EDILIZIA

ILARIA GIANNETTI, ANGELO BERTOLAZZI,
ANDREA MIANO, MANUELA BONANO,
LUISA BERTO (edited by)

SAFEGUARD OF MODERN URBAN HERITAGE

A Cross-Disciplinary Research for Knowledge, Monitoring, and Risk Analysis

FRANCOANGELI

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This volume is the result of research conducted as part of the project PRIN 2022 "SMUH - Safeguard of Modern Urban Heritage: a cross-disciplinary webGIS for knowledge, monitoring, and risk analysis" [PRIN2022 – C.P. 2022M7W3BM]. The project, coordinated by the University of Rome Tor Vergata (PI Ilaria Giannetti), involves the following research units: University of Padua (RU Angelo Bertolazzi), University of Naples Federico II (RU Carlo Del Gaudio/Giacomo Iovane), IUAV University of Venice (RU Luisa Berto), CNR-IREA (RU Manuela Bonano). The volume collects the contributions presented by the various authors at the conference "SMUH - Safeguard of Modern Urban Heritage: a cross-disciplinary webGIS for knowledge, monitoring, and risk analysis", held at the DICII Department of the University of Rome "Tor Vergata" on 16/12/2025.

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2. RESEARCH PERSPECTIVE AND MORE CASE STUDIES

Introduction

Ilaria Giannetti[1], *Angelo Bertolazzi*[2], *Andrea Miano*[3], *Manuela Bonano*[4], *Luisa Berto*[5]

This volume collects the outcomes of the multidisciplinary research project, funded under the PRIN 2022 call, "SMUH – Safeguard of Modern Urban Heritage: a cross-disciplinary webGIS for knowledge, monitoring and risk analysis", presented at the conference held in Rome on December 16th, 2025, at the University of Rome Tor Vergata. The project is multidisciplinary in nature and brings together five research units coordinated by the University of Rome Tor Vergata. The disciplinary research sectors involved are Architectural Engineering along with Structural Engineering, represented by the research units of the University of Naples Federico II and IUAV University of Venice, and Satellite Monitoring, represented by the CNR IREA research unit.

The project stems from multidisciplinary research regarding the application of satellite measurements for the structural and building monitoring of built heritage, with specific reference to buildings constructed with "modern" materials from the end of the Nineteen century throughout the Twentieth century. Densely populated Twentieth-century cities are characterized by buildings and infrastructures that require, on one hand, continuous maintenance to extend their useful life in accordance with current building standards and, on the other, a cultural operation aimed at their precise recognition as part of the architectural and technological heritage of "modernity". In this sense, the development of methods and tools dedicated to integrating structured, easily accessible knowledge frameworks with advanced monitoring methods and predictive simulation models represents an urgent task to support joint actions for safeguarding the built environment.

1 University of Rome Tor Vergata, Department of Civil Engineering and Computer Science Engineering.

2 University of Padua, Department of Civil, Architectural and Environmental Engineering.

3 Pegaso Telematic University, Department Engineering, Naples, Italy.

4 Institute for Electromagnetic Sensing of the Environment (IREA)-National Research Council (CNR), Naples, Italy.

5 University IUAV of Venice, Department of Culture of the Project.

In this context, the project aimed to develop, test, and make accessible a multidisciplinary method for safeguarding the built heritage in the urban areas of the "Twentieth-century city", based on the combination of knowledge frameworks derived from extensive documentary research, structural vulnerability analysis, and interferometric techniques – specifically Differential Interferometric Synthetic Aperture Radar (DInSAR) – for measuring surface deformation phenomena. Specifically, the investigation methodology is divided into three actions: first, the acquisition, analysis, and spatial representation of data derived from extensive documentary research to build exhaustive knowledge frameworks of existing buildings and infrastructures; second, the acquisition, analysis, and spatial representation of measurements obtained from satellite data using DInSAR techniques to identify ongoing surface displacement phenomena; and third, the assessment of structural vulnerability classes based on the knowledge frameworks and the refinement of these analyses based on the satellite measurement results conducted in the second phase.

The method was tested on two exemplary case studies, namely two Twentieth-century districts in the cities of Verona and Rome which, located near the Adige and Tiber rivers respectively, present a diverse catalog of building types and construction techniques, as well as specific environmental conditions. In particular, the Verona case was used to apply the method at the urban scale, while the Rome case supported the development of analyses at the building scale. For the development of the investigations and the dissemination of results, the research relied on the construction of a webGIS platform, extended to three-dimensional representations and governed by conceptual representations of information data. Upon completion of the research activities, the platform became the primary tool for disseminating results through interactive thematic maps useful for decision-making processes in preventive conservation planning.

In this regard, besides being a user-friendly tool for enhancing remote sensing techniques for structural and building monitoring, the platform integrates paths for the historical-cultural valorization of the built environment. This is based on the conviction that promoting knowledge of Twentieth-century heritage is the primary action in the safeguard process. The platform provides a spatial representation of heterogeneous data – ranging from historical documents from local archives to time-series data from satellite remote sensing and risk maps – necessary for understanding buildings and infrastructures, while also supporting the implementation and extension of a specific investigation methodology aimed at assessing structural vulnerability and defining predictive scenarios.

The volume is structured into two parts: the first is entirely dedicated to the investigations conducted at the urban scale on the *Borgo Trento* district in Verona, while the second part includes further testing of the proposed method on the Rome case study at the building scale, along with a series of possible extensions regarding the tools and applications of the working method. Specifically, in the first part, the methodology is presented in its three aforementioned phases, followed by the design of the webGIS platform and its first demonstration test in *Borgo Trento*. This neighborhood, characterized by a Twentieth-century urban fabric heterogeneous in techniques, building types, and infrastructures, is considered particularly suitable for verifying the functionality of the webGIS platform. Furthermore, a first possible extension of the platform was tested on the Verona case study, based on the construction of a 3D urban-scale information model using the Industry Foundation Classes (IFC) interoperability standard, accessible via open-source programmable viewers.

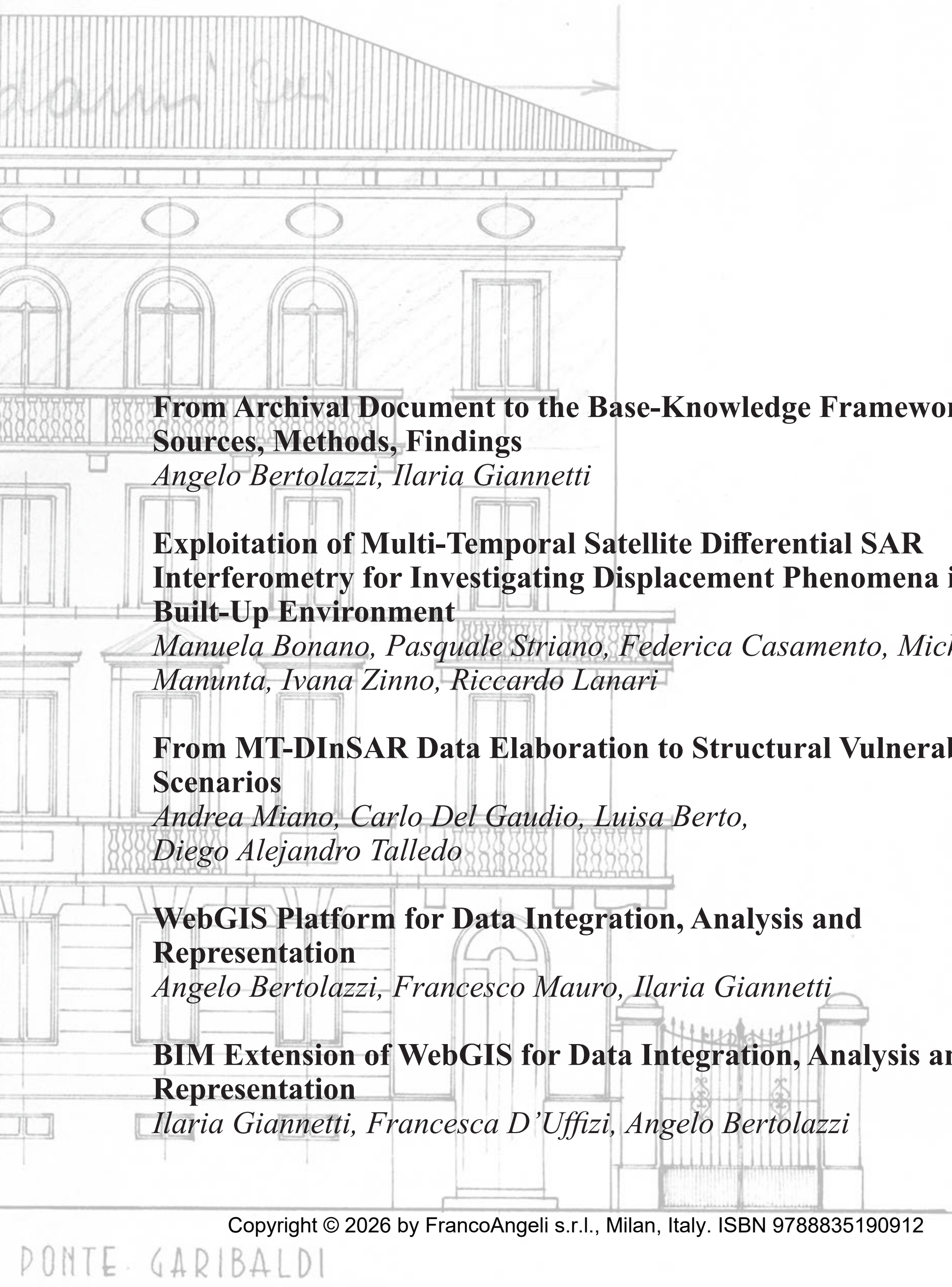
The second part of the volume collects the outcomes of the method's application at the building scale, focusing on the *Regina Margherita* School in Rome. This contribution highlights the significant advantages of BIM and GIS integration in supporting satellite measurement analysis for structural monitoring in the case of an exemplary building for the variety of techniques and construction solutions present in its historical evolution, from its construction in the 1880s to its expansion in the 1950s. Also at the building scale, this section presents a contribution dedicated to the application of predictive structural assessment models in cases of imposed settlements and seismic action, applied to an "archetype" building with a reinforced concrete frame. Another contribution focuses on the collection and organization of knowledge data regarding Twentieth-century bridges, referring to *Ponte della vittoria* (1949-51) in Verona area through the construction of dedicated BIM models.

Finally, one contribution focuses on an urban block from the Rome area to explore the automatic construction of 3D urban information models compliant with the CityGML standard for potential integration in satellite monitoring of buildings and infrastructures. The volume concludes with a reflection on the use of data collected and organized through digital platforms for the contemporary transformation of the Twentieth-century city.

In conclusion, within the heterogeneity of the results achieved, this book aims to pose a fundamental research question regarding the integration between the knowledge of the built environment – extended to its historical and technological stratification – and current monitoring and predictive simulation techniques: to what extent can the digital structuring of historical and technical memory be transformed from a mere collection of information into an epistemological device capable of substantiating the construction of reliable predictive models?

PROSPETTO SUL NUOVO LUNGADIGE PRESSO

1. THE CASE STUDY OF *BORGO TRENTO* IN VERONA



From Archival Document to the Base-Knowledge Framework: Sources, Methods, Findings

Angelo Bertolazzi[1], *Ilaria Giannetti*[2]

The Twentieth century densely populated cities are characterized by many buildings and infrastructures that require, on the one hand, ongoing maintenance to extend their useful life in accordance with current building standards and, on the other, a cultural operation aimed at their timely recognition as part of the architectural and technological heritage of the Twentieth century-Modernism. A valuable resource, fundamental to the joint achievement of both actions, is hence represented by the historical and technical documentation preserved in the local archives and relating to the process of design, construction, and management over time of Twentieth-century buildings[3].

Unlike pre-industrial architectural heritage, where a lack of sources represents the primary obstacle to knowledge – requiring extensive investigations of the building (as a document of itself) – for Twentieth-century built stock, the breadth of archival collections gathering the documents produced by the various actors in the construction process, is at the same time a valuable resource and an obstacle. To obtain historical and technical

1 University of Padua, Department of Civil, Architectural and Environmental Engineering.

2 University of Rome Tor Vergata, Department of Civil Engineering and Computer Science Engineering.

3 The data mining actions to «collect, manage, and systematize the historical construction data» were implemented at first within two different project: *ARCOVER – Archivi del Costruito Veronese in Rete* (2017-21) directed by prof. Angelo Bertolazzi at Department ICEA (University of Padua) and *USTevereARchivi – L'Ufficio Speciale del Tevere e dell'Agro Romano: un archivio per la storia e la sicurezza del territorio* (2022-24) directed by prof. Ilaria Giannetti at Department ICII (University of Rome Tor Vergata). Bertolazzi A. and Giannetti I., "Il contributo dell'Architettura Tecnica per la conoscenza e la conservazione del patrimonio costruito: un progetto per la valorizzazione degli archivi del Genio Civile". In *L'Architettura Tecnica fra transizione e rinnovamento*, edited by Diana L., Marmo R. and Vitiello V., 109-113. Napoli: Luciano Editore, 2024; Bertolazzi A., Giannetti I. and Mornati S., "Dalle carte di archivio alla salvaguardia del costruito: il contributo dell'Architettura Tecnica". In *La Terza Missione nel settore dell'Architettura Tecnica*, edited by Monteleone A, Rodonò G. and Tardo C., 197-210. Napoli: Luciano Editore, 2025.

information immediately accessible to the process of knowlegde, preservation, and valorization of the existing buildings, it is necessary to collect, organize, and compare a large quantity of documents, typologically heterogeneous and belonging to "disordered" collections, according to thematic or chronological criteria.

The archival organization of document collections produced by the actors in the construction process in the era of "technical reproducibility" follows highly inconsistent criteria due to the stratified use of the documents, their extreme proliferation, and, last but not least, the heterogeneity of the media and document types.

1. The Modern City and its Documents: the *Borgo Trento* Case Study

Whithin the SMUH project, the *Borgo Trento* district in Verona is selected as case study exploting the documentary collections held in the historical archives of the city of Verona. The district area is approximately 77 hectares in the North-West of Verona, in a strip of land – once called "*la Campagnola*" – formed by the first bend of the Adige river where until the Nineteenth century there were agricultural crops and grain mills[4]. In 1861, the construction of the Austrian Arsenal "*Kaiser Franz Josef I*" was completed, marking the beginning of the settlement of the area. The choice fell on "*la Campagnola*" because it was an area outside the inhabited centre to which it was connected by the medieval *Scaligero* bridge (for exclusive military use) and the metal Neville bridge (1856-64) and, above all, for its proximity to the postal road to Trento which constituted the main communication route with the Adige Valley and therefore with Austria[5].

4 This represents a good field to test the SMUH methodology. The neighborhood presents a variety of elements that reflect the complexity of Twentieth-century construction: the presence of a heterogeneous building landscape in terms of typology (single-family and multi-family residences), functionality (schools, residences, and urban bridges), and environment (river banks, green spaces, and public spaces); chronologically, *Borgo Trento*'s buildings and infrastructures belong to a period spanning from the 1920s to the 2000s. The neighborhood belongs to the 2nd District of the Municipality of Verona (2,768 hectares) together with the neighborhoods of Avesa, Parona, Ponte Crencano, Quinzano, Valdonega which have a population of 12,804 inhabitants. Municipality of Verona. *I quartieri della città di Verona. Differenze e similarità*. Year 2022. p. 36.

5 The "*Kaiser Franz Josef I*" Arsenal was designed in 1859 by the engineer (major) Conrad Petrasch, director of the *Genie-Direktion* of Verona, on the basis of a smaller project than the initial solution presented to Field Marshal Josef Radetzky in 1854. The decision to build an arsenal was part of a more general project to expand the fortress of Verona, which had also led to the strengthening of the *Porta Vescovo* railway station and its workshops (1859-60) and the

The building development of the area, especially from a residential perspective, dates to the late Nineteenth century, when the military role of the city within the Kingdom of Italy had diminished. From 1884 onwards, *Borgo Trento* became an important hub for urban services, as the gateway to the Verona-Caprino Veronese railway and the horse-drawn *omnibus* service, which constituted the main connections to the northern areas of the province. However, the greatest boost to the development of this district came after the First World War with the approval in 1924 of the Building Regulations for the City of Verona, which also included plans for the expansion of the suburbs, in line with the provisions of the previous Master Plan of 1914, which had been left unfinished due to the outbreak of war[6]. The main function as a residential neighbourhood for the middle class, was identified starting from the 1920s, and remained as a forecast of all the urban planning tools of the city, from the National Competition for the *Piano Regolatore Generale* (P.R.G.) in 1932, to its definitive version (1938-39) by the architect Plinio Marconi, who also signed the *Piano di Ricostruzione* (1948) and the *Piano Regolatore Generale* (1951-57)[7].

In the context of the residential transformation of the district the *Ufficio del Genio Civile* and the *Ufficio Tecnico* of Municipality did several works and infrastructure. The first one built the new embankments from *Catena* to *Garibaldi* (1928-31) bridge. For the stretch of the "*la Campagnola*" from *Catena* to *Scaligero* bridge, a scarp wall was built with a walkway at road level and one almost at river level. Along the second stretch, however, between *Scaligero* and *Garibaldi* bridge, a high wall of rubble masonry with an external brick facing and a Veronese stone crown was built – according to the Nineteenth century design[8].

construction of the *Santa Marta* food factory (1863-65) as well as the forts of the second entrenched camp (1860-65); these works became necessary after the loss of Lombardy following the Second War of Independence (1858-59). Jacobacci V., *La piazzaforte di Verona sotto la dominazione austriaca 1814-1866*. Verona: Cassa di Risparmio, 1980, 156-162; Bozzetto L. V., "Vienna e Verona. Gli arsenali dell'imperatore". In *Verona e Vienna. Gli arsenali dell'imperatore*, edited by Bozzetto L. V., 51-54. Verona: Cierre Edizioni, 1996.

6 Giavoni L., "L'espansione urbana e la cinta magistrale di Verona agli inizi del Novecento". In *Verona del Novecento. Opere pubbliche, interventi urbanistici, architettura residenziale dall'inizio del secolo al Ventennio (1900-1940)*, edited by Vecchiato M., 171-175. Verona: Cierre Edizioni, 1998; Morganti M. and Basso M., *Borgo Trento. Un quartiere del Novecento tra memoria e futuro*. Verona: Cierre Edizioni, 2010, 22-25.

7 Pavan L., "I piani di espansione fino agli anni '30". In *Urbanistica a Verona (1880-1960)*, edited by Brugnoli P., 111-147. Verona: Ordine degli Architetti, 1996; De Mori M., *Percorsi Arcover: I Piani Regolatori del Comune di Verona*. https://www.arcover.it/percorsi/i-piani-regolatori-del-comune-di-verona [accessed on: 10/12/2025].

8 The construction of the new embankments completed the project to re-channel the urban area, decided upon following the Adige flood of 1882 and carried forward in several stages.

The Municipality of Verona set two new bridges (*Catena* and *Vittoria*) and rebuilt the old *Garibaldi* metallic bridge for a better connection between the Borgo Trento district with the historic centre[9]. The development of Verona immediately after the end of World War I prompted the City Council to build a new bridge that would connect the neighborhood with the outer ring road towards the Brescia main road. The first project – regarding an iron bridge – was approved by the Council on December 15th 1925; in December 1926 the construction of the bridge was approved but with reinforced concrete structures, and the following year the call for tender issued; it was won by the Turin-and-Rome-based *Società Anonima Bertelè* company, which had a strong experience in this field. Eng. Carlo Scarafia and Turin Arch. Mario Dezzuti worked on the project[10].

The bridge had three lowered arches, the central one with a 38.50 mspan and a 5.85 m rise, the side ones a 34.00 m span and a 4.95 m rise. In all, the bridge was 112.50 m long; the total width amounted to 14 metres – 10 of which taken by the roadway and 4 by the two sidewalks. The pillars were 3.00 metres thick and their massive cement-concrete foundation walls sank as deep down as 6.50-7 m below the riverbed; the abutments had been built resorting to similar foundation systems. It was an arch bridge with stiffened deck; its structure consisted in reinforced concrete continuous vaults whose width varied from 30cm at the crown to 40cm. at the skewbacks; they supported the substructure of the deck, made up of a series of longitudinal and transverse trusses topped by a 13 cm-thick horizontal slab; the whole was connected by means of 30×30 cm square-section reinforced concrete pilasters. The need to protect the structures of the bridge from the swirling of water suggested the gables should be filled: so, the bridge ended up looking like a traditional brickwork masonry bridge, though it looks were enhanced by the stone ornaments of the piles and by stone-and-iron parapets[11] .

Stendardo L., *Cantieri sull'Adige. Trasformazioni urbane a Verona negli anni Trenta*. Verona: Edizioni ZeroTre, 2020, 18-20; Bertolazzi A. and Giannetti I., *L'Adige a Verona: ingegneria e città (1882-1895)*. Verona: Edizioni ZeroTre, 2025, 17-24.

9 For *Ponte della Vittoria* a deep historic and construction analysis is in the second part of the volume, related to the digitalization process through simplified HBIM models. The latter topic is also strictly related with the digitalization of residential buildings in *Borgo Trento* by an analogous methodology in the fifth chapter.

10 Archivio Generale del Comune di Verona (ACVr), Contratti, Busta: 6721; Repertorio: 17064; Date: 11/02/1929; Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.32; Date: 23/01/1947.

11 Building works started in 1928 and ended on September 6th 1929; it was unveiled on October 28th 1929 and tested on January 31st 1930. The total cost of the bridge was 1,750,000 lire, with further 2,000,000 lire spent on repairing the roads leading to the bridge; the repairs of the left bank proved quite complex and led to build the *Lungadige Attiraglio*, which was

The increasing traffic towards the growing *Borgo Trento* district, as well as the construction works to build the massive *Lungadige Campagnola* embankments, suggested that Nineteenth century Neville iron bridge (1864) should be substituted. So, on 24th February 1932 the city Council ruled that the old bridge was to be substituted with a new reinforced concrete one: the tender for bids was published the same year on August 22nd; again the *Società Anonima Bertelè* won the tender on 11th March 1933, after solving the problems posed by Soprintendenza concerning the piles' shape[12].

The project was drawn by Arch. Mario Dezzuti and by Milan Polytechnic Prof. Eng. Luigi Santarella as regards the structural calculations. The bridge had in 3 lowered arches: the central one with a 31.00 m span and a 2.48 m rise; the two side ones 26.00 m spans and 1.80 rises: The total length of the clear span was 89.00 m, the width 14.00 m. The piles were 3metres-thick at the skewbacks, their foundation bases lay 7 m deep below the riverbed. The bridge structure was cell-type and consisted in 9 reinforced concrete longitudinal 0.35 m-thick walls connected by transversal walls; the outside slab was 16 cm-thick, the inside vaulted slabs were 0.40 cm-thick, which increased to 0.45 cm where they joined at the top[13]. The structure typology had been prompted even in this case by the need to build a light, though sturdy, bridge, capable of supporting even the stone cladding required by *Soprintendenza*, though Santarella first project had not accounted for it. In order to build the abutment on the right, a radical demolition of the massive Nineteenth century embankment was necessary; as regards the left abutment, instead, the works for the bridge proceeded side by the side with the ones for the massive *Campagnola* embankment.

The tender contract was signed on 23rd December 1933; the works started on 10th February 1934, and ended when the bridge was unveiled on 21st April 1934, after only the structure had been provisionally tested; the final test, carried out by Eng. Umberto Zanolini, dates to February 1936, when the bridge was already operational. The four piles were adorned with statues by Ruperto Banterle representing Garibaldi-themed allegories. The cost of the bridge was 1,150,000 lire[14].

completed in 1932. Archivio Generale del Comune di Verona (ACVr), Contratti, Busta: 6721; Repertorio: 17064; Date: 14/10/1934; Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.32; Date: 23/01/1947.

12 Archivio Generale del Comune di Verona (ACVr), Contratti, Busta: 1933; Repertorio: 21834; Date: 25/09/1932.

13 Archivio Generale del Comune di Verona (ACVr), Contratti, Busta: 1933; Repertorio: 21834; Date: 25/09/1932.

14 Archivio Generale del Comune di Verona (ACVr), Contratti, Busta: X-11-1; Repertorio: n.a.; Date: 08/09/1936.

The *Borgo Trento* district suffered few damages during the Allies' bombings in the last months of the World War II, specially in the buildings surrounding the *Arsenale*, at that time still used for military purpouses[15]. Major distructions followed the blast of the Verona bridges during the night between the 24th and the 25th April: not only the structures were destroyed but also the residential buildings next to the bridges themselves.

The first step towards rebuilding bridges to re-connect the opposite banks permanently was the meeting of *Commissione per i ponti di Verona*, held on May 19th 1945. The decisions were taken according to the urgency of restoring traffic mobility in the city as well as in the province; the decision was to rebuild as soon as possible at least one bridge (possibly either *Catena* or *Umberto* bridge) and to delay the reconstruction plans of historical bridges. The following meeting (23rd May) saw also the presence of Eng. Umberto Zanolini, who had been an adviser of the Verona town council; the organisational requirements of rebuilding the bridges were decided, in particular as regards the jurisdiction and the procedures to be followed in the tenders. The decision was taken to build *Umberto*, *Garibaldi* and *Catena* bridges first together the *Albaredo* and *Sega* – outside Verona and at Cavaion Veronese – bridges the latter two outside the city[16].

The first bridge to be rebuilt, according to the decision taken by the bridge commission was *Catena* bridge. The connections between the two banks of the Adige needed to be resumed as soon as possible (as already stated by the council in its 30th November 1945 resolution). At first it was decided to re-use the remaining structures as far as possible, stabilising and strengthening the right arch; this would however cause the works to last longer, and the opening of the bridge was set in March 1947; in January 1946 it was decide to rebuild the bridge from scratch following the same design of the former one[17].

The *Ufficio dei Lavori Pubblici* therefore committed the works to the I.C.C.A. company that – under the name of *S. A. Bertelè* company – had built the original bridge in 1929; the Verona Amedeo Baraldi company de-

15 Visintin F., "Le distruzioni belliche e la ricostruzione". In *Urbanistica a Verona (1880-1960)*, edited by Brugnoli P., 249-279. Verona: Ordine degli Architetti, 1996.

16 The Commision was composed of: Aldo Fedeli (Mayor), Giuseppe Trabucchi (Deputy Mayor), Eng. Francesco Meloni, and Eng. Praloran (*Ufficio del Genio Civile*), Eng. Bisi and Severi *(Ufficio Tecnico Municipale*), Arch. Pietro Gazzola (*Soprintendenza di Verona*) and Eng. Biasioli (Bertelé company); all works were funded by the Allied Military Government (A.M.G.). Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.21; Date: 19/05/1945 and 23/05/1945.

17 Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.21; Date: 13/01/1946.

Fig. 1 – *The SMUH methodology: the project worked with the different archival collections in an integrated manner; the data mining was allowed by crossing the different archives (vertically) to have the information concerning every single element (horizontal), both buildings and infrastructures. This led to a transversal and comprehensive knowledge by the filling the gaps in each archives [SMUH, 2025].*

molished the remains and remove the rubble collapsed into the river. The project was drawn up by the I.C.C.A. company with Milan Polytechnic Eng. Arturo Zanusso as consultant and the Eng. Francesco Meloni as supervisor for the *Ufficio del Genio Civile*. The new bridge followed the same pattern as the original one: three reinforced concrete segmental arches with strengthening slabs connected by means of pilasters and filled gables. Even the sizes were the same as the ones in the previous bridge: the central arch span measured 38.50 metres and the lateral ones span 34.00 – the total span amounted to 112.50, the width to 14.00. The only change occurred in the decorations, which were considerably modified; the railings were to be rebuilt using stone, as per explicit request of the Verona city Council. The bid for tender was issued on November 8th 1945; the works completed on January 17th 1947 when the metal railings and lighting were installed, though the bridge had been unveiled and opened to the traffic on August 15th in the presence of Mayor Aldo Fedeli.

The reconstruction of *Garibaldi* bridge, decided in May 1945, started on 25th October when 21 companies were invited to tender for bids following the project set by Ufficio del Genio Civile[18]. Also, in this case the new bridge was to be identical to the old one as far as its general look was concerned, excepting the parapets, about which a tender was launched on 14th March 1946[19]. Greater problems were posed by the structural choices: the *Ufficio del Genio Civile* decided the existing pile and the abutments should be kept in order to cut times and costs; this, however, entailed performing the tricky task of fitting the existing structures to the new ones, so as to restore the original cell-type structure.

The project of the Milan-based *Bruno Chiesa* company won the tender; it was signed by Prof. Eng. Arturo Danusso from the Milan Polytechnic that had drawn the project for the cell-type structure of *Vittoria* bridge in 1925. Such choice appeared to be the most viable one, even though on 26th November 1945 Eng. Umberto Zanolini had suggested an alternative hypothesis, according to which resorting to a simple reinforced concrete vault would prove more economical, as well as more capable of withstanding structural dislocations at the skewbacks.

18 By 25th November only the *Bortolussi Marson* (Mantova), *Brazzoli & Babbi* (Verona), *Cerutti* (Milano), *Bruno Chiesa* (Milano) and *Ragazzi* (Milano) presented a proposal. Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.25; Date: 19/11/1945 (*Bortolussi Marson* bid); 20/11/1945 (*Brazzoli & Babbi* bid); 19/11/1945 (*Cerutti* bid); 19/11/1945 (*Bruno Chiesa* bid) and 16/11/1945 (*Ragazzi* bid).

19 Archivio Generale del Comune di Verona (ACVr), Contratti, Busta: X-5-1 24433; Repertorio: 1946; Date: 14/03/1946.

The tender was signed on 20th March 1946, as soon as the remaining arch was demolished and the rubble removed from the river. For the casting, the formwork chosen consisted in a single metal centring; developed above the road surface[20]. The bridge was inaugurated on 6th November 1947 and it was tested on the following day; the total cost of its reconstruction amounted to 26,461,000 lire.

Although the neighborhood had not been seriously damaged, in the years immediately following the end of the war the first transformations of the buildings began to take place (adding floors, extensions, replacements) that would define the development lines of *Borgo Trento* during the years of the economic boom[21]. Already in 1951, 618 apartments were built, an increase of 263% compared to the previous year, with a trend that would grow throughout the 1960s thanks to the availability of large free plots: in 1955 nearly half ot the Campagnola is unbuilt, but by 1970 it's plenty on multidwelling buildings[22].

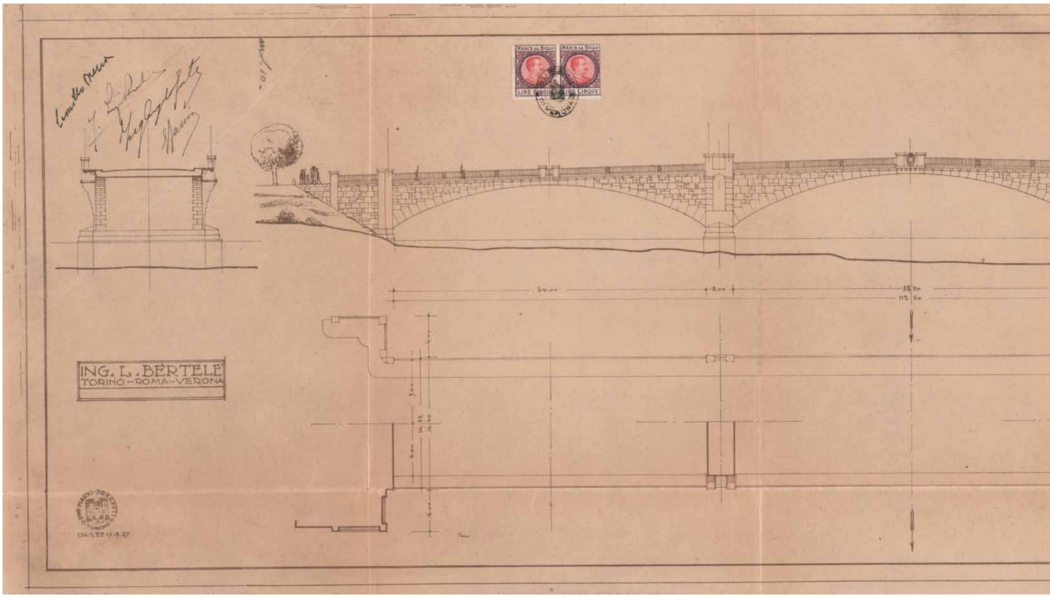
The 1957 *Piano Regolatore* planned also a direct link between *Borgo Trento* and the old historical district San Zeno throught a bridge set on the axis of Viale della Repubblica-Piazzale Cadorna[23]. Since the public bid that had been published in 1961 to celebrate the 100th anniversary of the Unity of Italy had been unsuccessful, in 1963 the city council committed the project to the then internationally famous Eng. Pier Luigi Nervi. The executive project and the calculations took only three months; the work was however contracted only in 1967 because authorizations – above all the ones that were to be issued by *Soprintendenza* – were delayed: it objected to the bridge being built out of mi-

20 The system was designed and built by the SAE company from Milan. However, the centring collapsed during the concrete casting on 2nd December 1946, forcing to stop the building for a while. The works were resumed under the direction of Eng. Filippo Beorchia Nigris (*Ufficio del Genio Civile*). Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.24; Date: 12/12/1946.

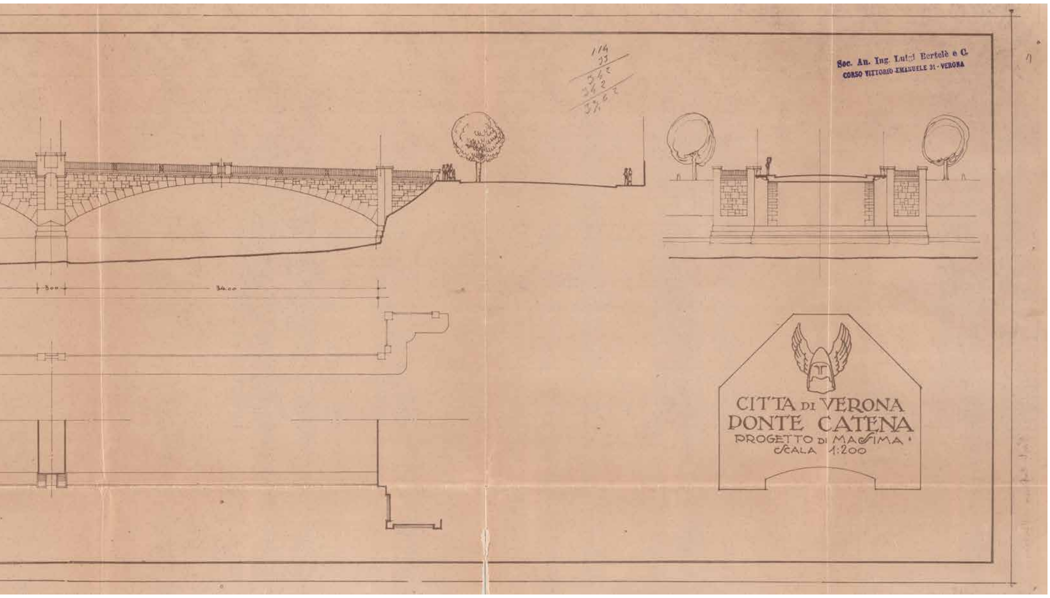
21 The *Piano di Ricostruzione* (1948) first and then the *Piano Regolatore Generale* (1951-57) both signed by Arch. Plinio Marconi, confirmed the residential function of *Borgo Trento* but with a different intensive approach. Morganti M., "Tutela e urbanistica a confronto nella ricostruzione del centro di Verona". In *Verona, la guerra e la ricostruzione*, edited by Vecchiato M., 128-165. Verona: La Grafica Editrice, 2006; Morganti M. and Basso M., *Borgo Trento*, op. cit, 33-37.

22 The *Piano Regolatore Generale* – but also the *Piano di Ricostruzione* – augmented the building indexes to maximize the profit and suggested to concentrate the higher buildings on the main axes (via 4 Novembre, via 24 maggio and via Pratosanto). Morganti M. and Basso M., *Borgo Trento*, op. cit, 39-40.

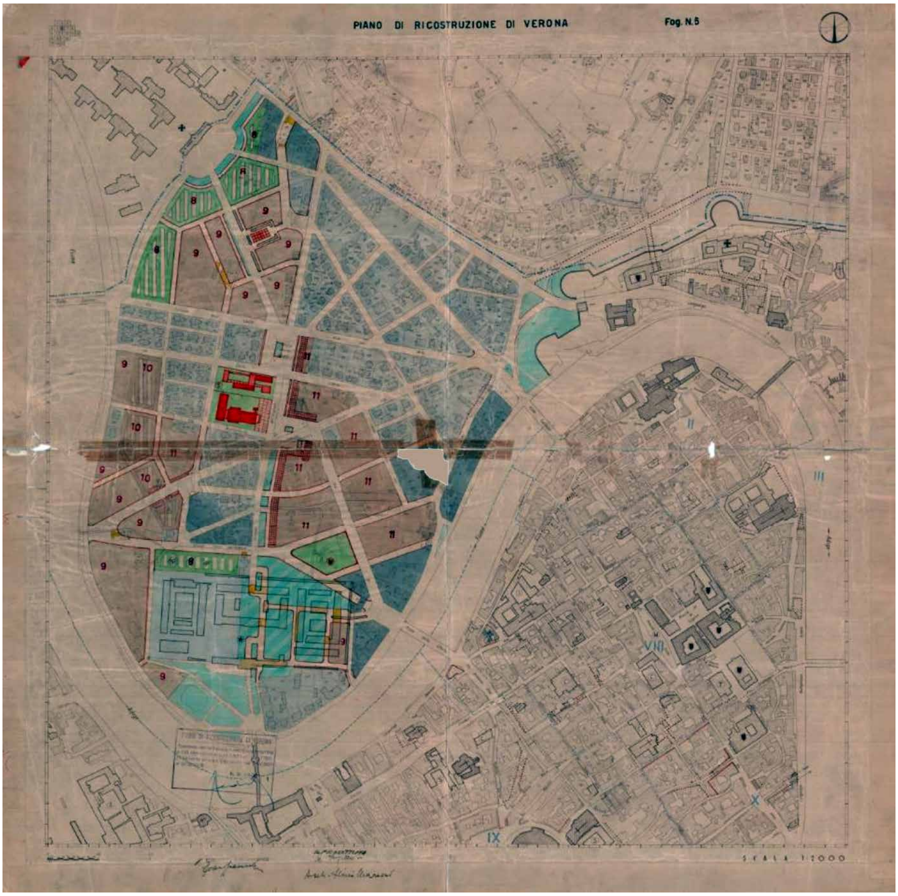
23 As far back as 1938, Municipality planned a new bridge that would connecting the two districts, *Borgo Trento* and San Zeno, but this didn't become reality until 1957, since the local Soprintendenza tried to oppose to this option. Bertolazzi A. and Savoia R., I *ponti in cemento armato a Verona nel Novecento*. Verona: edizioni ZeroTre, 2022, 41.



Figg. 2-4 – Catena *bridge (1928-29): original project (top) designed by Eng. Carlo Scarafia and Arch. Mario Dezzuti for the Turin-and-Rome-based company S*ocietà Anonima Bertelè*; the new bridge connected Borgo Trento with the south ring road (bottom, left) in the background there are the houses for the* Cooperativa edificatrice Postelegrafonici*; the bridge blasted at the end of the Second World War (bottom, right) as all the Verona bridges. [ACVr, Contratti, f. 153, rep.17064; ASVr, Fondo Genio Civile, Lastre Fotografiche, f .348; ACVr, Carteggi, f. CA.X.510].*



Figg. 5-6 – *Next page. The Reconstruction Plan (1946-48): it was signed by Arch. Plinio Marconi and it planned new buildings in Borgo Trento (top) beyond the damage repair of the city infrastructure, like* Catena *bridge (bottom) that was one of the first to be reconstructed (1946-47); the design – following the original one – was made by* Ufficio del Genio Civile *with Eng. Arturo Danusso as consultant for I.C.C.A. company. [ACVr, Ufficio Urbanistica, PDR/1948; ASVr, Lastre Fotografiche, f.229].*


PIANO DI RICOSTRUZIONE DI VERONA
Fog. N.5

sgivings regarding the increased traffic impacting on the San Zeno area, rather than regarding the formal features of the bridge.

After all hesitations were solved, the bid for tender saw the Trento-based *Edilbeton Srl* company as winner; their bid was in fact more cost-efficient than the one tendered by *Nervi-Bartoli* company that is why Pier Luigi Nervi ceased working on the project. The new reinforced concrete structure has an overall length of 126.49 m and an 18.40 meters width; the central arch span is 62.00 m, and the side arches span 34.40 m each. The structure of the bridge follows the continuous beam pattern, which is simpler than the multiple-arch one and more efficient than the supported-beam one, since it allows slimmer sections. Nervi resorted to a cell-like, variable-section beam; thicker at the skewbacks, where the values of the moments and of the shear stresses were highest; also, the shapes of the sections varied: at the skewbacks they were trapeze shaped, at the crowns reversed-trapeze shaped. In this way the side faces of the beam took the shape of a hyperbolic parabolic, namely of a double-curved surface[24]. The reinforced concrete piles were 5.60 m thick at water level and were supported by lean cement-concrete foundation struts embedded as far down as 8 m below the riverbed. The surfaces of the piles were clad in Verona stone slabs, so as to protect them from water erosion. The works were started in February 1967, directed by Eng. Litterio Consolo: the new bridge was named *Risorgimento* and was unveiled on May 4th 1968[25].

As pointed before *Borgo Trento* district had a residential function since eartly Twentieth century. Today it presents an important layered tissue and the buildings can mainly be traced back to four phases:

1. the first (1924-1934) was characterized by the construction of single or semi-detached villas (1-2 floors) according to a model like to the "garden city" and with an eclectic and *Art Nouveau* style that denotes a bourgeois client. A special case is the construction of 66 apartments for the *Cooperativa edificatrice Postelegrafonici* on a large plot in the western part of the "*la Campagnola*" area, near the the *Catena* bridge[26]. The construction techniques in both cases involved the use of traditional stone and brick walls with plaster and decorative stone

24 Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.37; Date: 03/01/1967.

25 Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.37; Date: 03/01/1967; Sassone Mario. "Ponte del Risorgimento, 1963-1968". In *Pier Luigi Nervi. Architettura come sfida*, edited by Olmo Carlo and Chiorino Christiana, 178-181. Milano: Silvana Editoriale, 2010.

26 The project was designed and implemented by engineer Adolfo Zorzan, head of the *Ufficio Tecnico* of Verona Municipality, between 1922 and 1924. In the 1960s many houses were destroyed or heavly modified following the economic boom and its building pressure.

elements in the burgeois houses, while the horizontal structures were predominantly wooden floors;

2. the second phase (1935-1950) was characterized by multi-story buildings (3-5 stories) for the middle class, particularly between Vittoria and Garibaldi bridge and along the embankment that connects them. Here, the buildings form a single and hogeneous facade infollowing a modernist style, with the systematic use of reinforced concrete frames and brick-cement floors, initially inserted into traditional masonry and later independent from the infill walls;
3. the third phase (1951-1970) was characterized by intensive and speculative construction of multi-story buildings (4-7 floors) that filled the free lot left by the previous construction phases. The use of reinforced concrete frames complete with brick-cement floors was widespread, and for infill walls there was a progressive transition from traditional stone and brick walls to those made by solid and, thereafter, perforated bricks;
4. the fourth phase (1971-1990) saw on the one hand kept the settlement system of the previous two decades with the construction of multi-storey buildings, and on the other some two-three-storey buildings of the 1920s and 1930s were replaced by new intensive multi-storey buildings.

The crossing data from different archives – like for the infrastctures (bridges and embankments) – was the tool to find the building date and the construction system[27].

2. The Archive Sources: Data Mining for *Borgo Trento* District

The research area was explored through various archives in the city of Verona and crossing the data from different archival funds to have a complete knwoledge framework[28].

27 The sources for the analysis of the buildings in Borgo Trento were primarily the *Edilizia Privata* Archives of the Municipality of Verona, whose data for the years 1920-1945 were found in the archives of *Ufficio Distrettuale Imposte Dirette* (U.D.I.D.), housed at the Archivio di Stato di Verona. The Photographic Collection of the Verona *Biblioteca Civica* and Photographic Plate Collection of the *Ufficio Statale del Genio Civile* (also in the *Archivio di Stato di Verona*) allowed for dating and identifying the construction aspects of the buildings. This latter had a great relevance as the photographic campaigns conducted to certify the work on the embakements or the construction/reconstruction of the urban bridges also give informations about the private construction sites that gradually progressed during the public works.

28 Within the above-mentioned project *ARCOVER – Archivi del Costruito Veronese in Rete* (2017-21), the research group focused at first on the fund *Ufficio Distrettuale Imposte Dirette*,

The analysis started from the archives of the Verona Operational Unit of the *Ufficio Statale del Genio Civile*, which assumed great relevance both for the type and quantity of documents relating to the infrastructure but in general for the transformations of the area in a period ranging from the 1920s to the 1970s. This archive includes documentation produced by the *Corpo Reale del Genio Civile* and consists of files preserved as they were received and a series of individually numbered registers. The documentary material concerns various types of work and interventions relating to roads, factories, bridges, navigation of the Adige river, ports, lighthouses and beacons, land reclamation, prisons, telegraphs, municipal works, police and public safety, and public waters.The collection consists of 2,586 folders, 466 registers, 8 bundles, and more than 6,000 photographs, for a total of 520 linear meters, which preserve the Office's activities between 1920 and 1987. This collection, not yet reorganized, contains documentation produced by two distinct bodies, which managed the execution of public works in Verona and its province at a peripheral level between the early Twentieth century and the 1950s: the *Servizio Generale*, i.e. the ordinary structure, and the *Ufficio Speciale* per gli edifici governativi, created by Giolitti in 1911 for the construction of the ministerial buildings and abolished in 1928, when its responsibilities went to the *Servizio Generale*[29].

