].

5. DISCUSSION OF FIRST RESULTS

As the result of the survey conducted on the main digital archives of interest, a management model is being developed, to be shared with the Municipality of Genoa, for the creation of a new digital archive aimed at providing access, by the principles of Open Science and FAIR Data, to the documentation related to the most significant examples of contemporary public architecture in the city. This model will define the selection of software for archival inventory and digital library, as well as digital acquisition parameters, file formats, and archiving and metadata standards, all aligned with the NPD Guidelines. Agreements will also be established with holding institutions for the digital loan of fonds, as well as with the heirs of the creators, to enable public access and use of the materials through a university institute.

Conceived as a unified repository, the archive is designed to promote transparency, accessibility, and collaborative knowledge production. Its alignment with Open Science reflects a commitment to democratizing access to archival content, enabling its use by scholars, professionals, institutions, and a broader public. The FAIR framework informs the structured data description, combining general archival standards with architecture-specific metadata to enhance discoverability and machine readability. Adherence to national and international standards also guarantees long-term accessibility and preservation.

In its initial phase, the project will be based on the prototype focused on post-war Genoese museums, with the primary objective of displaying and communicating to different audiences the documentary material selected and digitized during the archival investigation. Although centered on these case studies, the prototype is conceived as a scalable and interactive platform for exploring the broader city's contemporary production. Items will be organized according to the traditional archival hierarchy (holding institution, fond, binder, folder) and classified by type (document, drawing, photograph), as displayed in the relational database structure. Building on this foundation, the archive will incorporate semantic tagging, interpretive filters, and thematic paths to support navigation and improve Findability and Accessibility. These features will enable layered readings of the projects, revealing not only technical and design aspects but also the sociocultural contexts in which they were conceived and transformed. The integration of Linked Open Data protocols and interactive APIs will further promote cross-domain interoperability, support data reuse, and foster wider engagement. (Figure 5).

In line with Open Science objectives, the archive will be designed as an evolving and participatory plat-

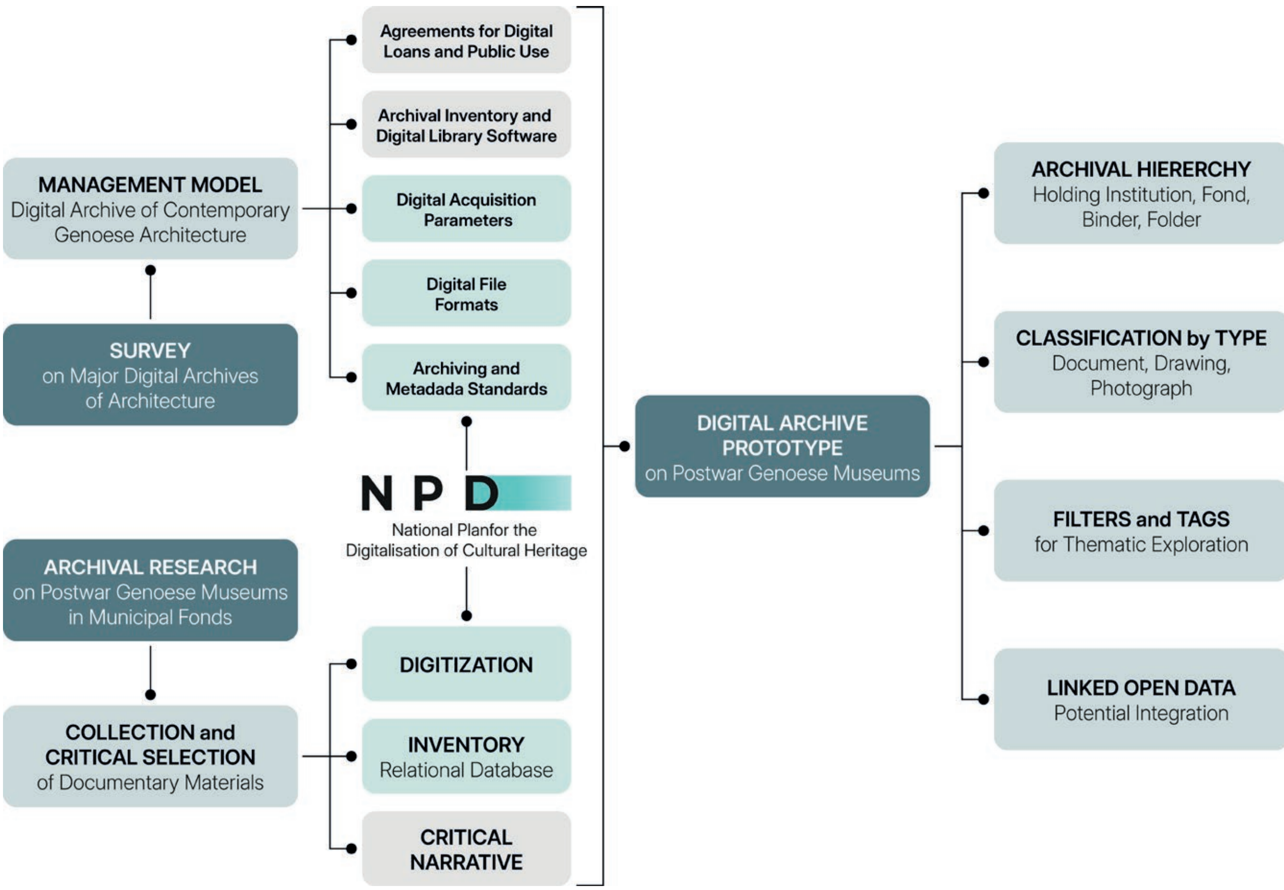

Figure 5. Workflow for the Digital Archive of Contemporary Genoese Architecture, diagram showing the development process of the digital archive from initial surveys and archival research to the creation of a prototype. Original elaboration by the authors.

form, expandable through future acquisitions and collaborations with public and private archives. These partnerships will enrich the collections and encourage dialogue between disciplines and institutions on regional, national, and international levels. Drawing on the experience of the LigurArch900 application, the long-term ambition is to create a unified digital access platform dedicated to contemporary Genoese architecture. In addition to documentary materials, this portal would include descriptive records, thematic essays, multimedia galleries, and interactive tools such as virtual tours, supported by linguistic and semantic analysis technologies enabling personalized queries.