The analysis of the *Genio Civile* archival fund allowed to understand the infrastructural context of Borgo Trento in its main components (embankments, bridges) both from an historical and construction perspectives. In the 1930s, the Office carried out intense activity in completing the embankements works along the urban section of the Adige, designed by the *Ufficio Tecnico* of the Municipality of Verona in 1883-85, which finishing was made necessary after a further flood of the Adige in 1926. The construction sites mainly concerned the left bank: between 1928 and 1936, the works to protect the banks of the *Lungadige Attiraglio*, *Campagnola* and *San Giorgio*, renamed "*del Littorio*", were completed – based on a project by the same *Ufficio del Genio Civile*[30].

the fund of *Ufficio Statale del Genio Civile* and the *Cartografia* fund, all of them preserved in the *Archivio di Stato di Verona*. Bertolazzi A., Savino M. and Siviero L., "Il progetto ARCOVER: una piattaforma webGIS per una rete degli archivi del costruito nel territorio veronese". In *Archivi digitali per la città contemporanea. Documenti, strumenti e modelli per la conoscenza del patrimonio costruito*. Bertolazzi A., Eramo E., Giannetti I. and Siviero L., 13-47. Milano: FrancoAngeli, 2025.

29 Bertolazzi A. and Stendardo L., "Dagli archivi in rete al museo diffuso dell'ingegneria: il fondo del Genio Civile di Verona e la sua valorizzazione". In *Atti dell'8° Convegno Nazionale Storia dell'Ingegneria*, edited by D'Agostino S., d'Ambrosio A. and Romana F., 137-146. Napoli: Cuzzolin, 2020.

30 Stendardo L., *Cantieri sull'Adige,* op. cit., 10-27.

These works were integrated with the construction (or reconstruction) of urban bridges, that was made necessary by the increase in traffic that accompanied Verona's urban development. The *Catena* (1928-29), *Vittoria* (1928-29), and *San Francesco* (1929-30) bridges were built in a short time, while the *Garibaldi* (1933-35), *Navi* (1934-36), *Umberto* (1935-37), and *Aleardi* (1939-40) bridges were rebuilt. The costruction of these bridges – designed by the *Ufficio Tecnico* of the Municipality of Verona – was monitored by the *Ufficio del Genio Civile*, which verified both the hydraulic and structural aspects and, in the executive part, the progress and final works' payment[31]; The *Ufficio Statale del Genio Civile* office's commitment to urban bridges increased immediately after the Second World War, when their reconstruction was part of the vast effort to repair war damage suffered by Verona[32].

An analysis of the documents relating to the *Borgo Trento* bridges from the *Ufficio del Genio Civile* immediately highlighted the fragmentation of the Twentieth-century archives, due not only to events common to all archives (dispersion and loss of material) but also to the specialization of expertise resulting from the development of technical knowledge. The material produced by the *Ufficio del Genio Civile* primarily concerns hydraulic aspects (calculation of the hydraulic cross-section and pier foundations) and technical aspects (design, sizing and verification of the bridge's vertical and horizontal structures, material testing, construction management, accounting, and final settlement of the works). Documents on the architectural and urban planning aspects that led to the construction of the structure are instead missing or fragmentary.

These gaps were filled by further research in other archives: documents relating to the bridge design competitions, as well as *Archivio Generale del Comune di Verona*, while the *Soprintendenza* archives provided a comprehensive overview of the challenges of integrating the bridge structures into the urban context and the landscape constraints that influenced the technical choices (i.e. the cladding the reinforced concrete structures in local stone and the use of riverbed piers rather than single-span solutions). Further researches were conducted in the

31 Bertolazzi A. and Savoia R., *I ponti in cemento armato a Verona nel Novecento*, op. cit., 29-32.

32 As pointed in the previous paragraph between 1945 and 1947, the Verona Office supervised the design and construction of the first five rebuilt bridges: *Catena*, *Garibaldi*, *Umberto* bridges, moreover the ones at Cavaion and Albaredo. Subsequently, it carried out technical coordination (hydraulic and structural aspects, procurement, and construction management) for the reconstruction of the *Navi* (1947-49), *Aleardi* (1949-50), *San Francesco* (1949-51), and *Vittoria* (1951-53) bridges. This activity was added to the supervision during the reconstruction of the historic bridges, *Scaligero* (1949-51) and *Pietra* (1957-59) and finally the construction of two new bridges over the Adige, the *Risorgimento* bridge (1966-68) by Pier Luigi Nervi and the *Unità d'Italia* bridge (1968-71).

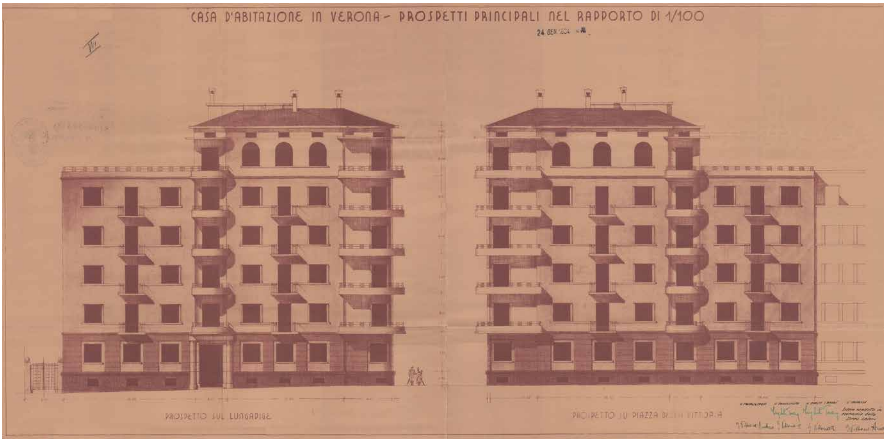


Fig. 7 – *Residential buildings in* Borgo Trento*: the U.D.I.D. archives conserve the documents regarding the private buildings built from 1920s to 1960s like the multistorey dwelling designed by Eng. Antonio Tonzig in 1934. [ASVr, Fondo U.D.I.D., f. 1184].*

Fig. 8 – Campagnola *embankment: during the 1930s the* Ufficio del Genio Civile *completed the project to save the city from the Adige flood, through massive embankments designed in 1880s by* Ufficio Tecnico *of Verona Municipality. The photographic survey made by* Genio Civile *not only attests the embankment works but also they witnesses the transformation of the urban tissue, allowing the dating and the construction system analysis of the buildings, like the Tonzig's one on the right. [ASVr, Fondo Genio Civile, Lastre Fotografiche, f. 10].*

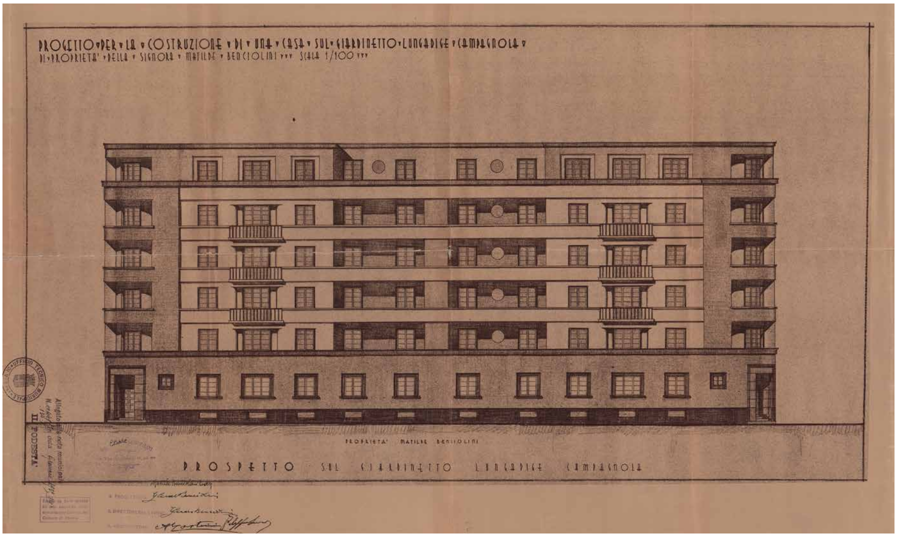


Fig. 9 – *Residential buildings in* Borgo Trento*: since the Municipality Archives from 1900 to 1944 were lost during the Second World War, the U.D.I.D. files are very important to have the data concerning many 1930s buildings, like the multistorey dwelling designed by Eng. Italo Mutinelli and Eng. Cesare Benciolini, one of a well-known Modernist buildings. [ASVr, Fondo U.D.I.D., f. 1747].*

Fig. 10 – Borgo Trento *during the 1930s: the photographic surveys of Ufficio del Genio Civile have also general views of the district. These pictures record the steps of the building activity and by crossing with historical maps and cartography allow to define the age of buildings at least according to the decades foreseen by the SMUH taxonomy. [ASVr, Fondo Genio Civile, Lastre Fotografiche, f. 11].*

Gabinetto Fotografico of the Verona Civic Library allowing the integration of photographs taken by the *Ufficio del Genio Civile* during the construction site to certify the progress of the work.

This research methodology – by crossing data from different archives or archival collections – proved useful also for the analysis or civil residential building in *Borgo Trento*. The projects of the public and private buildings, are collected in the A*rchivio Generale del Comune di Verona*, divided into two different collections: the one of the *Carteggi* and *Contratti* in the first case and in the *Edilizia Privata* in the second. The latter is an operative fund since it also collects applications currently submitted for building permits (renovation and new construction). From the perspective of understanding urban tissue and their transformations over time (typological, construction, and material aspects), these funds is an invaluable source of information, although not easily accessible due to the sensitivity of personal data and real estate ownership. In the specific case of Verona, a further problem is the loss of data relating to the period 1920-45 due to the destruction of the Municipality Archives during the war in 1945[33].

The opportunity to fill this significant gap was provided by the analysis of the collection of the former *Ufficio Distrettuale Imposte Dirette* (U.D.I.D.), which constitutes a "double" of the lost municipal archives, collecting many original designs for new buildings constructed from the early twentieth century, and especially after the First World War, when the tax exemption was introduced to support veterans of the First World War, extended to a whole range of types (public housing, homes for the disabled peoples, homes for railway workers, *Istituto Nazionale per le Case degli Impiegati Statali* (I.N.C.I.S.) housing for state employees, and homes for private citizens), with the aim of also encouraging the recovery of the construction sector in Verona. The archive consists of 194 folders containing the plans for 1,624 buildings, for a total of 2,320 drawings. Each file contains the building permit issued by the Municipality, the certificate of commencement of construction, the project, the certificate of completion, and the certificate of habitability[34]. In the case study of *Borgo Trento* this fund proved very useful since many documents were

33 Bertolazzi A., Savino M. and Siviero L., "Il progetto ARCOVER: una piattaforma web-GIS per una rete degli archivi del costruito nel territorio veronese", op. cit., 13-47.

34 As previously noted, these documents represent an important addition to the *Edilizia Privata* Archives of the Municipality of Verona for the years prior to 1945: more than half of the collection, precisely 50.56% (1,173 documents), refers to this historical period. Another aspect that makes the U.D.I.D. collection important from a practical standpoint is the fact that almost all projects also include the original certificates of habitability. Mazzei R., "Il fondo U.D.I.D. e l'Archivo di Stato di Verona". In *Verona in trasformazione 1920/1960. Catalogazione dei progetti edilizi ex-U.D.I.D.*, edited by Bertolazzi A. and Segala I., 9-13. Verona: Editoriale Polis, 2017.

found concerning the 1920s and 1930s original buildings: many of these were demolished or heavly modified in the 1950s and 1960s. So, it was possible to cross the data from U.D.I.D. archive with the *Edilizia Privata* to understand the materiale modifications of the buildings, while – again – the photographs from the *Gabinetto Fotografico* of the Verona Civic Library, the *Ufficio Statale del Genio Civile* and the ones from the files of *Edilizia Privata* helped to understand the construction and material features and a quite precise dating of the buildings.

The building age was also assessed by the analysis of the *Borgo Trento* cartography. This is particularly scattered, since the multiplicity of offices that during the Twentieth century contributed to producing the maps and documentation for the management of the territory.

The cartographic material can be divided into two main categories: the maps used for urban planning of the Municipality of Verona and the cadastral maps produced for tax reasons. In the first case, the documentation includes various documents kept in the *Settore Pianificazione* of the *Ufficio Urbanistica* which collects the documentation of previous plans, from the first *Piano Regolatore Genarale* (1939) to the *Piano di Ricostruzione* (1948) and the subsequent *Piano Regolatore Generale* (1957), with the modifications of 1966 and 1971, until the *Piano Regolatore Generale* (1997) with the 1999 variation. This collection is completed by other planning tools such as detailed plans, specific urban plans from 1920s[35].

Another significant portion of the cartography is represented by the cadastral maps preserved in the *Archivio di Stato di Verona*. These include the preparatory Austrian Land Registry (1835-42) and the updated ones (1849 and 1897), the latter of which reports the work on the retaining walls built following the Adige flood of 1882. The 1953 updates to the Italian Land Registry come from the *Ufficio Distrettuale Imposte Dirette* (U.D.I.D.), extremely interesting documents because they represent the city and its territory at a time of great transformation following the end of the Second World War. The *Ufficio Pianificazione Territoriale e Urbanistica* preserves the maps of the updated Austrian Land Registry (1890) and the preparatory

35 An important document completing the series of urban plans is the 1924 Building Regulations. Along with the technical specifications for buildings, they also contain the plans for expansion, taken from the previous 1914 *Piano Regolatore*. These sought to develop the city in parts, prior to the 1932 competition for the *Piano Regolatore Generale* (P.R.G.), which implemented a first overall plan. Pavan L. "I piani di espansione fino agli anni '30", op. cit., 111-147; De Mori M., *Percorsi Arcover: I Piani Regolatori del Comune di Verona*. https://www.arcover.it/percorsi/i-piani-regolatori-del-comune-di-verona [accessed on: 10/12/2025].

Figg. 11-12 – Borgo Trento *development during the 1960s: thanks to the cartography like E.I.R.A. it's possible to elaborate the building transformation from the end of the 1950s to the end of 1960s, by comparing the E.I.R.A. 1960 (top) and E.I.R.A. 1970 maps; this allow to define the age of buildings by crossing the pictures conserved in the Edilizia Privata fund. [ACVr, Ufficio Urbanistica, EIRA 1960; ACVr, Ufficio Estimo, EIRA 1971].*

(1900) and initial (1907) Italian Land Registry, along with subsequent updates (1913, 1925, 1928, 1938, 1953, and 1969)[36].

The analysis of *Borgo Trento* evolution was also made possible by the E.I.R.A. cartographic series from 1960, 1971, and 1997, preserved respectively at the *Ufficio Pianificazione Territoriale* e *Urbanistica and the Ufficio Patrimonio ed Estimo*. These maps allowed a quick and easy interpretation of the built environment in relation to other territorial matrices (infrastructure, natural elements) present in the area[37].

3. Exploiting the Base Knowledge Framework: the Definition of a Reference Taxonomy

The cross-referenced analyses of the collected documents allow to perform in-depth morphological and constructive analyses of the considered buildings. Documents provide consistent data, at the scale of the individual building, to assess its historical evolution and characterize its building details. To organize the documents-derived information and facilitate their use to the subsequent structural vulnerability assessment, a specific set of standard informative parameters is defined and adopted as reference taxonomy. This taxonomy, encompasses both the primary geometric characteristics of the buildings and a foundational knowledge framework covering their history, function, and technical descriptions.

The geometrical features of the buildings are described within a specific set of informative parameters which comprise: the urban position, the characterization of the plan and the elevation geometries in terms of the generic definition of regularity, based on the principle of symmetry, the number of stores, the type of roof, and the geometric characterization of the openings at the bottom store. A detailed presentation of the set of parameters used to describe the geometrical feature are described in table 1.

36 The chronological sequence of the documents and the completeness of the Italian Land Registry maps allow an interesting interpretation of the evolution of the relationship between the built and natural environments in *Borgo Trento* throughout the Twentieth century.

37 The E.I.R.A. cartography was produced by the *Ente Italiano Rilievi Aerofotogrammetrici*, which operated from 1934 to 1977. It was based on aerial surveys conducted by the agency until its bankruptcy in 1977 and on images taken by other companies until the early 2000s, when satellite images began to become the basis for territorial cartography. The E.I.R.A. maps of Verona are at a scale of 1:5000, and for 1971 they are also available at a scale of 1:2000. Bertolazzi A., Savino M. and Siviero L., "Il progetto ARCOVER: una piattaforma webGIS per una rete degli archivi del costruito nel territorio veronese", op. cit., 13-47. Milano: FrancoAngeli, 2025.

Table 1 – *The geometrical parameter considered in the taxonomy.*

Code	Geometrical Parameter
bd_h	Hight of the building [value in meters]
bd_ns	Number of stories of the building [numeric value]
bd_pls	Plan surface [value in m^2]
bd_plst	Plan surface type [Rectangular L-shape, H-shape, T-shape, U-shape Curved Irregular (no symmetry)]
bd_upos	Urban position [Detached building Adjoining building(s) on one side Adjoining buildings on two sides Adjoining buildings on three sides]
bd_pr	Plan regularity [yes/no]
bd_er	Elevation regularity [yes/no]
bd_rt	Roof Type [Flat Pitched with gable hands Pitched and hipped]

The set of informative parameters related to the base knowledge framework comprise: an alphanumerical code to the identify the building; the construction period; the function; the number of occupants; a schematic classification of the building shape; the in-depth characterization of the load-bearing structure and the building components; the record of the history of the building, ranging from the design to the construction site and embedding the damage history and the maintenance interventions; the actual state of the building derived from fast surveys. The consistence of the value assigned to each parameter is assessed by reporting the source of the data, referring to the documental sources, the fast surveys and the derived information. For example, the construction period of a single building block can be directly detected from the archival documents, such as the habitability certificate of a building, or derived from historical cartographies: in the first case, the year of construction can be assessed, in the second case, the decade of construction.

The historical documents related to each building are coded with a unique ID that identify the archival source. The reference taxonomy, with the considered set of informative parameters and the related wording, is presented in the table 2.

Table 2 – *Set of standard informative parameters defined by the reference taxonomy for the 43 waterfront buildings (from archival data at the building scale and fast visual inspections).*

Code	**Description of the parameter**
bd_id	Alphanumeric code to identify the building
bd_doc	Alphanumeric code to identify the archival sources
bd_funct	Function of the building
bd_no	Number of occupants
bd_ch_asse	Cultural heritage constrains
bd_usb_year	Year of the habitability certificate
bd_cns_age	Decade of construction
bd_tech	Building technology
bd_str_type	Structural typology
bd_state	Actual state from visual inspection
bd_damage	Damage detectable from visual inspection
bd_damage_cause	Cause of damage from documental evidence
bd_up	Maintenance intervention

An example of the valorization of each informative parameter, referring to a sample building is, thus, presented in the following table 3. Referring to table 3, all the valorized parameters refer to the cross-referenced analyses of the documentation conserved in the U.D.I.D. fund, and the documentation conserved in the *Edilizia Privata* fund. The detection of the overall actual state of the buildings (poor, moderate, good) and the detection of the damage (referring to the building envelope) are performed by fast visual inspection based on fast on-site photographic surveys.

For the building located in central part of the considered area, the same set of the geometrical description is adopted while a specific subset of informative parameters is considered embedding few crucial data derived from the described secondary sources and urban cartographies. A detail presentation of the syntenic informative parameters related to the buildings in the central area is presented in table 4.

The presented taxonomy is, thus, exploited in the subsequent phase of the workflow, related to the first step of the structural vulnerability assessment which grounds on the base knowledge framework.

Table 3 – *The informative parameter of the taxonomy referring to a sample building for the 43 waterfront buildings (from archival data at the building scale and fast visual inspections).*

Code	Valorized Parameter for a sample building
bd_id	018-Armellini
bd_doc	[UDID, EP]
bd_funct	Residential
bd_no	0-50
bd_ch_asse	Yes [*Landscape*]
bd_usb_year	1955
bd_cns_age	1950-1960
bd_tech	Load-bearing masonry, reinforced concrete elements
bd_str_type	Wall system
bd_state	Moderate
bd_damage	none
bd_up	1959

Table 4 – *Set of standard informative parameters defined by the reference taxonomy for the buildings in the central area (from historical cartographies and fast visual inspections).*

Code	Description of the parameter
bd_id	Alphanumeric code to identify the building
bd_funct	Function of the building
bd_ch_asse	Cultural heritage constrains
bd_cns_age	Decade of construction
bd_tech	Building technology
bd_state	Actual state from visual inspection
bd_damage	Damage detectable from visual inspection


Fiume

Exploitation of Multi-Temporal Satellite Differential SAR Interferometry for Investigating Displacement Phenomena in the Built-Up Environment

Manuela Bonano[1], *Pasquale Striano*[1], *Federica Casamento*[1,2], *Michele Manunta*[1], *Ivana Zinno*[1], *Riccardo Lanari*[1]

Understanding and monitoring ground and structural displacements in urban areas is a growing societal and scientific priority, driven by the increasingly high exposure to natural and anthropogenic hazards and by the need to ensure sustainable development, infrastructure security, and climate resilience. In this scenario, the exploitation of remote sensing measurements achieved by processing large satellite Synthetic Aperture Radar (SAR) data sets related to an area of interest through the multi-temporal Differential SAR Interferometry (DInSAR) techniques, allows detecting and analysing surface displacements over wide areas on Earth, with high accuracy and limited operating costs, thus contributing to assess and preserve the health conditions of single buildings and infrastructures over the extended built-up environment.

In the project framework, we concentrated on the advanced DInSAR technique referred to as Full Resolution Parallel Small BAseline Subset (FR P-SBAS) approach, which has been applied in different scientific and operational contexts, demonstrating its capability to detect and investigate, in short time frames, a large variety of deformation phenomena related to the built-up heritage. The FR P-SBAS technique extensively exploits HPC architectures based on CPU and GPU devices, to efficiently perform, in short time frames, long-term, multi-temporal DInSAR analyses at different spatial resolutions (for regional and local-scale investigations), which are suitable for identifying and monitoring deformation phenomena related to both natural and anthropic hazards. Moreover, the FR P-SBAS approach allows exploiting SAR data characterized by native high spatial resolution (on the order of a few meters) to perform high-resolution DInSAR analyses related to extended urban areas, through the generation of deformation time series at the maximum SAR image spatial resolution. This permits the accurate map-

1 Institute for Electromagnetic Sensing of the Environment (IREA)-National Research Council (CNR), Naples, Italy.
2 University of Naples “Parthenope”, Department of Engineering, Naples, Italy.

ping, in short time frames, of a wide range of displacements associated with complex built-up environments and localized displacements, such as those affecting critical infrastructures and individual buildings, thus helping assess building vulnerabilities and support risk mitigation strategies.

By focusing on the two case studies relevant to the extended urban areas of Roma and Verona, this Chapter aims to investigate how the multi-temporal DInSAR measurements can support early-warning strategies for infrastructure management and urban planning, as well as risk assessment frameworks and decision-making processes for the resilience and safety in the built environment. Accordingly, we present the results achieved by applying the FR P-SBAS approach to the whole X-band SAR data archives, collected since 2011 in Stripmap mode (~3×3 m spatial resolution) from the first- and second-generation COSMO-SkyMed (CSK/CSG) satellite constellations of the Italian Space Agency (ASI), over the selected metropolitan areas. These data are particularly suitable for investigating the spatial/temporal variations of localized displacements associated with anthropogenic hazards, as well as for assessing the health conditions of critical infrastructures.

1. Introduction

In recent decades, monitoring the state of health of single buildings and transport infrastructures related to extended urban areas has become increasingly important, as a result of the degradation processes linked to the natural aging of structures, the increase in traffic loads – often exceeding those considered at the design stage – and exposure to particularly aggressive environmental factors. Moreover, the impact of climate change is also relevant due to the increased frequency of extreme weather events such as intense rainfall, floods, landslides, and significant thermal excursions, which intensify the stresses to which urbanized areas are subjected, consequently increasing the risk of damage and instability phenomena.

In this context, the use of innovative and reliable technologies for the detection, control, and monitoring of deformation phenomena plays a key role in evaluating the state of health and safety of the built-up environment. Traditional structural monitoring methods, based mainly on periodic visual inspections, in situ experimental tests, and on the installation of dedicated instrumentation—such as strain gauges, accelerometers, and GNSS systems—while providing highly accurate and pointwise information, present significant limitations related to their installation and management costs, the limited spatial coverage of measurements, and the complexity of carrying out systematic monitoring of a large number of structures and buildings at the territorial scale.

In recent years, satellite remote sensing techniques based on the use of radar data acquired by Synthetic Aperture Radar (SAR)[3] sensors have played an increasingly important role in monitoring and, more generally, in the safety control of the built environment, thanks to their ability to perform remote measurements of the sensor-to-target distance with wide spatial coverage, independent of illumination conditions (day and night measurements) and all-weather, with relatively low environmental impact and limited costs when compared with traditional methods, particularly for what concerns the extent of the analyzable area or the observation period. Among SAR data processing techniques, Differential SAR Interferometry (DInSAR)[4] has emerged as a particularly effective tool for identifying and analyzing ground and structural displacements over large areas. By computing the phase difference (interferogram) between pairs of SAR images acquired over an area of interest at different times and from slightly different orbital positions, the DInSAR technique permits to generate spatially dense and highly accurate maps (fractions of the used wavelength) of surface displacements, projected along the sensor Line of Sight (LOS) and measured in terms of movement toward or away from the SAR sensor.

Over recent decades, the evolution of conventional DInSAR techniques toward advanced, "multi-temporal" approaches have further expanded the capability to map and analyze slow surface displacements associated with both natural and anthropogenic environments, exploiting large sequences of SAR images acquired over a ground scene[5]. Among the various multi-temporal DInSAR techniques, the Small BAseline Subset (SBAS) approach[6],

3 Franceschetti G. and Lanari R., S*ynthetic Aperture Radar Processing*. Boca Raton, FL: CRC Press, 1999.

4 Gabriel A. K., Goldstein R.M. and Zebker H. A., "Mapping small elevation changes over large areas: differential interferometry". *Journal of Geophysical Research* 94 (B7) (1989), 9183-9191; Bürgmann R., Rosen P. A. and Fielding E. J., "Synthetic aperture radar interferometry to measure Earth's surface topography and its deformation". *Annual Review of Earth and Planetary Sciences* 28/1 (2000):169-209.

5 Ferretti A., Prati C. and Rocca F., "Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry". *IEEE Transactions on Geoscience and Remote Sensing* 38/5 (2000), 2202-2212. DOI: 10.1109/36.868878; Werner C., Wegmüller U., Strozzi T. and Wiesmann A., "Interferometric point target analysis for deformation mapping". In *Proceedings IEEE IInternational Geoscience and Remote Sensing Symposium*, 2003, 4362-4364. DOI: 10.1109/igarss.2003.1295516; Crosetto M., Monserrat O., Cuevas-González M., Devanthéry N. and Crippa B., "Persistent scatterer interferometry: A review," *ISPRS Journal of Photogrammetry and Remote Sensing* 115 (2016): 78-89. DOI: 10.1016/j.isprsjprs.2015.10.011.

6 Berardino P., Fornaro G., Lanari R. and Sansosti E., "A new algorithm for surface de-

originally developed by researchers at IREA-CNR in 2001, can provide accurate spatial and temporal information on surface displacements occurring over a given time interval along the investigated area, through the generation of displacement time series and mean deformation velocity maps starting from large sequences of satellite SAR images.

A key point of the SBAS-DInSAR approach is its ability to follow the temporal evolution of the deformation phenomena at different spatial scales (small, large, and huge) by generating deformation time series at multiple spatial resolutions, commonly known as regional-scale and local-scale analyses[7]. The former enables the extraction of average LOS displacement measurements over areas extending across several hundred square kilometers, whereas the local-scale SBAS analysis allows for a more detailed investigation over specific areas of interest, making it possible to detect even highly localized deformation patterns, such as those affecting transport infrastructures, buildings, or single parts of them[8].

Over the past twenty years, the SBAS-DInSAR technique has proven to be an effective tool for supporting land monitoring and protection activities, thanks to its ability to monitor both natural (such as those related to hydrogeological instability, seismic events, and volcanic activity) and anthropogenic surface deformations, as those associated with ground subsidence/uplift in highly urbanized areas with related consequences for the stability of buildings and infrastructures. Today, the new frontier of research is moving toward the effective use and application of advanced DInSAR techniques in operational contexts[9], such as infrastructure monitoring, risk management, and decision-support processes. This requires, on the one hand, the development of updated interferometric processing techniques and, on the other

formation monitoring based on small baseline differential SAR interferograms". *IEEE Transactions on Geoscience and Remote Sensing* 40/11 (2022): 2375-2383.

7 Lanari, R., Mora O., Manunta M., Mallorquì J. J., Berardino P. and Sansosti E., "A Small-Baseline approach for investigating deformations on full-resolution differential SAR interferograms". *IEEE Transactions on Geoscience and Remote Sensing* 42/7 (2004): 1377-1386.

8 Manunta M., Marsella M., Zeni G., Sciotti M., Atzori S. and Lanari R., "Two-scale surface deformation analysis using the SBAS-DInSAR technique: A case study of the city of Rome, Italy". *International Journal of Remote Sensing* 29/6 (2008): 1665-1684.

9 Giudicepietro F. *et al.*, "First evidence of a geodetic anomaly in the *Campi Flegrei Caldera* (Italy) ground deformation pattern revealed by DInSAR and GNSS measurements during the 2021-2023 escalating unrest phase". *International Journal of Applied Earth Observation and Geoinformation* 132 (2024), 104060. DOI: 10.1016/j.jag.2024.104060; Scifoni S. *et al.* "On the joint exploitation of long-term DInSAR time series and geological information for the investigation of ground settlements in the town of Roma (Italy)". *Remote Sensing of Environment* 182/9 (2016): 113-127. DOI: 10.1016/j.rse.2016.04.017.

hand, the efficient use of advanced High Performance Computing (HPC) infrastructures to effectively manage and process large sequences of interferometric SAR data and, where appropriate, extract value-added information from the advanced DInSAR products generated.

Within this framework, a parallel and automated algorithmic solution of the SBAS technique, known as Parallel Small BAseline Subset (P-SBAS) approach[10], has recently been developed for medium spatial resolution analyses for regional- and continental-scale applications and has been successfully applied in numerous scientific and operational contexts[11]. This approach is based on the use of distributed HPC computing infrastructures, also accessible through cloud computing environments[12], and on multi-node, multi-core, and multi-thread parallel computing strategies aimed at the automatic and parallel processing of large interferometric stacks at medium spatial resolution. Unfortunately, the size of full spatial resolution SBAS datasets, which may include hundreds or thousands of interferometric data pairs and hundreds of millions of pixels to be processed at the full spatial resolution of the exploited SAR sensors, is approximately two orders of magnitude larger than that of typical medium-resolution datasets. This can have a significant impact on the overall computation time and on efficient SAR data management, representing a real bottleneck if addressed with conventional implementation approaches.

Therefore, to improve the processing times resulting from the SBAS-DInSAR processing chain aimed at investigating full resolution SAR images, and to achieve high efficiency in terms of scalability and computational performance, a recently developed algorithmic solution called Full Resolution

10 Casu F. *et al.,* "SBAS-DInSAR parallel processing for deformation time-series computation". *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 7/8 (2014). DOI: 10.1109/JSTARS.2014.2322671; Manunta M., De Luca C., Zinno I., Casu F., Manzo M., Bonano M., *et al.,* "The Parallel SBAS Approach for Sentinel-1 Interferometric Wide Swath Deformation Time-Series Generation: Algorithm Description and Products Quality Assessment". *IEEE Transactions on Geoscience and Remote Sensing* 57 (2019): 6259-6281. 10.1109/TGRS.2019.2904912.

11 Lanari R. *et al.,* "Automatic generation of Sentinel-1 continental scale DInSAR deformation time series through an extended P-SBAS processing pipeline in a cloud computing environment". *Remote Sensing* 12/18 (2020), 2961. DOI: 10.3390/RS12182961; Festa D. *et al.,* "Nation-wide mapping and classification of ground deformation phenomena through the spatial clustering of P- SBAS InSAR measurements: Italy case study". *ISPRS Journal Photogrammetry Remote Sensing* 189 (2022): 1-22. DOI: 10.1016/j.isprsjprs.2022.04.022.

12 Zinno I., Casu F., De Luca C., Elefante S., Lanari R. and Manunta M., "A cloud computing solution for the efficient implementation of the P-SBAS DInSAR approach". *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 10/3 (2017): 802-817.

Parallel-SBAS (FR P-SBAS)[13] has further expanded the ability to investigate and monitor localized displacement phenomena over very large areas associated with both natural and anthropogenic risk scenarios, enabling the generation of displacement time series at the maximum spatial resolution of the exploited SAR data. This methodology is based on the large use of HPC computing architectures, as well as parallelization techniques based on Graphics Processing Units (GPUs), aimed at analyzing, within limited time frames and with high computational efficiency, a wide range of deformation phenomena associated with the built-up environment. In particular, the FR P-SBAS technique is especially suited to detecting highly localized displacements affecting individual buildings and infrastructures in anthropogenic risk contexts, with significant application benefits in the fields of geotechnics, urban area monitoring, and the safety of infrastructures and bridges.

2. The Full Resolution P-SBAS Processing Chain

The FR P-SBAS processing chain is designed to generate advanced DInSAR products at the full spatial resolution of the SAR sensors (mean deformation velocity maps and, for each single coherent pixel, full resolution deformation time series), by leveraging both single-look (SL) full-resolution differential interferograms and medium-resolution interferometric results derived from the multi-look (ML) interferograms used in regional-scale P-SBAS analysis. In figure 1, the scheme of the simplified block diagram of the FR P-SBAS processing chain is shown, highlighting the four main macro-blocks of the multi-temporal FR P-SBAS interferometric approach[14], aimed at generating deformation time series at full spatial resolution. The first step of the pipeline is relevant to the estimation of the High Pass (HP) residual interferometric phase components, carried out by applying the modulo-2π subtraction of the medium-resolution DInSAR products derived from the regional scale analysis (low-pass deformation, orbital ramps, Atmospheric Phase Screen, etc.) from the full resolution differential interferograms $\Delta\phi^{FR}$. This allows us to get an estimate, on a pixel-by-pixel basis, of the HP residual interferometric components $\Delta\phi_i^{HP}$, as in figure 1, made up of both linear and non-linear phase terms. To properly retrieve the HP residual linear (with respect to $b_i^{\perp}$, $\Delta\,\xi_i$, Δt_i and ,

13 Bonano M. *et al.,* "New Advances of the P-SBAS Approach for an Efficient Parallel Processing of Large Volumes of Full-Resolution Multitemporal DInSAR Interferograms". *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 18 (2025), 2317-2341, doi: 10.1109/JSTARS.2024.3507542.

14 *Ibidem*.

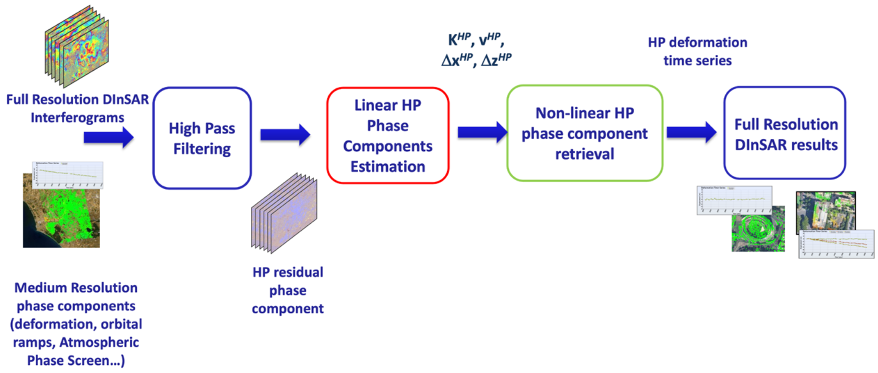


Fig. 1 – *Simplified block diagram of the Full Resolution P-SBAS processing chain. The blue blocks (first and fourth) represent the steps based on multi-core parallelization strategies; the red (second) and green (third) ones, instead, highlight the new fine-grained parallel steps of the FR P-SBAS pipeline implemented with GPU CUDA architectures.*

ΔT_i) phase components, a phase unwrapping step is carried out on a pixel basis (see red block in figure 1) by estimating the linear HP phase terms through the maximization of the temporal coherence factor γ[15].

Once the residual linear phase components are estimated, in correspondence to the pixels where the temporal coherence value γ is greater than a selected threshold, they are modulo-2π subtracted from $\Delta\phi_i^{HP}$, thus obtaining the non-linear HP deformation phase term. It can be reasonably assumed that the resultant HP deformation time series is restricted within the (-π,π] interval; therefore, the non-linear deformation $d^{nonlinear}$ is retrieved without requiring any additional phase unwrapping operation by applying the SVD method (green block in figure 1). Finally, the linear and non-linear deformation components together with the thermal dilation factor k^{HP} associated with single structure deformation phenomena are added up to the medium resolution measurements to reconstruct the overall full resolution DInSAR results (FR displacement time series).

The FR P-SBAS processing chain has deeply demonstrated its effectiveness for investigating and monitoring localized displacements in the built-up environment at the scale of single buildings and infrastructures. Nevertheless, to move from a single building to a regional/national scale full resolution analysis, which requires hundreds of millions of pixels to be processed, we performed an important re-design of the parallel full resolution processing

15 Bonano M. *et al.*, “Long term ERS/ENVISAT deformation time-series generation at full spatial resolution via the extended SBAS technique”. *International Journal of Remote Sensing* 33 (2012): 4756-4783.

chain, aimed at exploiting innovative hardware and software parallel solutions to speed up the processing. In this way, it is possible to generate, in short time frames, advanced full resolution DInSAR deformation time series, guaranteeing good scalability and high quality of the retrieved interferometric products[16]. In particular, the most computationally intensive blocks of the full spatial resolution P-SBAS chain (central blocks highlighted in red and green in figure 1), where more traditional parallelization strategies based on multi-core/multi-node CPU-only techniques were originally applied (with poor efficiency in terms of computation time and data load balancing), have been completely re-engineered from an algorithmic point of view and implemented to fully exploit parallel computing architectures such as GPUs. These architectures are capable of effectively handling and processing enormous volumes of full resolution DInSAR data sequences, ensuring high efficiency in terms of processing speed, computational load, and scalability performance.

3. The FR P-SBAS Analysis OverExtended Built-up Environments

We present the main results relevant to the deformation analyses, related to extended built-up environments, achieved through the FR P-SBAS approach carried out by processing large stacks of SAR datasets over the urban areas of Rome and Verona.

In this context, the use of high- and very-high resolution SAR sensors (from about 10 m down to less than 1 m) makes it possible to fully exploit the capabilities of the FR P-SBAS approach for mapping and monitoring localized displacements associated with infrastructures and individual buildings in large urban areas, with millimetric accuracy. Among these, the X-band satellite SAR data (with 3.1 cm wavelength) acquired by the first- (CSK) and second- (CSG) generation of the COSMO-SkyMed constellation of the Italian Space Agency (ASI) through the Map Italy program[17] are certainly the most suitable for this kind of application. Thanks to their high spatial resolution (approximately 3 m in the so-called Stripmap mode, both along the direction parallel to the flight direction -azimuth- and along the perpendicular direction -range), these sensors are strategic for detailed mapping and monitoring, representing a valuable tool for the analysis of localized deformation phenomena in large urban areas at the scale of indi-

16 Bonano M. *et al.,* "New Advances of the P-SBAS Approach for an Efficient Parallel Processing of Large Volumes of Full-Resolution Multitemporal DInSAR Interferograms", op. cit.

17 ASI, Italian Space Agency, *Upgrades Access To MAPITALY Data*, https://www.asi.it/en/2023/12/asi-italian-space-agency-upgrades-access-to-mapitaly-data [accessed on 1/12/2023].

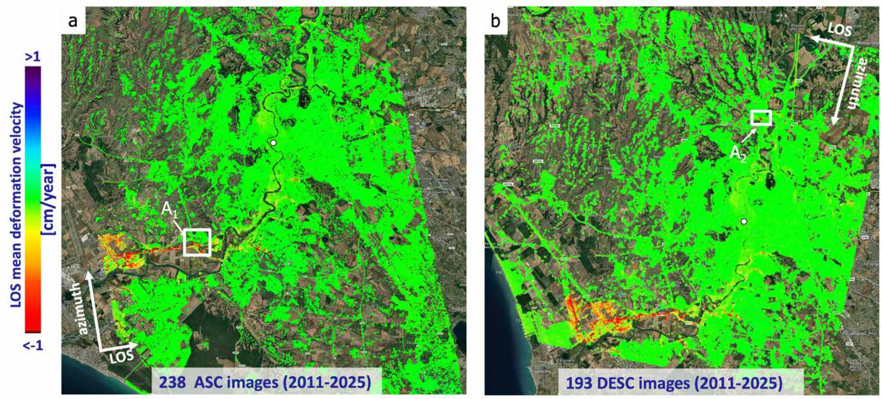


Fig. 2 – *Geocoded maps (in false colors) of LOS mean deformation velocities, in [cm/year], obtained from the FR P-SBAS processing of CSK/CSG data acquired from ascending (a) and descending (b) orbits for the extended area of Rome, each referred to its own temporal interval. The maps are overlaid on two optical images of the analyzed area. The white circle represents the reference point, located close to the Colosseum area. The areas in the white rectangles identified with A1 and A2 correspond to the zoomed views of figure 3.*

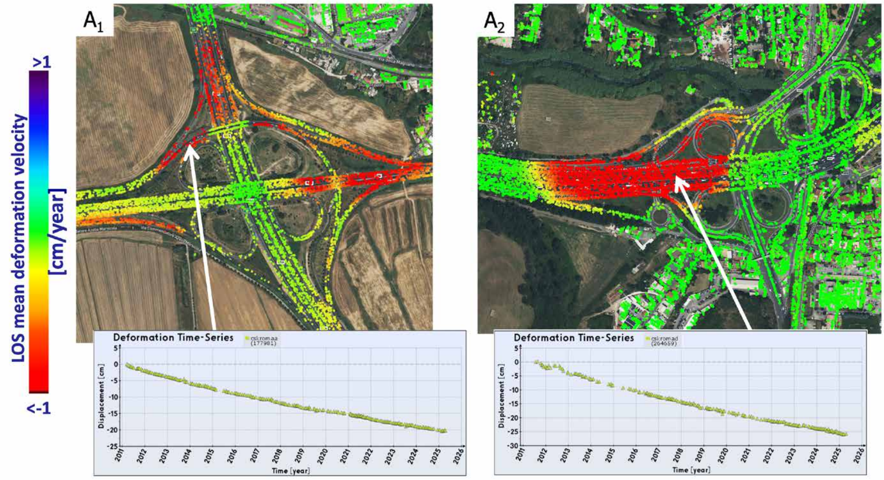


Fig. 3 – *Zoomed views of the FR P-SBAS results relevant to the Roma-Fiumicino Airport A90-A91 highway (A1) and the ring-shaped Grande Raccordo Anulare (GRA) motorway (A2), highlighted in the white rectangles in figure 2. For both areas the deformation time series of selected coherent pixels are also shown in the two plots.*

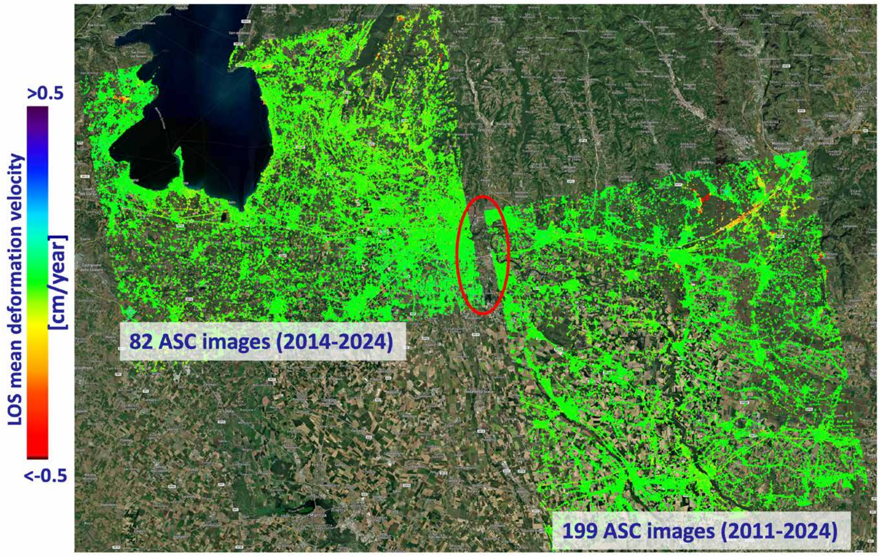


Fig. 4 – *Geocoded maps (in false colors) of LOS mean deformation velocities obtained from the FR P-SBAS processing of the CSK and CSG data, ascending orbits, for the area of Verona, each referred to its own track and temporal interval. The red circle represents the area within the Verona municipality with missing information.*

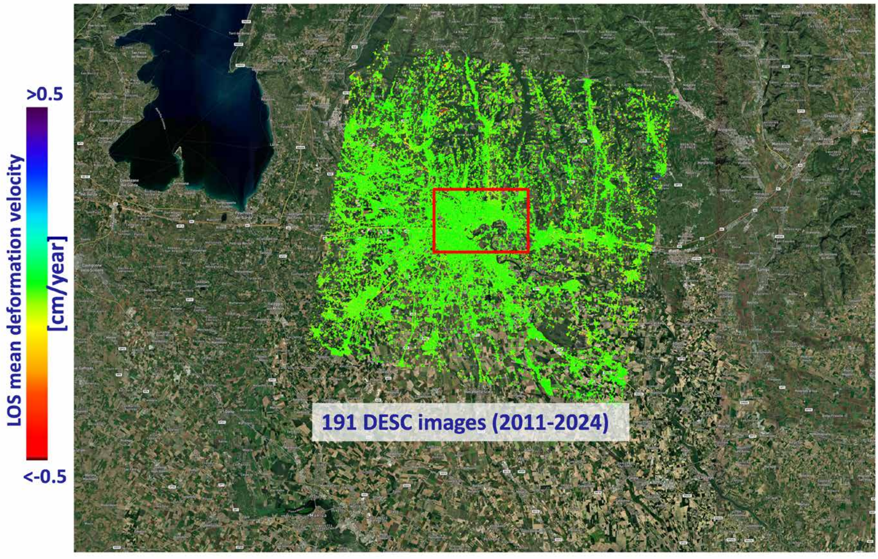


Fig. 5 – *Geocoded map (in false colors) of the LOS deformation velocity obtained from the FR P-SBAS processing of the CSK/CSG data, descending orbits, over Verona in the 2011 – 2024-time interval. The red rectangle represents the area investigated in the zoomed view of figure 6.*

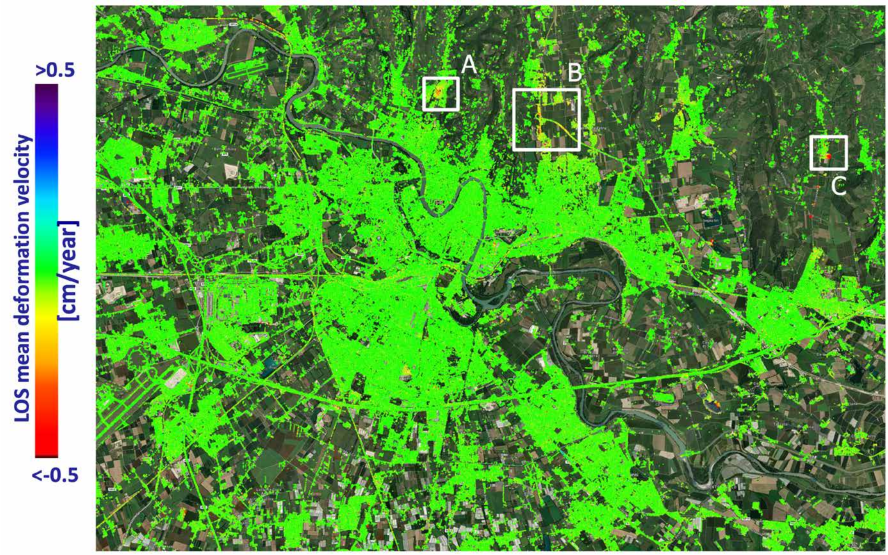


Fig. 6 – *Zoomed view of the FR P-SBAS results relevant to the Verona municipality, highlighted in the red rectangles in figure 5. The white rectangles labelled as A, B and C correspond to the zoomed view of figure 7.*

vidual buildings, with the capability to detect even differential movements (intra-building movements) associated with single buoldings or portions of them.

3.1 The Rome Case Study

The first case study is relevant to the city of Rome (Italy). With this respect, two sets of SLC (Level L1) images were identified: the first consists of 238 CSK/CSG SLC images from ascending orbits covering the period from March 2011 to April 2025, and the second consists of 193 descending CSK/CSG SLC images spanning the interval from July 2011 to April 2025.

The processing of these CSK/CSG datasets through the FR P-SBAS approach allowed us to generate, for the entire area of interest, the main advanced interferometric products, which consist of mean displacement velocity maps for the whole area and, for each coherent point (i.e., with temporal coherence values greater than 0.35), the corresponding full resolution LOS deformation time series. Figure 2 shows the LOS mean deformation velocity maps for ascending (figure 2a) and descending (figure 2b) orbits, for the whole metropolitan area of Rome, each referred to its own temporal interval. The information relevant to the mean deformation velocity was geocoded and overlaid (in false colors) on an optical image of the area; the pixels where the deformation measurement is affected by decorrelation noise are excluded from the false-color map. Finally, the reference point of the FR P-SBAS processing is located close to the Colosseum area in the historic city center.

In this FR P-SBAS analysis, several subsiding zones with a deformation rate of more than 1 cm/year can be distinguished, such as the Roma-Fiumicino Airport highway (A1 in figure 3) and the *Grande Raccordo Anulare* (GRA) motorway (A2 in figure 3). These findings, very likely due to the natural consolidation of the alluvial deposits, are in general agreement with those presented in other works and confirm the capability of the implemented FR P-SBAS processing chain to generate long-term full resolution deformation time series.

3.2 The Verona Case Study

The second case study is relevant to the city of Verona (Northern Italy). In this context, the selected CSK/CSG SLC datasets collected from ascending and descending orbits over the city of Verona and processed through the FR P-SBAS approach are relevant to three different tracks: two ascending and one descending orbit, respectively. Indeed, the selected descending track is well centered with respect to the city center; on the contrary, no single ascending frame was able to fully cover the entire city; accordingly, we had to select and process two CSK/CSG ascending datasets relevant to two adjacent ascending tracks. In particular, the first ascending dataset consists of 199 SAR data, mainly covering the South-Eastern part of Verona, which is made of 170 CSK (track HI-04) and 29 CSG (track STR-006) SLC images related to the period from April 2011 to March 2024. The second ascending one is smaller with respect to the previous one in terms of the number of SAR images, and covers the Western part of Verona up to Lake Garda. It consists of 82 CSK (track HI-03) SLC images, with no CSG data, covering the August 2014-January 2024 time interval. The last dataset is the descending one, which perfectly covers the whole city, and is made of 191 SAR data with 154 CSK (track HI-05) and 37 CSG (track STR-007) SLC images related to the period from May 2011 to February 2024.

The FR P-SBAS processing of such huge datasets required a large HPC infrastructure, made available through the IREA-CNR facilities, and the efficient exploitation of parallel hardware and software architectures. In particular, the availability of GPU-accelerated computing resources allowed the management of large data volumes and the generation of a huge number of full resolution DInSAR interferograms, ensuring reduced processing times while preserving

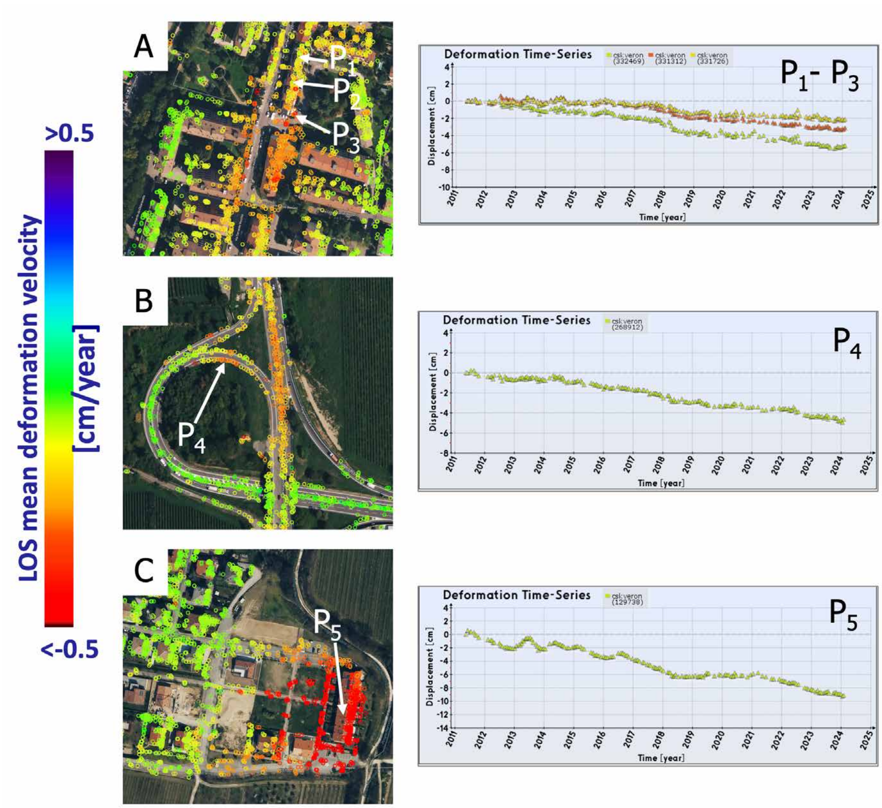


Fig. 7 – *Zoomed views of the FR P-SBAS results shown in the white rectangles in Fig. 06, corresponding to: A) a differential settlement of an urban area North of Verona; B) a transport infrastructure; and C) the effect of soil compaction with a non-linear displacement behaviour near the town of Marcellise. The plots of the LOS FR displacement time series for some coherent pixels (from P1 toP5) are also reported in the corresponding graphs.*

full spatial resolution. This permitted the generation of advanced interferometric products over the entire urban area of Verona, including mean deformation velocity maps and full resolution LOS deformation time series for all coherent (from an interferometric viewpoint) targets, thus enabling an accurate characterization of ground deformation phenomena at the scale of individual buildings and infrastructures.

For both the ascending and the descending datasets, geocoded maps of the mean LOS deformation velocity were produced over the entire investigated area (see figure 4 and figure 5).

These maps, expressed in cm/year, provide a synoptic view of the spatial distribution of ground motion, clearly highlighting both stable zones (represented in green in the false-color maps) and areas affected by localized deformation phenomena (depicted in red color). By processing the two selected adjacent ascending tracks, the largest part of the Verona municipality was covered, except for the central part of the historical city center. This is clearly visible in figure 4, where the geocoded LOS deformation velocity maps relevant to both ascending tracks are reported; the red circle between the adjacent frames highlights the missing area.

Overall, the achieved FR P-SBAS results for the Verona case study demonstrate the capability of the approach to provide reliable, high-resolution deformation mapping and monitoring over complex urban environments, supporting long-term geohazard assessment and infrastructure monitoring applications. In particular, we focus on the descending CSK/CSG dataset, which fully covers the Verona urban area, and investigate the possible deformation signals of the FR P-SBAS analysis.

In figure 6, the zoomed view of the geocoded LOS mean deformation velocity map of the descending dataset is shown. The high spatial resolution of the X-band SAR sensors allows detecting a large number of coherent points within the P-SBAS velocity maps. The FR P-SBAS results do not show any significant regional deformation pattern, thus revealing a general stable behaviour of the entire urban area. Instead, we can detect some clusters of coherent pixels, characterized by a temporal coherence value larger than 0.35, exhibiting a subsidence of a few mm/year embedded within predominantly stable behaviour. This is consistent with deformation mechanisms typically associated with urban environments, as differential settlement, soil compaction, or infrastructure-related effects (as we can see in figure 7).


Fiume

From MT-DInSAR Data Elaboration to Structural Vulnerability Scenarios

Andrea Miano[1], *Carlo Del Gaudio*[2], *Luisa Berto*[3], *Diego Alejandro Talledo*[3]

The structural vulnerability assessment of large building portfolios increasingly requires integrated methodologies capable of combining engineering-based seismic models with continuous, wide-area observations of the built environment. In this perspective, vulnerability is not only a static attribute derived from typological classification and structural modelling, but a dynamic quantity that can be progressively refined as new evidence becomes available, including monitoring-derived information on long-term deformation trends. Satellite multi-temporal interferometry (MT-DInSAR) provides such evidence by enabling the remote measurement of millimetric ground and structural displacements over multi-year time windows, thus revealing slow kinematic processes such as settlements, differential movements or slope-related instabilities, which may act as precursors of damage or as pre-existing degradation conditions that influence seismic performance. In parallel, probabilistic seismic risk frameworks based on faceted building taxonomies and standardized fragility models offer an effective way to scale vulnerability assessment at urban and district level, balancing the need for representativeness with the limited availability of detailed structural information.

This chapter therefore presents a unified workflow that bridges these two domains: starting from MT-DInSAR data elaboration and interpretation, deformation indicators are extracted and used as a support tool for structural assessment; subsequently, buildings are classified through the GED4ALL taxonomy and associated with ESRM20 fragility functions to generate probabilistic damage and loss scenarios under seismic input. Finally, the framework is extended to account for the effect of slow-moving settlements, showing how monitoring-derived deformation patterns can be incorporated as a rational ba-

1 Pegaso Telematic University, Department Engineering, Naples, Italy.
2 University of Naples Federico II, Department of Structures for Engineering and Architecture.
3 University IUAV of Venice, Department of Culture of the Project.

sis to update seismic fragility curves, thus enabling a more realistic and time-dependent representation of vulnerability in complex urban environments.

1. MT-DInSAR Data: Interpretation and Analysis

Satellite Synthetic Aperture Radar (SAR) is an active microwave remote sensing technology that enables systematic observations of the Earth's surface by transmitting electromagnetic pulses and measuring the backscattered signal, acquiring complex-valued images in which both amplitude and phase are stored. Since SAR sensors operate independently of sunlight and can acquire data in almost all-weather conditions, they represent a uniquely robust source of information for continuous monitoring campaigns, especially when long time series are needed and when optical imagery is strongly limited by atmospheric conditions. SAR images are acquired by side-looking sensors along the satellite flight direction (azimuth) and along the viewing direction (range), and their geometry differs from that of optical images due to intrinsic distortions such as foreshortening, layover and shadowing, which affect visibility and interpretation in dense urban environments and steep topography[4]. Over the last decades, several satellite constellations have provided SAR datasets suitable for interferometric analysis, including ERS-1/2, ENVISAT, COSMO-SkyMed and Sentinel-1, with different wavelengths and spatial resolutions, enabling the investigation of deformation phenomena at multiple scales.

By exploiting the phase information of repeated SAR acquisitions, Differential SAR Interferometry (DInSAR) and its evolutions enable the measurement of surface displacement between observations. The physical principle is that the phase difference between two acquisitions contains information about changes in the sensor-target distance; after removing the phase contribution of topography (typically using a digital elevation model), the residual interferometric phase can be interpreted as a displacement signal[5]. To overcome the limitations of conventional two-image

4 Bamler R. and Hartl P., "Synthetic Aperture Radar Interferometry". *Inverse Problems* 14/4 (1998): 1-54. DOI/URL 10.1088/0266-5611/14/4/00; Hanssen Ramon F., *Radar Interferometry: Data Interpretation and Error Analysis*. Dordrecht: Kluwer Academic Publishers, 2001. DOI/URL 10.1007/0-306-47633-9.

5 Bamler R. and Hartl P., "Synthetic Aperture Radar Interferometry", op. cit; Rosen P. A., Hensley S., Joughin I.R., Li Fuk K., Madsen S. N., Rodriguez E. and Goldstein R. M., "Synthetic Aperture Radar Interferometry". In *Proceedings of the IEEE* 88/3 (2000): 333-382. DOI/URL 10.1109/5.838084.

DInSAR – particularly the sensitivity to temporal decorrelation and atmospheric artifacts – advanced multi-temporal interferometric approaches (MT-DInSAR) have been developed, capable of producing stable and accurate displacement information through the combined processing of large datasets (often tens to hundreds of acquisitions). These approaches include families of methods commonly referred to as Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS) techniques, introduced and consolidated in the early 2000s and now widely adopted in both scientific and operational contexts[6].

It is important to note that interferometric measurements are not direct absolute ground movements: they are differential both in time (with respect to a selected reference acquisition) and in space (with respect to a selected reference point, which represents a target on the ground that is assumed as stable). As a consequence, the measured deformation should always be interpreted as a relative variation, consistent with the chosen temporal and spatial reference, and systematic biases may arise if the reference point selected is not truly stable. Additionally, the measurement is inherently directional: the interferometric displacement is retrieved as the component projected along the satellite Line of Sight (LOS), i.e., the direction joining the sensor to the target, and therefore represents a one-dimensional projection of an actual three-dimensional motion. This is a central aspect for engineering interpretation, since it implies that the same observed LOS velocity may correspond to different physical kinematics depending on the local geometry and on the actual dominant direction of movement[7].

The outputs of interferometric MT-DInSAR methods typically are represented as a georeferenced cloud of measurement points (often referred to as Persistent Scatterers, PS), each associated with geographic coordinates and elevation in a global reference system (e.g., WGS84), the mean LOS velocity, and the corresponding time series of cumulative LOS di-

6 Ferretti A., Prati C. and Rocca F., "Nonlinear Subsidence Rate Estimation Using Permanent Scatterers in Differential SAR Interferometry". *IEEE Transactions on Geoscience and Remote Sensing* 38/5 (2000): 2202-2212. DOI: DOI/URL 10.1109/36.868878; Ferretti A., Prati C. and Rocca F., "Permanent Scatterers in SAR Interferometry." *IEEE Transactions on Geoscience and Remote Sensing* 39/1 (2001): 8-20. DOI: DOI/URL 10.1109/36.898661; Berardino P., Fornaro G., Lanari R. and Sansosti E., "A New Algorithm for Surface Deformation Monitoring Based on Small Baseline Differential SAR Interferograms". *IEEE Transactions on Geoscience and Remote Sensing* 40/11 (2002): 2375-2383. DOI/URL 10.1109/TGRS.2002.803792.

7 Talledo D., Miano A., Bonano M., *et. al*., "Satellite radar interferometry: Potential and limitations for structural assessment and monitoring". *Journal of Building Engineerng* 46, 103756 (2022). DOI: DOI/URL 10.1016/j.jobe.2021.103756.

splacement. The spatial uncertainty of each point is linked to the sensor resolution cell: depending on the satellite and acquisition mode, the radar resolution may range from a few meters to several tens of meters, and therefore each measurement point should not be interpreted as a "dimensionless" instrument but rather as a stable coherent response associated with a ground patch controlled by resolution and scattering mechanisms. Modern datasets commonly include, together with velocity and displacement time series, the LOS geometry information (e.g., direction cosines of the LOS versor), enabling physically consistent projection operations and the combination of multiple viewing geometries – when available – to estimate displacement components such as vertical and East-West deformation. Indeed, when interferometric observations are available from both ascending and descending geometries, the LOS displacement measurements can be combined to estimate at least a partial decomposition of the displacement field. In the general form, the LOS measurements for a given geometry k can be expressed as the projection of the 3D displacement vector $\mathbf{d} = [d_E\ d_N\ d_U]^T$ (the subscripts E, N and U representing respectively East-West, North-South and Vertical direction) onto the corresponding LOS unit vector $\mathbf{n}_k=[n_{E,k}\ n_{N,k}\ n_{U,k}\ ]^T$ whose components represent the cosine directors:

$$d_{LOS,k} = n_{E,k}d_E + n_{N,k}d_N + n_{U,k}d_U$$

Considering only one sensor constellation (like for instance Cosmo-SkyMed or Sentinel-1 Constellations) the results are given for two distinct geometries, ascending and descending (therefore in previous equation k is equal to ASC or DES). In this way the following system of two equations can be written:

$$\begin{cases} d_{LOS,ASC} = n_{E,ASC}d_E + n_{N,ASC}d_N + n_{U,ASC}d_U \\ d_{LOS,DES} = n_{E,DES}d_E + n_{N,DES}d_N + n_{U,DES}d_U \end{cases}$$

which is an underdetermined system. In practical applications, because conventional SAR acquisition geometries provide limited sensitivity to the North-South direction (indeed the LOS is mainly sensitive to vertical and East-West components), it is commong to neglect the component d_N assuming it is small respect to the other components. Under this simplifying assumption, the problem redusces to two equations in two unknowns that can be written in matrix form as:

$$\begin{bmatrix} d_{LOS,ASC} \\ d_{LOS,DES} \end{bmatrix} = \begin{bmatrix} n_{E,ASC} & n_{U,ASC} \\ n_{E,DES} & n_{U,DES} \end{bmatrix} \begin{bmatrix} d_E \\ d_U \end{bmatrix}$$

The validity of the decomposition depends on the consistency of the reference definition and on the spatial correspondence of the scatterers (or their aggregates) between ascending and descending datasets, which should be carefully addressed in dense urban contexts, where different viewing geometries may illuminate different radar scatterers even over the same structural asset.

The interpretation and engineering use of MT-DInSAR measurements require a careful discussion of uncertainties and limitations, which originate from both the radar acquisition geometry and the processing assumptions. The dominant sources of uncertainty include atmospheric phase delays, residual orbital and topographic errors, noise due to decorrelation, and limitations in phase unwrapping and deformation modeling[8]. From an operational standpoint, three main uncertainty components are particularly relevant: (1) georeferencing accuracy, i.e., the positional uncertainty of measurement points in plan and elevation (often of the order of meters), which affects the association of radar targets to individual structural elements; (2) mean velocity uncertainty, which can reach the order of 1-2 mm/year in well-conditioned multi-temporal products; and (3) displacement time-series uncertainty, typically a few millimeters, though dependent on dataset characteristics and processing choices[9]. Moreover, since SAR is side-looking, visibility constraints and geometric distortions can strongly affect urban scenarios, generating spatially non-uniform measurement densities and leaving shadowed areas without data coverage. These limitations do not reduce the value of MT-DInSAR products; rather, they emphasize the need for dedicated data elaboration steps to transform the radar-derived point measurements into reliable indicators suitable for engineering-oriented interpretation, vulnerability screening, and scenario generation.

2. Results on the Verona Case Study Area

For the Verona case study, and specifically for the *Borgo Trento* district along the Adige riverfront, the use of satellite deformation measurements was conceived as an operational support for identifying and characterizing ongoing slow kinematic phenomena potentially relevant for structural vulnerability scenarios. The interferometric products were obtained through an MT-DInSAR

8 Hanssen Ramon F., *Radar Interferometry: Data Interpretation and Error Analysis*, op. cit.; Rosen P. A., Hensley S., Joughin I. R., Li Fuk K., Madsen S. N., Rodriguez E. and Goldstein R. M., "Synthetic Aperture Radar Interferometry", op. cit.

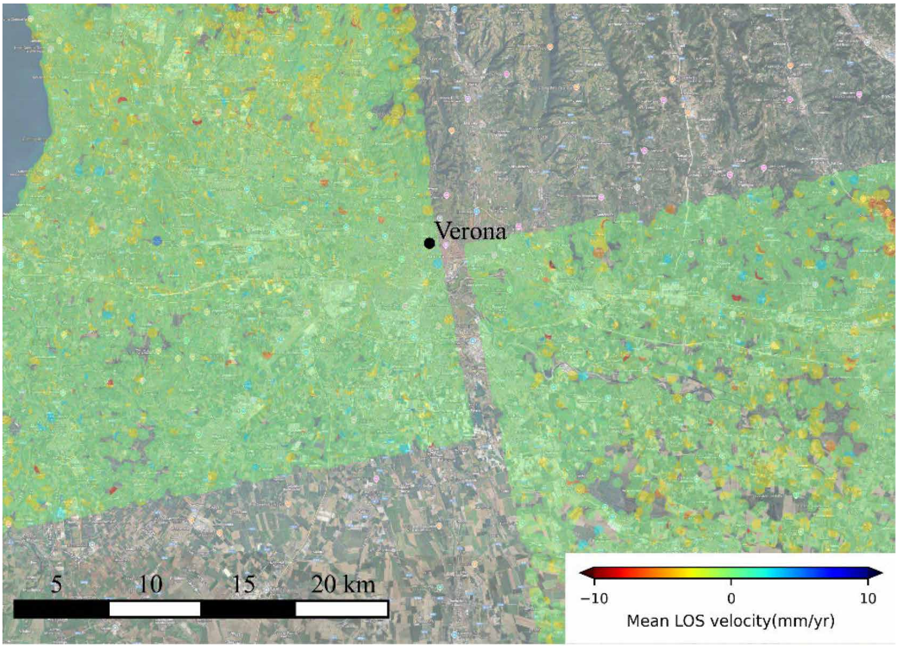
9 Crosetto M., Monserrat O., Cuevas-González M., Devanthéry N., and Crippa B., "Persistent scatterer interferometry: A review". *ISPRS Journal of Photogrammetry and Remote Sensing* 115 (2016): 78-89. DOI: 10.1016/j.isprsjprs.2015.10.011.

approach based on the Small Baseline Subset (SBAS) algorithm developed by CNR-IREA, applied to approximately 190 COSMO-SkyMed (CSK) Single Look Complex (SLC) images covering the period 2011-2024, with a standard spatial frame of roughly 40 km × 40 km. The outputs were delivered as tabular datasets in CSV format, organized into 16 strips, each containing a set of georeferenced measurement points (PS) associated with a sufficiently stable radar response. For each PS, the datasets include: geographic coordinates and topographic height, mean annual displacement velocity along the LOS, direction cosines describing the LOS unit vector, and the complete displacement time series spanning the full observation period.

A specific elaboration pipeline was then developed to transform these raw interferometric point clouds into structured information layers suitable for analysis, interpretation and visualization within a GIS/WebGIS environment. First, an ad-hoc importer was implemented to enable the bulk ingestion of the large number of CSV files generated by the SBAS procedure. The importer was realized through a Python routine based on PyQGIS libraries, designed to read, parse, standardize and reformat the tabular data into a structure consistent with the subsequent analyses. The processed points were therefore converted into a spatially indexed geodatabase, enabling efficient spatial querying, fast visualization, and systematic filtering/aggregation operations.

At the urban scale, PSs were first explored through velocity maps representing the distribution of the mean LOS deformation rate. These maps allow a rapid detection of spatial patterns and clusters of non-stable behavior. The results for the general area of Verona are depicted in figure 1 where negative values (in red) indicate movements away from the satellite, positive values (in blue) indicate movements towards the satellite, while gree indicate stable PSs. The outcomes highlighted an overall stable scenario over the historical center, with localized deformation signals in peripheral/morphologically complex sectors (e.g., mountainous areas north of the city and localized sectors in the urban fabric). Within the *Borgo Trento* area of interest, the point cloud density associated with CSK X-band acquisitions permitted a detailed view of the deformation field at the scale of individual blocks and waterfront buildings. Also from these results a substantially stable situation can be observed in figure 2.

To support multi-scale analysis and to optimize interactive exploration on the WebGIS platform, the point-based interferometric dataset was further transformed into a set of derived products through a grid-based spatial resampling (subsampling) strategy. In particular, a multi-resolution grid hierarchy was defined (cell sizes 100 m, 50 m, 25 m, 10 m and 5 m), enabling an adaptive representation of the deformation information depending on the visualization scale and computational requirements. For each grid cell (also referred to as



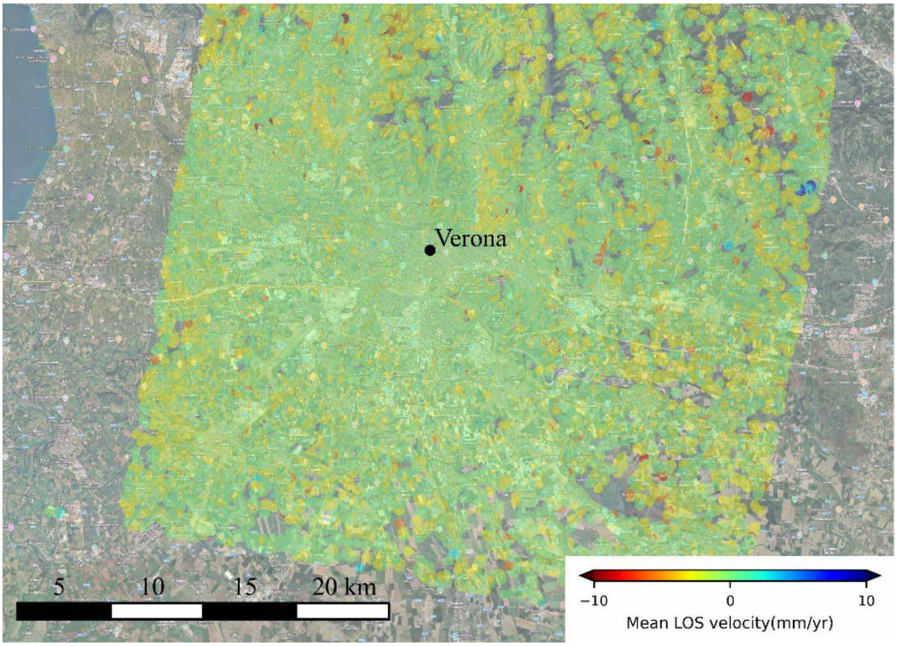


Fig. 1 – *Mean velocity along LOS in the area around Verona for: (top) ascending dataset; (bottom) descending dataset.*

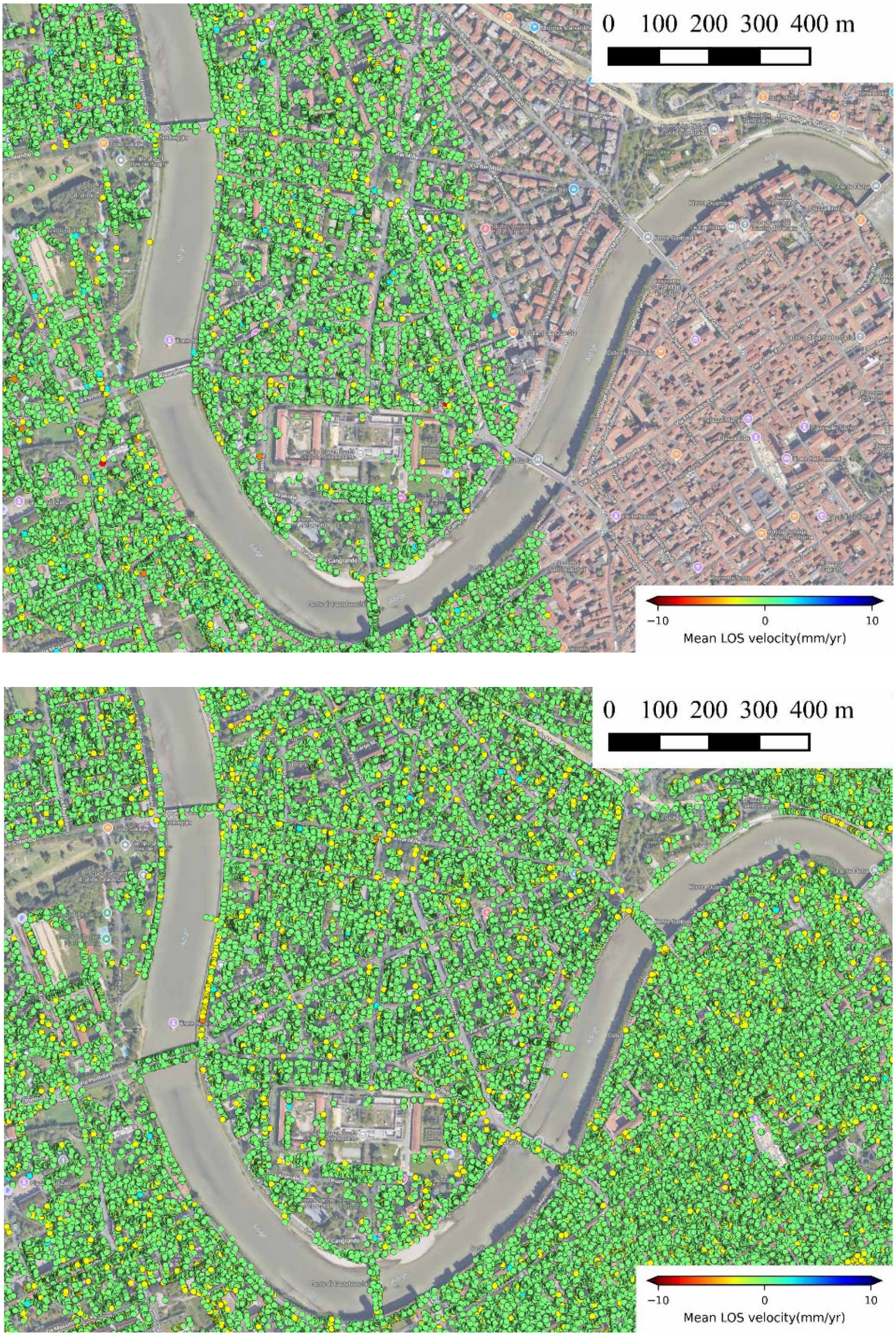


Fig. 2 – *Mean velocity along LOS in the study area of* Borgo Trento *for: (top) ascending dataset; (bottom) descending dataset.*

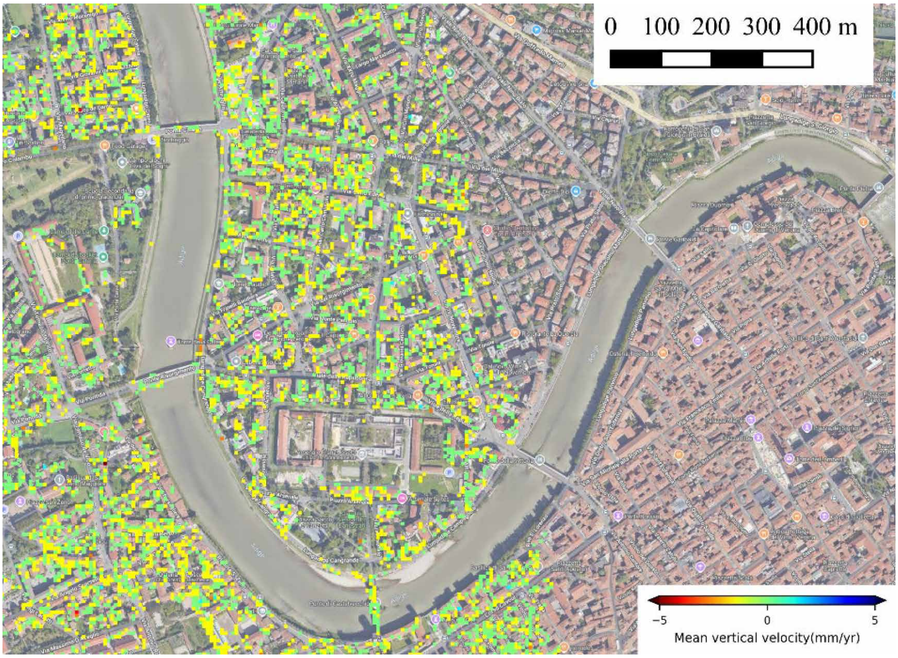
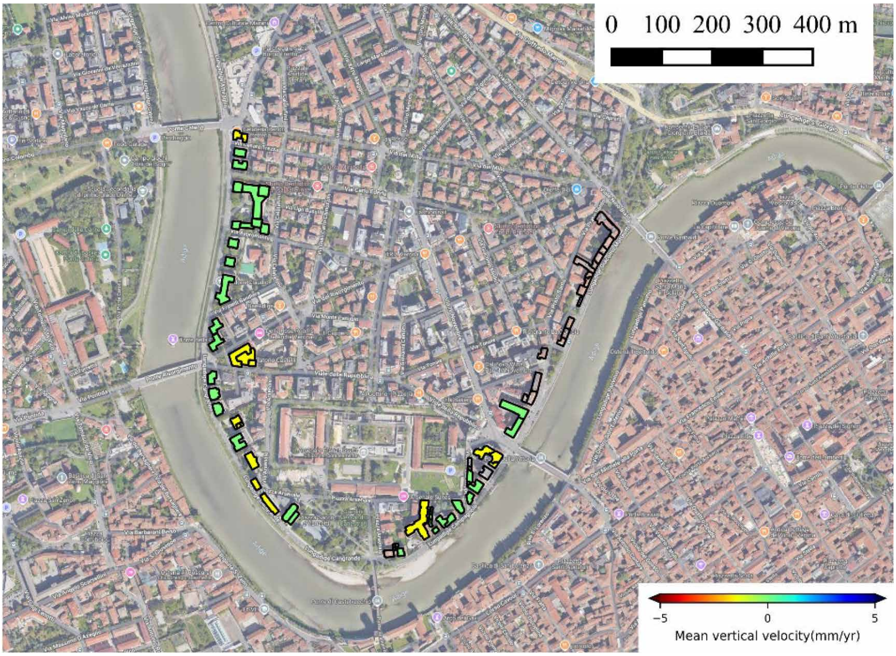


Fig. 3 – *Vertical velocity in the study area of* Borgo Trento *obtained by grid sub-sampling with grid size of 10 m.*

pixel), the pipeline computes the mean LOS velocity, and the entire displacement time series, both derived by averaging the values of all measurement points falling within the cell. This step serves multiple purposes: it reduces noise, provides spatial continuity useful for thematic mapping, and produces a harmonized raster-like product that can be efficiently handled in web applications without losing the temporal evolution of deformation. The resulting outputs can be displayed as velocity maps at any resolution and queried to retrieve representative time series for any portion of the urban territory. For the sake of example, the result for a grid size of 10 m is depicted in figure 3.

A further elaboration step addressed the combination of multiple viewing geometries. When both ascending and descending orbit datasets are available, the grid-based products were used as a common spatial support for coupling the two LOS measurements at cell level. This enables the estimation of the vertical and East-West components of deformation, thus providing a more interpretable representation of the deformation field than the LOS-based products. The outcome of this step is a set of thematic maps describing vertical and horizontal deformation patterns across the study area, which are particularly useful for interpreting potential settlement processes, riverbank-related instability, and differential building motion at urban scale.



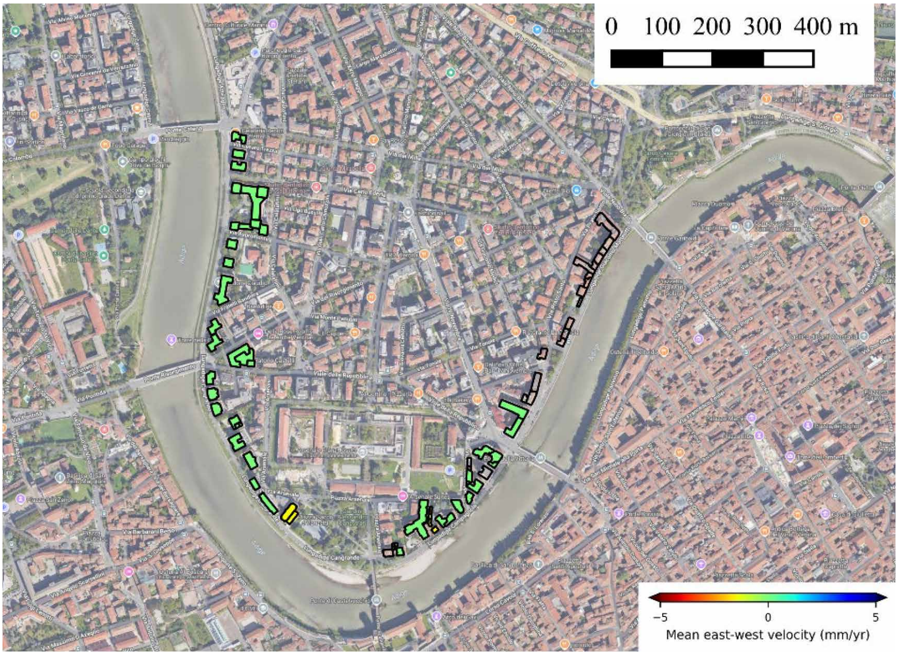


Fig. 4 – *Velocity components for the selected buildings in the study area: (top) Vertical; (bottom) East-West.*

Finally, to explicitly connect deformation measurements to the built environment, the pipeline included a building-based elaboration in which interferometric points were spatially associated with individual building polygons. This was achieved through GIS-based spatial joins between the PS database and the building inventory. Since the planimetric location of interferometric points is affected by a non-negligible uncertainty (order of meters), each building polygon was expanded by a suitable buffer compatible with the expected geolocation accuracy (for this dataset in the order of 2 m), ensuring that points physically attributable to the building façade/roof are not discarded due to small offsets. For each building unit, synthetic indicators were then computed, including the mean LOS velocity, its dispersion (standard deviation), and the average LOS geometry parameters. Where both orbit geometries are available, the same association step allows building-level estimates of the vertical and East-West deformation components. The results obtained for the *Borgo Trento* riverfront sample (43 building units) are depicted in figure 4. This analysis showed generally limited deformation rates, with only a few buildings presenting mean velocities exceeding approximately 1 mm/year, providing a quantitative basis for the subsequent scenario analysis and vulnerability refinement.

3.Procedure for Seismic Vulnerability Assessment of a Building Portfolio Using Faceted Taxonomies and Probabilistic Damage Scenarios

*3.1 Definition of Building Characteristics from Multiple Source*s

The first step of the procedure consists in constructing a base knowledge framework for each building unit, integrating geometric, structural, functional, and historical information derived from multiple sources. For the considered case study, documentary surveys were conducted by cross-referencing archival material, administrative records, historical cartography, and rapid visual inspections. This multi-source approach is essential for private residential buildings, where detailed design documentation is often unavailable.

Archival documents provide consistent information on construction period, original function, building evolution, and past interventions, while field surveys support the identification of current structural configuration, apparent material quality, and state of conservation. To ensure traceability and reliability, each attribute is associated with its source (documented, observed, or inferred).

A standardized set of informative parameters is defined to organize the collected data. These parameters include: urban position, plan and elevation regularity, number of storeys, roof type, ground-floor openings, construction period, occupancy, load-bearing system, construction materials, damage history, and maintenance level. This structured knowledge base represents the minimum dataset required for subsequent taxonomy assignment and vulnerability evaluation.

3.2 Assumption of Building Taxonomy According to GED4ALL

The collected building attributes are mapped onto the GED4ALL faceted taxonomy, which extends the original GEM framework to multi-hazard applications. GED4ALL describes buildings through independent facets such as construction material, lateral load-resisting system, height class, age, occupancy, plan and vertical irregularity, exterior walls, roof and floor systems, and foundation type.

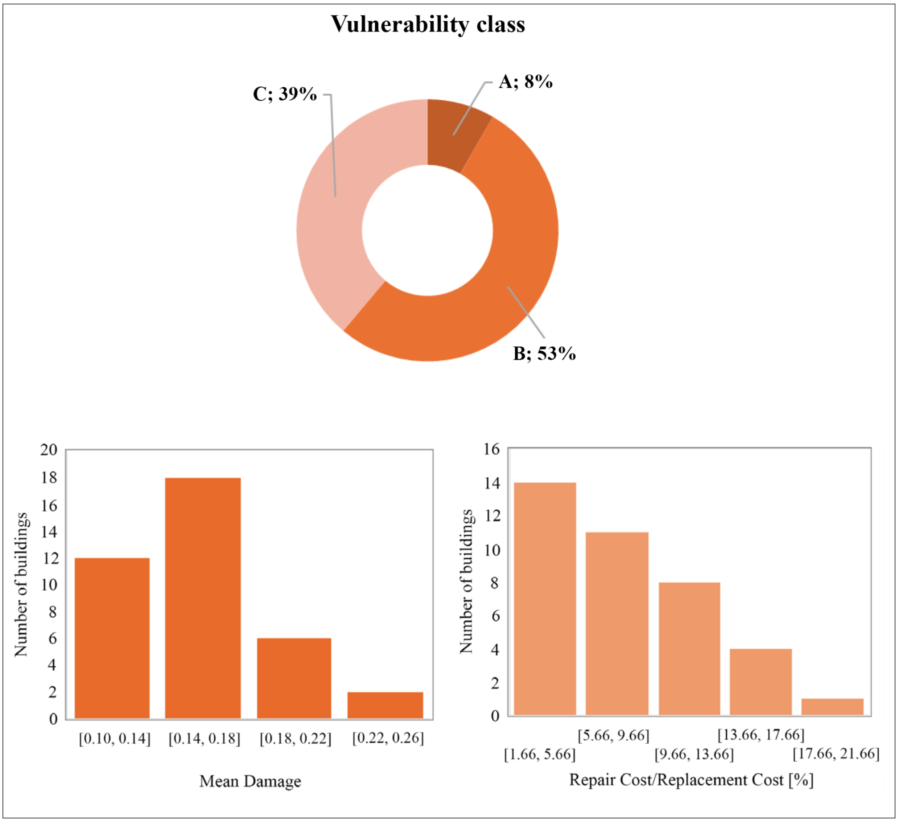
The use of a faceted taxonomy allows regional construction practices and historical specificities to be fully captured without forcing buildings into overly broad vulnerability classes. Each building is encoded through a taxonomy string, which acts as a compact yet comprehensive descriptor of its structural typology. This approach enables consistency across large inventories while preserving the possibility of refinement when additional data become available. Figure 5 shows the distribution of the vulnerability classes for the selected study area.

Given the scale of the analysis, only a subset of the available facets – those most influential on seismic response – is systematically employed. This pragmatic reduction ensures operational feasibility while maintaining engineering relevance.

3.3 Attribution of Fragility Curves from ESRM20

Structural vulnerability is quantified by assigning fragility functions derived from the European Seismic Risk Model 2020. ESRM20 classifies buildings according to construction material, lateral load-resisting system, ductility level, and height class. The primary materials considered include unreinforced and reinforced masonry, reinforced concrete, timber, steel, and composite systems.

Four discrete damage states are adopted: slight (DS1), moderate (DS2), extensive (DS3), and complete damage (DS4). Slight damage is assumed to initiate at 75% of the yielding displacement to account for non-structu-



Figg. 5-6 – *Vulnerability classes for the selected buildings (top) and mean damage and repair costs for the selected buildings (bottom).*

ral damage, while complete damage corresponds to ultimate displacement capacity. Intermediate damage states are evenly distributed between these limits. Aleatory uncertainty is explicitly incorporated in the fragility functions.