Several technological infrastructures are under consideration for the prototype, with the goal of long-term integration into a more comprehensive digital library. One option is DoGe (Digital object Genova) [22], the University of Genoa's digital library based on the open-source platform DSpace-GLAM, which enables preservation, full-text search, and thematic navigation. Another is the Biblioteca Digitale Ligure (BDL) [23], a regional initiative that aggregates materials from local institutions into structured digital collections supporting diverse media. A third candidate is I.PaC (Infrastructure and Digital Services for Cultural Heritage) [24], developed by the MiC Digital Library, which offers advanced cloud services, predefined data models, AI integration, and APIs for domain-specific and cross-domain interoperability.

6. CONCLUSION

Archives, as collections of direct sources, reports, photographs, sketches, drawings, and models, provide the necessary pieces with which to assemble the map of the architecture closest to us, yet also the most fragile and exposed to upheavals: a heritage too recent to receive the same protection and recognition of value reserved for historic buildings, but old enough to require maintenance or adaptation. In this context, the archive becomes an irreplaceable resource for ensuring the coherence of conservation choices with the essence of the work, on which current designers and restorers can refine their skills, returning to the creative stages from which the author's choices originated.

In addition to the primary function of managing and inventorying the documentary heritage, carried out according to archival practices that have become more rigorous over time due to national and international standards, archives can prove to be strategic tools for the valorization of contemporary architecture. Through a cultural and communicative strategy, they can become a starting point for engaging local communities and reaching broader audiences, extending beyond traditional stakeholders. In this sense, the research highlights the active function of archives as a foundation for constructing a language capable of narrating and enhancing not only the content [25], but also of revealing new meanings and values to be rediscovered.

In the past, as information about architecture was mainly found in books, specialist journals, and exhibition reviews, the protection and preservation of cultural heritage were tasks for experts. Today, these issues need to be shifted to new platforms that take advantage of digital opportunities. These tools go beyond mere preservation, offering access to a broader audience that often lacks the specific knowledge to interpret this heritage and must be made aware of and empowered to understand its value and potential. It's not only a matter of communicating contemporary architecture, but also of drawing attention to the built and lived spaces and to their significant contribution to the debate on quality of life in our cities, despite the technical complexities of the field.

7. ACKNOWLEDGEMENTS

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8. AUTHORS CONTRIBUTIONS

Giovanna Franco: Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Writing - original draft; Writing - review & editing.

Elena Geria: Conceptualization; Data curation; Investigation; Methodology; Visualization; Writing - original draft; Writing - review & editing.

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Analysis of Residential Buildings: Design and Implementation of a Database

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Abstract. Preliminary investigations and analyses for building assets' renovation require considerable time and resources. Being able to assess, in advance and on a large scale, how to address these assets would allow reducing issues to existing buildings as a priority. This research project aims to demonstrate how a data-driven approach can help make informed decisions and better allocate available resources. Starting with a sample of 468 buildings constructed in the city of Bologna between 1945 and 1965, the study led to the creation of a comprehensive database consisting of 468 records and 211 fields, grouped into 16 macro-categories. These fields represent the catalogued characteristics for each building; 95 of them were directly surveyed, and 116 were derived from the processing performed on the first 95 attributes. Each building is associated with various types of information to provide an overall framework (e.g., technical, typological, morphological, etc.). At the end of the database development, queries were performed to assess both the construction characteristics of the building sample and the qualitative performance in terms of structural, energy, and planimetric distribution. The results provide an indication of the building and show how in-depth analyses can serve as the foundation for a decision support system (DSS).

Keywords: Database, Data-driven approach, Residential building, Building performance.

1. INTRODUCTION

At the end of World War II, Italian politics recognized that the construction sector was the key to the country's economic recovery. The famous slogan of the *Democrazia Cristiana* (Christian Democrat Party), "not all proletarians, but all owners" [1], sums up the concept and the urgency to provide every family or citizen with a home. In this particular context, a large number of residential buildings were built, as many as 50 per cent of the total current housing stock dates back to the period 1946-1979, according to ISTAT data [2]. These buildings were often designed and constructed in a short time, with inexpensive materials and basic techniques [3], in order to respond quickly to the needs related to reconstruction and the new demographic trend [4]. However, the poor quality of materials and the absence of strict regulations led, over time, to numerous critical issues in terms of structural safety [5-6], energy efficiency [7-8], and organization-distribution of living spaces [9]. Although the problems that similar buildings have are known, systematizing this knowledge on a large scale without homogeneous methods of investigation or evaluation is complex, as already pointed out by other works done in the field [10-11]. For this reason, creating an ordered repository is essential for decision-makers, as it can be further developed into a decision support system (DSS) that can facilitate informed policy-making. Analytical approaches based on extensive information collection have recently been explored with various objectives and in different fields. Interesting work in this area is developed by G. Uva et al. [12], who use the CARTIS [13] scheme to collect information for assessing the performance of existing buildings. More traditional data collection systems have lately been joined by procedures based on the generation of point clouds obtained with LiDAR [14] or laser scanner [15] technologies. However, the proposed solutions often concentrate on the development of a ready-to-use system for solving a specific problem; rarely is the focus shifted to the potential offered by a structured database and the importance of an organic process.

Based on this, a prototype of a queryable archive consisting of a finite set of buildings was developed with the possibility of being implemented in a decision-making platform. By consulting the archives of the Emilia Romagna Region (RER), access was gained to the original documentation (plans, sections, elevations, reports, etc.) for 468 residential buildings constructed in the city of Bologna in the two decades following World War II (1945-1965). The sample of buildings, financed either fully or partially through public funds, was analyzed from various perspectives. Based on the documentation obtained, a database was created, and each building is linked to specific information representing its key characteristics.