By cross-referencing the GED4ALL taxonomy strings with the ESRM20 building classes, an appropriate set of fragility curves is assigned to each building for all damage states, providing a probabilistic description of seismic performance.

3.4 Ground Motion Definition and Damage Scenario Generation

The seismic input is defined within a probabilistic framework using the national seismic hazard model (MPS04). Ground motion intensity measures, including peak ground acceleration and spectral ordinates, are extracted for the study area for selected return periods. Local site conditions are accounted for through stratigraphic soil classification.

Damage probabilities are computed by combining the hazard input with the assigned fragility functions, allowing the generation of spatially distributed damage scenarios for the building portfolio. Loss scenarios are subsequently derived using damage-to-loss ratios from established literature. The procedure supports scenario analyses for different exceedance probabilities and can be iteratively updated to account for cumulative damage or monitoring data. The results in terms of mean damage and repair costs for the selected buildings are depicted in figure 6.

4. Updating of the Seismic Fragility Curves Based on the Active Settlements

The proposed procedure provides a transparent, scalable, and engineering-consistent framework for seismic vulnerability assessment of building portfolios. By integrating faceted taxonomies, standardized fragility models, and probabilistic hazard input, it enables robust damage and loss estimation while preserving flexibility for future updates. This approach is particularly suited for resilience-oriented planning and dynamic risk assessment in complex urban environments. Then, this first seismic evaluation could be updated by considering also a precedent damage that can occur on the structure. This can also be done with a continuous updating of the seismic vulnerability once the data from monitoring come. Herein, it is explained how to “update” the seismic vulnerability with reference to a typological 6 floors buildings. By integrating the data from satellite measurements, analogous updating can be done for all the considered buildings. The flowchart presented in figure 7 provides an overview of the methodology adopted for the derivation of the updated seismic fragility curves. The procedure starts with the definition of the structural model of the typological building selected for the analyses. In the specific case study examined, the integration of missing structural parameters was carried out by relying on a simulated design project, code provisions, and relevant indications available in the scientific literature. Subsequently, a pushover analysis is performed by applying code-prescribed lateral force distributions to the structure in its deformed configuration, which results from the application of gravity loads and slow-moving settlements following pre-defined paths. Following this step, an equivalent single-degree-of-freedom (SDOF) system is derived from the pushover analysis of the multi-degree-of-freedom

Table 1 – *Damage states identification.*

	Infills	Beams	Columns
DS1	F_{cr}	M_{cr}	M_{cr}
DS2	F_{max}	M_y	M_y
DS3	F_{res}	M_{max}	M_{max}
DS4	---	M_{ult}	M_{ult} or 80% N_{max}

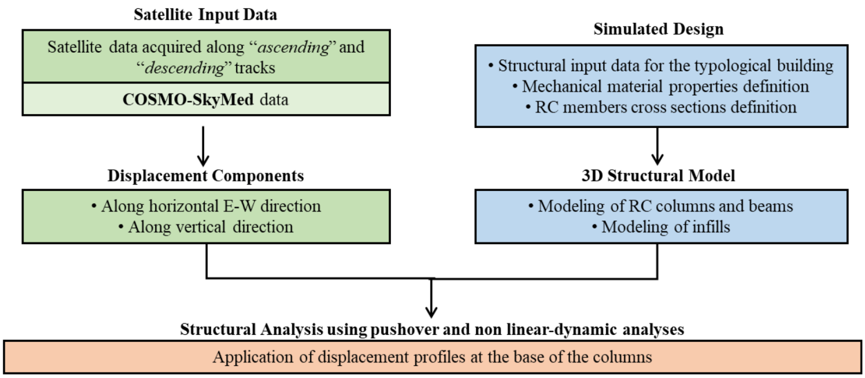


Fig. 7 – *Flowchart of the proposed methodology.*

(MDOF) structure, and the corresponding damage states are identified. Finally, for seismic fragility evaluation, Cloud Analysis is applied to the equivalent SDOF system, and the resulting parameters are used to derive the seismic fragility curves.

The present study adopts the Damage States (DS) concept, consistent with the building-level damage classification defined by the European Macroseismic Scale (EMS-98)[10]. This classification framework provides a comprehensive qualitative and quantitative description of damage levels affecting different building components, with progressively increasing severity. Given the mechanically based nature of the present investigation, these damage descriptions are herein interpreted in terms of engineering demand parameters. Specifically, parameters such as interstorey drift ratio and axial displacement are selected to represent the initiation of damage mechanisms corresponding to the EMS-98 damage grades for individual structural and non-structural components. The relationship between EMS-based damage levels and engineering demand parameters is establi-

10 Grünthal G. *European macroseismic scale1998 EMS 98*. Luxembourg: Centre Europèen de Géodynamique et de Séismologie, 1998. DOI/URL 10.2312/EMS-98.

Fig. 8 – *Building techniques in Verona: the main innovation diring the 1930s was the r.c. and hollow bricks floors [ASVr, Fondo Genio Civile, scatola SN015].*

Fig. 9 – *Building techniques in Verona: the r.c. and hollow bricks floors replaced the wooden ones and, at first, they were combined with traditional masonry walls (stone blocks with clay bricks) until the mid 1960s in residential buildings [ASVr, Fondo Genio Civile, scatola 325].*

shed through phenomenological interpretations reported in existing literature[11]. In these studies, threshold values and associated uncertainties for different damage states were quantified through extensive analyses of experimental test results available at the time. Table 1 reports a synthesis of the used thresholds.

Then, the definition of the damage levels assigned to the archetypes is established as follows: DS1 (cracking of infill walls), DS2 (achievement of maximum strength in infill walls or of the yield curvature limit in structural elements), DS3 (achievement of the yield curvature limit in structural elements or of the residual strength of infill walls) and DS4 (achievement of the ultimate curvature of structural elements). For more information, it is possible to refer to Miano *et al*.[12].

A finite element model (FEM) has been developed to represent the building's structure. In this model, both beams and columns are represented as one-dimensional elements. Additionally, the infill panels have been modeled using an equivalent strut approach.

After completion of the pushover analysis, the subsequent step consists of deriving the equivalent SDOF system and identifying the locations of the defined damage states on the pushover curve. The equivalent SDOF model is obtained from the static pushover analysis of the MDOF structure, considering the assigned lateral load patterns.

Then, the attainment of a specific damage state is quantified through a system-level damage indicator defined as the critical demand-to-capacity ratio for that damage state (DCR), corresponding to the structural component that governs the onset of damage[13]. In practice, DCR is formulated in a purely deformation-based manner as the maximum value among all structural elements of the ratio between the deformation demand (e.g., chord rotation or displacement) and the corresponding deformation capacity associated with the considered damage state. This concept can be directly extended to the equivalent elastic-perfectly plastic (EPP) SDOF system, where DCR is defined as the ratio between the displacement demand of the SDOF system and the displacement corresponding to the onset of the damage state mapped from the MDOF model.

11 Miano A., Mele A., Del Gaudio C., *et. al*., "Updating of the seismic fragility curves for RC buildings subjected to slow-moving settlements". *Journal of Building Engineering* 86, 108907 (2024). DOI: DOI/URL 10.1016/j.jobe.2024.108907.

12 *Ibidem*.

13 Jalayer F., Ebrahimian H., Miano A., "Record-to-record variability and code-compatible seismic safety-checking with limited number of records". *Bulletin of Earthquake Engineering* 19/15 (2021): 6361-6396. DOI/URL 10.1007/s10518-020-01024-6.

For seismic performance assessment and retrofit fragility evaluation, Cloud Analysis is adopted [3]. In this study, the Cloud Analysis is applied to the equivalent SDOF EPP system, as discussed in detail in [2]. Upon application of a set of ground motion records, the critical demand-to-capacity ratio for the selected limit state (DCR) is computed for each record, resulting in a dataset that constitutes the cloud response. The statistical characteristics of this response are obtained by performing a logarithmic linear regression on the cloud data, which is equivalent to fitting a power-law relationship in the original arithmetic scale. This regression yields a relationship describing the median DCR demand as a function of the spectral acceleration level:

$$\eta_{DCR|S_a}(S_a) = a \cdot S_a^b$$
$$\ln\left(\eta_{DCR|S_a}(S_a)\right) = \ln(a) + b \cdot \ln(S_a)$$

where ln(*a*) and *b* are regression coefficients. The logarithmic standard deviation, $\beta_{DCR|Sa}$, is computed as the square root of the mean squared residuals with respect to the regression curve:

$$\beta_{DCR|S_a} = \sqrt{\frac{\sum\left(\ln(DCR_i) - \ln\left(a \cdot S_{a,i}^b\right)\right)^2}{N-2}}$$

where DCR_i and $S_{a,i}$ denote the demand-to-capacity ratio and the corresponding spectral acceleration for the i-th ground motion record, and N is the total number of records in the cloud. The regression standard deviation is assumed to be constant over the range of S_a values considered. Finally, the seismic fragility curves derived from the Cloud Analysis framework are expressed as:

$$P(DCR > 1|S_a) = P(\ln DCR > 0|S_a) =$$
$$= 1 - \Phi\left(\frac{-\ln \eta_{DCR|S_a}}{\beta_{DCR|S_a}}\right) = \Phi\left(\frac{\ln \eta_{DCR|S_a}}{\beta_{DCR|S_a}}\right)$$

Different settlement distributions were applied to the three-dimensional building model. Both homogeneous (uniform) and localized settlement patterns were considered in order to represent different ground deformation scenarios as shown in figure 10. The magnitude of the imposed settlements was progressively increased during the analyses. This process was continued until predefined damage conditions were reached. Specifically, the analyses were stopped when Damage States DS1, DS2, and DS3 were attained. This approach allowed the assessment of the structural response under increasing levels of differential settlement.

For the sake of example, fragility curves are presented in figure 11 for the intact structure and for the structure pre-damaged to Damage State DS1 for settlements applied along the short side of the building. The fragility curve of the intact structure is represented by a solid line, while that of the pre-damaged structure is shown with a dashed line. These curves were obtained using the Cloud analysis procedure. The comparison highlights the influence of pre-existing damage on the structural vulnerability. The results illustrate how prior damage affects the probability of reaching higher damage states. This example is provided solely for illustrative purposes.

The seismic vulnerability assessment procedure previously defined is herein updated to explicitly account for the effects of pre-existing damage induced by slow-moving vertical settlements, while preserving unchanged the systematic definition of building characteristics from heterogeneous sources (i) and the adoption of the GED4ALL faceted building taxonomy (ii). The update primarily concerns the attribution of fragility functions (iii) and the ensuing probabilistic damage and loss scenarios (iv). In particular, baseline fragility curves derived from the European Seismic Risk Model 2020 (ESRM20) are modified to reflect the change in structural capacity associated with settlement-induced damage, as identified through satellite-based MT-DInSAR measurements. These measurements provide quantitative indicators of long-term vertical displacements at building scale, which, according to procedure above discussed, allow the quantitative estimation of cumulative pre-seismic damage. The updated fragility functions are finally employed within the same probabilistic hazard framework to generate revised damage and loss scenarios, enabling a time-dependent and condition-based representation of seismic vulnerability that can be continuously refined as new monitoring data become available.

5. Conclusions

This study demonstrates that the integration of monitoring-derived information on slow-moving settlements into portfolio-scale seismic risk assessment frameworks significantly enhances their physical realism and operational value. While the use of faceted taxonomies such as GED4ALL ensures a strong and flexible characterization of the built environment, the proposed update introduces a critical advancement by allowing seismic fragility to evolve as a function of pre-existing damage. The modification

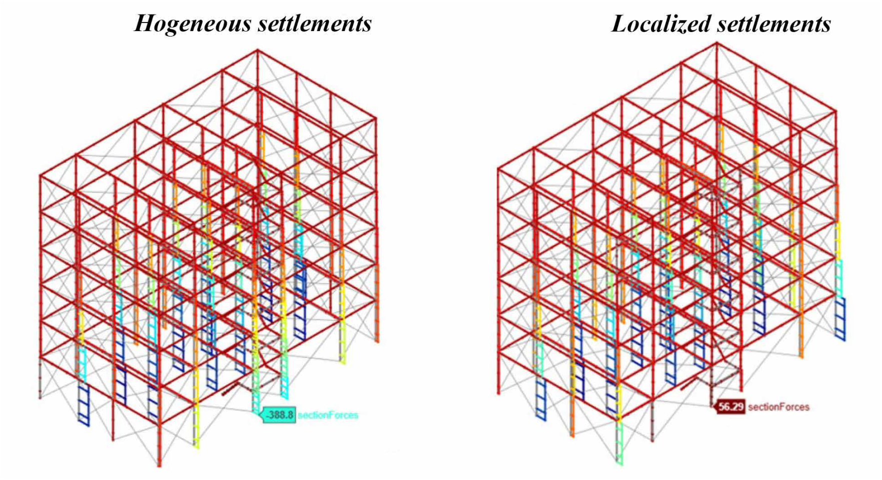


Fig. 10 – *Settlements distributions.*

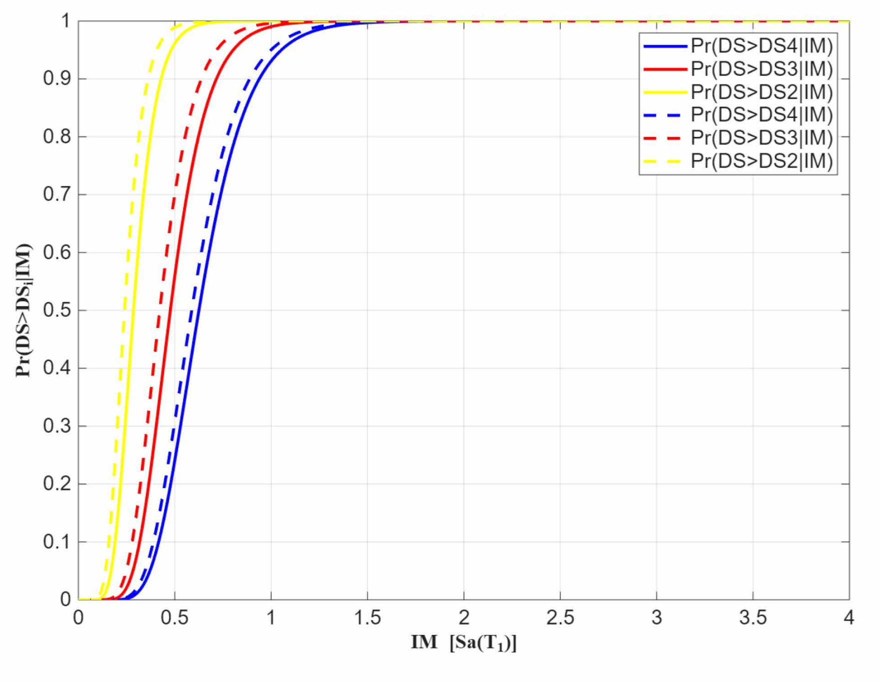


Fig. 11 – *Updated fragility curves.*

of ESRM20-based fragility curves through mechanically consistent modeling and Cloud Analysis enables the explicit consideration of cumulative degradation effects that are otherwise neglected in conventional large-scale assessments. The resulting framework supports dynamic vulnerability updating, bridging the gap between long-term monitoring, structural analysis, and probabilistic risk scenarios. This approach is particularly relevant for urban areas affected by subsidence or differential settlements and represents a significant step toward resilience-oriented, data-informed seismic risk management at territorial scale.

WebGIS Platform for Data Integration, Analysis and Representation

Angelo Bertolazzi[1], *Francesco Mauro*[1], *Ilaria Giannetti*[2]

The complexity of the data related to the Twentieth-century urban heritage, concerning both document and real-based information force to develop new tools dedicated to supporting the accessibility, the organization and the representation of structured knowledge framework. Following, on the one hand, the current digital paradigm of archival collections[3], and, on the other, the growing availability of real-based data, the development of such tools has significant impact on the current perspectives of applied research on the processes of knowledge, conservation, and valorization of buildings.

If the organization and the analysis of real-based data grounds on the use of digital tools, the use of the latters supports an expansion the public access to documentary collections, that are still marginalized within the usual fields of historical and archival research. This operation is fundamental to activate a worthy loop aimed at a broader process of "valorization" of existing buildings and infrastructures, strengthening the collective memory of the Twentieth-century city[4].

In this context, WebGIS systems represent, thus, an effective technological solution to collect, archive and structure large quantities of heterogeneous data, and, at the same time, it's significantly versatile for designing tools that focus on the user experience of such data . Indeed, WebGIS platforms produce an effective "spatialization" of heterogeneous digital objects that can be referred to in a broader sense of the built heritage and, on the other hand, constitute a valid tool for spatial representation of datasets structured

1 University of Padua, Department of Civil, Architectural and Environmental Engineering.
2 University of Rome Tor Vergata, Department of Civil Engineering and Computer Science Engineering.

3 Valacchi F., *L'archivio aumentato. Tempi e modi di una digitalizzazione critica*. Milano: Editrice Bibliografica, 2024.

4 Rojas E., "Urban Heritage for Sustainable Development. Culture: urban future, global report on culture for sustainable urban development", Unesco Report, CLT-2016/WS/18 (2016) 19.

according to semantically homogeneous sets. This latter functionality especially allows the spatial fruition of highly stratified information to be designed, organized into easy-to-read thematic clusters (for example “thematic maps”) for different levels of users.

1. The Design and Functionality of the SMUH WebGIS Platform

The SMUH WebGIS platform aims, on the one hand, to support the development an interdisciplinary methodology aimed at assessing the structural vulnerability of buildings, and, on the other hand, to function as an operational tool to support agencies responsible for the management and preservation of the built environment in urban areas.

The platform facse, thus, the organization and spatial representation of heterogeneous data, ranging from historical documents to satellite measurement, to the output of historical and structural analysis.

As mentioned, the SMUH WebGIS platform eases the development of a multidisciplinary methodology[5], with levereaging on the spatial analysis of heterogeneous, structured, and georeferenced data – including satellite measurements[6] – produces predictive assessments of the structural vulnerability of buildings[7].

Specifically, the investigation methodology is broken down into the following three steps: i) acquisition, analysis, and spatial representation of data from documentary research, with the goal of building a comprehensive knowledge framework of existing buildings and infrastructure; ii) acquisition, analysis, and spatial representation of measurements obtained from SAR (Synthetic Aperture Radar) satellite data, with the goal of identifying any ongoing displacement phenomena; iii) evaluation of buildings’ structural vulnerability

5 About the development of the SMUH project methodology by the SMUH research team: Di Carlo F. *et al.*, “On the integration of multi-temporal synthetic aperture radar interferometry products and historical surveys data for buildings structural monitoring”. *Journal of Civil Structural Health Monitoring* 11 (2021): 1429-47.

6 Concerning the methodology of satellite data analysis and their application to structural monitoring by the SMUH project researchers: Arangio S., Calò F., Di Mauro M., Bonano M., *et al.*, “An application of the SBAS-DInSAR technique for the assessment of structural damage in the city of Rome”. *Structure and Infrastructure Engineering* 10 (20104): 1469-1483; Talledo D., *et al.*, “Satellite radar interferometry: Potential and limitations for structural assessment and monitoring”. *Journal of Building Engineering* 46 (2022): 103756.

7 On the methodology of structural vulnerability analyses by SMUH project researchers: Del Gaudio C. *et al.*, “Seismic fragility for Italian RC buildings based on damage data of the last 50 years”. *Bulletin of Earthquake Engineering* 18 (2020): 2023-2059.

classes based on the knowledge frameworks and refining these analyses based on the results of the satellite measurements conducted in the second phase.

To accomplish these three tasks, the SMUH platform gathers all the data from the different Research Units of the project, allowing the collection and cataloging of archival data, as well as SAR data and their intersection with structural vulnerability analyses.

This chapter illustrates the main features of the SMUH WebGIS platform in relation to the proposed analysis methodology and, in detail, the user-oriented functionalities of the platform related to the production of structured, interactive knowledge frameworks derived from the research investigation. In this latter sense, the production of thematic representations guided by pre-defined or user-generated queries gives an additional information levels related to the current state of buildings (including monitoring data, structural vulnerability parameters, and potential risk).

The above metioned user-oriented functionalities of the platform are, here, presented referring to case study of the *Borgo Trento* district in Verona, which, located on a bend of the Adige river. This case study is exemplary for its environmental conditions and the complexity of the morphological and technological features of the Twentieth-century city's building and infrastructure heritage, serving as benchmark sample for further extensions of the platform[8].

2. The IT Architecture of the SMUH Platform

The SMUH WebGIS platform was entirely based on open-source technologies. From a technological perspective, it was therefore decided to base the platform project on an IT architecture consisting of two environments – backend and frontend – with separate tasks and functions: the backend allows for data storage and structuring, while the frontend allows users to interact with them. Specifically, the design of the frontend's public interface focused on the ability to produce "thematic maps" – some pre-defined and some user-generated – for the spatial interpretation of data relating to the different "information levels" necessary for understanding

8 For the application and development of the proposed methodology to the case study of the *Borgo Trento* neighborhood in Verona within the SMUH project: Giannetti I., Bertolazzi A., *et al*., "A Cross-Disciplinary Approach for the Safeguard of Modern Urban Heritage: Historical Investigation, Satellite Measurement, Structural Vulnerability Analysis". In *Envisioning the Futures - Designing and Building for People and the Environment. Colloqui.AT.e 2025*, edited by Albatici R., Dalprà M., Gatti M. P., Maracchini G., Torresin S., 349-367. Cham: Springer, 2025. DOI: https://doi.org/10.1007/978-3-032-06974-0_18.

the built environment, to its history, construction solutions, and current state, and articulated at the scale of individual buildings and infrastructure. A key aspect of the platform's design and construction is the use of entirely open-source systems. This choice is mandatory to ensure the prototype's accessibility, replicability, and scalability for the complex group of stakeholders involved in the Twentieth-century city management process (i.e. local authorities responsible for planning).

To fulfill these tasks, the platform relies on the combination of an open-source relational database with a server extension dedicated to managing and manipulating geospatial data: the open-source relational database is based on "PostgreSQL"[9] with the "PostGIS"[10] extension for storing, indexing, and querying geospatial data. The server is "Geoserver" an open-source Java application that allows users to share and modify geospatial data[11].

Regarding the platform's construction and usability, the first step was the implementation of the "PostgreSQL" relational database. The SQL-based system supports the management and querying of tabular files, even those of considerable complexity.

"PostgreSQL" does not natively offer support for geolocated tabular files. Therefore, using the PostGIS[12] integration, support for spatial data has been introduced, enabling advanced spatial queries, geographic relationship analysis, and accurate geospatial information visualization. The Manipulation of imported tabular data to produce thematic maps is handled by the "GeoServer" functionality, which leverages styles (SLD) from native QGIS files in Shapefile format[13].

To implement the visualization styles offered by "GeoServer", the use of "MapStore"[14] has been integrated, an open-source web application for creating, managing, and sharing interactive web maps. This application can import data from "GeoServer" and "PostGIS" in the standardized Web Map Service (WMS)[15] and Web Feature Service (WFS)[16] formats. In this way, the database's functionality, in terms of data storage, categorization,

9 PostgreSQL: https://www.postgresql.org. [Accessed on: 10/12/2025].

10 PostGIS: https://postgis.net/documentation/manual/. [Accessed on: 10/12/2025].

11 Geoserver: https://geoserver.org [Accessed on: 10/12/2025].

12 Obe R.and Hsu L. *PostGIS in action*. New York: Manning Publications, 2020.

13 "ESRI Shapefile Technical Description", An ESRI White Paper – July 1998: Report no. J-7855.

14 MapStore: https://docs.mapstore.geosolutionsgroup.com. [Accessed on: 10/12/2025].

15 Web Map Service (WMS): https://www.ogc.org/it/standards/wms/. [Accessed on: 10/12/2025].

16 Web Feature Service (WFS): https://www.ogc.org/standards/wfs/. [Accessed on: 10/12/2025].

and querying, is enhanced by the visualization capabilities provided by "MapStore", enabling highly intuitive navigation of geospatial data and facilitating the exploration of even highly heterogeneous data.

The system is then integrated with a cloud-based application that combines the "Mapbox"[17] library to display GIS data in a 3D environment with the ability to view and query BIM models of individual buildings in a GIS environment, leveraging the open Industry Foundation Class (IFC)[18] standard. The 3D integration is based on the combination of the ThreeJs[19] packages and the functionality of an open platform for cloud-based BIM model visualization (That Open Engine|web-ifc)[20] to process the territorial map, import, and query 3D information models with an IFC structure.

3. SMUH Platform: Information System and its Populating

Beyond the choice of open-source technological systems, which allow for the prototype's "technical reproducibility", the research considered another aspect fundamental to the platform's effective usability and scalability. This is an information system dedicated to representing the knowledge frameworks derived from the documentary research activity and relating to the Twentieth-century city's-built environment. To this end, a reference taxonomy was defined to quickly describe the history and costruction features of each building and infrastructures through standard sets of information parameters (potentially extendable and queryable automatically).

This taxonomy includes both a framework of fundamental knowledge regarding the history, function and technical descriptions of the building solutions adopted, as well as the primary geometric characteristics of the buildings, which are also considered fundamental for subsequent structural vulnerability analyses[21].

Specifically, the geometric characteristics of buildings are described within a specific set of information parameters that include: their urban loca-

17 Mapbox: https://www.mapbox.com/. [Accessed on: 10/12/2025].

18 Industry Foundation Class (IFC): https://technical.buildingsmart.org/standards/ifc/ifc-schema-specification. [Accessed on: 10/12/2025].

19 ThreeJs: https://threejs.org. [Accessed on: 10/12/2025].

20 That Open Engine|web-ifc: https://github.com/ThatOpen/engine_web-ifc. [Accessed on: 10/12/2025].

21 For the enrichment of the descriptive taxonomy for the purpose of using the information system for structural vulnerability analyses, the basis taxonomy is developed from: Silva V., *et al*., "A building classification system for multi-hazard risk assessment". *International Journal of Disaster Risk Science* 13 (2022), 161-177.

tion, the characterization of their plan and elevation geometry. This is in terms of a generic definition of regularity, based on the principle of symmetry, the number of floors, the type of roof, and the geometric characterization of ground-floor openings. The set of information parameters related to the basic historical-technical knowledge framework includes: an alphanumeric code to identify the building; the construction period; its function; the number of occupants; an in-depth characterization of the building's load-bearing structure and constructive components; a track record of the building's history, from design to construction, including damage history and subsequent maintenance interventions; and a visual assessment of the building's current condition derived from rapid surveys.

The "consistency" of the value assigned to each parameter is assessed by accurately reporting the data source, referring to primary documentary sources, information derived from secondary sources and from visual analysis. For example, the construction period of a single building unit can be determined directly from archive documents – such as a building's "certificate of habitability" – or derived from historical maps. In the first case, the construction period will be defined as the "year of construction" directly verifiable in the document; in the second case, it will be defined as the "decade of construction", derived from the interpretation of historical maps or photographs of the period.

Finally, the research adopted codes compliant with the data schema defined by the "National Synthesis Database (DBSN)" to allow direct integration of data from public geographic databases – that is, two-way communication with the databases after the platform has been built and populated – to identify the parameters belonging to the standard sets[22].

Two different databases were created to adjust the platform to the *Borgo Trento* specific case study: one for the buildings along the Adige river (coded as "EdificiLungargine") and the other for the inner area (coded as "EdificiInterni"). The two sets of buildings are distinguished based on the process adopted to acquire historical and technical knowledge: in the first case – the 43 buildings along the river – a thorough documentary search was conducted, encompassing several primary sources; in the second case – the 330 buildings in the inland area – a quick analysis was conducted based on a comparison of secondary sources.

Specifically, the historical analysis of the 43 buildings along the river involved cross-referencing two primary archival sources: the *Edilizia Pri-*

22 "Catalogo dei Dati Territoriali – Specifiche di Contenuto per il DBSN (Data Base di Sintesi Nazionale)", Version 4.0, 31st July 2023.

vata archive, held in the *Archivio del Comune di Verona*, and the archive of the former *Ufficio Distrettuale Imposte Dirette* (U.D.I.D.), preserved in the *Archivio di Stato di Verona*. For the 330 buildings in the inner area, we analyzed data from historical cartography, archive data collected for the 43 buildings along the riverfront – with reference to historical photographs showing the neighborhood's buildings throughout the various historical periods – and quick information gleaned from visual surveys[23].

In both databases, information derived from documents or from cross-referencing sources, was then entered into the platform according to the previously described standard sets of information parameters associated with the individual building unit to concisely represent its history, function, structure, and construction details.

For the database of buildings along the Adige river, an extended set of information parameters was adopted, while for the description of the buildings in the inner area, the same set was reduced to a subset of minimal parameters. Specifically, the set adopted for the inner area consists of only the parameters necessary to identify the building and to concisely describe the salient aspects of its history, construction anatomy, and current state.

Operationally, in the database "population" process, the sets of information parameters associated with both sets of buildings were initially compiled in tabular format (CSV) to simplify and extend the data collection process. Only subsequently were they entered into the WebGIS platform database through an automated procedure guided by a Python script. Specifically, the algorithm – developed from the "PyQGIS" libraries – populates information fields associated with individual georeferenced polygons identified by IDs – corresponding to the planimetric shapes of the buildings under consideration – using the popular vector format for spatial data storage in GIS, "Shapefile".

This allows for automatic recording of the location and shape of the features related to the building polygons, implementing an automatic association of the information attributes defined in tabular format. During the association phase, the minimum set of information parameters was therefore enriched by the direct link to the relevant digital file of archive documents, stored in the database of the same platform or accessible from external repositories, already available[24].

23 The Research Unit from University of Padua lead a new data mining action concernin the inner buildings to validate the expeditive analysis. Thereafter the data were collected inside the WebGIS platform expanding the database.

24 The possibility of integrating the document repositories of the ARCOVER platform or, more broadly, the documents already accessible in the SIAS "State Archives Information System" Digital Library, is currently under development and population. Bertolazzi A., Savino

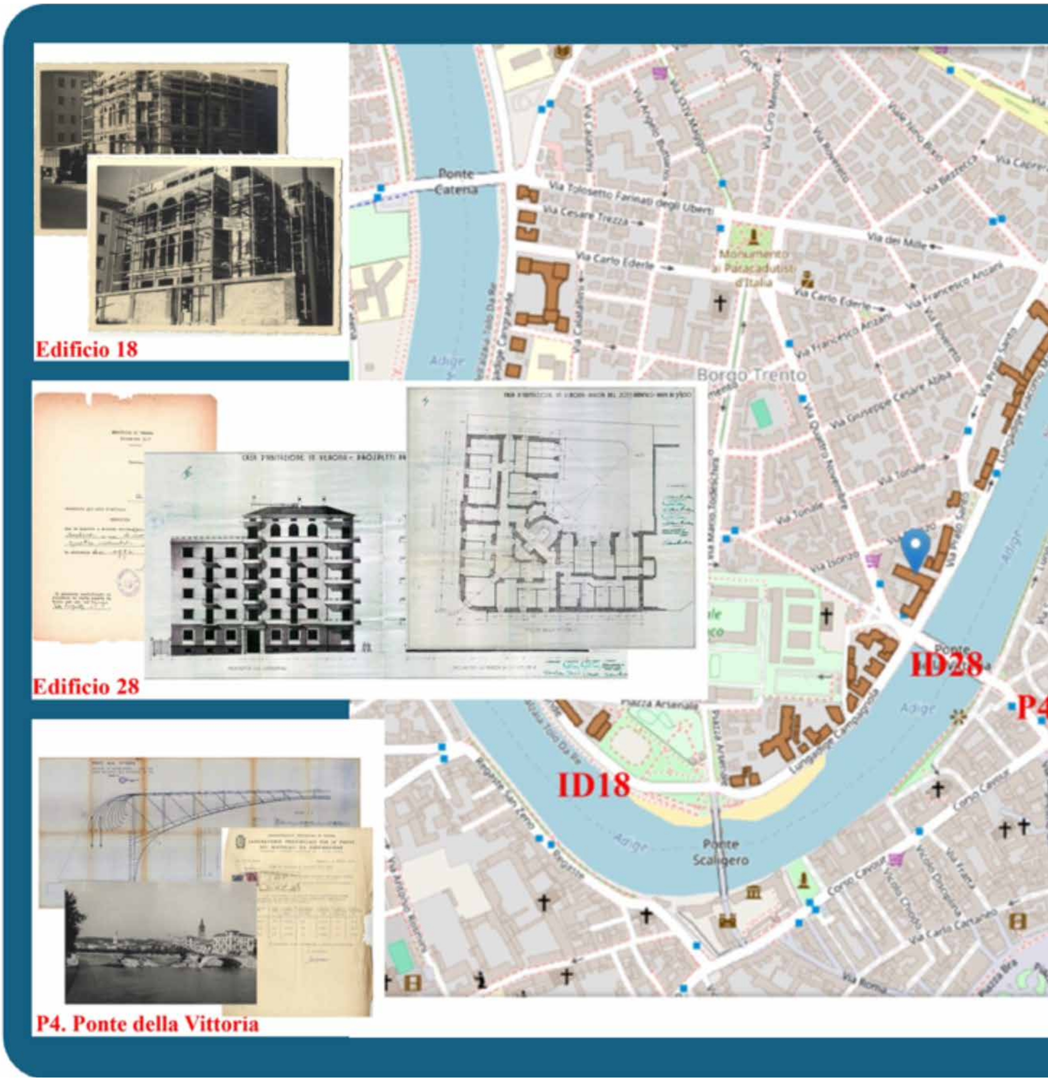
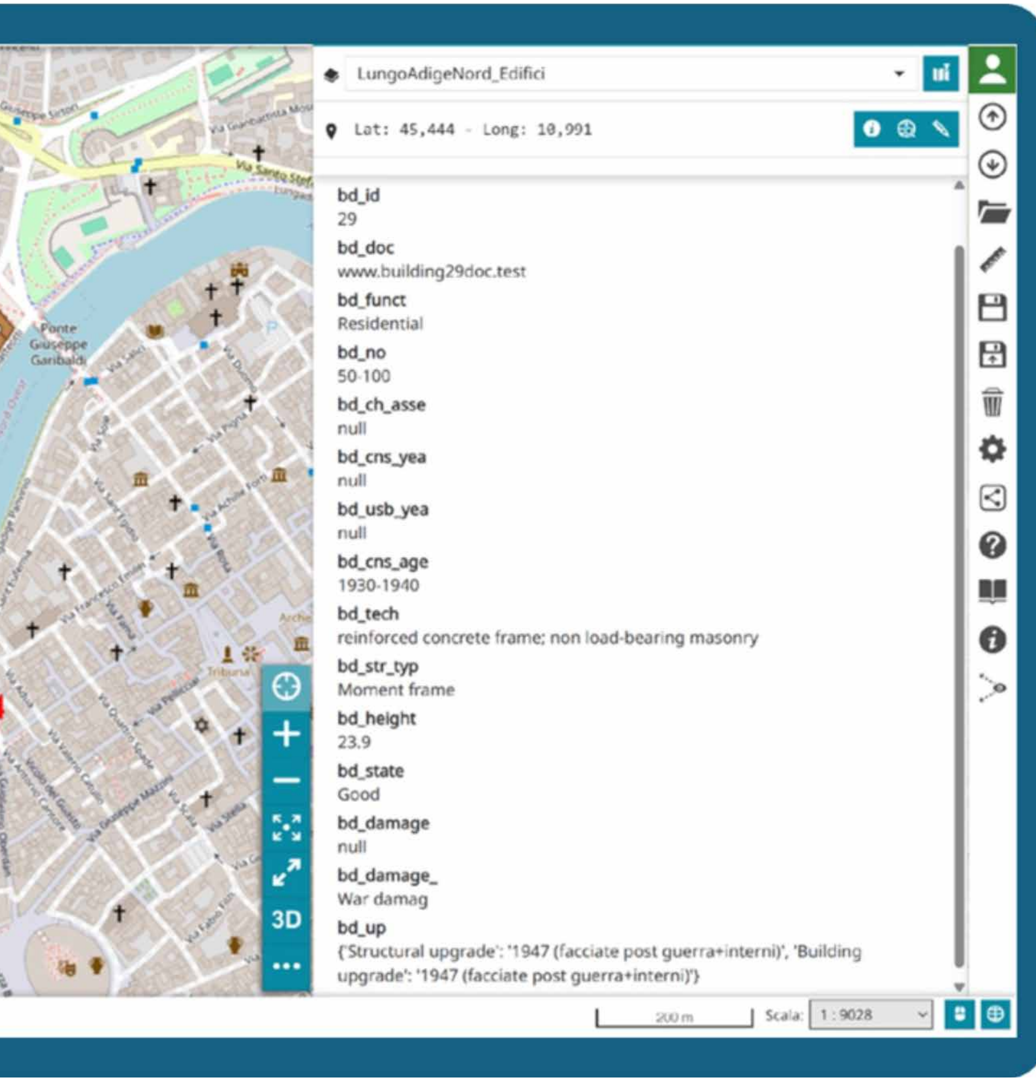


Fig. 1 – *The SMUH platform: a screen highlighting the standard information parameters for a single building, including a link to the relevant historical document archive, accessible throught the dedicated webGIS analysis interface. [SMUH, 2025].*


LungoAdigeNord_Edifici
Lat: 45,444 - Long: 10,991
bd_id
29
bd_doc
www.building29doc.test
bd_funct
Residential
bd_no
50-100
bd_ch_asse
null
bd_cns_yea
null
bd_usb_yea
null
bd_cns_age
1930-1940
bd_tech
reinforced concrete frame; non load-bearing masonry
bd_str_typ
Moment frame
bd_height
23.9
bd_state
Good
bd_damage
null
bd_damage_
War damag
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Ponte Giuseppe Garibaldi
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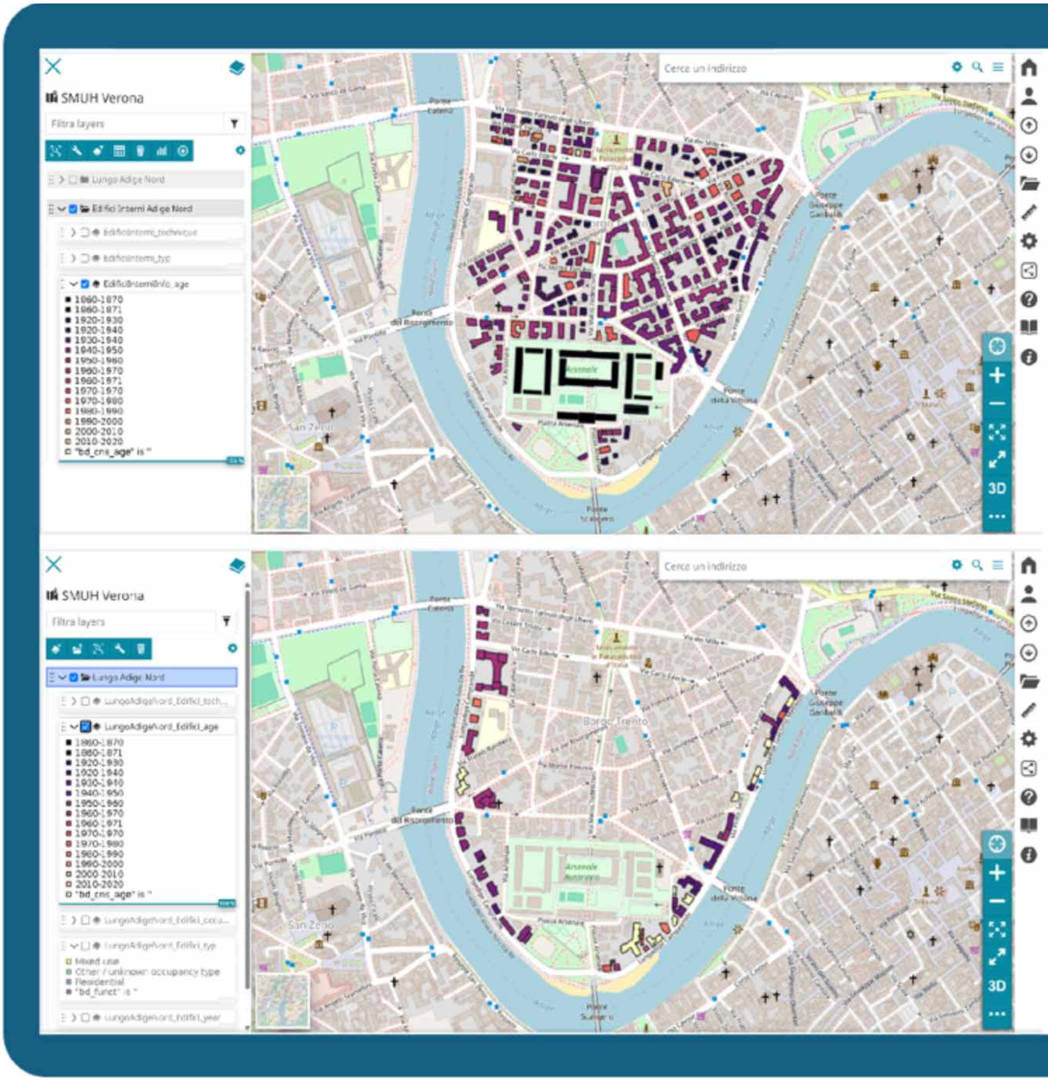
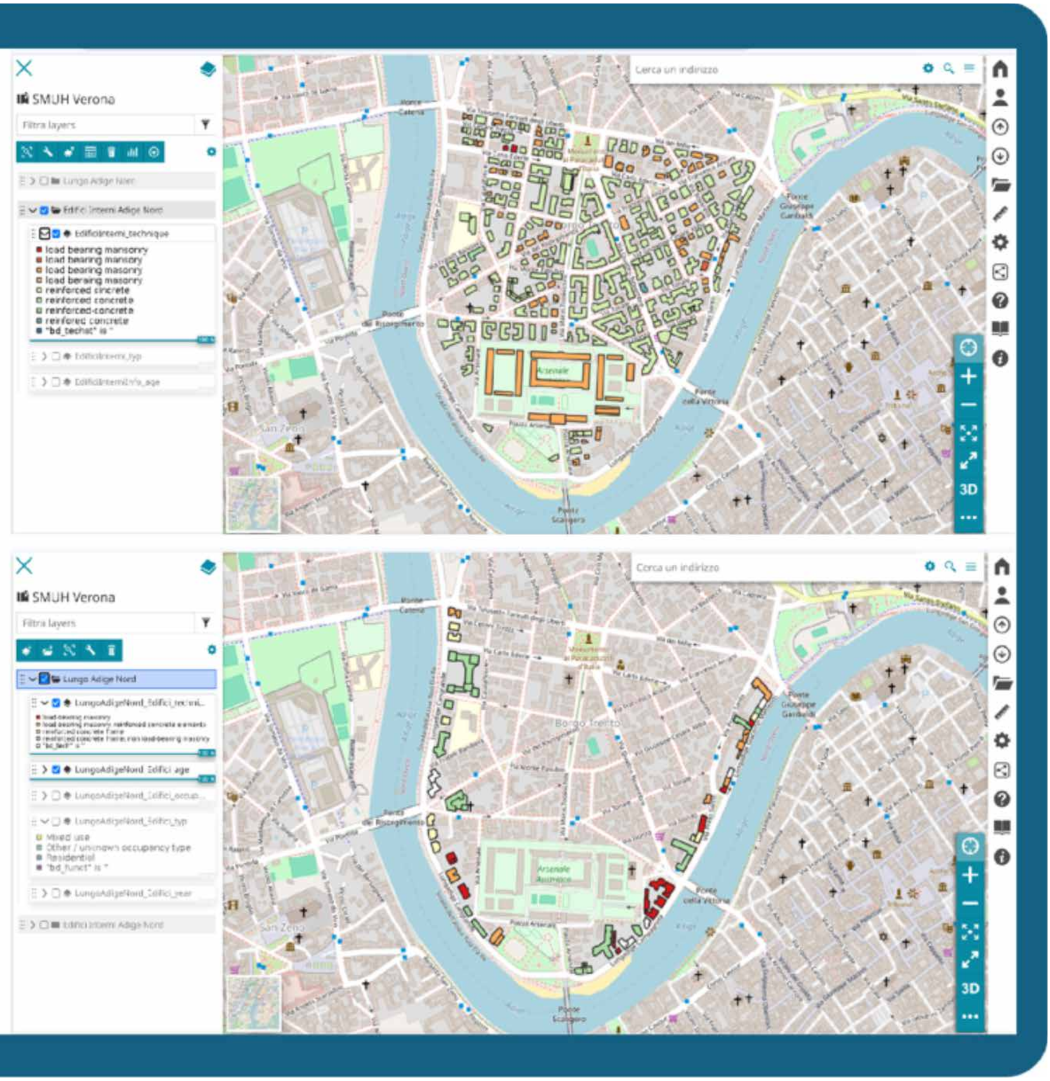


Fig. 2 – *The SMUH platform: screenshots showing examples of thematic maps of construction age (left) and building typologies (right), accessible thanks the open interface of the webGIS platform. [SMUH, 2025].*


SMUH Verona
Filtra layers
Cerca un indirizzo
load bearing mansonry
reinforced concrete
Arsenale
Ponte del Risorgimento
Ponte della Vittoria
Ponte Scaligero
3D
SMUH Verona
Filtra layers
Cerca un indirizzo
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LungoAdigeNord_Edifici age
Mixed use
Other / unknown occupancy type
Residential
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Borgo Trento
Ponte Catena
Ponte della Vittoria
San Zeno
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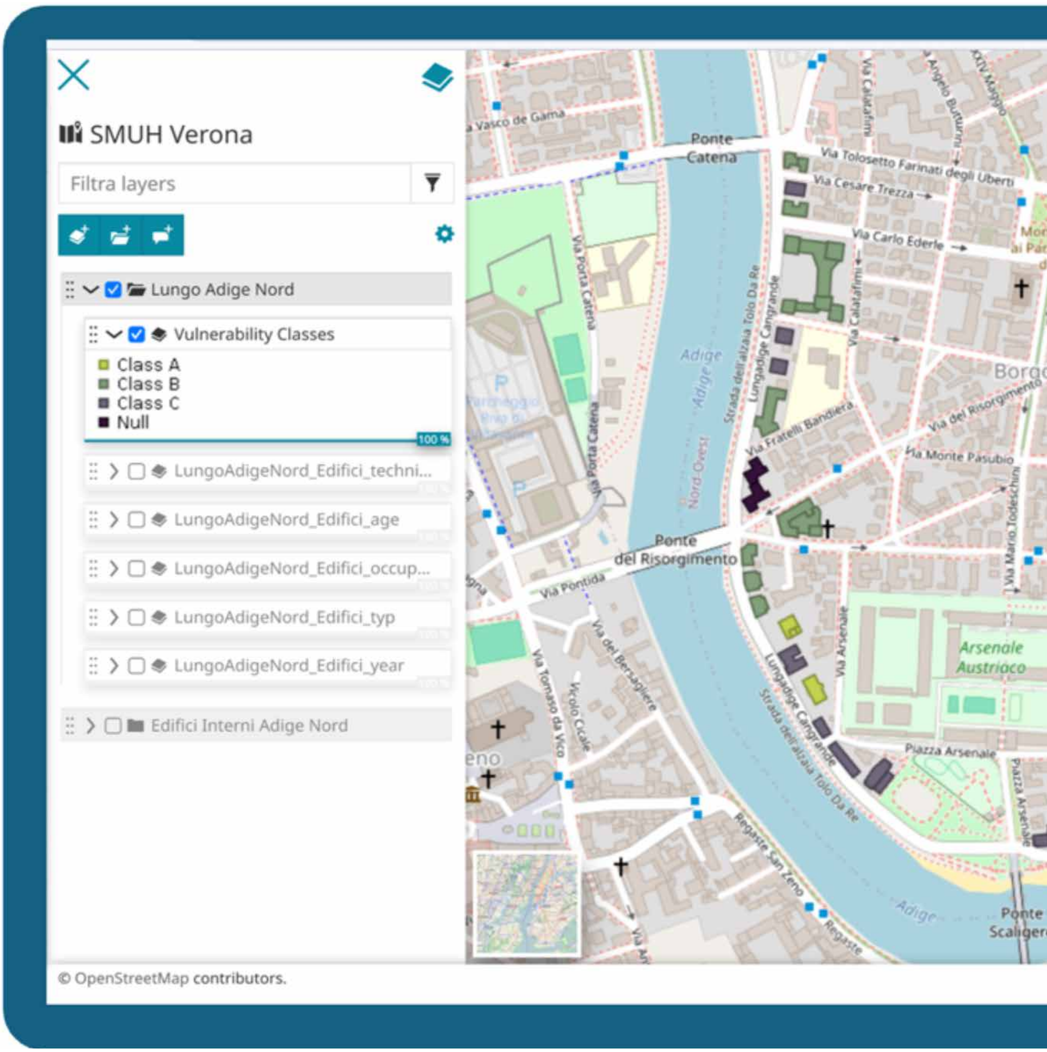
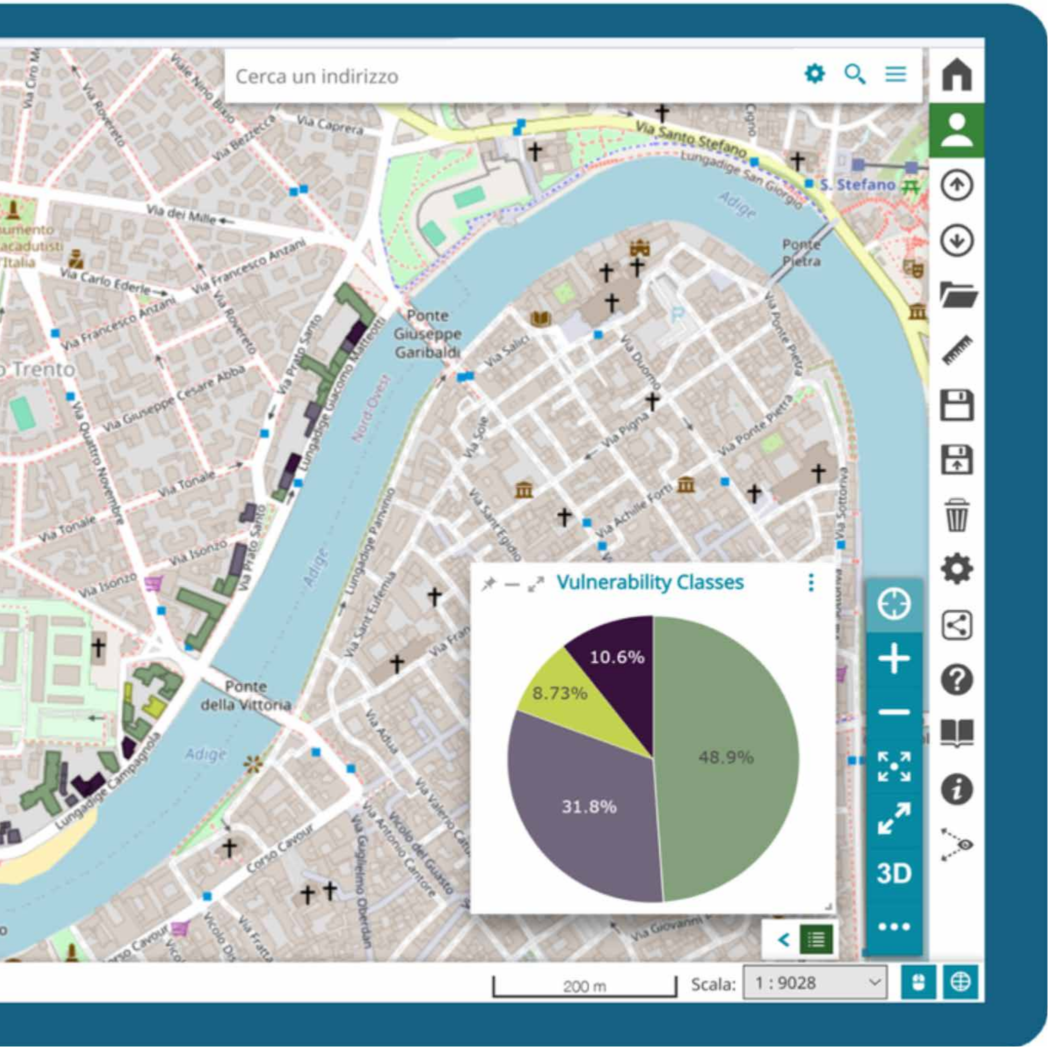


Fig. 3 – *The SMUH platform: screenshot showing the distribution graph of vulnerability classes for the sample of buildings under consideration and related thematic spatial visualization accessible from the open interface of the webGIS platform. [SMUH, 2025].*


Cerca un indirizzo
Via Santo Stefano
Lungadige San Giorgio
S. Stefano
Adige
Ponte Pietra
Ponte
Giuseppe
Garibaldi
Via dei Mille
Via Carlo Ederle
Via Francesco Anzani
Via Giuseppe Cesare Abba
Via Quattro Novembre
Via Tonale
Via Isonzo
Via Prato Santo
Lungadige Giacomo Matteotti
Via Duomo
Via Pigna
Via Ponte Pietra
Via Sole
Via Sant'Egidio
Via Achille Forti
Lungadige Panvinio
Via Sant'Eufemia
Ponte
della Vittoria
Lungadige Campagnola
Corso Cavour
Via Guglielmo Oberdan
Vulnerability Classes
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8.73%
48.9%
31.8%
3D
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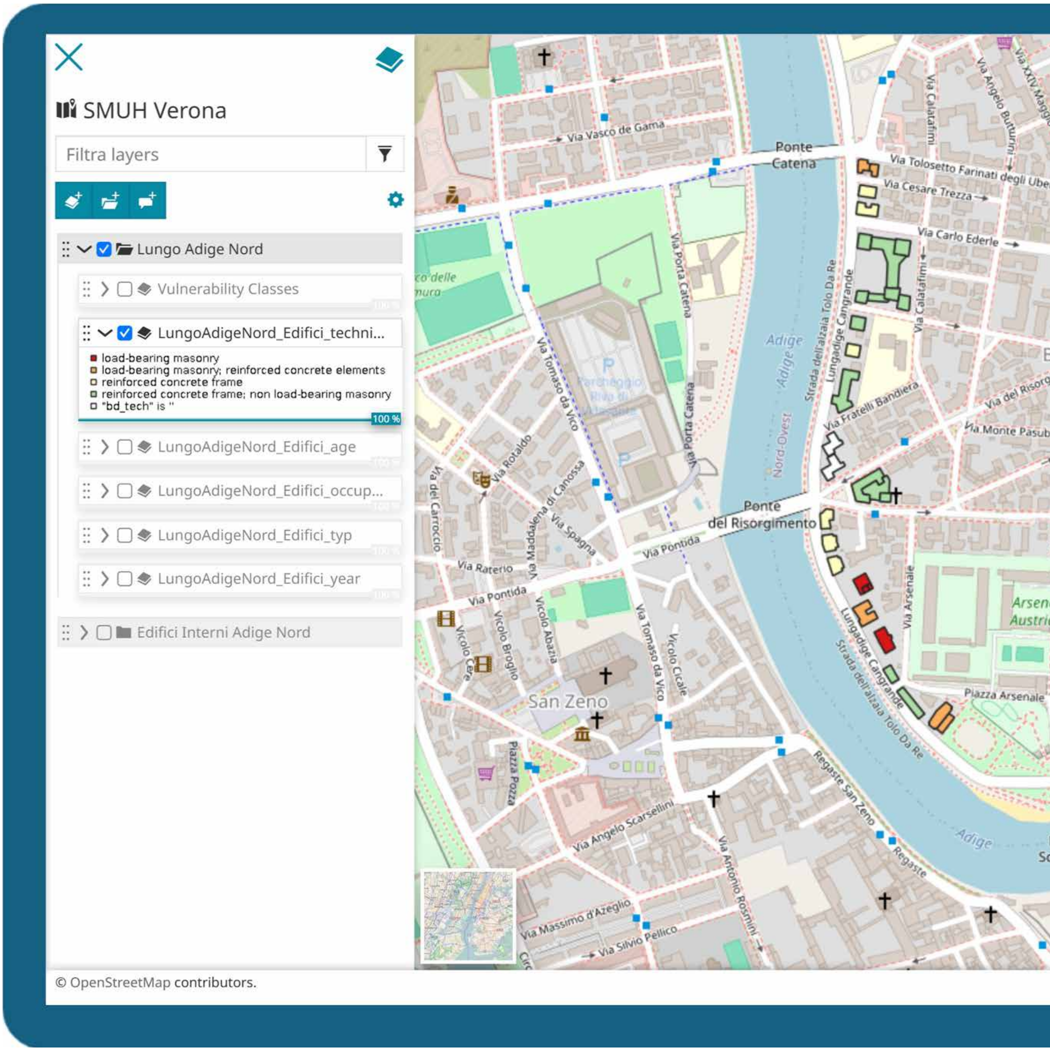
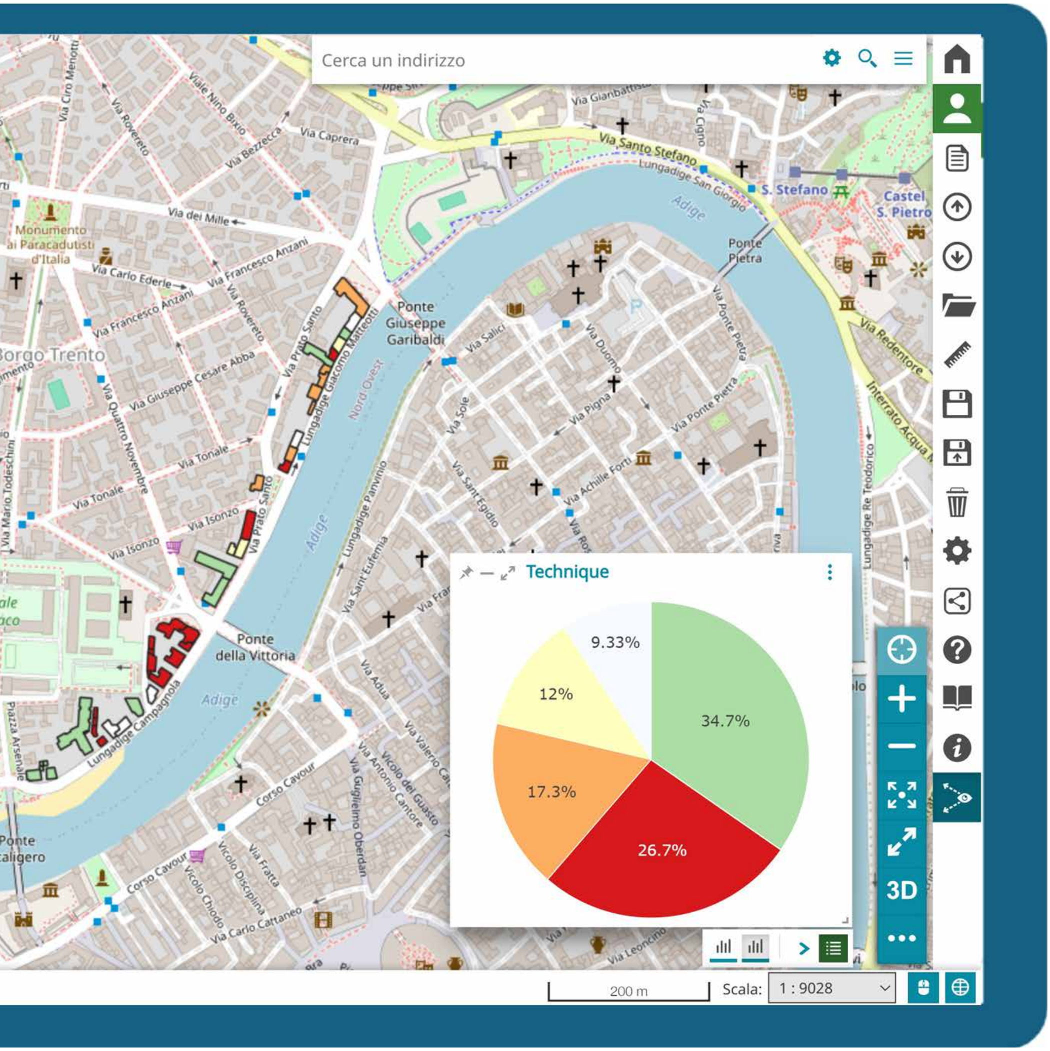


Fig. 4 – *The SMUH platform: screen showing the distribution of building typologies for the sample of buildings under examination and the related thematic spatial visualization accessible from the public interface of the webGIS platform. [SMUH, 2025].*


Cerca un indirizzo
Technique
9.33%
12%
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Ponte della Vittoria
Ponte Pietra
Borgo Trento
Adige
S. Stefano
Castel S. Pietro

Fig. 5 – Borgo Trento *district: the embakment during the mid 1920s before the hydraulic works carried forward by Ufficio del Genio Civile [ASVr, Fondo Genio Civile, scatola 11].*

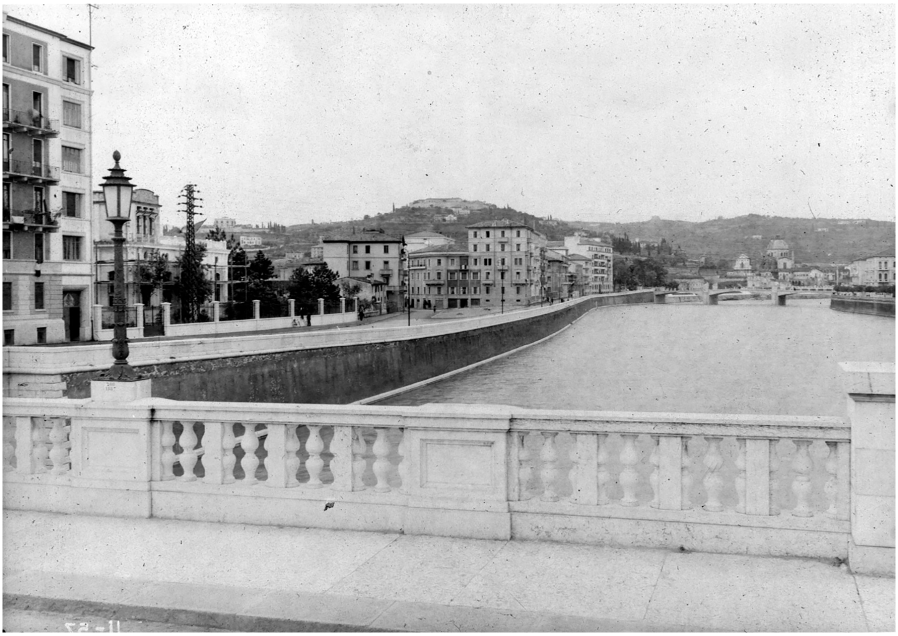


Fig. 6 – Borgo Trento *district: the embakment after the hydraulic works with the new residential buildings constructed during the mid 1930s [ASVr, Fondo Genio Civile, scatola 11].*

4. Data Access for the *Borgo Trento* District in Verona

The technological capabilities of "Mapstore" allowed for the development of an extremely intuitive interface for end users to access data. Specifically, the platform's home screen features a drop-down menu on the left: the menu contains a series of layers containing pre-built "thematic maps" that can be directly viewed. The same screen also features a menu to freely query the database's information parameters, allowing for the real-time construction of user-defined "thematic maps".

Free data consultation is also supported by other, more traditional visualization methods, such as graphs or tables that complement and expand the spatial representations offered by the "thematic maps". For example, while the map can represent the spatial distribution of buildings classified by construction period, the corresponding graph can briefly visualize the percentage distribution of construction periods for a given sample of buildings. Similarly, for example, when using pre-processed data stored in the database, while the map displays the distribution of buildings characterized by a given "structural vulnerability" index, the corresponding graph also provides a summary representation of the percentage distribution of the values for that index.

By integrating spatial representation capabilities into a traditional data visualization dashboard, the platform prototype provides structured knowledge frameworks that can be directly used to support the decision-making process of bodies responsible for planning interventions on existing buildings.

Furthermore, a specific platform feature is dedicated to the use of metadata and digital copies of archive documents – assignabled to individual building and infrastructure units – to support a broader process of "heritageing" the Twentieth-century city: a pop-up window, activated from the information fields associated with the representation of the individual building or infrastructure, links each feature in the model to the metadata and digital reproduction of the related archive documents. In particular, each set of documents is enriched, through standardized and automated queries, by a corresponding minimum set of metadata, compliant with the standards of archival description, referable to the "archival unit" or to the single "documentary unit".

M. and Siviero L., "Il progetto ARCOVER: una piattaforma webGIS per una rete degli archivi del costruito nel territorio veronese". In *Archivi digitali per la città contemporanea. Documenti, strumenti e modelli per la conoscenza del patrimonio costruito*, Bertolazzi A., Eramo E., Giannetti I., Siviero L., 13-47. Milano: FrancoAngeli, 2025.

Fig. 7 – Borgo Trento *district and the planned city: the Piano Regolatore map of 1954 [ACVr, Ufficio Urbanistica]*.

Fig. 8 – Borgo Trento *district and the real city: the 1955 aerophotogrammetric survey [ACVr, Ufficio Urbanistica].*

The interactive interface of the webGIS platform is designed to produce thematic maps that represent the fundamental knowledge framework for building units and the results of vulnerability and risk assessments. For the case study, a series of thematic maps at the individual building scale were developed to represent the foundational knowledge gathered from documentary analysis.

These include several pre-set maps that are directly accessible to the end-user via a drop-down menu (i.g. construction period, divided into years and decades; presence of war damage, referring to Second World War; presence of renovation intervention, with related period; construction techniques; structural typologies; functions, referring to the original and the on after renovation; number of occupants).

For more expert users, the platform also allows for the generation of additional thematic maps or the visualization of results using charts, based on the information available in the database.

At the same time, through the integrated web app, described in the following capther, a 3D extension of the platform allows users to view BIM models of individual building units in IFC format: users can query these information parameters through a pre-set filter that corresponds to a standard, easy-to-read set.

5. Conclusions

Within the SMUH project, the development of the WebGIS platform achieved two goals: the development and extension of a survey methodology aimed at assessing the structural vulnerability of existing buildings, and the collection, archiving, and representation of heterogeneous (and time-expandable) data relating more broadly to the built heritage of urban areas. Throughout the project, the platform enabled the joint work of a specialized team of researchers with vertical expertise, leveraging a common database, powered by functions for data analysis and spatial visualization. Upon completion of the analyses, through the development of specific functions dedicated to data representation, the platform constitutes a working prototype for the development of an easy-to-use application for potential public and private stakeholders responsible for managing the built heritage of urban areas, as a support for the decision-making process.

The IT architecture tested – based entirely on open-source systems – has proven particularly efficient for managing the stratified and heterogeneous data sets needed to develop comprehensive knowledge frameworks relating to the Twentieth century building heritage. The spatialization of historical and technical information, accessible through "thematic maps" represents an efficient tool for extending the understanding of the historical and construction characteristics of individual buildings to comprehensive knowledge frameworks relating to the "urban fabric". Thus, this platform functionality proves to be a valuable tool for planning processes, also facilitating public participation based on data transparency.

Therefore, considering future development prospects, in the current scenario opened by the diffusion of data analysis tools supported by AI models, it is possible to imagine the integration of a "guide" to data queries, facilitating access even by the general public. To this end, the rigorous semantic description of the data stored in the platform prototype – based on standardized information systems – supports their interrogation by "artificial" users, allowing the integration of prompts written in "natural" language into the platform's public interface for data access.

BIM Extension of WebGIS for Data Integration, Analysis and Representation

Ilaria Giannetti[1], *Francesca D'Uffizi*[2], *Angelo Bertolazzi*[3]

There is an urgent need to develop innovative research approaches and tools to enhance the "documentary double" that characterizes the design, construction, and management of the modern urban heritage – heavily transformed during the Nineteenth and Twentieth centuries – within current processes of knowledge, conservation, and valorisation of existing buildings and infrastructures. Such tools must be dedicated to the standardization of information flows and the simplified accessibility of the historical and technical data preserved in local archives. Accordingly, this chapter presents the design and development of an extension for the SMUH webGIS platform, described in the previous chapter. This extension is dedicated to the integration of georeferenced 3D and information models, which can be navigated and queried via a web app accessible without specialized IT skills. Particular attention is paid to the design of a standardized information workflow for integrating data from documentary sources, while respecting archival description standards and ensuring compatibility with the ontologies adopted by national geographic databases. At the same time, the chapter introduces the development of an open viewer designed for the interactive and simplified use of 3D and information models produced in accordance with the Industry Foundation Classes (IFC) standard.

1. Design and Construction of the Informative Model

In a research context strongly oriented toward the creation of urban-scale digital models[4], based on three-dimensional representations obtained throu-

1 University of Rome Tor Vergata, Department of Civil Engineering and Computer Science Engineering.

2 University of Rome Tor Vergata, Department of Civil Engineering and Computer Science Engineering, Reseach Fellow SMUH project.

3 University of Padua, Department of Civil, Architectural and Environmental Engineering.

4 Biljecki F., Stoter J., Ledoux H., *et al.*, "Applications of 3D city models: state of the art

gh automatic and semi-automatic acquisitions of the "as-built" state of existing buildings[5], the design of an information workflow is particularly urgent. Such a workflow must allow for the integration of data derived from the analysis of documentary sources with the data representation ontologies adopted by public geographic databases. This integration is essential to extend the use of these digital models to support knowledge-building processes regarding modern urban heritage, also aimed at current conservation and valorisation efforts for existing buildings and infrastructure[6].

In this regard, the development of data representation schemes – ontologies – dedicated to integrating information from heterogeneous documentary sources into urban-scale digital models is based on a dual coherence: with archival description standards on one hand, and with those adopted in public geographic databases on the other. In light of the current "massive" digitalization of historical archives – with particular reference, for example, to historical land registry archives[7] – a data representation scheme conceived in this way would enable the establishment of a standardized and automatable information flow. This would facilitate the broader use of historical and technical information acquired from documentary sources related to the built heritage.

With these premises in mind, the following section presents an experimental prototype of a web application that enables the management of an information workflow. This workflow is based on enriching the data representation ontology currently adopted by public geographic databases – with specific reference to the *Database di Sintesi Nazionale* [National Synthesis

review". *ISPRS International Journa of Geo-Information* 4 (2024): 2842-2889. DOI: https://doi.org/10.3390/ijgi4042842.

5 Lasorella M. and Cantatore E., "CityGML-based model for the recovery and management of built cultural heritage: a systematic review towards digitalized processes". *City, Territory and Architecture* 12/10 (2025). DOI: https://doi.org/10.1186/s40410-025-00259-7; Colucci E., De Ruvo V., Lingua A., *et al*., "HBIM-GIS integration: from IFC to CityGML standard for damaged cultural heritage in a multiscale 3D GIS". *Applied Sciences* 10 (2020) 1356. DOI: https://doi.org/10.3390/app10041356.

6 Spreafico A. and Serafico F., "3D WebGIS for Ephemeral Architecture Documentation and Studies in the Humanities". *Heritage*, 7 (2024), 913-947. DOI: https://doi.org/10.3390/heritage7020044; Vernizzi C. and Droghetti V., "From archival research to the digitization of existing architectural heritage: methods and processes compared". *Disegnare Con*,18 (2025). DOI: https://doi.org/10.20365/disegnarecon.34.2025.4; Granado Castro G., Aguilar Camacho J., Vaca-Castaneda V., "Geo-visualisation applied to archival heritage: a transversal interpretation of historical architectural projects". *Disegnare Con* 18 (2025). DOI: https://doi.org/10.20365/disegnarecon.34.2025.7.

7 From the "Imago" project launched in 1997 by the *Archivio di Stato di Roma* to the current project of digitalization of historical land regitsry archives at national level: https://imagoarchiviodistatoroma.cultura.gov.it/progetto.html. [Accessed on 25/09/2025].

Database] (DBSN)[8] – with the international standard for archival description (ISAD G). This system can be integrated into 3D and information models compliant with the "Industry Foundation Classes (IFC)" data model[9]. For the interactive navigation and querying of these 3D information models, a web viewer was developed, which can be used without specialized IT skills.

Specifically, the development of the web app was divided into the following actions, which are described in detail in the subsequent paragraphs: i) analysis of the *Database di Sintesi Nazionale* ontology and selection of the fields of interest for describing the built heritage of the modern city; ii) progressive enrichment of the information parameters, consistent with the DBSN ontology, dedicated to integrating the information contained in the documentation preserved in local historical archives; iii) production of a metadata set for a selection of archival documents, in accordance with point (ii); iv) development of the IT architecture and the viewer interface for navigating georeferenced 3D and information models.

The proposed working methodology is applied to the case study of the *Borgo Trento* district in Verona – previously introduced in the previous chapter of this volume – based on the data already available in the SMUH webGIS platform database.

1.1 The Ontology of the National Synthesis Database (DBSN)

The DBSN Ontology constitutes the semantic and structural framework of reference for the management and organization of geospatial data relating to the Italian territory and the built environment. Developed to ensure data homogeneity and interoperability at the national level, it is essential for the processes of territorial knowledge, management, and planning. The adoption of the DBSN Ontology is particularly relevant for studies aiming to integrate different information systems, as it provides a common semantic language for the exchange of information[10].

The DBSN Ontology adopts a hierarchical and tripartite structure that systematically classifies territorial objects from general to specific categories. This structure is organized into: *Strati* [Layers], *Temi* [Themes], and *Classi*

8 DBSN: https://www.igmi.org/it/dbsn-database-di-sintesi-nazionale. [Accessed on 25/11/2025].

9 IFC: https://www.buildingsmartitalia.org/standard/standard-bs/industry-foundation-classes-ifc/. [Accessed on 25/11/2025].

10 "Catalogo dei Dati Territoriali – Specifiche di Contenuto per il DBSN (Data Base di Sintesi Nazionale)", Versione 4.0, 31 luglio 2023, https://www.igmi.org/dbsn_supporto/dbsn/dbsn_specs.pdf. [Accessed on 25/11/2025].

Table 1 – *Hierarchical structure of Layer 02 of the DBSN ontology, including the themes and classes considered in this study.*

Layer: 02	**Buildings and Anthropization [*Immobili e Antropizzazioni*]**
Theme: 0201	Built environment [*Edificato*]
Class: 020102	Single Building [*Edificio*]
Theme: 0203	Infrastructures [*Opere delle infrastrutture di trasporto*]
Class: 020301	Bridge [*Ponte]*
Theme: 0205	Hydraulic Infrastructures [*Opere idrauliche*]
Class: 020502	Embankment [*Argine*]

[Classes], presented according to a hierarchical criterion.

The Layer represents the highest level of the hierarchy, identifying macro-systems or the main components of the territory. These include, for example, the built environment, the hydrographic network, or soil characteristics.

The Themes are subcategories of the Layers that specify the main systems described within a layer. They subdivide the macro-system into sets of logically related elements. For instance, within the layer "*Immobili e Antropizzazioni*" (Buildings and Anthropized Areas), one can find Themes such as "*0201: Edificato*" (Built-up areas) or "*0203: Opere delle infrastrutture di trasporto*" (Transport infrastructure works).

The Class represents the finest level of classification and defines the specific typology of the geospatial object. Classes are the discrete and manageable elements (i.e. buildings, bridges, roads) to which descriptive and geometric information is associated. Classification at the class level is fundamental to ensuring precision in data modelling.

Each element within this structure (Layer, Theme, Class) is uniquely identified by alphanumeric codes and a concise name, thus facilitating automated indexing and consultation.

In the framework of this study, which focuses on existing buildings and infrastructure located in urban areas, only Layer "*02: Immobili e Antropizzazioni*" (Buildings and Anthropized Areas) is considered, including the following related Themes: "*0201: Edificato*" (Built-up areas), "*0203: Opere delle infrastrutture di trasporto*" (Transport infrastructure works), and "*0205: Opere idrauliche di difesa e di regimentazione idraulica*" (Hydraulic defense and regulation works)[11]. Indeed, this layer and the selected themes include suffi-

11 "Il modello GeoUML – Regole di interpretazione delle specifiche di contenuto per i DataBase Geotopografici". Allegato 2 al Decreto della Presidenza del Consiglio dei Ministri, Regole tecniche per la definizione delle specifiche di contenuto dei database geotopografici 10 novembre 2011. Gazzetta Ufficiale n. 48 del 27/02/2012 – Supplemento ordinario n. 37.

cient classes to describe the various categories of buildings and infrastructure found in urban areas (buildings, roads, bridges, river embankments). Table 1 shows the hierarchical structure of Layer 02, including the themes and classes taken into consideration in this study.

1.2 The Enrichment of the DBSN Ontology for the Archival Data Integration

Each model object belonging to the Themes previously extracted from the DBSN ontology is associated with a vast set of information parameters; they're divided into descriptive attributes and metadata related to the integration of archival sources. For a single building or structure belonging to the Themes "*0201: Edificato*", "*0203: Opere delle infrastrutture di trasporto*", and "*0205: Opere idrauliche di difesa e di regimentazione idraulica*", a specific set of descriptive parameters is considered. These are consistent with the information fields already populated in the SMUH webGIS platform and can be easily "aligned" with the set of standard information parameters included in the DBSN.

The set of descriptive parameters associated with each building or infrastructure element contains: a unique identification code (identified by the code "bd_id"); an extended name (identified by the code "bd_name"); the function (identified by the code "bd_funct"); the presence of historical-artistic constraints/protections (identified by the code "bd_ch_ass"); the characterization of the prevailing construction technique (identified by the code "bd_at").

For the management of information derived from historical archives, the additional parameter "instance metadata" ("meta_inst"), derived from the DBSN data scheme, is considered. The "meta_inst" parameter is an essential information attribute within the DBSN ontology[12].

Its primary function is to identify and trace the source of origin or the nature of the data associated with a specific instance of an element (for example, a single building or a road). It does not describe the object itself (such as its function or material), but rather its supporting information.

In the original DBSN scheme, "meta_inst" is presented as a numerical code that refers to a predefined list of sources. This allows to the distinction and automated querying of the "data source" – distinguishing, for instance, whether the data is derived from field surveys, technical mapping, orthophotos, or official administrative sources – and its "reliability". Indirectly, the source code suggests the level of accuracy and the reference period of the

12 "Catalogo dei Dati Territoriali – Specifiche di Contenuto per il DBSN (Data Base di Sintesi Nazionale)", Versione 4.0, 31 luglio 2023, https://www.igmi.org/dbsn_supporto/dbsn/dbsn_specs.pdf. [Accessed on 25/11/2025].

provided data. An example of an original value associated with the parameter in the DBSN scheme is code 05 (dato_pa), which identifies data coming from official Public Administration sources.

In the present work, as part of the prototype development, the “meta_inst” parameter is leveraged as a semantic anchor point to integrate information from local historical archives into the DBSN geospatial scheme through an extension of the original code 05. In particular, by treating 05 (dato_pa) “Public Administration Data” as a generic data level, a possible extension is envisioned with code 0590, which is considered a subclass associated with the archives of local authorities. This contains a further subclass – 0590n – necessary for identifying specific archival funds. In this way, the extension of code 05 allows the DBSN instance to be linked directly to the physical storage location of the historical document, achieving primary objectives related to “documentary traceability”.

Consequently, every geospatial element receives a direct standardized reference (a specific “meta_inst” code) attesting to the presence of documentary resources usable in knowledge, conservation, and valorization processes. In this sense, extending the “meta_inst” parameter not only certifies the origin of the data but also makes historical documentation operationally available for the management, maintenance, and study of the built environment by users at various levels, even those without specific archival research skills. In summary, the meta_inst parameter constitutes a new linking key between a standardized geospatial model (DBSN) and the structuring of historical and technical information, facilitating the retrieval of original documentation preserved in historical archives.

By associating the extended “meta_inst” (for example, with class “020102: Building”), archival documentation takes on a fundamental supporting role. This process not only enhances the existing information in the DBSN by inserting data verified by documentary evidence but also allows the addition of new parameters essential for the management and knowledge of the built environment, such as the exact year of construction or the chronology of subsequent maintenance interventions.

To ensure the unique identification of individual building structures and the integration of additional documentary sources from the massive digitalization of historical land registries, the methodology also provides for the possible overwriting of the unique code “bd_id” related to objects in class “020102: Building”. This directly links the population of this field to regional land registry records, based on data that can be integrated into the national DBSN database. Table 2 provides a summary of the alignment of the proposed information parameters with the standard fields already present in the DBSN.

Table 2 – *Alignment of the proposed information parameters with the standard fields already present in the DBSN.*

DBSN	SMUH Prototype
Edic_id	bd_id (identification code of the building)
Edific_nome	bd_name (name)
Edific_uso	bd_function (building function)
Edific_mon	bd_ch_asse (ex lege constrains)
Edific_at	bd_at (construction techniques)
Meta_ist	bd_meta (identification of the archive; documentary collection)

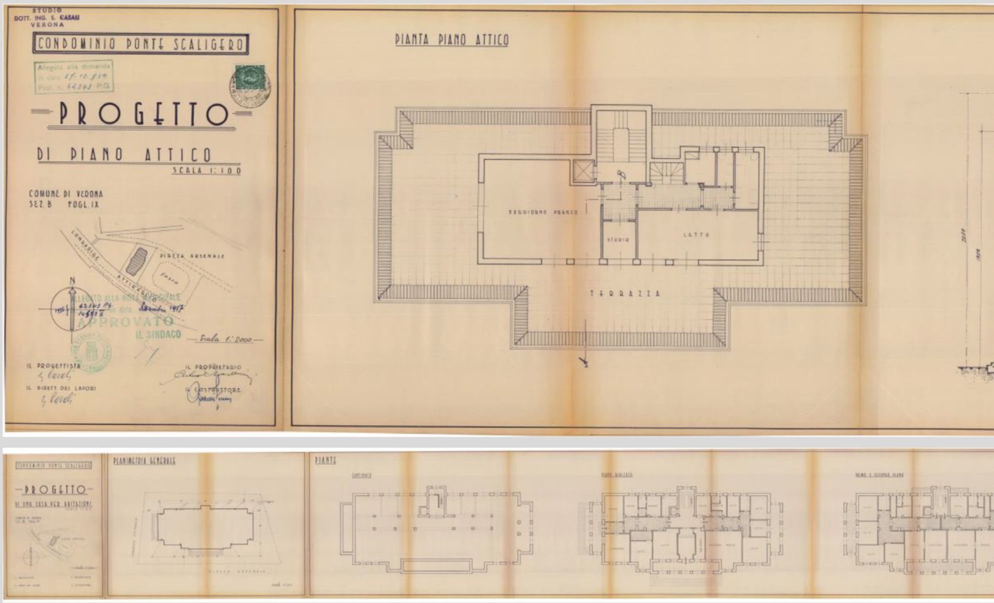
To support a unique association between individual archival documents and the building or infrastructure units represented in the model, the development of this prototype proposes an extension of the descriptive data fields for documentary units, with reference to the ISAD (G) international standard[13].

While ISAD(G) serves as the reference framework for the description of archival funds, it is not inherently designed to communicate directly with the information models adopted in construction and for the description of historical built heritage. To make the documentary heritage directly "readable" by information models related to the built environment in a broader sense, the inclusion of two new fields is proposed. These fields, described below, aim to integrate minimum descriptive sets into the archival description record built upon the ISAD(G) standard as show in the figure 01.

The first field is identified by the code “bd_id” and aims to provide a unique identification of the building structure represented in the document, in relation to the data present in national geographic databases (DBSN). This field will be populated with a unique identification code for the building, directly derived from the nomenclature adopted in national geographic databases. By inserting this code into the archival record, a direct, unambiguous association is established between the document (e.g., a building permit project) and the representation of the building within the national geospatial database.

The second field, defined by the code “meta_inst”, is dedicated to the transcription of the repository entity's code and the code assigned to the specific structure of the archival funds. This is preceded by the codes associated with the extended metadata of the DBSN ontology presented in the previous paragraph (0590-0590n), enabling a one-to-one link between the documentary source and the individual entity within the geospatial model.

13 Italian translation of the ISAD G. https://icar.cultura.gov.it/standard/standard-internazionali/isad-g. [Accessed on 25/11/2025].



ISAD Data

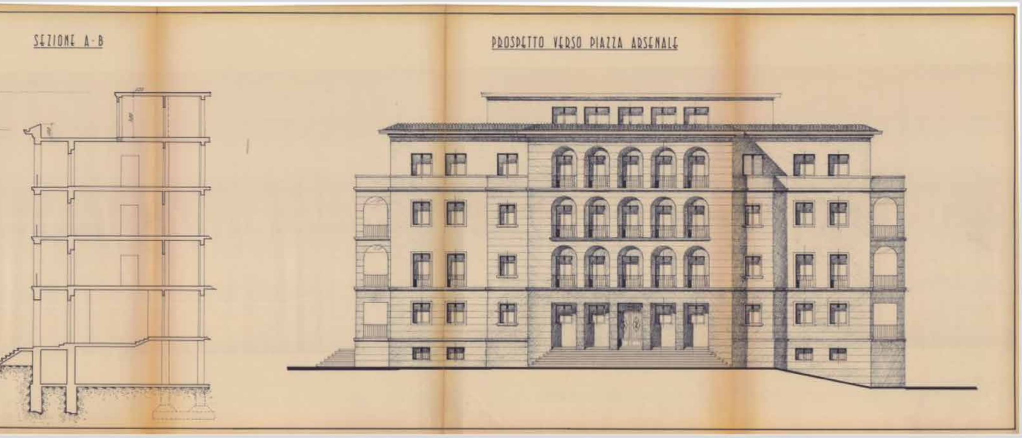
Standard fields

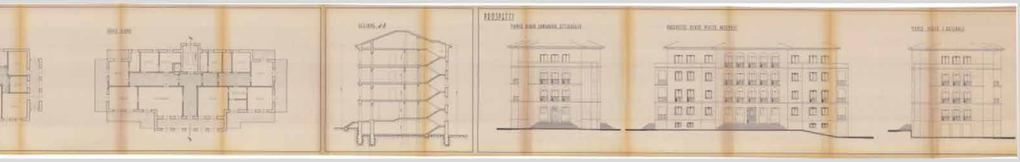
Name of the folder: Armellini Arturo
Date: 1955
Archival Layer: unità archivistica
Consistency: 5 disegni, 1 documento dattiloscritto

Proposed Extension of data

Edific_id: from DSBN (or Regional Cadastre)
0590_01: ASV, Fondo UDID

Fig. 1 – *Proposal for the enrichment of the National Synthesis Database (DBSN) ontology for the enhancement of data from documentary collections preserved in local government archives: enrichment hypotheses for building and infrastructure artifacts, with specific reference to two buildings in the* Borgo Trento *district in Verona, a case study of the SMUH project.*


SEZIONE A-B
PROSPETTO VERSO PIAZZA ARSENALE



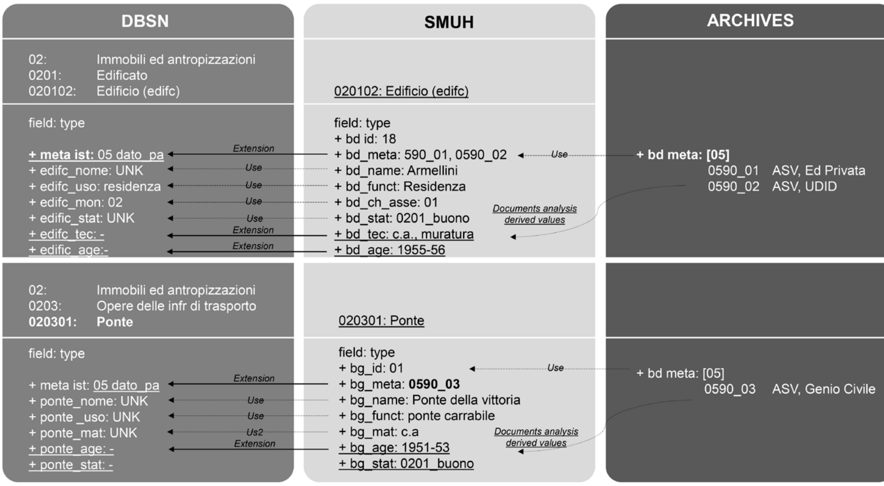


Fig. 2 – *Proposal for the enrichment of the ISAD(G) sheet fields to control and automate the information flow aimed at using historical and technical documents – preserved in archives of the built environment – within current processes of knowledge, conservation, and enhancement of existing buildings, through alignment with the information fields of the National Synthesis Database (DBSN).*

This proposed extension of the descriptor fields for documentary units represents a fundamental step in supporting the automation of integration processes for archival data into urban-scale information models. It creates a bidirectional information flow and enables its use by two different levels of users: on one hand, the link allows the user of the 3D information model to trace back to the archival source – providing summary information regarding the repository and the creator; on the other hand, the same link allows for the direct connection of the archival source to the relative building structures, uniquely identified by codes extracted from national geographic databases.

2. For a Modular Open-source BIM/GIS City Model

The three-dimensional geospatial visualization of informative data is achieved by integrating traditional GIS maps and BIM models, compliant with the IFC standard, through the development of a dedicated web-app. The choice to work on BIM/GIS integration for 3D visualization in GIS systems, rather than developing the same visualization based on the "CityGml"[14] standard for 3D

14 In this regard, it is important to emphasize how the readability of the models produced within the scope of this work for the construction of the webApp is guaranteed even when applying open access cloud platforms, such as the case of the Cesium ION platform, the current bench-

GIS development, was primarily dictated by the desire to make the platform an open modular system. This allows for future extensions through the population of BIM models – compliant with the IFC standard – potentially produced by professional communities active in the area.

GIS and BIM representations, which by nature are not natively connected, were therefore linked and made jointly operational in a web environment accessible via the cloud. A cloud-based system is thus structured into a highly customized web application, directly accessible by the user and based on the combination of various open-access libraries for data management and visualization[15].

The application is based on the combination of the 'Mapbox'[16] library to display GIS data in a 3D environment, with the possibility of viewing and querying BIM models of individual buildings in a GIS environment, utilizing the open Industry Foundation Class (IFC) standard.The platform allows for the integration of a set of information parameters – entirely extensible – at both the individual building and urban scales. In this sense, the platform enables the real-time construction and visualization, including in a three-dimensional environment, of thematic maps already presented in the previous chapter regarding the 'traditional' interface of the SMUH webGIS platform, by leveraging specific clusters of information parameters that can be 'filtered' and 'selected'.

Therefore it is possible, for example, to visualize the spatial distribution of construction periods or construction techniques at an urban scale, thus transforming historical and technical data contained in the information attributes related to single buildings or infrastructure projects into dynamic and usable information for territorial analysis. On a technological level, the platform's cloud-based architecture ensures the coexistence of structured information and intuitive data navigation, supported by three-dimensional representations of individual buildings and infrastructure projects. Consistent with the objectives of the SMUH project, the platform design integrates the possibility of a simultaneous reading of three-dimensional models and satellite data information, with specific reference to the positioning of Permanent Scatters and related datasets composed in historical series.

mark for consulting IFC models in a 3D GIS environment and a very useful alternative to the construction of customized webApps. The most recent 3D Tiling functionalities offered by 'Cesium Design Tiler' were released simultaneously with the construction of the SMUH project's webApp. Cesium: https://cesium.com/platform/cesium-ion/. [Accessed on 25/11/2025].