The designed database consists of 468 individual records (one for each building) and 211 unique fields (one for each catalogued attribute). The fields are organized into 16 macro-categories, which begin with the most general information and proceed progressively toward a qualitative assessment of the building condition in terms of structural integrity, energy efficiency, and spatial and organizational layout. Data integration was also carried out in parallel within a geographic information system (GIS), linking the data to the spatial locations of the respective buildings within the city of Bologna. The data entry process into the database was initially carried out manually, covering the first 95 fields. In the second phase, the information was processed and automated, with the aid of geographic and geometric parameters obtained through the GIS system, leading to the definition of the remaining 116 fields. Figure 1 shows the location of buildings in the city of Bologna.

Once the database was fully defined, queries were performed to assess both the general and specific characteristics of the analyzed sample. The results offer insights into the key characteristics of the housing stock under investigation and identify the main critical issues that emerged. Additionally, they show the potential of a data-driven approach and its compatibility with a DSS.

2. CRITERIA AND DATABASE ORGANIZATION

2.1 Sources and data collection

The aim of the database is to provide comprehensive insights into the building sample through targeted queries, addressing both general aspects (such as year of construction, contractor, etc.) and qualitative assessments of building performance (e.g., structural integrity, energy efficiency, criticality, etc.). As a result, the information associated with each record is extensive (211 fields) and covers diverse aspects, acquired either as numerical values or textual descriptions.

The need to gather a significant amount of data, given that physical surveys of the buildings were not feasible, directed the research toward the documents kept in the RER archive. This archive contains numerous files of buildings constructed in the immediate postwar period with public funding. In addition to floor plans, these files are equipped with comprehensive construction documentation, which would otherwise be unavailable (such as metric calculations, special contract specifications, etc.). These drawings, produced by the original designers, provide detailed technical specifications of the buildings, ranging from layout choices to structural details like beam reinforcement.

Information not directly obtainable through archival surveys was supplemented with assumptions based on field regulations at the time, particularly in the areas of sanitation [16], structural design [17-19], and social housing [20], as well as from the most widely used design handbooks [21-22]. This parallel research not only provided additional parameters functional for data collection but also led to the creation of specific categories within the database (such as those related to structural safety). The data collection approach enabled: (1) the extraction of information directly from primary sources, without subsequent processing, (2) an expansion of the knowledge base using alternative sources beyond the archives, (3) the development of a coherent overview of the most recurrent modes of construction in the period studied, and (4) the acquisition of a vast

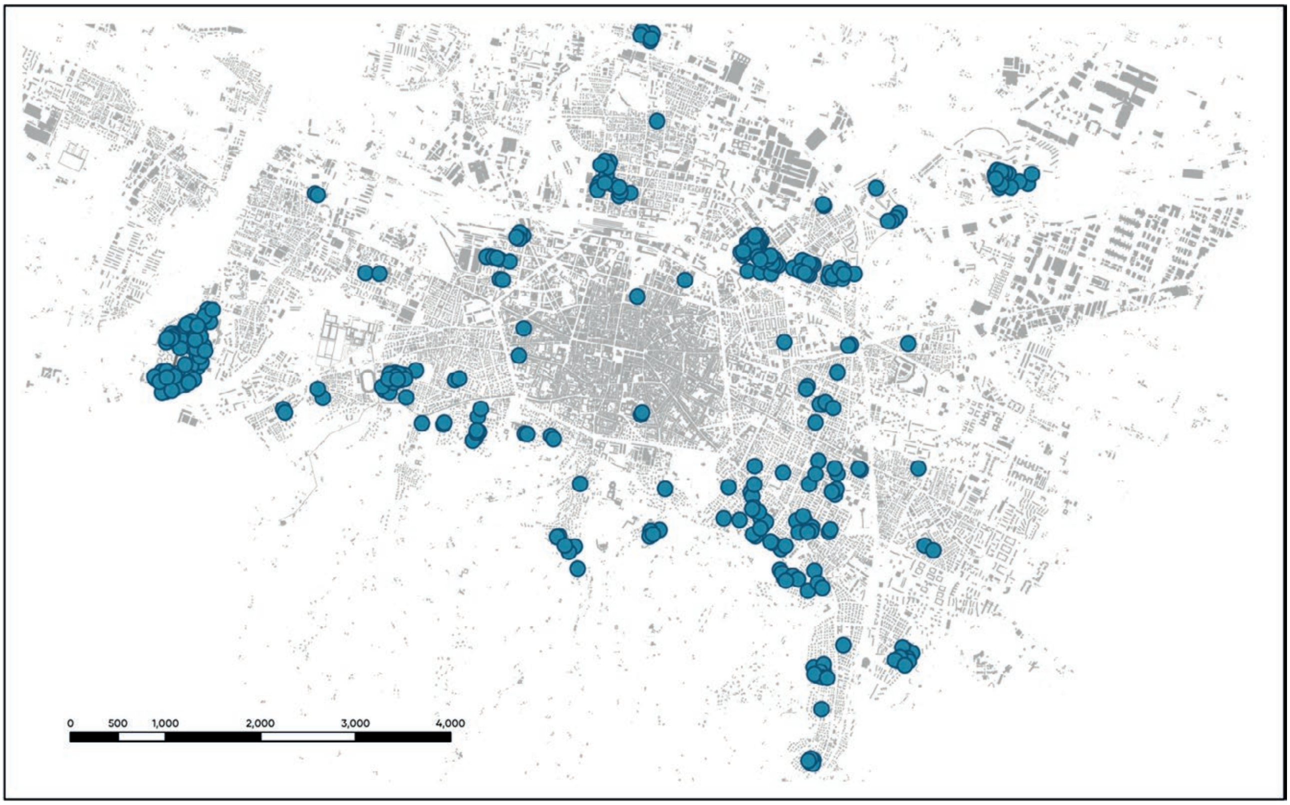

Figure 1. Location of the buildings investigated in the city of Bologna. Source: author elaboration.

amount of information in a short time frame and in a cost-effective manner. On the other hand, the approach considered does not allow for the achievement of the accuracy of data that would be obtained with field surveys. However, this issue is to be considered tolerable given that the analysis performed is intended as a "preliminary" phase, useful to understand the most significant aspects of the heritage under investigation and to direct (limited) economic resources to the most critical areas of the built environment. Detailed analyses can then be focused on specific buildings, making the whole process more economical and flexible. The variety of sources used required the standardization of the collected data to ensure comparability and ease of reference [23]. To ensure clarity and consistency, some input parameters were labelled with appropriate abbreviations (e.g., "structures made of unreinforced brick masonry with a thickness of 28 cm" are abbreviated as "MP-28"). Variable units (kN, daN, or kg) were converted to standard units. A data dictionary was developed and updated as the database was compiled, including metadata related to the cataloguing process. The use of consistent terminology and comparable units not only facilitated the query process, but also allowed the addition of a further 116 fields to the original data using the methods summarized below.