15 On the application of the CityGml for knwoledge reggered to the historical building heritage in Italy. Pepe M., Domenica C., Vincenzo S. A., Angelini M. G. and Garofalo R. A. "A CityGML Multiscale Approach for the Conservation and Management of Cultural Heritage: The Case Study of the Old Town of Taranto (Italy)". *ISPRS International Journal of Geo-Information* 9/7 (2020). DOI: 449. https://doi.org/10.3390/ijgi9070449.

16 Mapbox: https://www.mapbox.com/. [Accessed 25/11/2025].

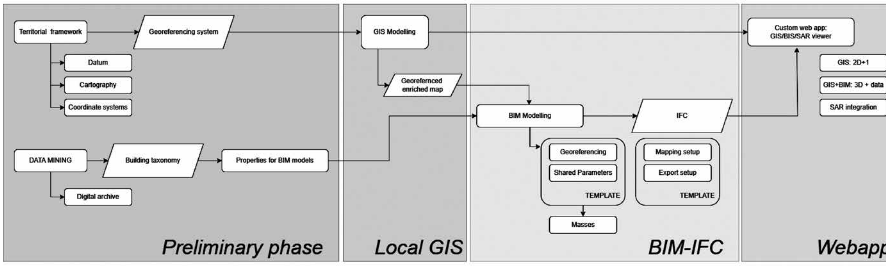


Fig. 3 – *Workflow for the construction of the WebApp.*

2.1 The Construction of the Cloud-based Platform

From a technical point of view, the process is based on 3 phases following the preliminary research phase: authoring modelling (BIM), IFC export and validation; acquiring and organizing the map through data integration (GIS); and combining BIM and GIS in a layered, cloud-based platform (webApp).

Looking at file extensions, ".ifc" is the core for getting building data; ".shp", ".geojson", and ".geotiff" are the main data sources used to build the territorial map, enriched with relevant data from the DBNS ontology.

The IFC model is intended as a simplified volume representing the enclosure of every single building: solids and voids can be used to create the building's external surfaces.

In this project, we used Autodesk Revit® as a BIM authoring tool. Using "Masses", we obtained the geometry of the building object, treated as a single component (multiple solids are allowed within the same mass). Finally, we assigned materials to represent the building (the best approach is to use one material for roofs and one for vertical enclosures) and enriched the model with data. Be sure to define a solid data structure that can be easily exported to IFC, since this is the interoperability exchange format for the viewer. In this project, we opted for a list of custom parameters defining naming conventions, data types, and sample values to improve comprehension. This is what Shared Parameters in Revit stand for. Every model uses the same parameters to ensure consistency and standardise the IFC export setup.

To enable GIS-BIM exchange, every geometry on the 2D map must be enriched with a common attribute to support calls for additional data and to integrate the BIM project at the exact position in the GIS environment. This is why we opted to prepare the territorial map in QGIS, integrate geometry and data from different sources, including DBNS, and finally export it as a .shp for use in "Mapbox" and for web application access.

The integration of BIM and GIS is built on top of "ThreeJs"[17] and That Open Engine | web-ifc[18] open libraries: the first is a global library for rendering 3D in the cloud, the latter is an open platform to view IFC models in a browser. Specifically, Mapbox is the key to integrating BIM and GIS data: this library uses a three-dimensional scene to view GIS data sources (geometry and data); the same scene is used to integrate the IFC model, rendered by "That Open Engine", preserving the entire IFC data structure.

The map is intended as a layered middle element of the chain: it must be comprehensive in its own right as GIS content and, on request, be integrated with BIM models.

Our Mapbox map is a mixed output built on top of: Opengeodata for street classification and general data, Custom territorial data for representing terrain as 3D (including effective altimetry), Custom SAT files for buildings, integrating many attributes from regional and national databases, and adding the relevant attributes for our analysis (we specifically over-layered SAR data).

To view IFC in the cloud, we used That Open Engine, an open library that converts IFC geometry and data, making them available in the cloud. To speed up the viewer, the current project uses fragments and linked properties, following That Open Engine's approach. We first extracted IFC data into JSON files for each building, then used these files in the app to access the relevant information displayed in the Properties floating window.

It is important to keep everything organised and to treat the entire GIS-BIM project as a database, where data and geometry flow from the GIS to the BIM side and vice versa, with the possibility of being layered by specific Levels of Development (LOD).

2.2 A First Test on the Case Study of **Borgo Trento** *in Verona*

The methodology for integrating and enriching information data, in accordance with the standardized information flows presented in the previous paragraphs, was applied to the case study of the *Borgo Trento* district in Verona. The research focused the area between *Ponte del Risorgimento* and *Ponte della Vittoria*, which was already used for the development of the SMUH platform prototype. As described more extensively in the previous chapter, this area is distinguished by a rich 20^{th}-century building heritage, with constructions mainly built between 1920 and 1980, and by the presence of both contemporary and historical bridges rebuilt after Second World War.

17 ThreeJs: https://threejs.org. [Accessed 25/11/2025].

18 Open Engine | web-ifc: https://github.com/ThatOpen/engine_web-ifc. [Accessed 25/11/2025].

Since the period of construction, the city's historical archives preserve a significant amount of data relating to the building heritage within in the analysed area. For the study, four main documentary collections were considered, preserved at the State Archives of Verona and the Municipal Archives of Verona. As extensively discussed in the previous chapter, two key funds were examined for research relating to buildings: the *Edilizia Privata* fund and the fund of the former *Ufficio Distrettuale Imposte Dirette* (U.D.I.D.), conserved respectively at the *Archivio Generale del Comune di Verona* and *Archivio di Stato di Verona*. For infrastructures and bridges, the research focused on the *Lavori Pubblici* and the *Ufficio del Genio Civile di Verona* funds, preserved in the *Archivio Generale del Comune di Verona*, and the *Archivio di Stato di Verona*.

The overlapping and cross-consultation of these sources enabled the collection of a significant amount of historical and technical data, fundamental for an in-depth understanding of the individual structures. Regarding buildings, for example, the U.D.I.D. fund preserves a valuable documentary series related to tax assessments for new buildings (period 1920-1960). This includes graphic drawings, photographs, and certificates of habitability or usability. Such data offers a significant enrichment of the information already present in the *Edilizia Privata* fund. Similarly, for bridges and infrastructure, the *Genio Civile* fund preserves projects and construction site documentation for works carried out between 1920 and 1970, substantially integrating the information contained in the *Lavori Pubblici* fund.

In order to guarantee the proper conservation and classification of information derived from these archival sources, the extension of the "meta_ist" parameter of the DBSN ontology was carried out. The identified archival sources (i.e. U.D.I.D., *Genio Civile*, etc.) were inserted as subclasses of the generic category "*05_90: Archivi di Enti Locali*" (Local Authorities Archives). In detail, the data enrichment process allows for the integration of heterogeneous data from historical archives into the standardized semantic schema of the DBSN Ontology.

In the specific case of a building structure from the case study in question, belonging to class "*020102 Edificio*", the minimum and standardized information parameters present in the DBSN cartography were initially associated. In this phase, not all parameters were valued: for example, the "meta_ist" parameter is set to the generic value "05 dato_pa", indicating only a generic origin of the data from the "Public Administration"; other fields, such as "edific_nome" (building name), are unknown, while essential parameters for information enrichment, such as "edific_age" (relating to the age or year of construction), are not present in the original DBSN schema but are provided in the minimum sets for subsequent integration.

The core of the methodology is the recovery of archival sources: in this phase, the “meta_ist” parameter is used to access the set of extended values that specify the archival subclasses created ad hoc for the case study, in this case: “05_90 (*Archivi Enti Locali*)”, and its branches that identify the specific funds such as “05_90_01 (ASR Edilizia privata)” and “05_90_02 (ASR, UDID)”. Leveraging the information contained in the documentary sources, the DBSN object is updated through PATCH (update) and POST (addition) operations, resulting in full enrichment through the valuation of all information parameters contained in the standardized sets.

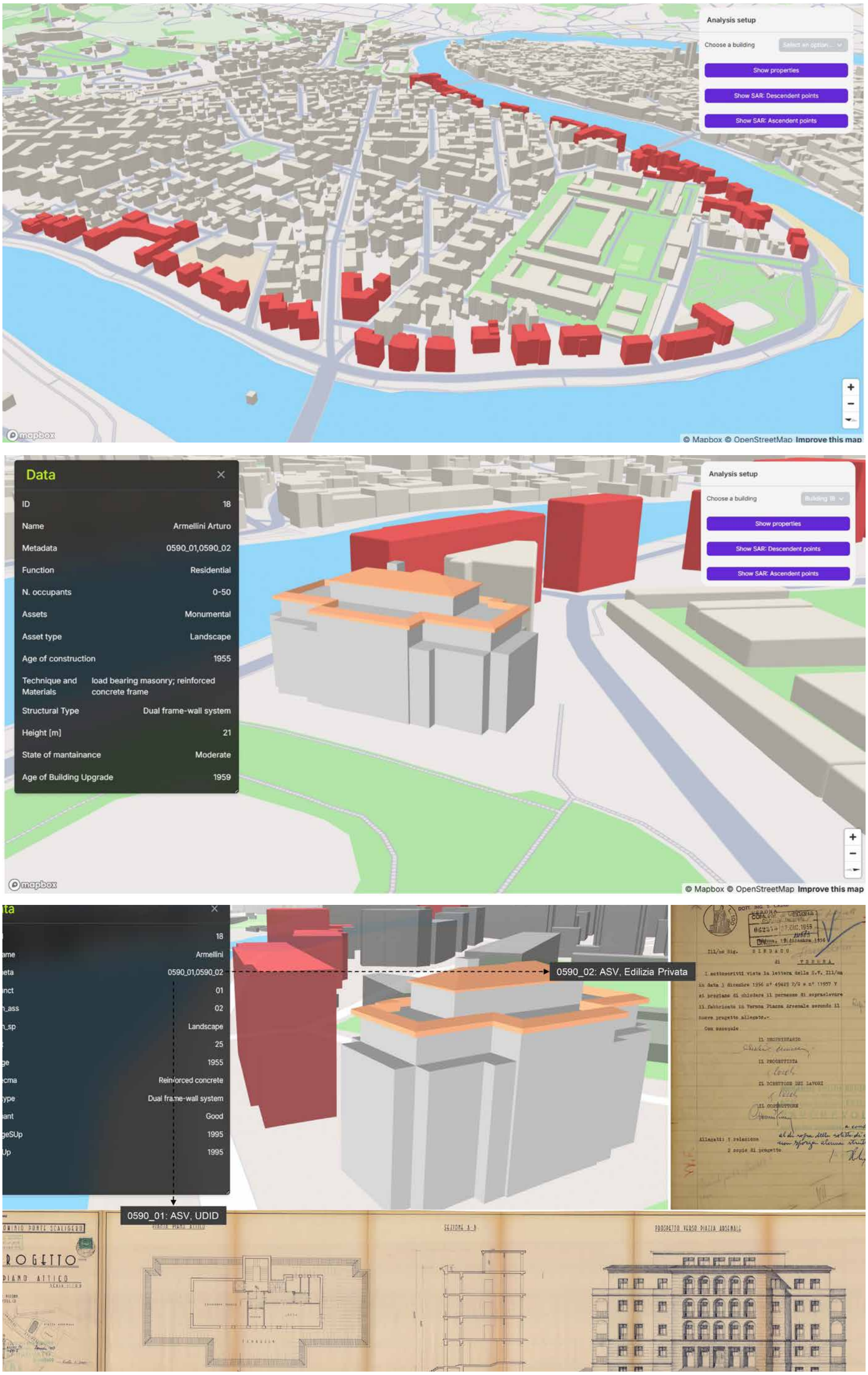
In the "enrichment" phase, the field “bd_meta” is populated with the specific codes of the archival funds used, thereby establishing that the information derives from [0590] and specifically from [0590_01 (ASR, Edilizia privata)] and [0590_02 (ASR, UDID)]. In this way, the data is semantically linked to its documentary evidence. In the same manner, descriptive parameters are updated with verified values, such as “bd_name” = “Armellini” and “bd_ch_ass” = “01 (monumentale)”.

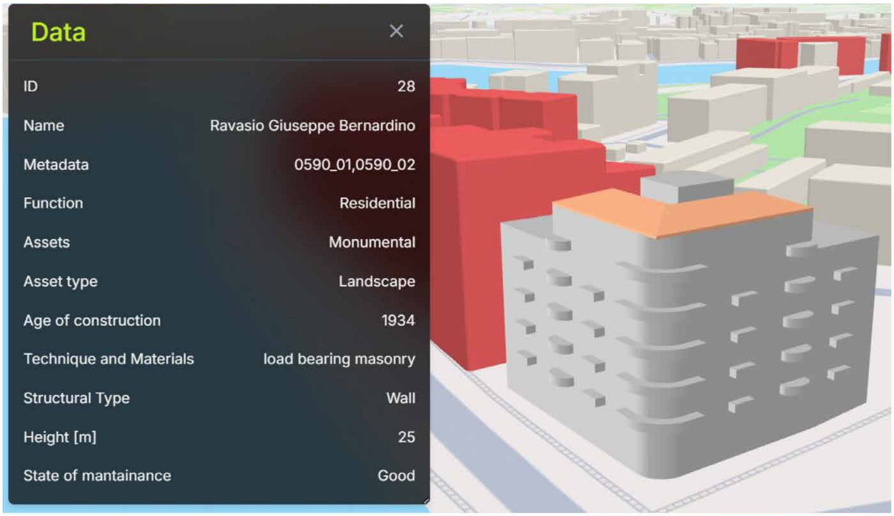
Finally, new parameters are introduced that were not provided for in the base schema but are considered essential for the knowledge of the building structures, such as the year of construction (bd_age = 1955) and the year of the last structural update (bd_ageSup = 1995), obtained from archival documentation. Furthermore, the parameter “bd_id” is added, containing the unique code derived, in this specific case, from the Regional Cadastre, to resolve the problem of spatial identification of the individual building within the GIS information system.

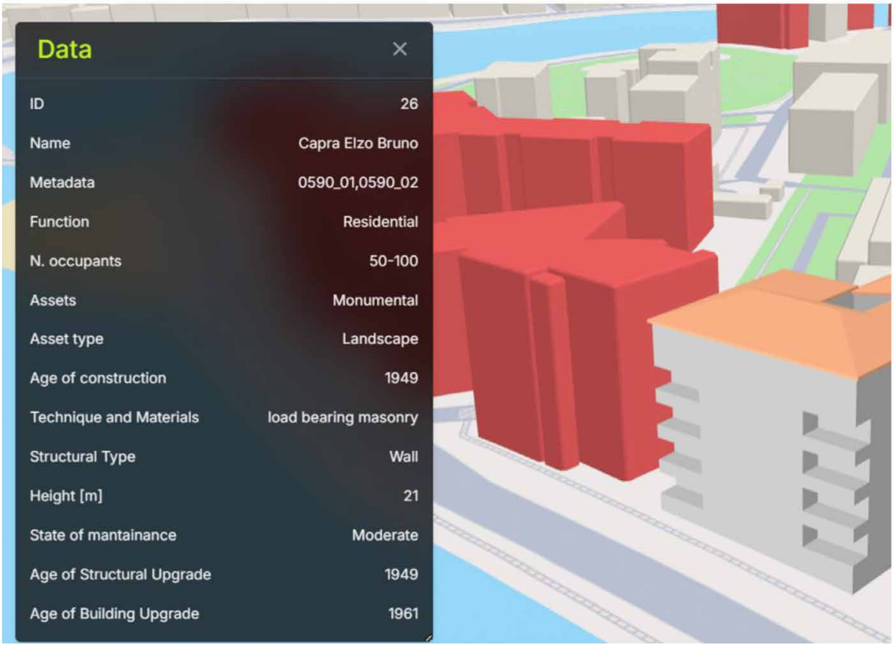
The aforementioned methodology is evident in the web app, which presents different scenarios that display only the data relevant to your needs.

When you open the app, Coarse LOD is used to display a three-dimensional map of *Borgo Trento*, with streets and building volumes, using a GIS 2D+1 approach: the map is limited to Borgo Trento, and the buildings being investigated are rendered in red. Only the common data is available at this stage.

The medium detail level provides a deeper understanding of individual buildings and requires BIM integration: you ask for a specific building, the app queries the database for geometry and data (on the IFC side), hides the corresponding GIS 2D+1 geometry, and inserts the BIM model at its geographic location. The interface lets you choose a medium detail level, focusing on a specific building: you can navigate the geometry, evaluate the volume enclosure in a more stable configuration, and request data using the dedicated command. Properties appear in a custom floating window, showing the effective relationships between BIM-GIS and DBSN.


Analysis setup
Choose a building
Show properties
Show SAR: Descendent points
Show SAR: Ascendent points
© Mapbox © OpenStreetMap Improve this map
Data
ID 18
Name Armellini Arturo
Metadata 0590_01,0590_02
Function Residential
N. occupants 0-50
Assets Monumental
Asset type Landscape
Age of construction 1955
Technique and Materials load bearing masonry; reinforced concrete frame
Structural Type Dual frame-wall system
Height [m] 21
State of mantainance Moderate
Age of Building Upgrade 1959
0590_02: ASV, Edilizia Privata
0590_01: ASV, UDID





Figg. 4-6 – *(opposite page) Home page of the WebApp relating to the case study of the Borgo Trento district in Verona (top); query of the information fields relating to building no. 18 (centre) and query of the information fields relating to building no. 18 embedding connections with the documents (bottom).*

Figg. 7-8 – *Page of the WebApp relating to the case study of the Borgo Trento district in Verona: query of the information fields relating to buildings no. 26 and no. 28.*

Fig. 9 – *Page of the WebApp relating to the case study of the Borgo Trento district in Verona: query of the measurement points (ascending orbit) relating to building no. 18.*

Fig. 10 – *The integration of the ICF model and the SAR data in the open-source 3DGIS platform Cesium ION: query of the measurement points (ascending orbit) relating to building no. 18 (colours indicates the gradation of the mean velocity of displacements).*

Finally, there is a Fine level of detail available using the 'Show SAR data' commands: the app adds SAR data as a new layer on top of the scene, visualizing both the IFC building and the points of analysis, with the possibility to analytically navigate the results of the analysis in a dedicated floating window.

The approach used in this project can be considered a basic methodological framework for integrating BIM and GIS environments and external data. Nowadays, multiple infrastructures are available that can use IFC to access geometry and data and insert buildings into the territorial context. The logic used for the Mapbox-That Open Company web app can be extended and replicated across different platforms, and further extended depending on the library used. For testing purposes, we configured a basic Cesium environment, adding a sample building with SAR data.

3. Conclusions

The application to the case study demonstrates, therefore, how adopting the DBSN ontology structure enables the effective integration of historical and technical information derived from archival documentation, thereby supporting the transformation of generic or missing data into precise, spatially linked, and rigorously structured information. The adoption of the DBSN ontology therefore proves to be particularly efficient for structuring information related to the built heritage with strong semantic links, simplifying and standardizing the interrogation of information models at an urban scale.

At the same time, the integration of DInSAR data allows for a visual verification of the positioning of Permanent Scatterers and a simultaneous reading of the in-depth knowledge frameworks related to the individual building and the historical series of surface displacements relative to the area in which said building is located. Furthermore, the case study demonstrates the effectiveness of modular BIM-GIS integration for constructing three-dimensional and information models at an urban scale, useful for the precise analysis of building and infrastructure assets. In this sense, the adoption of the IFC standard guarantees a potential rigorous standardization of information flows despite a marked simplicity in producing the models themselves, based on well-known BIM Authoring application.

2. RESEARCH PERSPECTIVE AND MORE CASE STUDIES

Historical Analysis and open BIM-3DGIS for Satellite Data-based Structural Monitoring: the Regina Margherita *School Building in Rome*

Fabio Di Carlo[1], *Ilaria Giannetti*[1], *Alberto Meda*[1], *Stefania Mornati*[1], *Zila Rinaldi*[1]

The conservation of built heritage in the contemporary city represents multidisciplinary challenge, necessitating a rethinking of established operational practices. Indeed, it is essential to move beyond purely conservative approaches – often restricted to localized, reactive maintenance and restoration efforts – towards of continuous monitoring strategies and preventive conservation actions[2]. The built heritage of Italian cities, a palimpsest of heterogeneous building materials and technological solutions, is inherently vulnerable to structural and building degradation. These phenomena are continuously exacerbated by local environmental issues and anthropogenic pressures stemming from intensive urbanization[3].

Against this backdrop of widespread fragility, this paper aims to develop an operational protocol based on the synergistic convergence of three technological domains: HBIM (Heritage Building Information Modeling), GIS (Geographical Information Systems), and DInSAR (Differential Interferometry Synthetic Aperture Radar) for the acquisition of satellite measurements[4]. The integration of these tools aims to create a multi-source "Digital

1 University of Rome Tor Vergata, Department of Civil Engineering and Computer Science Engineering.

2 On the theoretical framework of preventive conservation for heritage object see: Wickens J. D. J., "Preventive Conservation: Continuously Defining Itself at the Crossroads of Theory and Practice". *Journal of the American Institute for Conservation* 1/13 (2024). DOI: https://doi.org/10.1080/01971360.2024.2348924.

3 On the building heritage and climate change scenarios see for example: Zamboni I., "Patrimonio costruito e cambiamenti climatici: stato dell'arte, prospettive e competenze multidisciplinar". *Archeologia dell'architettura* 28/2 (2023): 2038-6567.

4 On the use of Satellite radar interferometry for structural monitoring bases on a similar multidisciplinary approach a see for example: Talledo D. *et al*. "Satellite radar interferometry: Potential and limitations for structural assessment and monitoring", *Journal of Building Engineering* 46 (2024); Di Carlo F. *et al*. "On the integration of multi-temporal synthetic aperture radar interferometry products and historical surveys data for buildings structural monitoring", *Journal of Civil Structuctural Health Monitoring* 11 (2021):1429-47; Giannetti I., Bertolazzi

Twin", facilitating the preservation of built assets by simultaneously accounting for material aspects and the dynamic phenomena of their surrounding territorial context.

HBIM is thus employed as an information database that organizes and transmits the historical record of the design, construction, and lifecycle of the structure, alongside the physical and mechanical properties of materials and the diagnostic assessment of building and structural pathologies. GIS integration situates the 3D information model of the building within its wider territorial and urban context. Simultaneously, the GIS environment supports the interpretation of satellite measurements which, obtained via the DInSAR technique, enable the detection of slow displacements affecting the building structure.

The case study of the *Regina Margherita* school in Rome is very meaningful since it is a public building whose main core was designed and constructed in the late Nineteenth century[5]. Over time, it has undergone significant structural and architectural transformations and is situated in an urban area adjacent to the course of the Tiber river. This study demonstrates how a multi-source digital model, resulting from the integration of HBIM, GIS, and DInSAR data, can support decision-making for structural risk mitigation, shifting the preservation of built heritage toward predictive maintenance strategies. By correlating the construction history and subsequent transformations – represented within the HBIM model – with displacement trends extracted from satellite measurements, it is possible to identify intervention priorities, thereby supporting the decision-making processes of stakeholders responsible for asset management.

1. Methodology

The methodological protocol proposed in this research is structured into four main actions: i) historical-critical research on the building under investigation and diagnostic investigations for the assessment of its current state and the physicomechanical properties of the construction materials; ii)

A., *et al.*, "A Cross-Disciplinary Approach for the Safeguard of Modern Urban Heritage: Historical Investigation, Satellite Measurement, Structural Vulnerability Analysis". In *Envisioning the Futures - Designing and Building for People and the Environment. Colloqui.AT.e 2025*, edited by Albatici R., Dalprà M., Gatti M. P., Maracchini G., Torresin S., 349-367. Cham: Springer, 2025. DOI: https://doi.org/10.1007/978-3-032-06974-0_18.

5 The material on the case study is collected within a research collaboration agreement within the *I Municipio* of Roma Capitale and the Department of Civil Engineering and Computer Science Engineering, University of Rome Tor Vergata.

construction of an HBIM "case" model dedicated to the organization of the historical and technical knowledge acquired about the structure during the first phase; iii) acquisition of datasets related to satellite measurements; iv) integration of the BIM model into a 3D GIS environment for the simultaneous interpretation of the building's anatomy and the measurements obtained from satellite data.

The construction of the knowledge base is understood as a critical systematization of data obtained from documentary sources and diagnostic investigations. In particular, the historical knowledge base is established through rigorous archival research. Documentary research is followed by the phase of on-site investigations through a survey plan that allows for the identification of construction details that remained uncertain following the historical research, as well as the current physicomechanical characterization of the building materials.

The knowledge derived from documentary surveys and on-site investigations is organized through the construction of an HBIM model, developed at the scale of individual construction elements. This model is designed according to the Level of Information (LOI) required for the subsequent execution of an accurate structural diagnosis.

The management of uncertain data is addressed through the integration of metadata that qualifies the reliability of the information by specifying its source, such as "data derived from documents", "data derived from on-site investigations", or "data inferred by analogy". This approach allows for a clear distinction between documented components and hypothesized parts.

In parallel with the HBIM modelling of the building, SAR (Synthetic Aperture Radar) data, derived from the processing of images captured by satellite constellations, such as COSMO-SkyMed (COnstellation of small Satellites for Mediterranean basin Observation - CSK) or Copernicus Sentinel-1, are acquired and exploited. In particular, the protocol adopted uses the MT-DInSAR (Multi-Temporal Differential Interferometry Synthetic Aperture Radar). To this aim, CSK ascending (ASC) and descending (DES) datasets are processed applying the Small Base-Line Subset (SBAS) method, by obtaining displacement time series and mean velocity maps of the measurement points (PSs).

In the final phase of the research, the satellite data and the HBIM model are integrated within a 3D GIS environment. Interoperability between the systems is guaranteed using the IFC (Industry Foundation Classes) standard format, which ensures the persistence of semantic information during the transition from a proprietary modeling application (BIM) to a spatial analysis one (GIS).

2. The *Regina Margherita* School Building (1886-1954): From Document to HBIM

The *Regina Margherita* school is located in via Madonna dell'Orto; it was designed in 1884 and built between 1886 and 1888, and it was among the first public schools for both boys and girls in Rome. On July 2nd, 1888, Queen Margherita of Savoy, King Umberto I consort, inaugurated the building dedicated to her, marking the start of a public-school construction campaign for the new capital of the Kingdom. In 1895, the building underwent a project to roof the terrace on via Anicia, creating rooms on the attic floor. In 1900, the *Regina Margherita* school – celebrated by the press of the time as "the first school in Rome that can be defined as such" – was exhibited at the Paris International Exposition. Between 1951 and 1953, the building had a vertical extension project, by adding a second floor of classrooms and the partial transformation of the original block.

The construction history of the building is outlined through documentation found in the following three archives: the Archivio Storico Capitolino – Building Inspectorate (1887-1930) and Building Commission (1871-1931); the Archive of the former 5th Division (Public Building), held by the Municipality of Rome; the Heritage Archive (*Archivio del Patrimonio*) of the Municipality of Rome.

Consulting the *Archivio Storico Capitolino* and the *Archivio del Patrimonio* allowed for the acquisition of documentation regarding the original project (1888) and the terrace roofing works (1895). The archive of the former 5th Division provided documentation concerning subsequent interventions on the building (1930-55), including the vertical extension project (1951-53).

The crossing of information contained in the graphic documents (design drawings), technical reports (reports, measurement logs), and economic records (bills of quantities), aided by on-site surveys, has enabled a thorough understanding of the building's anatomy and the construction solutions adopted.

2.1 The History of the Building

In 1886, Gabriele D'Ambrosio – a municipal engineer also responsible for the "Enrico Pestalozzi" and "Vittorino Da Feltre" schools – was commissioned to draft, in accordance with Bongioannini's specifications, the design for a building capable of housing 600 male and 600 female students, bringing together for the first time a nursery school and primary schools. The project,

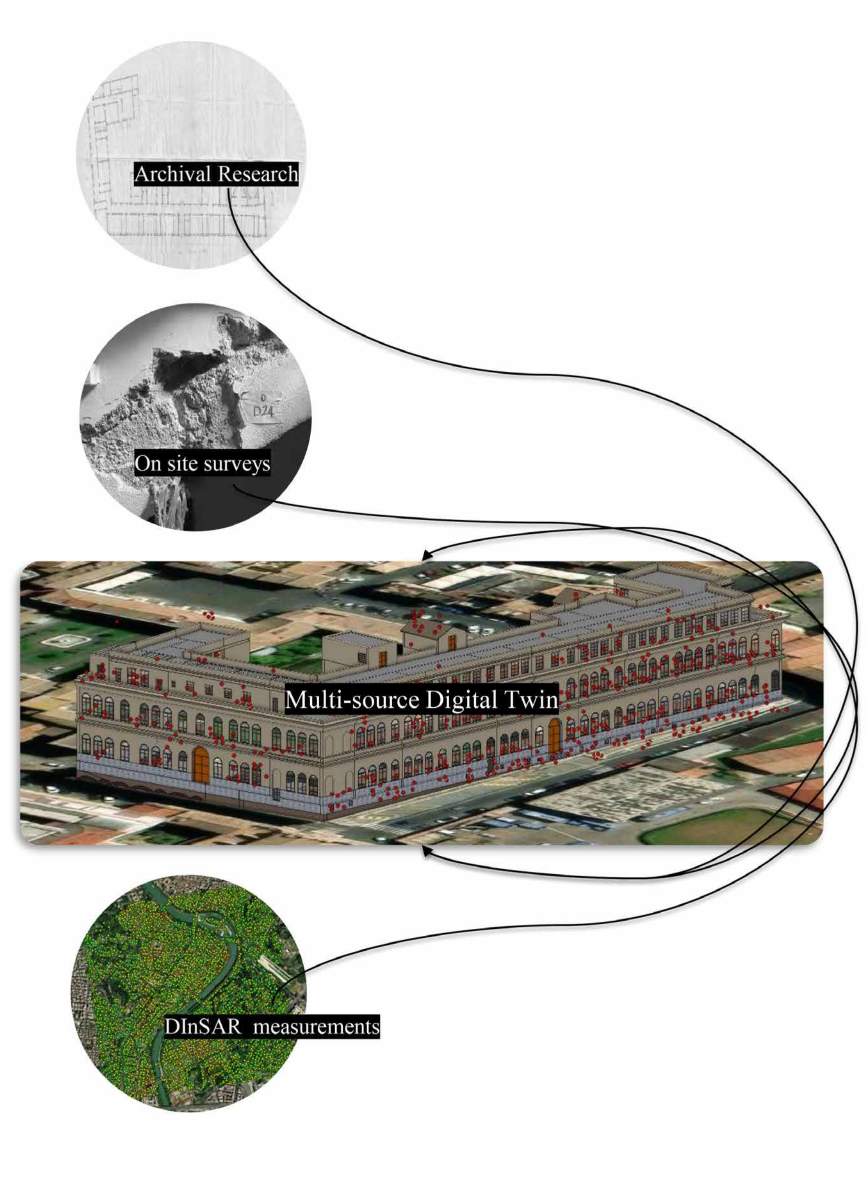
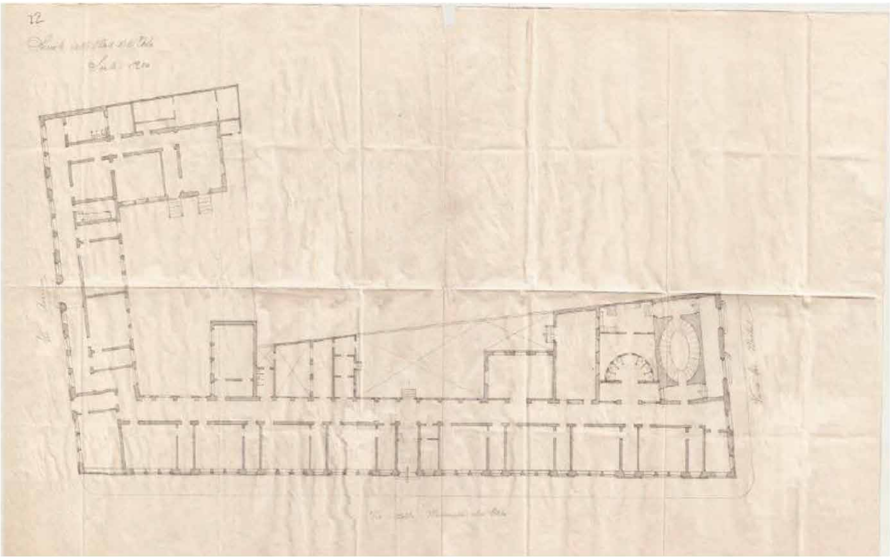


Fig. 1 – *Research Wokflow.*



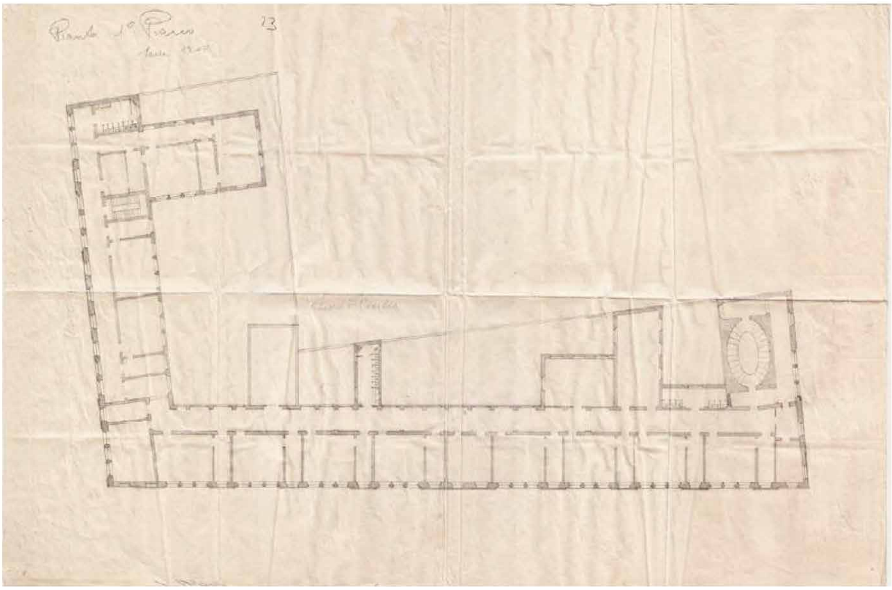


Fig. 2 – *Plans of the building project, 1886-88 (Archivio Storico Capitolino, Rip VI).*

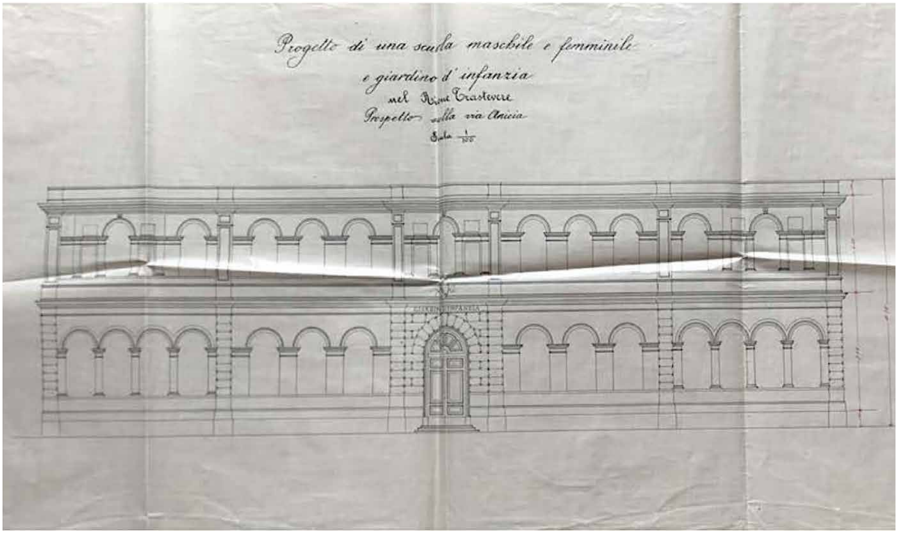


Fig. 3 – *Elevations of the building project, 186-888 (Archivio Storico Capitolino, Rip VI).*

with an estimated expenditure of 478,946.06 lire, was to be inspired by «utmost simplicity», respecting the «best artistic proportions" and devoid of "any ornamentation», to achieve a «severity of character [...] with the harmony of lines and proportions to satisfy aesthetic requirements»[6].

D'Ambrosio designed a two-story building with the main facade on via della Madonna dell'Orto, which housed the boys' entrance, and side facades on via di San Michele and via Anicia, where the girls' entrance and the kindergarten entrance were respectively located. On the fourth side, an internal elevation overlooked a courtyard bordering the Santa Cecilia monastery.

On August 9th, 1886, the Building Commission rejected an initial version of the project, inviting D'Ambrosio to modify the facades and study a new layout for the first floor; the new drawings were approved on August 18th.

The facades are characterized by large arched windows with iron frames, featuring hopper and pivoting opening systems. The windows are clustered in groups of three, aligned with the classrooms, and are separated by travertine pillars: rectangular with Doric capitals on the ground floor, and semi-octagonal with Corinthian capitals on the first floor. The elevations also feature sections of smooth rustication with low projection, stucco bands and cornices, and a travertine base plinth[7].

From the girls' entrance on via di San Michele (now walled up), access was provided to a large elliptical double-flight staircase, which was added to the project on January 3rd, 1887[8], along with the variations to the facade on via di San Michele. The staircase, constructed with iron beams, marble steps, and a wooden balustrade, was covered by an iron and glass skylight and led to the rooms on the first floor. In 1887, extensive correspondence between the Municipality and the Mayor of Turin testifies to the careful study conducted for the design of the semicircular restrooms and the heating system, based on the model of schools already built in Turin [9].

The project complies with the requirements later codified by the "Technical-Hygienic Regulation and Instructions for the implementation of the Law of July 8th, 1888, on school buildings, approved by Royal Decree (RD) no. 5808, November 11st, 1888". According to Article 4, buildings were required to be of

6 "Descrizione dell'opera", Archivio Storico Capitolino, Uff. V, div. III, tit. 9, b. 16.

7 Disegni di progetto, firmati G. D'Ambrosio, 1886, Archivio Storico Capitolino, Uff. V, div. III, b.16

8 "Lettera di G. D'Ambrosio al sig. Angelo De Bonis", 3 gennaio 1887, Archivio Storico Capitolino, Rip. V, div. III, b. 16, fasc. 1. La scala "elicoide" è presente anche nei progetti delle scuole "Enrico Pestalozzi" e "Vittorino Da Feltre", progettate da D'Ambrosio negli anni immediatamente successivi.

9 Corrispondenza tra il Sindaco di Torino e il Comune di Roma con disegni allegati, 1887, Archivio Storico Capitolino, Uff. V, div. III.

«solid construction, with a simple and elegant appearance [...]»; furthermore, classrooms had to be «located on the ground floor or the first floor [...] with south-east exposure; [...] the gymnasium was to have a height of no less than 6 meters», while the window surface area had to be equal to at least 1/6 of the classroom floor area.

On September 21st, 1886, a private tender was issued for the construction of the *Regina Margherita* School: the works, with a total amount of 550,000 lire, were to be carried out based on the provisions of the special tender specifications, with the obligation to be completed within 12 months[10].

The Municipality received 8 bids: the *Angelo De Bonis* company was awarded the contract with a discount of 26,752 lire. On October 5th, the result of the private tender was approved by the Capitoline Council, and on the 30th of the same month, the construction contract was signed between the Municipality and the *De Bonis* company. On November 3rd, engineer Mario Moretti, Director of Office V (Public Building) of the Municipality, handed over the site to the company.

The first stone was laid on December 5th, 1886: the designer, engineer D'Ambrosio, assumed the role of works director; the construction site commenced with excavations and the construction of the foundations. Between May 1st and November 30th, 1887, centering (formwork) was rented for the construction of the vaults and ceilings. The building, completed in April 1888, was officially handed over to the Municipality on September 12nd of the same year[11].

On July 2nd (1888), the inauguration ceremony took place in the presence of Queen Margherita of Savoy and Minister Boselli. The building consisted of 77 rooms, including: 31 classrooms; 26 changing rooms adjacent to the classrooms with direct access from both the rooms and the corridor; 2 bathrooms with 10 showers; an indoor and outdoor gymnasium, dining facilities (refectory), 1 gas kitchen, and 2 medical clinics; a radiator heating system. A commemorative plaque at the entrance on via Madonna dell'Orto records the fundamental milestones of the project and construction; a few months later, a second plaque was added on the opposite wall to commemorate the Queen's presence at the inauguration. The school began its activities with 724 male students and 259 female students.

10 Corrispondenza tra il Sindaco di Torino e il Comune di Roma con disegni allegati, 1887, Archivio Storico Capitolino, Uff. V, div. III.

11 Consegna del fabbricato per la scuola comunale Regina Margherita costruito dall'impresa Angelo De Bonis per conto del Comune via Madonna dell'Orto Archivio Storico Capitolino, pianta piano terreno, 1886, si nota la prima soluzione della scala su via di San Michele di Roma, Archivio Storico Capitolino, Uff. V, Div III., b. 157, f. 1.

On December 12nd, 1888, engineer Ignazio Roselli Lorenzoni was appointed as the project's tester. On April 10th, 1889, engineer Mario Moretti declared, following a site visit, that «all works are regularly executed with the exception of the stratified cement flooring, the plaster, and the paint», and noted an anomaly in the window frames on via Anicia. Specifically, the floorings showed «greatly increased cracking», proving that the cement was not of suitable quality. Furthermore, the iron window frames on the via Anicia elevation were oversized and ended below the sill, constituting an «intolerable defect». The building was officially tested in October 1889. The report mentioned the alleged demolition of ancient existing foundations during excavation. On November 2nd, 1889, D'Ambrosio responded by describing the demolished remains as «above-ground walls, entirely disconnected, which provided the company with a large quantity of high-quality tile rubble, all of which was used in the construction of the new foundations»[12].

In 1900, the school project was exhibited at the Paris International Exposition, along with educational materials and works created by the pupils attending the kindergarten and the primary schools (both boys' and girls' sections)[13].

In February 1895, the contract for the roofing of part of the terrace and other minor restoration works was awarded to the *Augusto Bannoni* company, for a planned amount of 6,000 lire. Existing documentation in the municipal archives does not allow for a detailed specification of the types of work carried out by the *Bannoni* company. The works likely involved the construction of a new block on the attic floor, specifically on the side facing via Anicia. An undated hand-drawn floor plan of a hypothetical attic floor is preserved at the Heritage Archive (*Archivio del Patrimonio*), while the actual existence of this attic level is confirmed by the list of drawings displayed at the Paris Exposition[14].

In 1919, the flooring of the corridors on all floors was officially tested and approved. In 1929, the school underwent extraordinary maintenance and restoration works, which were awarded in two lots (May 18th and August 14th) to the "*La Grande*" Anonymous Cooperative Society. On December 4th, 1930, an additional contract for cleaning and restoration works was assigned to the *Liborio Capitani* company. In 1948, a vertical expansion of the building was designed, involving the enlargement of the existing rooms on the terrace. The-

12 "Risposta di D'Ambrosio in merito alla relazione di collaudo", 2 novembre 1889, Archivio Storico Capitolino, Uff. V, Div III., b. 157, f. 1.

13 Archivio Storico Capitolino, Rip VI – Istruzione pubblica, titolario 1871-1890, titolo 35, b. 13, fasc. 1. "Le scuole comunali di Roma. Relazione sommaria per l'Esposizione Internazionale di Parigi del 1900", Officina Poligrafica Romana, Roma 1900.

14 Archivio Storico Capitolino, Rip VI – Istruzione pubblica, titolario 1871-1890, titolo 35, b. 13, fasc. 1.

se spaces were transformed into a new floor of classrooms, and two additional staircases were added. The works also involved renovations on the other existing floors. The project was entrusted to the *Francesco Carchella* company through two successive contracts dated January 8th and March 23rd, 1951, and the construction took place between 1951 and 1953[15].

On July 14th, 1953, the vertical expansion was handed over to the Municipality: 13 classrooms were built from scratch, while a new flat roof replaced the pitched roof of six existing classrooms (dating back to 1895?). Two new staircase blocks were also constructed: the one on the left spanning from the basement to the roof terrace, and the one on the right from the ground floor to the second floor. During this phase, the original elliptical staircase and its skylight were demolished, transforming that space into new classrooms across multiple levels. Additionally, two sets of restrooms were installed on every floor.

In support of the expansion works, a project was drafted for the demolition and reconstruction of the secondary staircase accessible from the via Anicia corridor. The existing staircase was deemed exceptionally steep, and the combined width of the building's three staircases was considered insufficient for the total number of students. The project for the new staircase, approved on October 9th, 1952, by the Ministry of Public Works (LL.PP.), involved a new reinforced concrete structure with independent foundations. The construction site, awarded via private tender to the same Carchella company, began on July 15th, 1954, and was completed on September 30th of the same year[16].

2.2 Construction Details

The *Regina Margherita* School building, designed under the direct supervision of the Ministry of Public Instruction inspector and the assessor, presents construction solutions in accordance with the requirements later codified by the "Technical-Hygienic Regulation and Instructions for the implementation of the Law of July 8th, 1888, on school buildings, approved by Royal Decree (RD) no. 5808, November 11th, 1888". According to these regulations, «construction materials must be of excellent quality among those most easily available locally [...]; the building must normally have a base-

15 "Licitazione privata lavori di sopraelevazione della scuola in via Madonna dell'Orto", Archivio Ex V Ripartizione del Comune di Roma, classe 5/3, fasc. 15.