The database was defined by some basic criteria (No. 4) to make it consistent with the type of work to be performed. (1) Autonomous records: each record, i.e., table row, was left autonomous and not dependent on other records in the table. Each record corresponds to a building. (2) Unique records: each record is unique; repetitions within the database are excluded. (3) Unique fields: each field, i.e., table column, represents an attribute assigned to the investigated building. Fields can be stand-alone (e.g., building address) or non-stand-alone (in the case of building characteristics and vulnerability assessment). In both cases, the information appears in the database only once, which makes the file smaller and avoids complications in the query phase. (4) Both records and fields have unique names and contain a single type of data. For example, a column whose data is expected in numeric form does not contain textual information, and vice versa. The database configuration that ensures compliance with these criteria (No. 4) was performed in advance to avoid such issues during the population phase. Any errors in data input were verified at the end by manually filtering the entered information.

These operations could be further automated in future developments of the method.

2.2 Database structure

The database was implemented using Microsoft Excel software. To rationally sort the fields used, 16 macro-categories were introduced, collecting them by themes: (1) documents and archiving, (2) general data, (3) typological characteristics, (4) housing unit characteristics, (5) construction characteristics, (6) finishes and facilities, (7) imported data - GIS, (8) processing - morphological data (9) processing - economic estimation data, (10) processing - construction characteristics, (11) processing - energy data, (12) processing - space organization and functionality, (13) issues - energy data, (14) issues - structural data, (15) issues - space organization and functionality, (16) building performance assessment - current situation.

The first six macro-categories (1-6) contain the information obtained directly from the analysis of archival material and sources; there is a total of 95 fields that describe the building in its basic parts. Among the data entered are: the address of the building, key cadastral references, names of stakeholders in the building process, number of floors, number of dwellings, type of dwellings, structure characteristics, and characteristics of the building envelope. For further consideration with respect to the first six macro-categories, please refer to the specific bibliography [24] where the topic is discussed in detail. The fields in the remaining macro-categories (7-16) are 116 in total and are derived from processing performed on the first 95 inputs or information retrieved from existing databases.

The “Imported Data - GIS” group includes 8 fields, with data derived from existing datasets [25], primarily processed by the Municipality of Bologna. These fields are linked to the database through the “GIS Building ID” attribute. The collected information includes, for example, the building’s neighborhood, the total floor area of the building (m²), its perimeter (m), the average value attributed to affordable housing in normal condition (€/m²), and the average value of civilian housing in excellent condition (€/m²), among others. Real estate valuation data is sourced from the *Osservatorio del Mercato Immobiliare* (real estate market observatory, hereafter referred to as OMI) databases, reflecting the average market values for a given area as of the first half of 2024. Figure 2 shows a portion of the buildings investigated in the San Donato area, colored according to size (building area).

The “Processing - Morphological Data” macro-category contains 17 attributes. These fields, defined as floats, provide quantitative information, primarily focusing on the size of the building and its main components. For instance, knowing the building height, the number

Figure 2. Investigated buildings in the San Donato area, classified by size (area). Source: author elaboration.

of residential floors, and the base area allows for calculating its heated volume (m³). Similarly, this approach enables the processing of other data, including: heated side area (m²), total side area (m²), total number of windows, window area (m²), roof area (m²), and balcony area (m²), among others.

The "Processing - Economic Estimation Data" category, the smallest among all defined categories, contains only three fields. These attributes are related to the average building values and morphological characteristics and include the assumed values for cellars (€), parking spaces (€), and balconies (€).

The "Processing - Construction Characteristics" macro-category includes 29 attributes of various types (string, float, or integer). It contains information on the stratigraphy of floors across different levels, categorized as: basement floor slab, ground floor slab, interfloor slab, and roof slab. The main constituent materials, thicknesses (cm), and additional data such as load-bearing capacity (if available), service limit state loads, and ultimate limit state loads are provided for each floor type. This category also defines the stratigraphy for each element that encloses the heated volume: vertical closure, base closure, and top closure.

The "Processing - Energy Data" category consists of 21 attributes, all aimed at quantifying the building energy performance. This analysis required the creation of an additional database, running parallel to the primary one, in which the thermo-hygrometric characteristics of the components enclosing the heated volume were defined. For each component, using Termus-G software [26], the following were calculated: the U-transmittance, surface mass, phase shift, periodic thermal transmittance and the ratio of the calculated transmittance to that imposed by regulations. Figure 3 shows the logical data model of a part of the data structure.

The stratigraphy calculation data were further processed using climate data on heating and cooling degree days for the city of Bologna, retrieved from the CBE Clima Tool web application [27]. This allowed for the calculation of parameters such as: global heat loss through transmission in winter (kWh/year), global heat loss through transmission in summer (kWh/year), global heat loss through ventilation in winter (kWh/year), global heat loss through ventilation in summer (kWh/year), ideal energy demand in winter (kWh/year), and ideal energy demand in summer (kWh/year).

The "Processing - Space Organization and Functionality" macro-category contains 7 fields. The collected information includes indicators designed to provide a summary assessment of the quality of life for inhabitants. Key parameters include: the average number of inhabitants per housing unit, the number of inhabitants per toilet, the usable square meters per inhabitant, parking spaces per inhabitant, and the crowding index, which is calculated as the ratio of the main rooms in a unit to the number of inhabitants. In the study, the term "main rooms" refers to bedrooms, living rooms, dining rooms, and kitchens that are not incorporated into another room (kitchenette). Therefore, a two-room apartment in which a single inhabitant lives will have an index of 2, while the same apartment, this time inhabited by two people, will have an index of 1.

The categories (13-15), which relate to energy data, structural data, and space organization and functionality, follow the same approach and collect a total of 24 fields. Each of these three groups aims to assess building performance within its specific domain, providing an initial synthesis of the collected and processed attributes. Specific fields (5, 13, and 6, respectively) were included to evaluate this performance, each based on boolean logic (true or false). Each of the 24 values is derived from a logical expression designed to verify the presence or absence of a particular condition defined in advance. For example, the first potential criticality in the "Issues - Energy Data" category concerns the transmittance value of vertical closures. Like all fields in the three categories, this field accepts only true/false values; in this case,

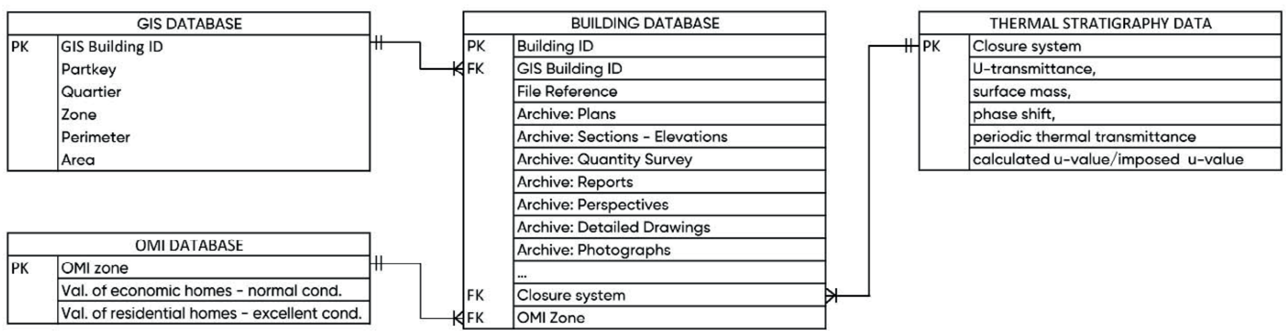

Figure 3. Logical data model of a part of the data structure. Source: author elaboration.

if the transmittance value exceeds the threshold set by current regulations, it returns true; otherwise, it returns false. The issues identified for the three groups include:

– high U (W/m^{2}K) transmittance-vertical closure; high U (W/m^{2}K) transmittance-base closure; high U (W/m^{2}K) transmittance-top closure; high U (W/m^2) transmittance-windowed surfaces; heating system inefficiency;
– elements-undersized to elevation loads-foundations; high degradation of materials-foundations; vertical-bearing structures-undersized to vertical loads; vertical-bearing structures-undersized to horizontal loads; vertical-bearing structures-high degradation of materials; horizontal-bearing structures-undersized to vertical loads; horizontal-bearing structures-deformable floors in their own plane; horizontal load-bearing structures-high degradation of materials; connections-absence connection of load-bearing element; connections-absence connection of load-bearing element-loft; structural configuration-significant torsional effects in case of earthquake; structural configuration-possible deformations concentrated on less rigid planes; nonstructural elements-high possibility of collapse of secondary-nonstructural elements to horizontal loads;
– inadequate private interior spaces; inadequate private exterior spaces; rigid interior organization; car parking inadequate to the number of inhabitants; need for elevator system; obsolete technological-plant systems;

The last macro-category, "building performance assessment - current situation", consisting of seven fields, aims to summarize the state of the building in relation to all the data collected. Specifically, it reports: the number of energy performance issues, the number of structural issues, the number of space organization and functionality issues, the total number of issues; the ideal energy demand (kWh/year) and the building's assumed value. Figure 4 shows the logical path from step 0 (source consultations) to the qualitative assessment of the building. Also shown diagrammatically are the parent-child relationships between the macro-categories.

At this point in the research, the collected data does not account for any variances during construction or punctual extraordinary maintenance work that may have been carried out over the years. It is believed that basing the data on a standardized source (in this case, the drawings required by the standard at the time) allowed for a consistent comparison across buildings, using a standard starting point. In addition, the underlying idea is that the original configuration of the building remained (in most cases) unchanged and that often the interventions were carried out for minor functional adaptations rather than total reorganization (structural, energy and distribution) of the buildings. Considering all the variants would require a volume of data that would make the system too complex to manage. Future applications could integrate interventions that made a substantial improvement in the performance of the entire building by preparing specific fields.

3. QUERIES AND RESULTS

The sample of buildings dates from the two decades 1945-1965. As shown in Figure 5, the 468 buildings are distributed throughout the period rather unevenly.

The largest number of buildings dates from 1951, 1955 and 1958, including 82 in 1958. The lowest values are evident in 1960 and 1962, with only two buildings constructed. The trend line, superimposed on the main curve, indicates intense activity in the early period, followed by a decline in construction, which became marked in the late 1950s.

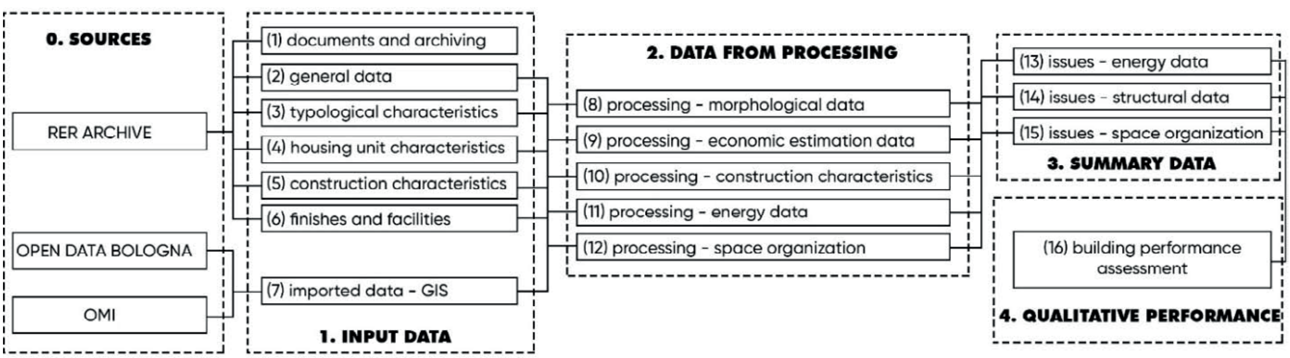

Figure 4. From data to qualitative performance of buildings. Outline of interactions at the level of macro-categories. Source: author elaboration.