16 "Licitazione privata demolizione e ricostruzione della scala pericolante della scuola in via Madonna dell'Orto", Archivio Ex V Ripartizione del Comune di Roma, classe 5/6, fasc.1924.

ment and be raised from the ground by at least 0.80 meters [...]; in buildings with more than one floor, the floor divisions should preferably be vaulted or have a double ceiling to dampen noise».

The anatomy of the various building elements was deduced by comparing the information contained in the original project documentation – project drawings, items from the summary estimate compiled by the *De Bonis* company in 1891 for the final payment of the works carried out (1886-88), and measurement books compiled by the *Carchella* company in 1953 for the final payment of the vertical expansion project (1951-53) – with the results of the on-site investigations.

The HBIM model was, therefore, constructed by adopting a philological method for the reconstruction of the geometry and technical characteristics of the construction elements, which were divided into: foundations, masonry, reinforced concrete structures, and floor slabs. The individual construction elements represented in the model are described below, with reference to their respective geometric and material characteristics; these characteristics were translated into information parameters within the model, associated with each individual instance.

According to the 1891 summary estimate for the final payment of the *De Bonis* company, the foundations consist of isolated masonry pillars connected by arches. The foundation excavation carried out in 1886 had a fixed width of 2 meters, while the depth was such as to "make the use of the burbera [manual pump/winch] and buckets necessary due to the presence of water". In this regard, on December 16th, 1886, the *De Bonis* company wrote to the Municipality of Rome expressing its concerns regarding the foundation system adopted, specifically in relation to the stability of the building, "also given the presence of water". According to the measurement books compiled by the company, underground walls were discovered during excavation: the materials obtained from the demolition of these walls were reused for the construction of the new pillar foundations. The pillars are made of rubble-filled cement masonry (*pietrame lavorato a sacco*) up to the springing line of the connecting arches. These are semi-circular arches (*a tutto sesto*), made of bricks with a thickness of 0.60 m. The spandrel masonry of the arches is entirely made of brick. Information regarding the foundation level was deduced from the test pits carried out in 1951, prior to the vertical expansion, with pits ranging in depth from 3.60 to 4.30 m. In 1953, new reinforced concrete foundations (single plinth) were planned for the reconstruction of the secondary staircase accessible from the via Anicia corridor. According to the project, the plinth was to be placed on a continuous wall with a width of 2.50 m and a depth of 8.00 m, measured at -1.10 meters from the ground floor.

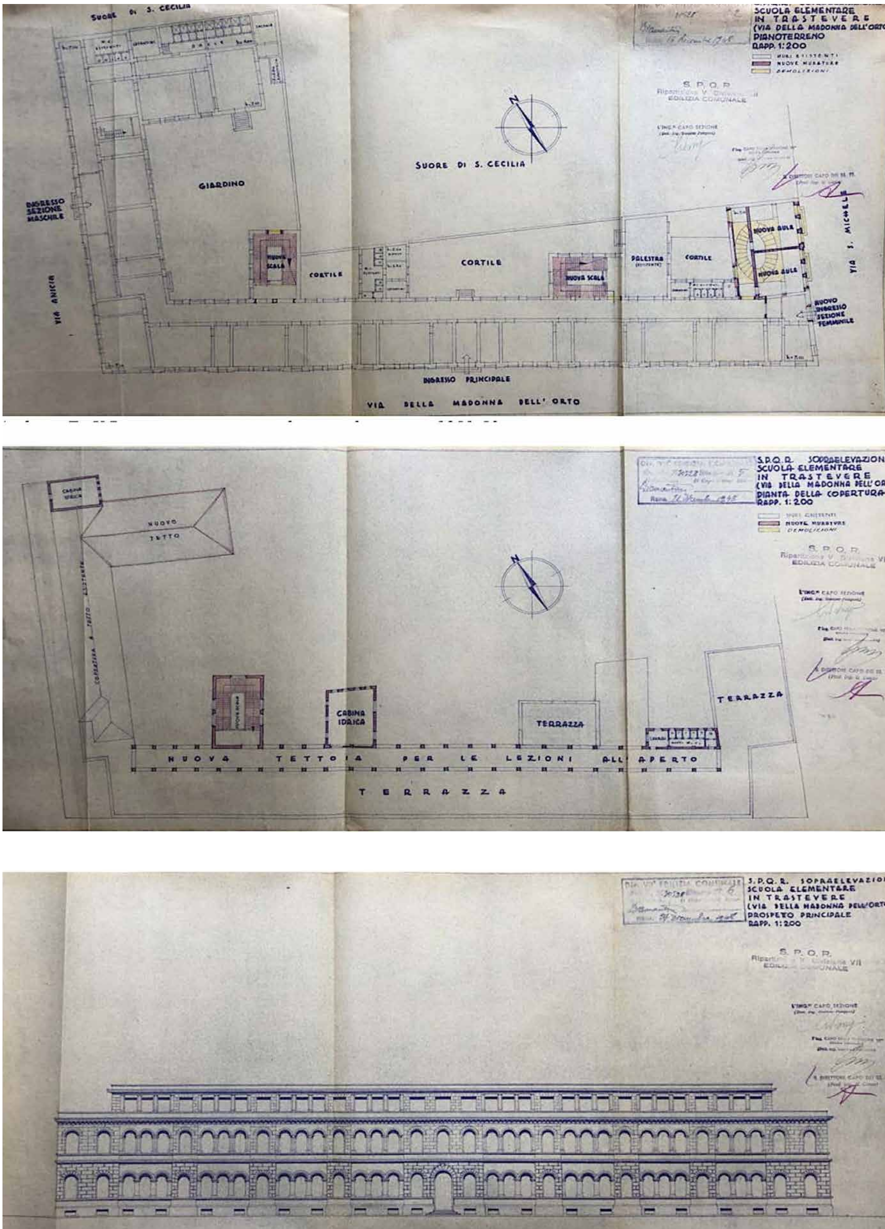
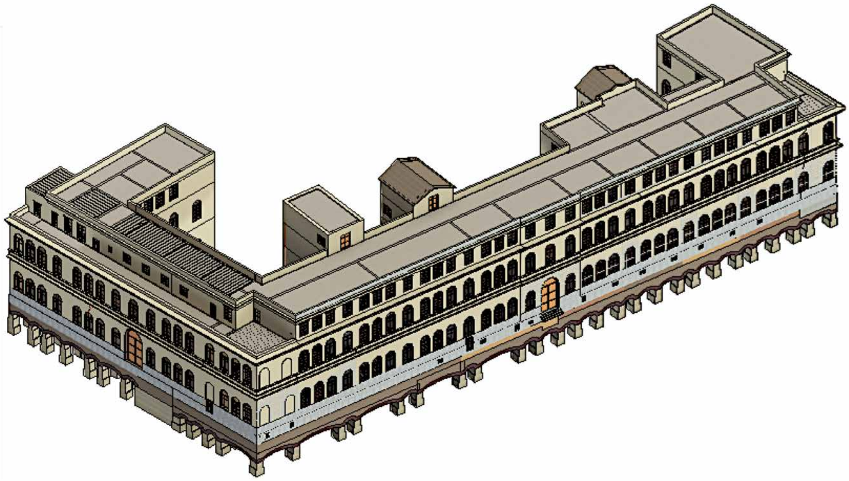


Fig. 4 – *Plans and elevations of the building's floor addition project, 1953 (Archivio Ex V Ripartizione del Comune di Roma).*



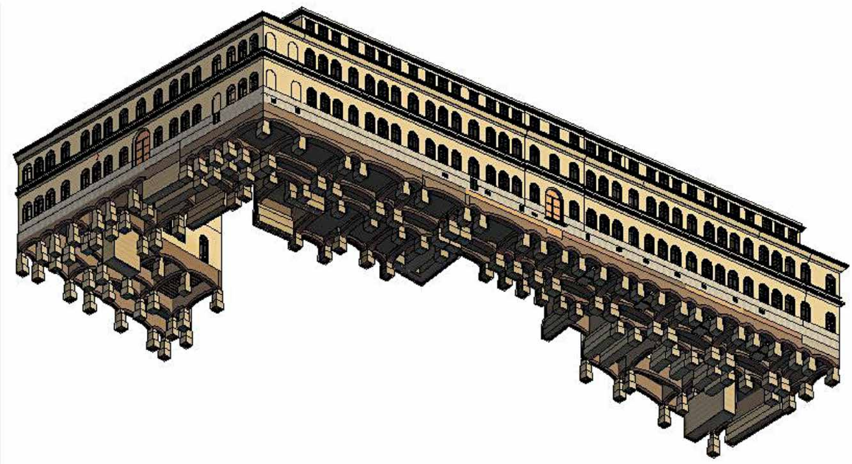


Fig. 5 – *Plans and elevations of the building's floor addition project, 1953 (Archivio Ex V Ripartizione del Comune di Roma).*

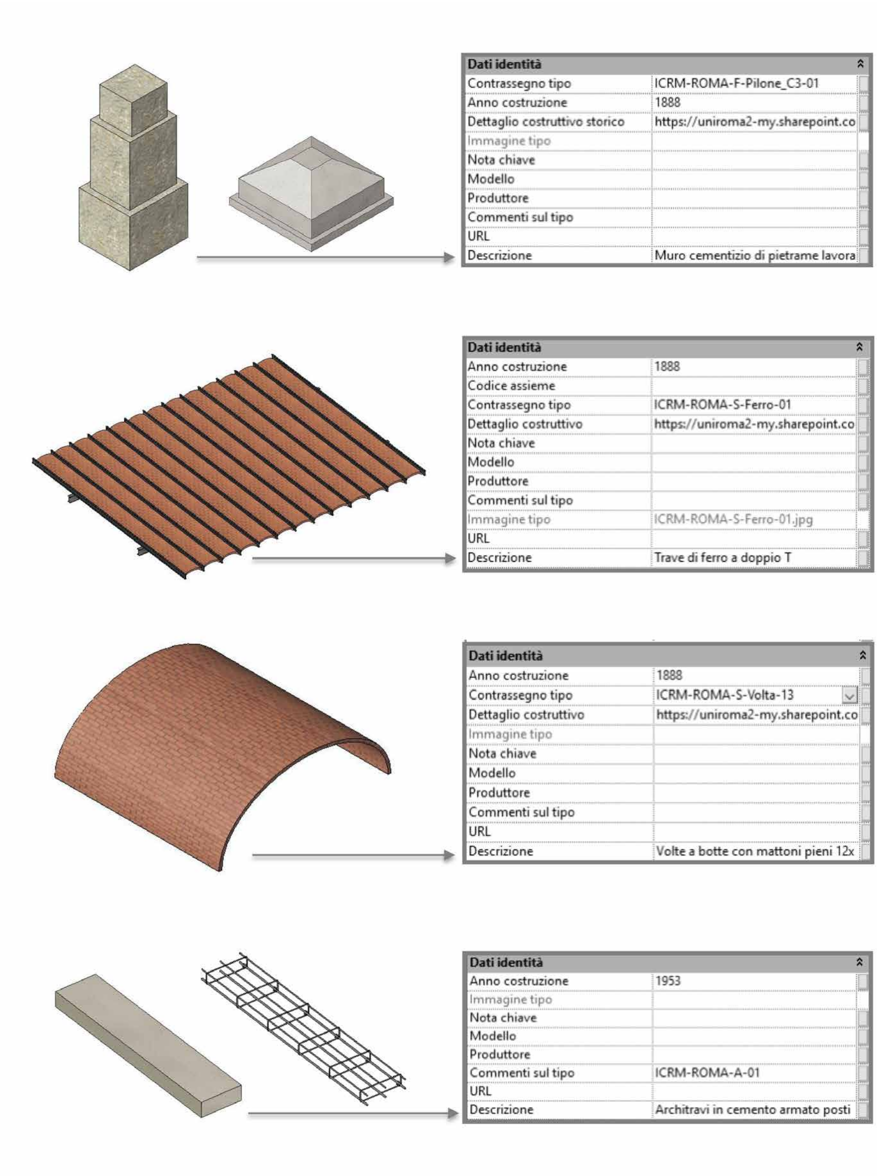


Fig. 6 – *Plans and elevations of the building's floor addition project, 1953 (Archivio Ex V Ripartizione del Comune di Roma).*

Regarding the elevation walls, consistent with what is reported in the original project documentation, the surveys conducted on the masonry have highlighted the presence of various masonry types, not all high quality, with poor or completely absent bonding (particularly on the second floor); vertical joints are not always staggered, and courses are not always horizontal. The wall thicknesses range between 45 and 48 cm, except for a section on the second floor of 18 cm; the plaster thickness is approximately 2.50-3 cm.In the basement, there are walls made of hand-worked stone for the elevation of the foundation wall with courses of solid bricks. On the same floor, there are also brick and mortar walls (brick height 4-5 cm, mortar thickness approx. 3 cm) with the presence of arched structures within the masonry and walls in rough-hewn stone. On the raised ground floor, from elevation 16.26 to 23.86 m, there are solid brick walls (brick height 4-5cm, mortar thickness approx. 3 cm), with joints that are not always staggered; in some portions, headers (diatones) are present; additionally, solid bricks are present for the construction of semi-circular arches connecting the foundation pillars. On the first floor, there are: solid brick and mortar walls, with more or less pronounced bonding (brick height 4-5cm, mortar thickness approx. 3 cm); walls made of hollow bricks and morta r joints.On the second floor, there are brick and mortar walls (brick height 4-5 cm, mortar thickness approx. 3 cm); walls made of solid and hollow bricks and mortar; solid brick and mortar walls (brick height 4-5 cm, mortar thickness approx. 3 cm) with a course of hollow bricks.

The vertical extension and partial transformation of the building's original body are characterized by the use of reinforced concrete structural elements integrated into the pre-existing masonry structure. This material was used to construct both the bond beams (*cordoli*) and lintels inserted into the masonry, as well as the load-bearing frames of the new volume, which replaced the previous spiral staircase. The measurement booklets prepared by the *Carchella* firm, which carried out the extension, provide the cement characteristics and the types and dimensions of the reinforcement bars. The new structure features a reinforced concrete frame consisting of 5 pillars, oriented parallel to the main direction of the compartment and connected to the perimeter walls via reinforced concrete edge beams. The cement used for the beams and pillars is type 600 or 800 kg/m^3.

The building featured an ample typlogical sample of slabs, described in the following. Corridors of the original building volume and the narrow spaces (formerly changing rooms) located between the classrooms are covered by barrel vaults with a 2.50 m span and a 1.00 m rise. According to the original project documentation, these vaults consist of solid bricks laid on edge (in foglio), bedded in cement mortar and backed with lightweight conglomerate, a construction method confirmed by surveys conducted during floor slab consolidation works in 2004 and 2021. The documentation further specifies that the classroom floor slabs in the original building section are composed of iron I-beams (a narrow-flange double-T profile) and brick jack arches, which are predominantly laid on edge. The beam heights and their spacing vary across the different rooms. During the consolidation works carried out in 2008, the identified stratigraphy consisted of marble grit cement tiles (*marmette*), a bedding layer, and a concrete screed or clay-concrete (*cretonato*) filling. Additionally, on the raised ground floor, some original refectory floor slabs were replaced with steel beams and hollow clay tiles (*tavelloni*).

The floor slabs of the vertical extension (1951-53) are made of reinforced concrete and masonry (*laterocemento*) and are anchored to the walls through reinforced concrete bond beams. According to the measurement booklets of the Carchella firm, these slabs have a total thickness of 30 cm or 42 cm, depending on the specific room. By comparing the data from these booklets with 2021 on-site surveys and contemporary technical manuals, it is hypothesized that these are hollow-core ventilated slabs, likely of the STIMIP type. The spacing and shape of the clay blocks on the underside (*intradosso*) and the absence of a top concrete slab (*soletta*) identified during on-site investigations are entirely consistent with this slab typology.

Regarding stairs, the spiral staircase, which was demolished in 1951, featured a structure consisting of iron beams, marble steps, and landings built with iron beams and hollow clay tiles (*tavelloni*). Similarly, the two stairwells constructed in 1951 feature an iron beam structure, marble steps, and landings made of iron I-profile-beams and hollow clay tiles. In contrast, the secondary staircase accessible from the corridor on Via Anicia has a reinforced concrete structure; the project drawings called for the construction of two pillars (which were never built) positioned on a new single-pad foundation.

3. Analysis of the DInSAR Datasets

For the case study analysed, data provided by the Institute for Electromagnetic Sensing of the Environment of the National Research Council of Italy (CNR-IREA) are used. These data derive from the elaboration, made through MT-DInSAR technique, of radar images captured by the CSK constellation between March 2011 and March 2019, in both ASC and DES orbits. [Figure 7] shows the measurement points of the quadrants related to the area in which the *Regina Margherita* School building is located, for both ASC and DES datasets. The measurement points are represented with a colour scale that shows the corresponding mean displacement velocity along the sensor's Line of Sight (LOS) – i.e. the line joining the satellite sensor with the target at ground level – expressed in mm/year. In accordance with the sign convention most used in the literature, positive velocity values correspond to movements towards the sensor, while negative values correspond to movements away from the satellite. A first qualitative assessment of the mean velocity values highlights the presence of higher movements away from the sensor in the areas near the Tiber River, compared to more distant areas.

The shown displacement measurements can be properly used to compute the displacement components along the horizontal (East-West and North-South) and vertical directions. Since LOS directions for both ASC and DES acquisition geometries are nearly perpendicular to the North-South direction, the displacement component along this direction is usually assumed to be null, enabling the assessment of the East-West and vertical components. Furthermore, since the displacement measurements along the LOS relative to the two acquisition orbits are not generally available for the same points, spatial resampling is necessary in order to combine the data relating to the two ASC and DES geometries. The spatial resampling is here performed by using two different approaches, named Grid-subsampling and Interpolation, both based on the preliminary definition of a regular grid. In particular, the area of interest is subdivided into 5 × 5 m square cells. The mesh size was chosen based on the spatial resolution of the source data.

In the first methodology, the mean value of the LOS displacement velocity of the measurement points falling within each cell is calculated for both orbits. Subsequently, for cells for which the average displacement velocity in the two acquisition geometries is known, a combination is performed, to evaluate the average displacement velocity along the vertical and East-West directions. An application related to a cell of the area of interest is shown in figure 7, together with the maps of the mean displacement velocity along the East-West and vertical directions, in figures 8 and 9.

The second methodology consists of applying spatial interpolation methods to available data, in order to produce interpolated maps of the components of the mean displacement velocity along the vertical and East-West directions. Figures 10 and 11 show the maps of the mean velocity components along the East-West and vertical directions, obtained using the Inverse Distance Weighted (IDW) interpolation technique.

Figures 12 and 13 show satellite data belonging only to the *Regina Margherita* School building – ASC and DES measurement points indicated with red and green colours, respectively – together with a representation of the points characterized by the highest values of the mean displacement velocity

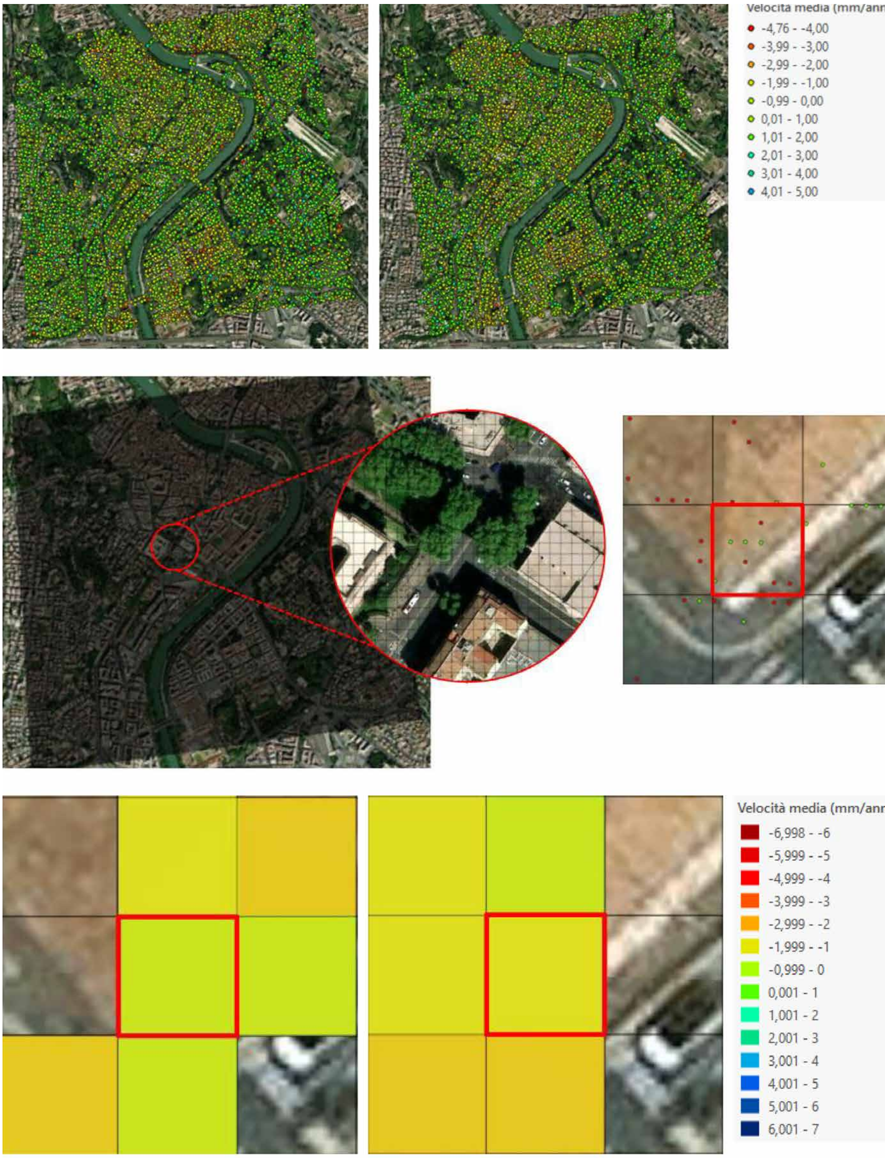


Fig. 7 – *Average displacement velocity map along the LOS (Line of Sight) for the quadrant of interest - descending and ascending orbits; data sampling grid; Grid-subsampling technique.*

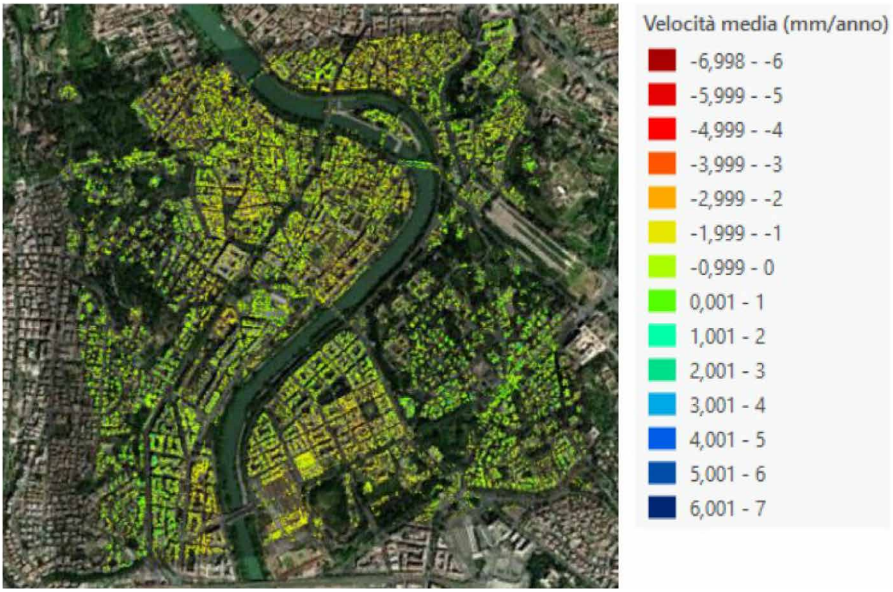


Fig. 8 – *Mean displacement velocity map in the vertical direction for the quadrant of interest – Grid-subsampling.*

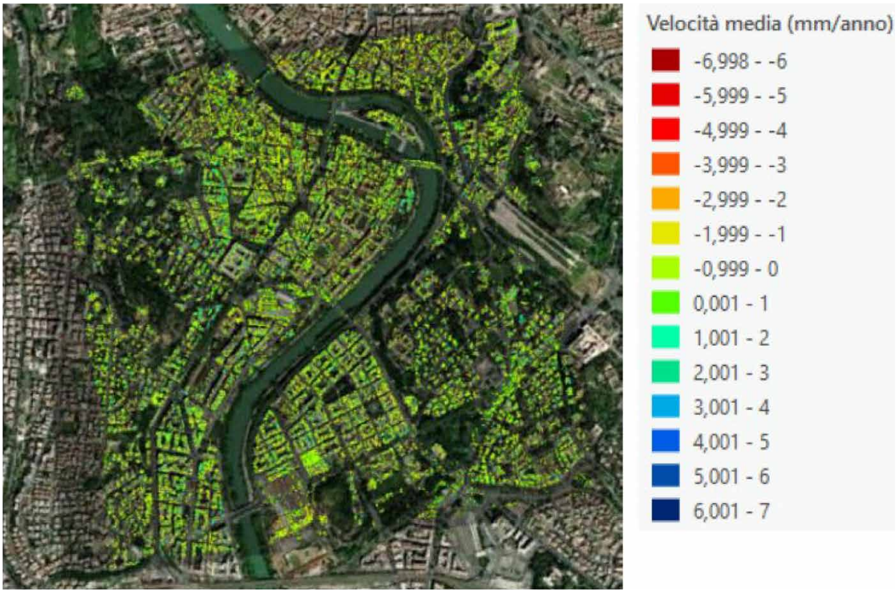


Fig. 9 – *Mean displacement velocity map in the horizontal direction for the quadrant of interest – Grid-subsampling.*

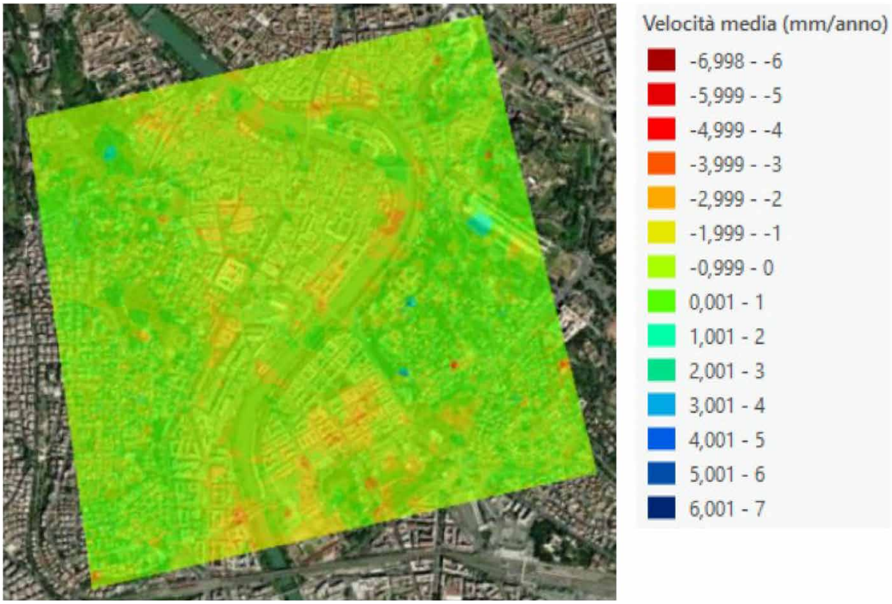


Fig. 10 – *Mean displacement velocity map in the vertical direction for the quadrant of interest - IDW interpolation.*

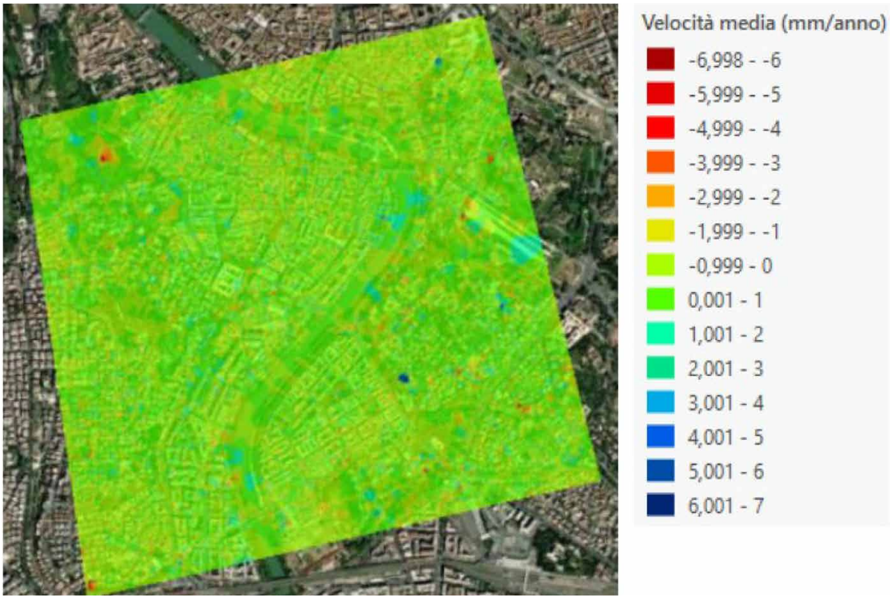


Fig. 11 – *Mean displacement velocity map in the horizontal direction for the quadrant of interest - IDW interpolation.*

Fig. 12 – *Satellite data relating to the building: ascending orbit (in red) and descending orbit (in green).*

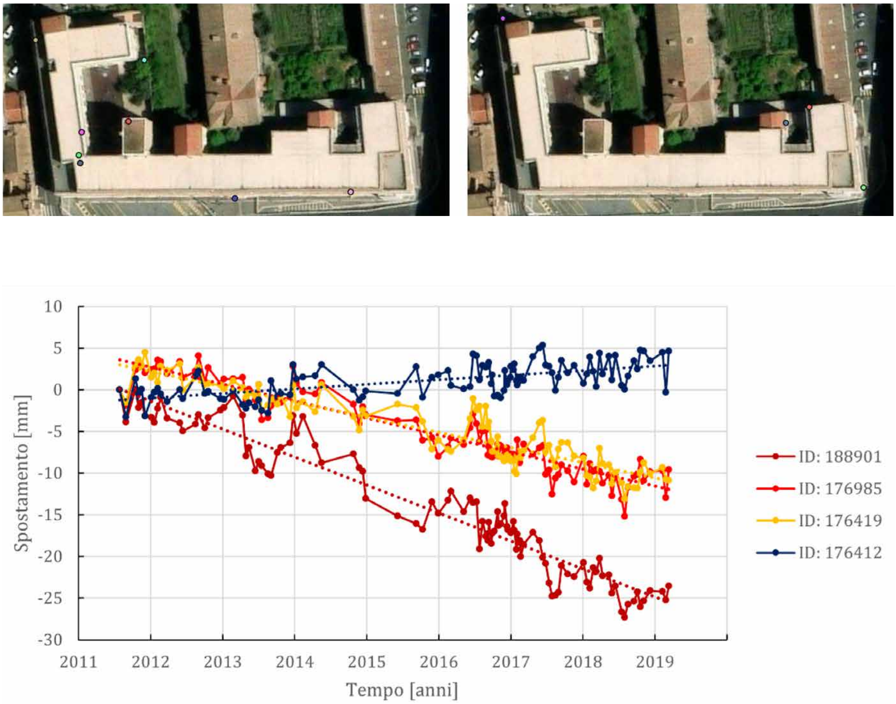


Fig. 13 – *Measurement points characterized by the highest values of the mean displacement velocity along the LOS, for both ASC and DES orbits. Displacement time series for four measurement points.*

Fig. 14 – *Integrated GIS visualization of the IFC model and building measurement points characterized by significant displacement velocity values (ArchGIS).*

Fig. 15 – *Integrated GIS visualization of the IFC model and building measurement points characterized by significant displacement velocity values (ArcGIS platform).*

along the LOS, for both ASC and DES orbits. As an example, the displacement time series of DES points having the highest mean displacement velocity are reported.

4. Integrating the Knowledge of the Building and the DinSAR Measurement

The final phase of the research focuses on the design of an integrated visualization interface that allows for the correlation of cognitive data collected and organized on the building with data derived from the analysis of satellite measurements. In this context, the spatial overlay of DInSAR data onto the three-dimensional HBIM model enables a critical reading of two main aspects: first, the positioning of satellite measurement points –Persistent Scatterers (PS) – in relation to the building's geometry and areas showing detectable damage; and second, a simplified understanding of the artifact's history and technical characteristics by querying the BIM model in correlation with satellite measurement visualizations.

To achieve this correlation, two specific aspects of the HBIM model were developed. First, a model was produced in IFC format to ensure interoperability with 3DGIS applications, specifically the Esri ArcGIS platform. The BIM model, translated into the IFC standard, was georeferenced with respect to a known benchmark, ensuring its readability in ArcGIS without any loss of information. Consequently, the IFC model is fully accessible within the 3DGIS environment regarding the entire set of parameters associated with each individual instance.

Satellite data, analyzed directly on the ArcGIS platform, were subsequently associated with the model. The interferometric results were exported from QGIS in ESRI Shapefile format, the de facto standard for geographic data storage in the geospatial industry, specifying WGS 84 (EPSG:4326) as the geographic reference system to maintain consistency with the coordinate model used for the analysis. This format, thanks to its modular structure (shp, shx, dbf, prj), ensures broad compatibility and facilitates processing within ArcGIS.

The interferometric data then underwent a spatial consistency check aimed at verifying the adherence of measurement points to the actual surface of the building. Specifically, the goal was to ensure that the detected PS were effectively located on the structure, excluding any spurious measurements caused by COSMO-SkyMed satellite measurement errors. To perform this check, a control volume ("shell") was modeled, in figure 14, by applying a buffer both inward and outward from the building's external geometry.

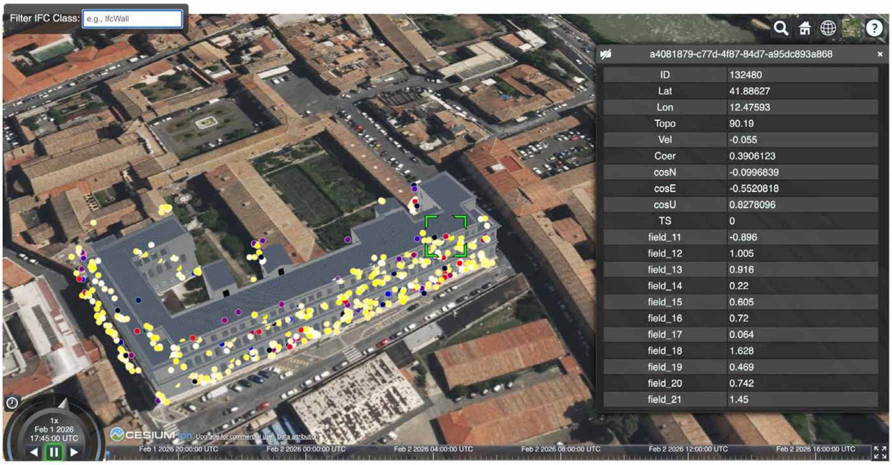


Fig. 16 – *Integrated GIS visualization of the IFC model and building measurement points (Cesium Ion platform).*

This shell acts as a spatial "filter": all interferometric points attributable to the school had to fall within it, confirming the correctness of their topographic assignment. This control volume was then imported into ArcGIS, where an automatic selection of interferometric points falling within the shell was performed as we see in figure 15.

Any point exceeding this envelope was considered potentially unrepresentative of the artifact's deformations. The analysis revealed that 87% of the interferometric points are indeed located within the control volume, confirming the validity of the clipping process and the reliability of the measurements. As for the remaining 13%, it is highly probable that these points represent measurements related to the interface between the building and the soil, or the ground connection level.

It is important to emphasize that the integrated visualization of the 3D building model and the DInSAR data was also tested using the open-access application Cesium ion, a cloud-based application dedicated to the representation and interactive visualization of 3D geospatial data. Based on the recent 3D Tiling functionalities offered by "Cesium Design Tiler", it is possible to visualize the geometry and informative data of IFC models in a 3DGIS environment.

The visualization interface of the Cesium ion platform, which can be customized using .html, integrates the rendering of the 3D information model with high-detail Digital Terrain Models (DTM) available in current national numerical databases. Alongside the 3D visualization of the structure's geometry, there is a pop-up window for the interactive interrogation of metadata (the set of informative properties present in the IFC model) related to the individual digital objects that make up the model. Metadata interrogation is supported by a filter applicable to the IFC classes of individual digital objects (for example: ifcbeam, ifcslab), thus assisting the user in reading information regarding the construction components of the represented building as depicted in figure 16.

5. Conclusions

The research conducted on the case study has demonstrated the effectiveness of the proposed methodological approach, marking a significant step in the development of advanced methodologies for the structural monitoring of built heritage by integrating HBIM, 3DGIS, and DInSAR interferometry.

The creation of the philological HBIM model enabled a highly accurate three-dimensional representation of the building under study, enriched with construction details and material characteristics. In parallel, the application of the DInSAR technique provided dynamic, long-term monitoring of deformation phenomena within the territorial context. The GIS integration of the HBIM model and the DInSAR data subsequently provided a simultaneous representation of the structure's construction anatomy throughout its historical evolution and the dynamics of the area's deformation phenomena over time.

In this sense, the proposed method allowed for the construction of two distinct data sets: on one hand, an organized archive of historical and technical knowledge related to the building – making information regarding its anatomy and history easily accessible – and, on the other hand, a database regarding the dynamics of deformation phenomena in the area.

Ultimately, the method produces a powerful digital tool – a digital model that can be utilized without specialized IT skills – to support planning processes. This approach is extendable to an urban scale and serves as a vital resource for the application of preventive conservation strategies.

Integrated Nonlinear Vulnerability Assessment of RC Frames under Imposed Settlements and Seismic Actions

Andrea Miano[1], *Carlo Del Gaudio*[2], *Giacomo Iovane*[1]

This case-study deals with the nonlinear modelling, calibration, and preliminary integrated vulnerability assessment of a six-story reinforced concrete (RC) building archetype, developed within the PRIN SMUH project on the basis of the knowledge framework within the. The study addresses the combined effects of pre-damage due to vertical settlements and subsequent horizontal actions, with the objective of quantifying how settlement-induced drift demands and axial-force variation modify the seismic response.

A comprehensive material characterization is implemented in OpenSeesPy using different constitutive laws. The structural model adopts a hybrid discretization strategy: nonlinear hinges for beams, distributed nonlinearity for columns, and a trilinear compression-only diagonal strut model for infills. A preliminary shear-crisis classification confirms that few columns experienced shear failure and require modification in their flexural response for the considered configurations.

Pushover analyses on the bare and infilled configurations reveal distinct collapse mechanisms. The bare structure exhibits a pronounced soft-story formation in the Y-direction due to geometric nonlinearity and high axial loads, whereas the infilled system shows soft-story mechanisms in both directions, with a sharper post-peak degradation driven by infill panel failure.

Settlement analyses impose spatially variable vertical displacements generated through a bivariate exponential function, enabling both localized and diffuse settlement patterns. Results demonstrate substantial axial-force variation under localized settlements, including inversion from compression to tension at the most affected columns, while diffuse settlements generate limited variations. The induced distortions produce drift patterns compatible with infill damage thresholds. These findings provide a validated nonlinear model and a

1 Pegaso Telematic University, Department Engineering, Naples, Italy.
2 University of Naples Federico II, Department of Structures for Engineering and Architecture.

first quantification of settlement-seismic interaction effects, forming the basis for the updated seismic vulnerability framework.

1. Introduction

Many RC buildings realized in Europe between the 1950s and 1980s were designed primarily for gravity loads, without specific seismic detailing, frequently affecteded by degradation processes related to aging, environmental exposure and ground instability. Among these, differential ground settlements induced by hydro-geological phenomena represent a critical source of structural vulnerability, as they can significantly alter the internal stress distribution, stiffness, collapse hierarchy and deformation capacity before the seismic phenomena. Despite their relevance, settlement-induced effects are rarely incorporated into conventional seismic assessment procedures, which typically assume an undeformed initial configuration.

Recent studies have shown that pre-damage due to settlements can substantially modify both the structural response[3] (1-2) especially through axial-force redistribution in columns and increased second-order effects. However, a systematic nonlinear framework capable of integrating settlement-induced pre-damage with seismic response assessment is still lacking.

Within this context, thit chapter aims at proposing and applying an integrated nonlinear assessment framework to RC frame archetypes with different heights (2, 4 and 6 stories). The study focuses on: (i) advanced nonlinear modelling strategies for capturing settlement-induced pre-damage; (ii) definition and tracking of Damage States (DS) across settlement and seismic analyses; and (iii) quantification of the influence of settlements on global seismic capacity, deformation demand and collapse mechanisms.

2. Case Study Buildings: Geometrical and Materials Features

Three RC frame archetypes with 6, 4 and 2 stories are considered. All buildings are designed for gravity loads only and they are representative of

3 Miano A., Mele A., Del Gaudio C., Verderame G. M. and Prota A., “Updating of the seismic fragility curves for RC buildings subjected to slow-moving settlements”. *Journal of Building Engineering* 86 (2024), 108907; Mele A., Miano A., Di Martire D., Infante D., Ramondini M., and Prota A., “Potential of remote sensing data to support the seismic safety assessment of reinforced concrete buildings affected by slow-moving landslides”. *Archives of Civil and Mechanical Engineering* 22/2 (2022) 88.

Table 1 – *Material features.*

Concrete	
Average cylindrical compressive strength	f_m=18 MPa
Allowable stress in compression-bending combination	$\sigma_{c,\,N+M}$=7.50 MPa
Allowable stress in compression "σc"	σ_c=1.59 MPa
Tangential stresses	τ_{c0} = 0.49 MPa τ_{c1} = 1.59 MPa
Steel	
Average yield stress	f_{ym}=322 MPa
Allowable stress	σ_s=161 MPa
Homogenization coefficient	n=10

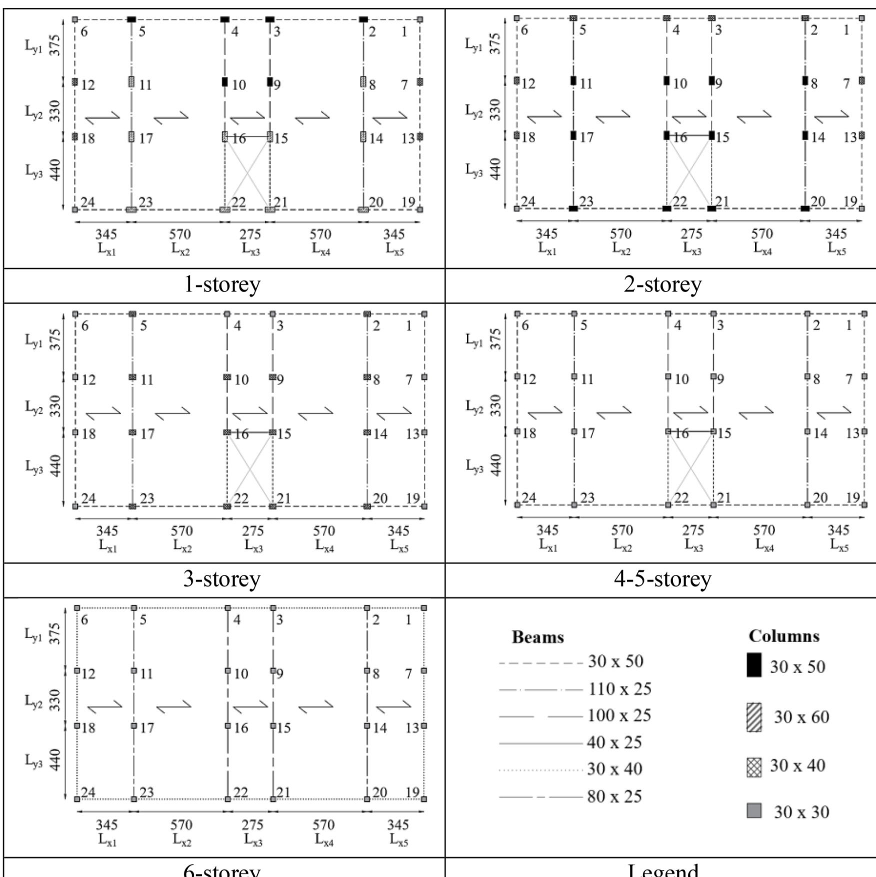


Fig. 1 – *The 6-stories buildings plan layout.*

residential RC construction practice in Italy before the introduction of current seismic codes. The plan layout is regular, with 4 frames aligned along principal X-direction and 6 frames aligned along principal Y-direction, while the masonry infill panels are present along the perimeter and internal frames. For 6-storey building, the interstory heights are constant above the first level, equal to 3.05m, while the first one is 3.40m (as we can see in figure 1).

The 2- and 4-storey buildings are derived from the upper levels of the 6-storey archetype, adopting the same structural member typologies and reinforcement layouts as the corresponding upper floors. This approach ensures geometric and mechanical consistency among the archetypes and allows for a direct comparison of the influence of building height on settlement-seismic interaction effects.