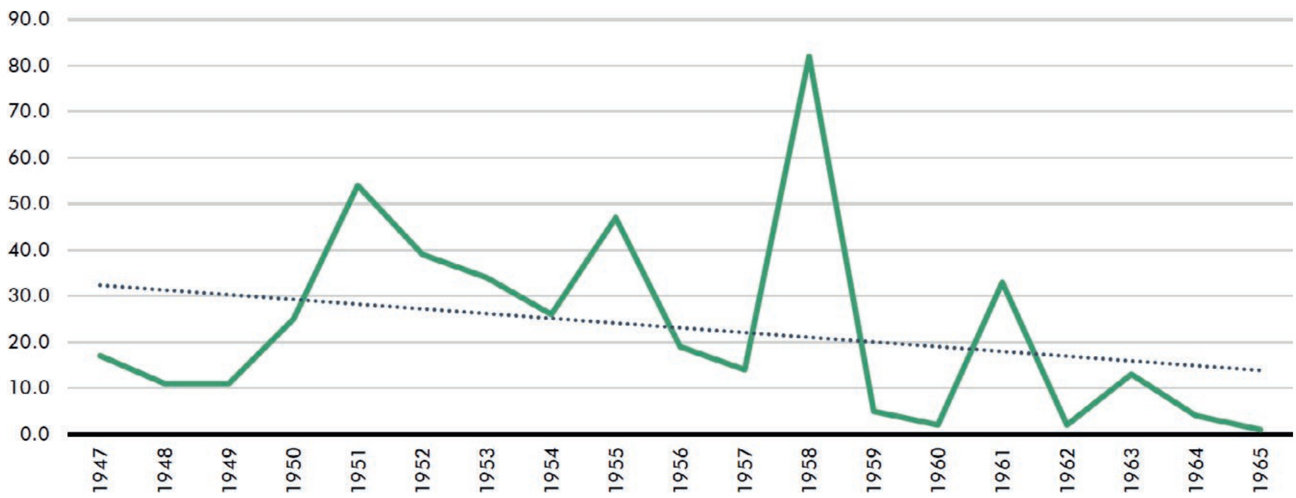

Figure 5. Logical data model of a part of the data structure. Source: author elaboration.

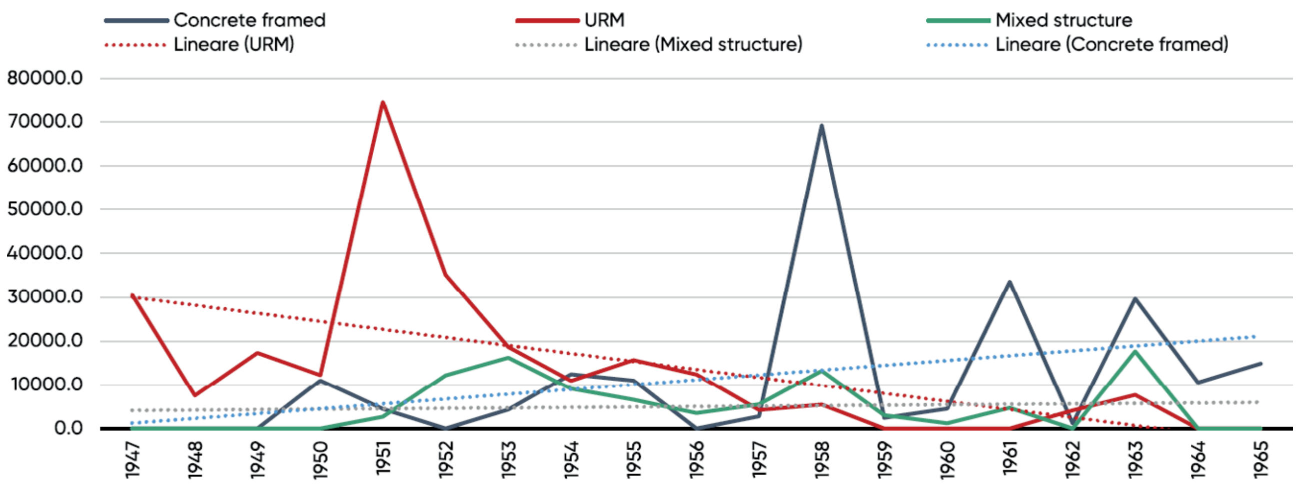

Figure 6. Square meters of gross usable area, realized per year, compared to the structural system employed. Source: author elaboration.

The stock of buildings analyzed showed three types of structures: concrete-framed buildings, unreinforced masonry (URM), and mixed structures (typically masonry perimeter structures and concrete center columns). URM buildings appear to be the majority (244), followed by concrete-framed buildings (147) and mixed-structure buildings (75). The graph in Figure 6 shows the square meters of usable floor area, realized by year, with respect to the system used. As before, the trend appears rather discontinuous and concentrated in two years: 1951 and 1958. The trend shows a massive use of masonry in the period following World War II, which quickly degraded and gave way to concrete-framed buildings beginning in the late 1950s. Mixed-structure buildings maintain a constant trend throughout the two decades.

Observing the total number of floors that characterizes the sample of buildings (including basement and attic) is also interesting. Most of the buildings are made of five (113), six (92) or seven floors (107), also considering basements and roofs; very few buildings exceed eight levels. The late introduction of concrete for the execution of vertical structures has probably determined the maximum number of floors that could be built in residential buildings, given the mechanical limitations that imposed the use of two- or three-headed Bolognese masonry, which, compared with other parts of the world during the same period, is medium-density housing. The buildings analyzed are more developed planimetrically and maintain a low height, in line with the traditional building type prevalent in the area. Figure 7 shows this by comparing the

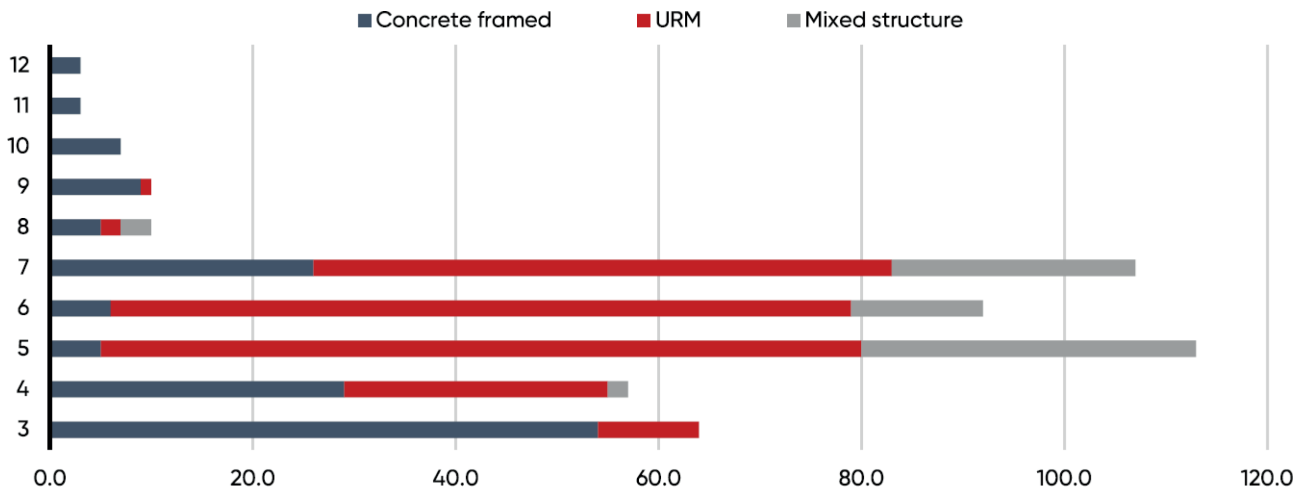

Figure 7. Number of total floors compared to buildings made per structural system employed. Source: author elaboration.

number of floors, y-axis, with the buildings constructed, x-axis, according to the structural system used.

From a performance perspective, the building sample shows significant heterogeneity in terms of the defined issues. Structurally, the buildings present between 1 and 6 issues, with 13 being the maximum number of issues attributable to a single structure. The two extreme values (1 and 6) relate to less than 7% of the buildings, while 35.41% and 33.69% of the buildings present 4 and 5 issues, respectively. The most common issues are related to the high deformability of the floors (both in-plane and out-of-plane), irregular structural configurations (both in plan and in height), and vertical structures that are not always adequate to withstand the seismic demand expected for the site. The latter assessment is derived from a generalization of the conditions that determine seismic demand: these are buildings for residential use (defined exposure), all built in an area with similar characteristics, assumed topographic category T1, subsurface C and an acceleration of 0.167g (defined hazard). No problems were found in terms of foundations, where qualitative assessments were performed based on geognostic tests made available by the Emilia Romagna region [28], likely due to the presence of basements (low foundation level) and non-excessive loads (limited number of floors). The structural materials are generally assumed to be in good condition, although, as is well-known, the reduced concrete cover on structural elements favors the corrosion of reinforcement bars and the progressive loss of load-bearing capacity of the elements [29].

The situation is much worse from an energy performance standpoint; the buildings show 5 issues out of the 5 (maximum possible). All the building closures are inadequate: vertical closures, horizontal closures (base and top), and window surfaces. The transmittance values (W/m^2K) are much higher than the standards required for such components. For example, the average transmittance of the vertical components in the sample is 1.56 W/m^2K, a value in line with what has been observed in other projects [30], while in the city of Bologna, located in climate zone E, the maximum allowable value after renovation must be 0.28 W/m^2K. Similar considerations apply to the other closure systems and windows.

The spatial and distributional organization presents a range of issues measured between 2 and 6, with 6 representing the maximum parameter. In percentage terms, buildings with 4 issues are the majority, accounting for 41.6% of the total, followed by those with 5, at 35.6%. These criticalities concern the lack of parking spaces, the absence of an elevator shaft (even in taller buildings), the lack of private outdoor spaces, and the inadequacy of internal spaces. The issues described in this macro-category are very common in the building sample, but they are the most challenging to resolve and would require a broader debate involving large-scale policy interventions. For instance, it might be more practical to build multi-level underground parking facilities serving an entire neighborhood rather than expensive and highly complex new underground garages for each individual building. Figure 8 shows briefly the number of structural issues, the number of energy performance issues, and the number of space organization and functionality issues detected in the group of buildings analyzed.

Overall, the sample exhibits a significant number of issues. Out of a total of 24 possible issues, the buildings present between 11 and 17, distributed in a Gaussian manner: the extremes concern less than 5% of the buildings, with percentages increasing as they approach the average value of 14, which applies to 45.3% of the

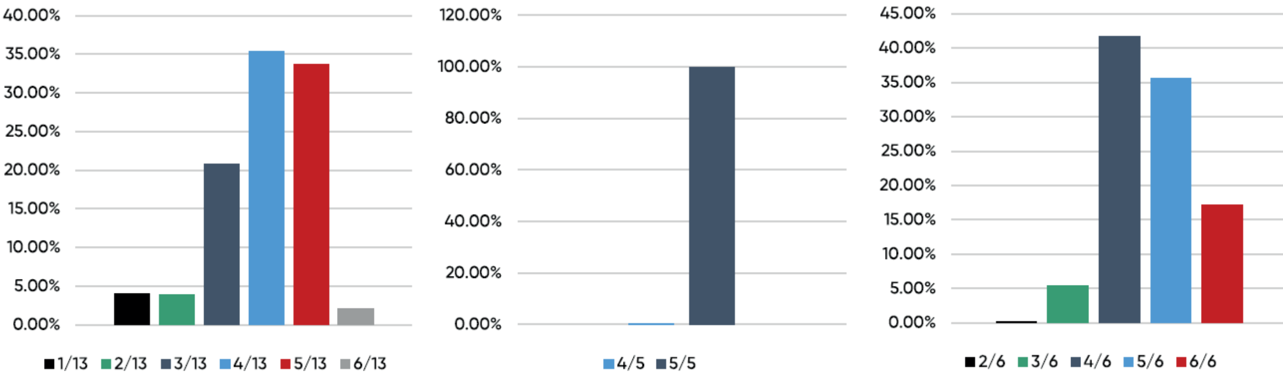

Figure 8. Critical issues detected per building. a) structural b) energy c) space organization and functionality. Source: author elaboration.

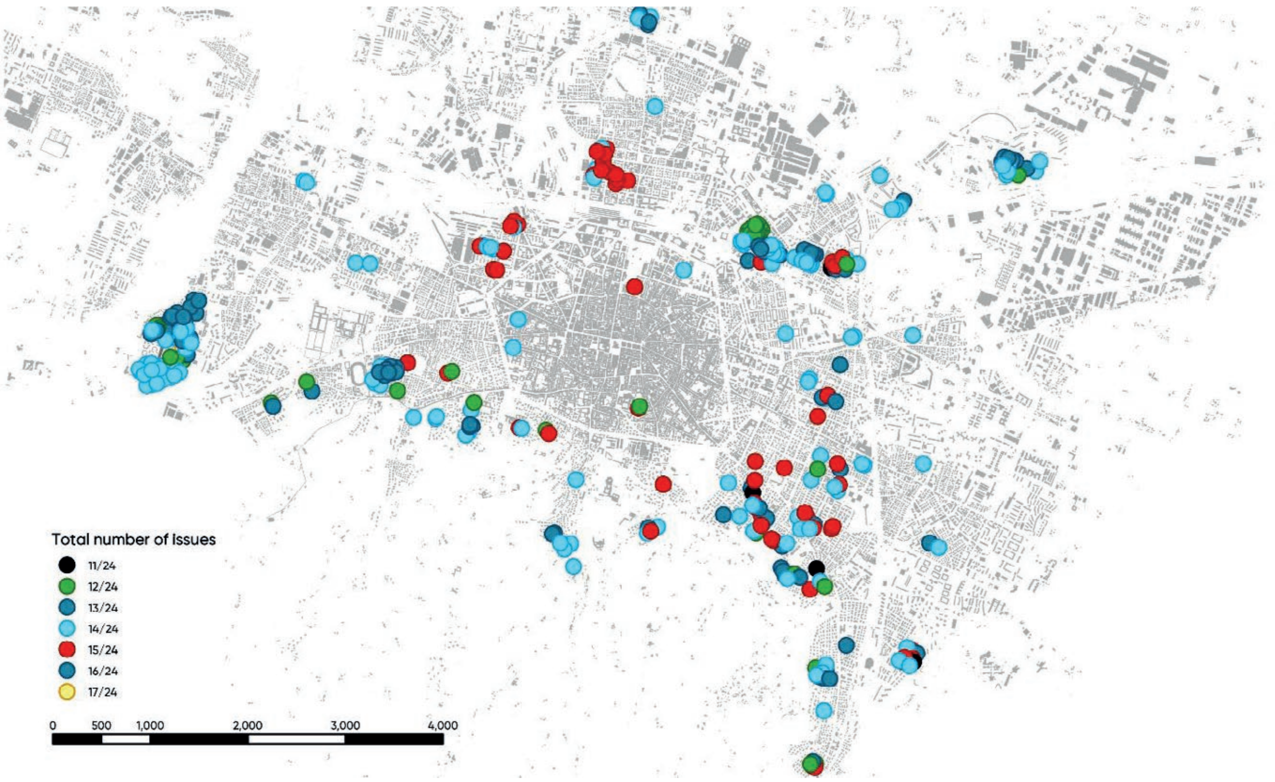

Figure 9. Total number of criticalities attributed to each of the analyzed buildings. Cartographic indication on the Bologna area. Source: author elaboration.

sample. Figure 9 shows the map of Bologna in which the buildings investigated are indicated with reference to the total number of issues attributed to each of them.

4. CONCLUSIONS

The study focused on the development of a database designed to systematize and harmonize the information collected on a stock of 468 existing buildings constructed in the municipality of Bologna between 1945 and 1965. The work aimed to demonstrate how a functional data structure can lead to informed and targeted decisions for the reference sample. Specifically, the database consists of 468 autonomous records, characterized by 211 unique fields. These fields are grouped into 16 macro-categories to facilitate queries and enhance the readability of the recorded information. Data processing derived from the archival documentation led to the definition of new parameters, both quantitative (e.g., number of parking spaces per inhabitant, number of beds, transmittance of closure systems) and qualitative (e.g., need for elevators, inefficient structural configurations). Thanks to this data, it was possible to hypothesize the performance of the investigated buildings in terms of structure, energy efficiency, spatial/distributional organization, and overall assessment.

The sample revealed multiple criticalities across all three main investigated areas. Structurally, the buildings exhibited an average of 4 issues out of 13 total, with slabs identified as the weakest element. In terms of energy performance, the buildings averaged 5 issues out of 5, highlighting significant problems in reducing heat loss. Regarding spatial organization and functionality, the stock averaged 4-5 issues out of 6, showing shortcomings that negatively affect residents' quality of life.

Queries provide an overview of building conditions that can be described both numerically and graphically, making data interpretation more intuitive. The outcome enables the design of intervention strategies targeted at individual buildings or the entire sample. Based on the large-scale results, resources can be allocated to perform a comprehensive analysis (field surveys, surveys, etc.) on the elements that have shown the most critical issues. For enhanced results, the system could be further developed by integrating artificial intelligence and a DSS, enabling predictive analyses and automating aspects of the decision-making process. The ability to modify or expand the input data provides opportunities to explore this approach further and adapt it to future specific research needs. For example, the following steps can include the most relevant building interventions (ignoring extraordinary maintenance confined to individual building units) that have been implemented over the years.

In conclusion, while recognizing the challenges (and costs) of implementing such a system on a large scale, the developed database offers a model for managing existing building stocks. It is compatible with specific DSS platforms that could promote more efficient resource allocation through a data-driven approach.

5. AUTHORS CONTRIBUTIONS

Conceptualization LS and GP , Data curation LS , Formal analysis LS, Investigation LS, Methodology LS and GP, Software LS, Validation LS and GP, Visualization LS , Writing original draft LS and GP, Writing – review & editing LS.

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