3. Numerical Investigation

3.1 Procedure of the Analysis

The numerical study is organized as follow, implemented and progressively automated in OpenSeesPy:

1. *Model features*: model generation and checks (geometry, masses/diaphragms, boundary conditions, element and material assignment).
2. *Pre-classification analysis of shear collapse*: carried out to verify the effectiveness of the modeling performed.
3. *Settlement analysis*: selected settlement distributions applied to detect the settlement level at which a prescribed Damage State (DS) is first attained.
4. *Non-linear static analysis*: performed on building configuration without settlement and on the pre-damaged configuration. During pushover, DS exceedance is tracked and mapped on the base shear-Roof Drift Ratio (RDR) curve.

This workflow is applied to the 6-storey archetype and then replicated on the 4- and 2-storey archetypes, which are mechanically consistent subsets of the 6-storey structure (upper 4 floors and upper 2 floors, respectively).

3.2 Model Features

Non-linear modelling of structural elements is conducted. Beams (figure 2a) are modelled by concentrating non-linearity at member ends through flexural hinges, while the central part of the member remains in elastic

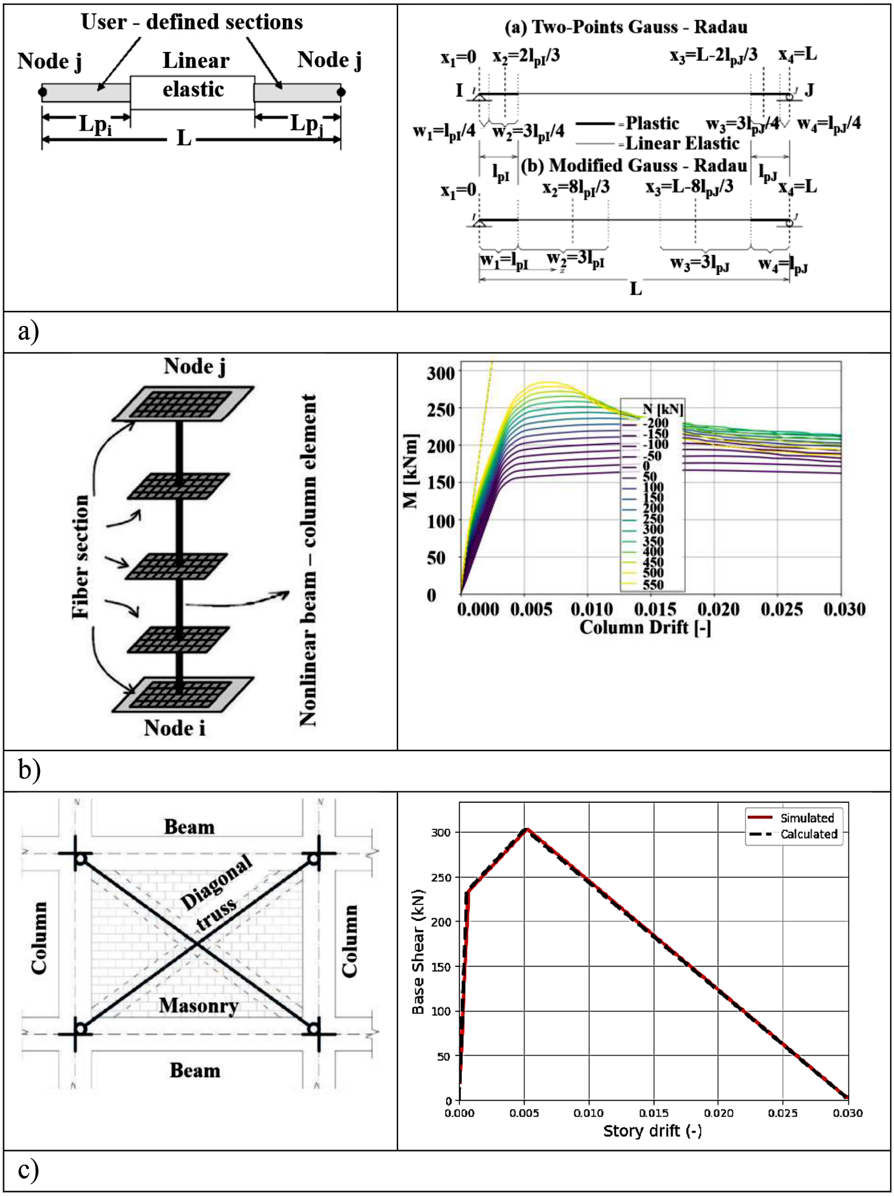


Fig. 2 – *a) beams, b) columns and c) infills model used.*

field. In particular, the “beam with hinges” element of the Opensees library, which allows to limit the plasticization phenomena of the sections in pre-established parts of the beam, was selected. The plastic hinge length (L_{pl}) was calculated as 1/6 of the element extension. Hinge calibration follows a section-based approach[4]. Columns (figure 2b) are modelled with distributed plasticity (Non-linear Beam Column Element). Masonry infills (figure 2c) are modelled using the equivalent diagonal strut approach implemented with two concentric truss elements per infill panel. Each truss is assigned a compression-only trilinear constitutive law[5], parameterized as:

F_{cr}: cracking force of the panel;

F_m: peak strength, taken as $1.3*F_{cr}$;

F_r: residual strength, taken as $0.01F_{cr}$ (equivalently $0.01F_m$);

K_3: post-peak stiffness, taken as 3% of the pre-cracking stiffness.

The three segments of the curve proposed by the authors reproduce the initial shear behavior of the uncracked panel, the subsequent equivalent rod behavior of the cracked panel, the unstable behavior of the panel beyond the maximum strength and the final state of the panel after complete failure, with a constant residual strength. The implemented constitutive law varies according to the length and width of the specific reference plane.

3.3 Pre-classification analysis of shear collapse

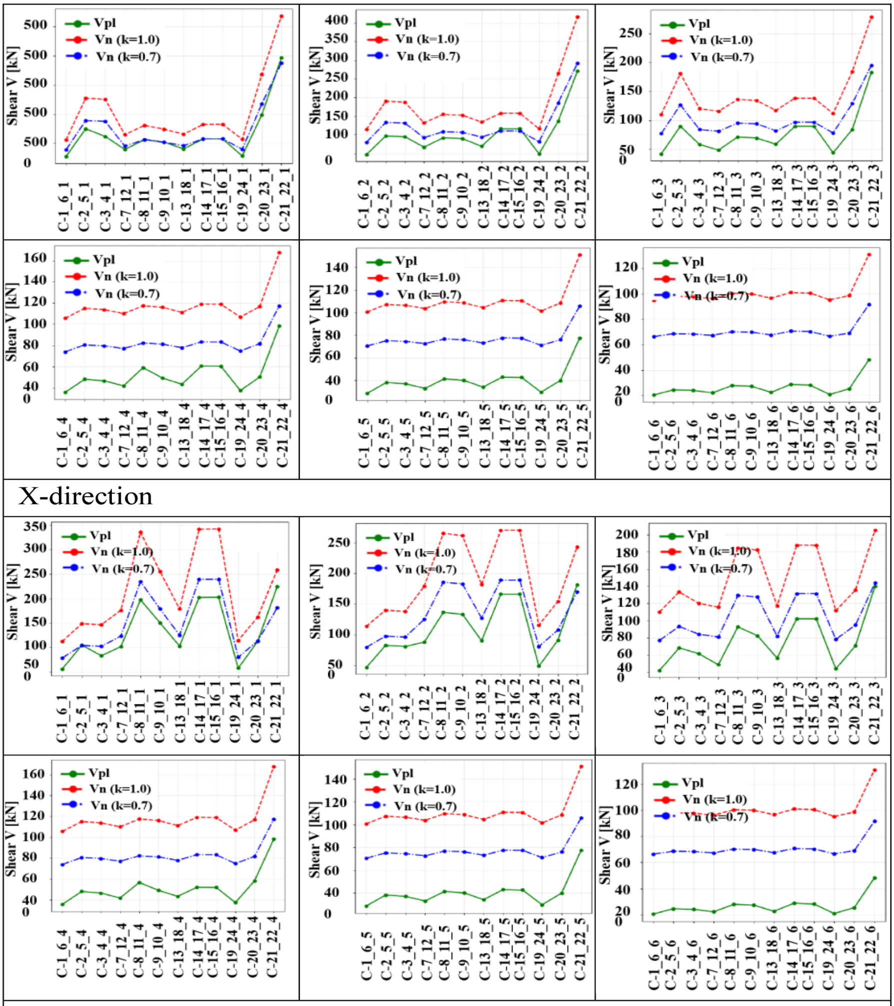
A preliminary shear collapse classification is performed on 6-storey building to identify potentially shear-critical columns. It consists of the comparison between the plastic shear of the columns assumed to be doubly fixed at the ends (V_{pl}) and the shear capacity (V_n) based on the concrete and transverse steel reinforcement bars strength, evaluated according to the formulation:

$$V_{pl} = \frac{M_{Rd}}{L_v} = \frac{2M_{Rd}}{H}$$

where M_{Rd} is the strength bending moment of the base sections of the columns, L_v is the shear length and H is the inter-storey height. From the

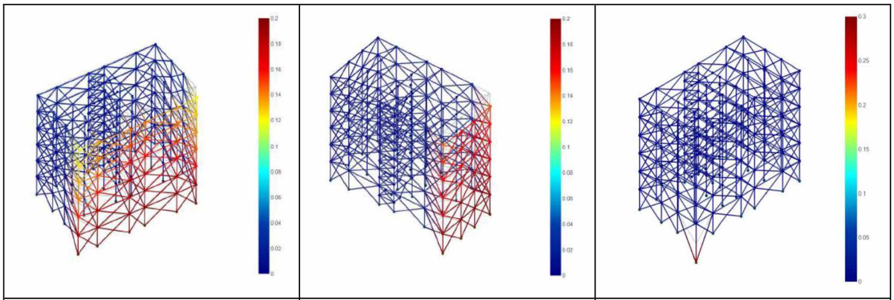
4 Scott M. H. and Fenves G. L., “Plastic hinge integration methods for force-based beam–column elements”. *Journal of Structural Engineering*, 132/2 (2006): 244-252; Scott, M. H., and Ryan K. L., “Moment-rotation behavior of force-based plastic hinge elements”. *Earthquake Spectra*, 29/2 (2013): 597-607.

5 Panagiotakos T. B., and Fardis M. N., “Seismic response of infilled RC frames structures”. In *11th world conference on earthquake engineering* (Vol. 23, p. 28). Oxford: Pergamon, 1996.



Vn (k=07) is the shear capacity according to the Sezen & M. formula considering the effect of degradation; Vn (k=01) is the shear capacity according to the Sezen & M. formula without considering the effect of degradation. The columns are labelled as C ”fixed wire”_”fixed wire”_”plane” as they have the same concrete cross-section and the same reinforcement when paired.

Fig. 3 – *Results of the pre-classification analysis of shear collapse.*



SS_1	SS_2	SS_3

Fig. 4 – *Structure deformation under the three distribution of settlements.*

comparison between V_{pl} and V_n, the columns can be classified as follows[6].

- $V_{pl} < V_n$: whether or not considering the effect of degradation in the Sezen formula, the column is defined as type "F" (ductile failure is expected);
- $V_{pl} > V_{n,max}$: where $V_{n,max}$ is the Sezen shear capacity in the absence of degradation, the column is defined as type "S" (fragile failure is expected);
- In intermediate cases, the column is defined as type "FS".

The results of the analysis in figure 3 show columns generally in intermediate condition or ductile failure while only a limited set of members is fragile shear failure-governed; for those, the bending response is modified to reflect a reduced deformation capacity consistent with brittle shear-related behaviour.

3.4 Settlement analysis

Imposed settlements on 6-storey building are generated using a bivariate exponential function described by the following formula:

$$\text{settlements}_{\{j,i\}} = SS * \exp\left(-\left(\frac{(i - X_{max,p})^2}{2 * s_X^2} + \frac{(j - Y_{max,p})^2}{2 * s_Y^2}\right)\right)$$

where SS is the maximum imposed settlement, sy is standard deviation in the y-direction, sx is standard deviation in the x-direction, Xmax,p is the position in x-direction of the maximum modeled displacement (SS), Ymax,p is the position in y-direction of the maximum modeled displacement

6 Setzler E. J. and Sezen H., "Model for the lateral behavior of reinforced concrete columns including shear deformations". *Earthquake Spectra* 24/2 (2008): 493-511.

(SS). As the dispersion increases in the corresponding direction, an increasingly uniform displacement pattern is generated, vice versa, a localized failure condition is obtained below a column. To ensure that the possible damage states on the structural elements were reached, the analyses were pushed up to a SS value equal to 20 - 30 cm for the different conditions ($L_{x,tot}$ and $L_{y,tot}$ are the total dimensions in plan of the building along x- and y-direction respectively). In particular, three different distributions of settlements were considered (figure 4):

1. Uniform settlement under the perimeter columns in the x-direction: SS1 = 0.20 m; $s_y = 0.1$; $s_x = 100$; $X_{max,p} = L_{x,tot}/2$; $Y_{max,p} = L_{y,tot}$
2. Uniform settlement under the perimeter columns in the y-direction: SS2 = 0.20 m; $s_y = 100$; $s_x = 0.1$; $X_{max,p} = L_{x,tot}$; $Y_{max,p} = L_{y,tot}/2$
3. Localized settlement under a corner column: SS3 = 0.30 m; $s_y = 0.1$; $s_x = 0.1$; $X_{max,p} = L_{x,tot}$; $Y_{max,p} = L_{y,tot}$

Following there are the results of the effects of settlement on the infill walls, columns and beams of the 6-story building and the identification of the corresponding Damage States (DS).

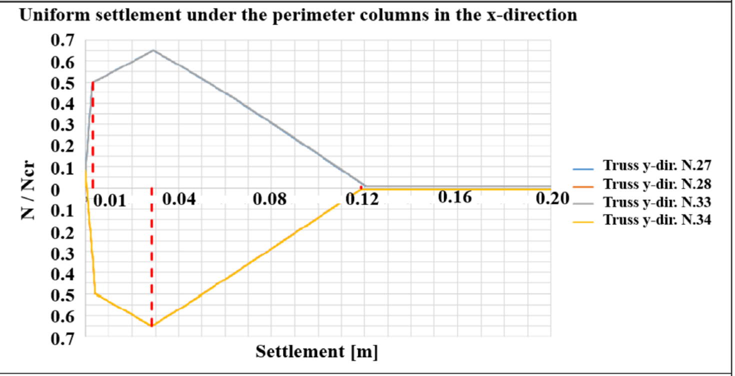
Based on the infill wall modeling criteria, three different DSs are associated with the achievement of F_{cr}, F_m and F_r. The following diagrams show the variation in the ratio between the normal stress and F_{cr}, as a function of the maximum settlement imposed on the infill walls connected to the affected columns. The data recorded exclusively for the first-level infill walls, where the most severe conditions occur, are shown. The DSs are identified at ratio values of 0.5, 0.65, and 0.0065, respectively, resulting from the division of the stress in the panel between the two trusses (figure 5).

Following the analyses, in table 2 the settlement values recorded corresponding to the DSs in the infill walls are shown.

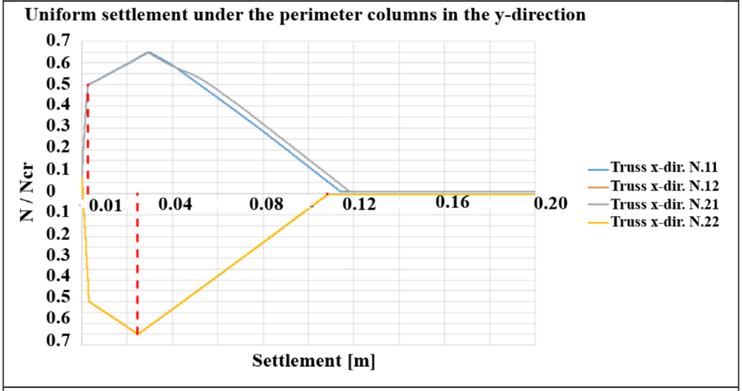
Table 2 – *Identification of DSs for infill walls based on imposed settlements.*

SS [mm]	**Distribution of settlements**	**DS**
2.6	Uniform for columns in y-dir	
2.7	Localized under corner column	Cracking
3.2	Uniform for columns in x-dir	
23	Localized under corner column	
25	Uniform for columns in y-dir	Maximum resistance
28	Uniform for columns in x-dir	
107	Localized under corner column	
108	Uniform for columns in y-dir	Residual resistance
119	Uniform for columns in x-dir	

SS= 20cm

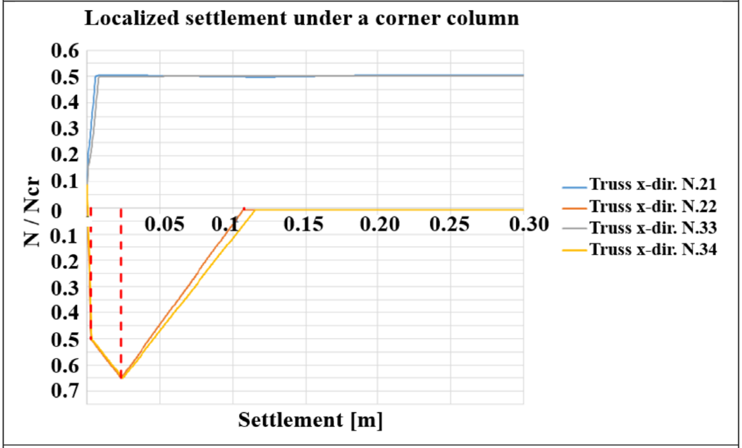


x-direction



y-direction

SS=30cm



x- and y-direction

Fig. 5 – *Variation in the ratio between the normal stress and Fcr.*

As for the columns, under imposed settlements, a variation in the axial stress value induced by gravitational loads occurs, by generating tension in the columns. The selected DS corresponds to reaching 80% of the column's tensile strength, calculated as the yield strength of the steel reinforcement bars alone. Following the analyses, in table 3 the settlement values recorded corresponding to the DSs in the columns are shown.

Table 3 – *Identification of DS for columns based on imposed settlements..*

SS [mm]	Distribution of settlements	DS
5.5	Localized under corner column	P24: 80%$N_{Rd(+)}$=262,20kN
15	Uniform for columns in y-dir	P6: 80%$N_{Rd\,(+)}$= 262,20kN
28	Uniform for columns in x-dir	P24: 80%$N_{Rd(+)}$=262,20kN

As for the beams, under imposed settlements, the beams immediately adjacent to the building facades show greater deformations. The selected DS corresponds to reaching a limit curvature identified as the capacity θy in terms of total rotation with respect to the chord upon reaching the yield stress, according to the following formula reported in the Italian national code[7]:

$$\theta_y = \phi_y \frac{L_V}{3} + 0.0013\left(1 + 1.5\frac{h}{L_V}\right) + 0.13\phi_y \frac{d_b f_y}{\sqrt{f_c}}$$

where Φ_y is the curvature at the yield stress of the end section, h is the height of the section, db is the average diameter of the longitudinal steel reinforcement bars, f_c and f_y are the compressive strength of the concrete and the yield stress of the longitudinal steel in MPa respectively. The data recorded exclusively for the first-level beams, where the most severe conditions occur, are shown. Under the imposed settlements of the columns along x-direction, the perimeter beams arranged in the orthogonal direction first reach the limit curvature Φ_y. The values of the curvature Φ_y were evaluated by using the VcaSlu software and a script appropriately created on Openseespy (figure 6).

The value of Φ_y for the perimeter beams of the first level in the x-direction, with a length of 3.45m is 0.0227, for those in the y-di-

7 DM 17/01/18 (2018) Norme tecniche per le costruzioni, Ministerial Decree. (in italian).

rection it is 0.0229. Following the analyses, in table 4 the settlement values recorded corresponding to the DSs in the beams are shown.

Table 4 – *Identification of DS for beams based on imposed settlements.*

SS [mm]	Distribution of settlements	DS
89	Uniform for columns in y-dir	Reaching Φ_y in x-direction
95	Uniform for columns in x-dir	Reaching Φ_x in y-direction

Based on the results of the analysis, the DSs are ordered according to their chronology of manifestation in table 5.

Table 5 – *Identification of pre-damage failures.*

Uniform settlement of the perimeter columns in the x-direction	
DS1	Cracking of the infill walls. SS= 0.0032m
DS2	Reaching the maximum infill resistance SS= 0.0282m
DS3	Reaching 80% of the tensile strength of the columns SS= 0.0285m
DS4	Reaching the yield curvature of the beams SS= 0.0946m
Uniform settlement of the perimeter columns in the y-direction	
DS1	Cracking of the infill walls. SS= 0.0026m
DS2	Reaching 80% of the tensile strength of the columns SS= 0.0155m
DS3	Reaching the maximum resistance of the infill walls SS= 0.0247m
DS4	Reaching the yield curvature of the beams SS= 0.0891 m
Localized settlement under a corner column	
DS1	Cracking of the infill walls. SS= 0.0027m
DS2	Reaching 80% of the tensile strength of the columns SS= 0.0055m
DS3	Reaching the maximum resistance of the infill walls SS= 0.0231m
DS4	Reaching the residual resistance of the infill walls SS= 0.1074m

3.5 Non-linear Static Analysis

Non-linear static analyses on 6-storey building were performed on both the structure in the undamaged configuration and on the structure pre-damaged by the established DSs. In total, the following non-linear static analyses were performed:

- 4 analyses in the undeformed building configuration (one in the positive direction and one in the negative direction for each main direction of the building): 2 on unfilled structure and 2 on filled structure;

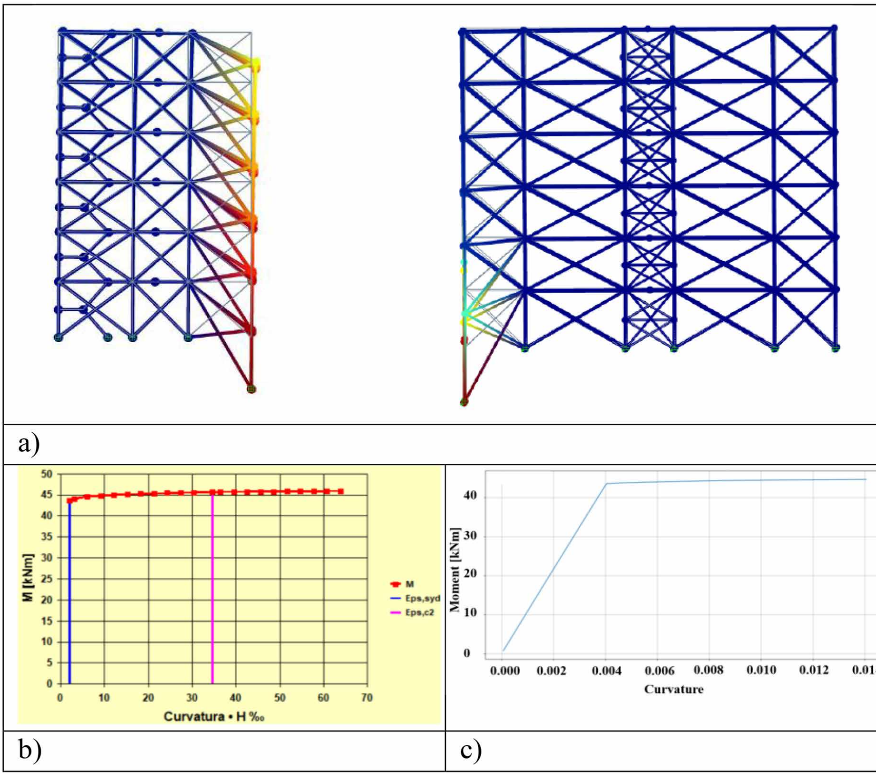


Fig. 6 – *a) Deformation of the structure in x-direction; Elastic limit curvature for perimeter beams calculated with b) Vcaslu and c) Openseespy.*

- 12 analyses for the pre-damaged building configuration at DS1 (one for each settlement distribution, direction and direction of push);
- 12 analyses for the pre-damaged building configuration at DS2 (one for each settlement distribution, direction and direction of push);
- 12 analyses for the pre-damaged building configuration at DS3 (one for each settlement distribution, direction and direction of push).

The analysis results are shown in terms of base shear-Roof Drift Ratio (RDR) curve, which is the ratio of the displacement at the top of the building and its height. For the uninfilled structure in undeformed building configuration, the pushover curve and the deformed configuration are shown below (figure 7).

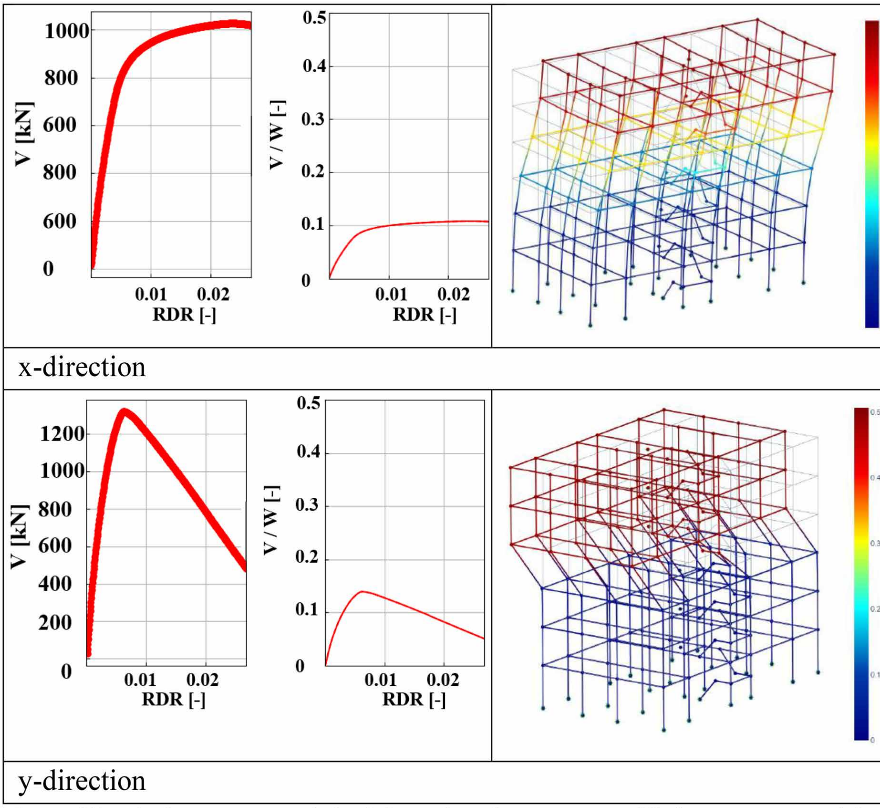


Fig. 7 – *Pushover curve and the deformed configuration uninfilled structure in undeformed building configuration along x- and y-direction.*

The stiffening effect and the non-negligible participation of the stairs block in the overall deformation mechanism are evident, particularly in the y-direction, where the uninfilled structure exhibits a soft-story mechanism, resulting in a significant reduction in the pushover curve, which is not observed in the x-direction.

As regards the structure with infill walls, the pushover curves for the x- and y-directions show a similar trend even with different resistance values (figure 8). In particular, once the peak base shear value is reached, the curves exhibit a rapid collapse, with the formation of a soft-storey mechanism in both x- and y-directions. It can be noted that, following the introduction of the infill elements, a different soft-storey mechanism develops as respect to the unfilled structure.

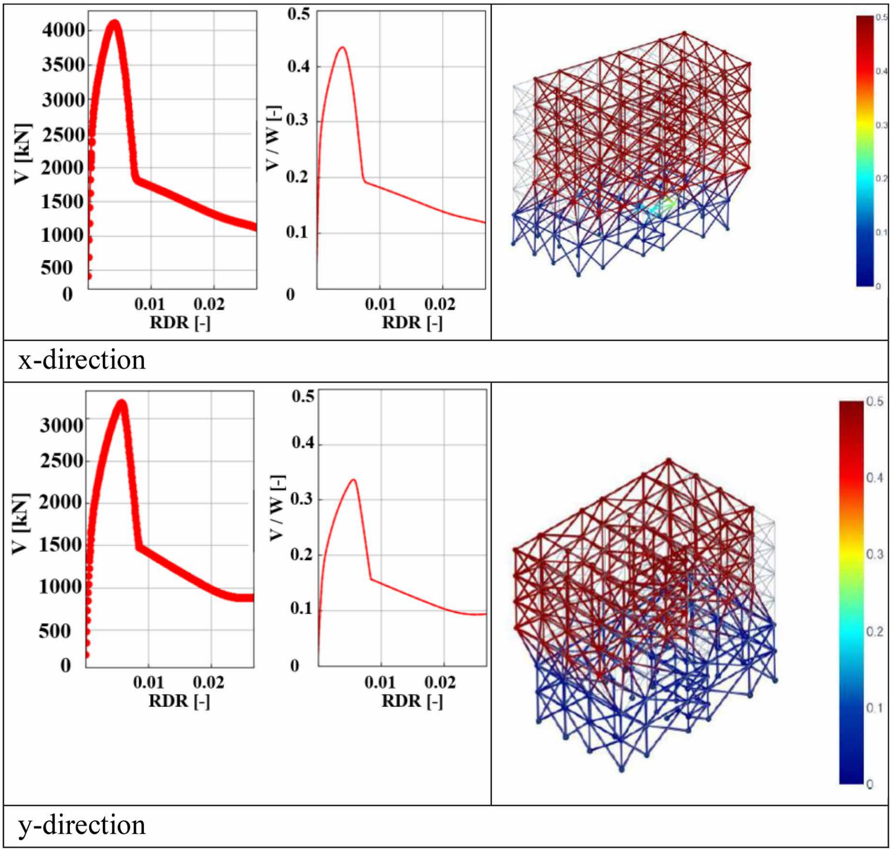


Fig. 8 – *Pushover curve and the deformed configuration filled structure in undeformed building configuration along x- and y-direction.*

Subsequently, non-linear static analyses were performed on the building in pre-damaged configuration. The procedure consisted of performing the gravity load and settlement analyses before the pushover analysis, recording the trend of the $N/(0.5F_{cr})$ ratio for each infill of each group step by step. Once the steps corresponding to the first achievement of each DS had been identified, it was possible to associate the relative "Roof Drift Ratio (RDR)" to the steps of interest in the analysis, thus visualising the evolution of the damage on the pushover curves (figure 9).

From the analysis results, it is possible to note that the structural elements and infill walls that first reach the damage are located on the first level of the structure and, therefore, near the settlements ap-

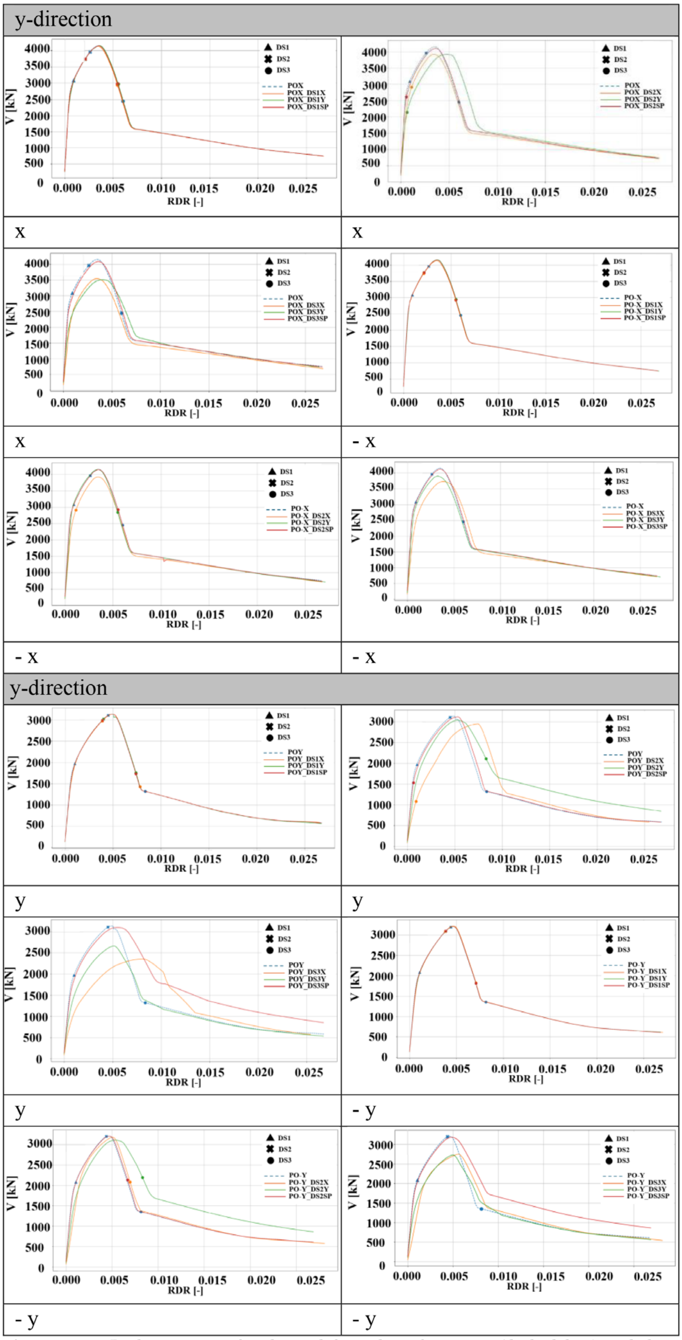


Fig. 9 – *Pushover curve for the undeformed configuration (dashed line) and the pre-damaged configuration.*

plied. When a lateral load distribution is applied to the structure, this observation is no longer immediate, as even the infill walls located on the levels where the building exhibits a soft-story mechanism are more stressed than those located on the lower levels. This is especially true for undeformed building configuration. It was reasonable to expect that as the amount of settlement imposed for each distribution increases, the overall capacity of the structure decreases compared to the undamaged configuration, evaluated as the maximum base shear resulting from the pushover curves.

3.6 Numerical Analysis on 4- and 2-storeys Buildings Archetypes

The same numerical procedure was applied to the archetype of the 4- and 2-storys buildings. In particular, below the results of the non-linear static analysis on the infilled structure in undeformed configuration (in the absence of settlement) are shown (figure 10).

From the analysis of the results, in the table 6 a comparison between the 6-, 4-, and 2-story buildings in terms of base shear are shown. In particular, the results are presented in terms of $\Delta V_{max,6-4}=1-(\Delta V_{max,6}/\Delta V_{max,4})$, $\Delta V_{max,4-2}=1-(\Delta V_{max,4}/\Delta V_{max,2})$ and $\Delta V_{max,6-2}=1-(\Delta V_{max,6}/\Delta V_{max,2})$, where $\Delta V_{max,6}$, $\Delta V_{max,4}$ and $\Delta V_{max,2}$ are the maximum base shear evaluated for 6-, 4- and 2-story buildings respectively.

Table 6 – *Comparison between the 6-, 4-, and 2-story buildings in terms of base shear.*

Direction	**V_{max} [kN]**			**ΔV_{max} [%]**		
	6-storey	**4-storey**	**2-storey**	**6-4**	**4-2**	**6-2**
+ x	4154.58	3907.94	3263.13	-5.94	-7.29	-12.79
- x	4154.45	3910.03	3622.14	-5.88	-7.36	-12.81
+ y	3133.80	2683.75	2324.28	-14.36	-13.39	-25.83
- y	3208.09	2726.2	2356.77	-15.02	-13.55	-26.54

Subsequently, non-linear static analysis was performed on the infilled structures in pre-damaged configuration. Specifically, the comparison between 6-, 4-, and 2-story buildings is shown below (figure 11). For the 6-story building, as an example, the pushover curve in + x-direction in the pre-damaged configuration corresponding to DS1 for uniform settlement under the perimeter columns on x-alignment is

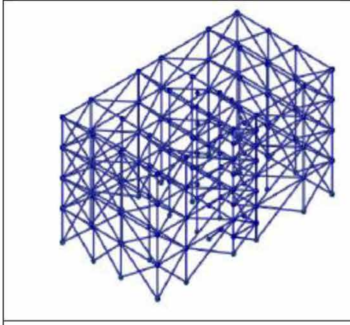
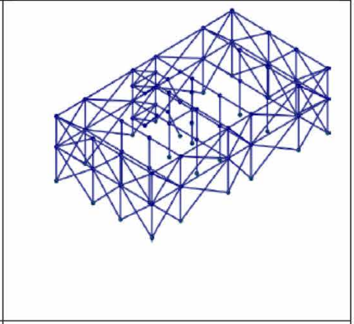
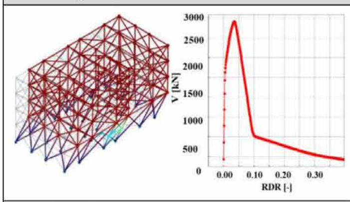
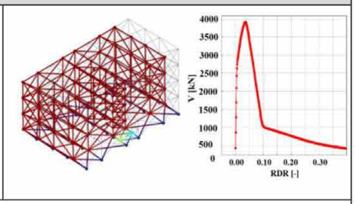
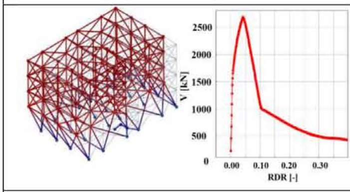
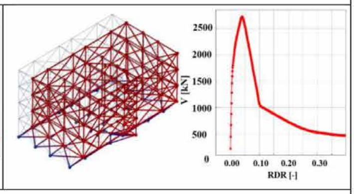
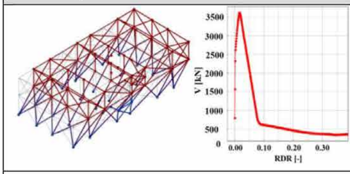
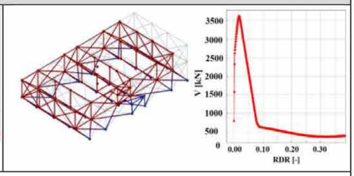
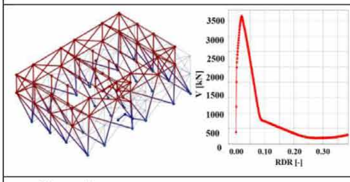
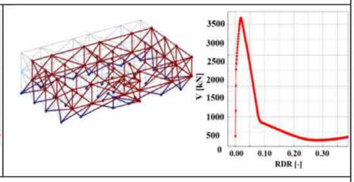
Numerical model	
	
4-storeys	2-storeys
Structure deformation and push-over curve	
4-storeys	
	
x-direction	
	
y-direction	
2-storeys	
	
x-direction	
	
y-direction	

Fig. 10 – *Numerical model and pushover curve for infilled structure in undeformed configuration.*

<table>
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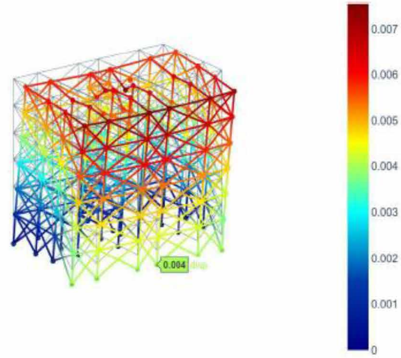
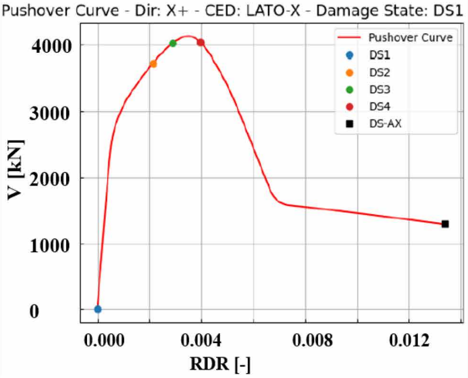
<tr><td>
</td><td>
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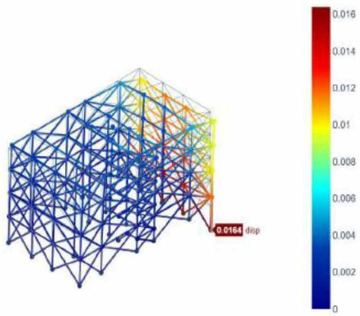
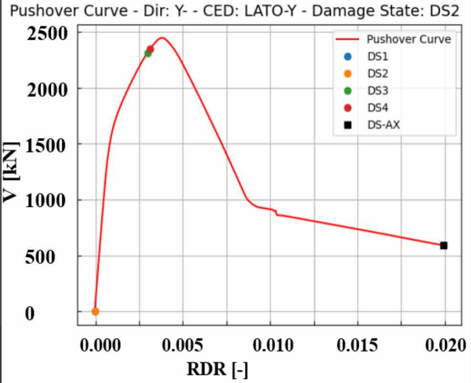
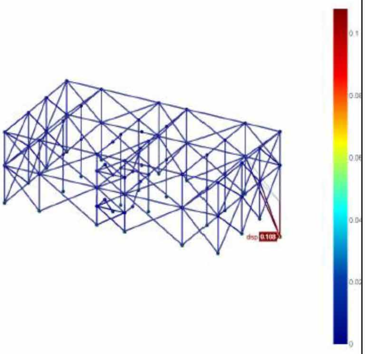
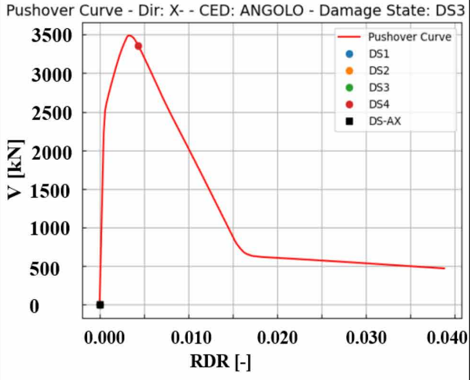
<tr><td colspan="2">4-storey</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">2-storey</td></tr>
<tr><td></td><td>
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Fig. 11 – *Structure deformation and pushover curve for infilled structure in pre-damaged configuration.*

shown. For the 4-story building, as an example, the pushover curve in - y-direction in the pre-damaged configuration corresponding to DS2 for uniform settlement under the perimeter columns on y-alignment is shown. For the 2-story building, as an example, the pushover curve in - x-direction in the pre-damaged configuration corresponding to DS3 for uniform settlement under the corner column is shown.

For the 6-, 4- and 2-story building, the value of pre-damage settlement is 4 mm, 16.4 mm and 108.0 mm respectively, while the maximum base shear value is $V_{max,6}$=4125.51 kN (- 0.70% compared to non-pre-damaged configuration), $V_{max,4}$=2446.90 kN (- 10.25% compared to non-pre-damaged configuration) and $V_{max,2}$=3488.93 kN (- 3.68% compared to non-pre-damaged configuration) respectively. Base shear values at which the DSs are reached are shown in table 7.

Table 7 – *Comparison between the 6-, 4-, and 2-story buildings in terms of base shear.*

Storey	$V_{DSi,j}$	$V_{DS3,-x}$			
		DS2	**DS3**	**DS4**	**DS-AX**
6	$V_{DS1,+x}$	3730.14	4022.15	4032.06	1287.58
4	$V_{DS2,-y}$	-	2314.70	2350.18	590.70
2	$V_{DS3,-x}$	-	-	3362.13	-

4. Conclusive Remarks

The aim of this study was to perform an assessment of the dynamic vulnerability due to pre-damage induced by hydro-geological phenomena on archetypal reinforced concrete (RC) buildings designed for gravity loads only, considering different numbers of storeys (2-, 4-, and 6-storeys), by means of non-linear static analyses.

The adopted approach can be summarized as follows:

- Identification of the settlement distributions to be applied. Three cases were considered: (i) Uniform settlement under the perimeter columns in the x-direction; (ii) Uniform settlement under the perimeter columns in the y-direction; (iii) Localized settlement under a corner column.
- Definition of the pre-damage levels assigned to the archetypes, established as: DS1 (cracking of infill walls), DS2 (achieve-

ment of maximum strength in infill walls or of the yield curvature limit in structural elements), and DS3 (achievement of the yield curvature limit in structural elements or of the residual strength of infill walls).

- Execution of analyses considering settlements only. The analyses provided the following orders of magnitude for the settlements associated with each damage state: DS1= 2 ÷ 4 mm; DS1= 2 ÷ 4 mm; DS3 = 20-30 mm for cases of uniform settlement of perimeter columns; 10.8 cm for the corner-column settlement case.
- Performance of pushover analyses on buildings in the pre-damaged configuration induced by the above settlements. From the resulting curves, the subsequent DSs reached were identified. In addition to those associated with the selected pre-damage conditions, DS4 (achievement of the ultimate curvature of structural elements) and a DS-AX (achievement of the tensile strength of columns) were also introduced. As expected, with increasing severity of the pre-damage level, the peak base shear of the pushover curves tends to decrease, except for a few cases in which, due to DS1, the base shear value is slightly higher than that recorded in the undamaged configuration. This inconsistency is attributed to numerical effects associated with nearly imperceptible settlements.

In general, in addition to the observations already discussed, it can be stated that, with respect to a pre-damaged building configuration, for the 6-storey building the settlement of a corner-column, although associated with DSs 2 or 3, has a less significant impact on the degradation of the peak structural capacity. Conversely, for the 4- and 2-storey buildings, all settlement distributions lead to a progressive reduction of the maximum base shear as the severity of pre-damage increases.

Construction History-based BIM for Knowledge and Management of Existing Bridges: the Ponte della Vittoria *in Verona*

Angelo Bertolazzi[1], *Francesco Sartore*[1], *Ilaria Giannetti*[2]

The preservation, management, and maintenance of existing infrastructure is one of the most significant challenges in contemporary engineering. The bridges present a huge amount of different structural typologies (beam, arch, truss, suspension, cable-stayed, and cantilever), different materials (stone masonry, iron and steel, reinforced concrete) which have been developed over the last two centuries. This great variety makes more difficult the analysis and the safe-guarde of existing bridges. However, the studies within the Construction History discipline can provide key data for the historical and technical knowledge of the existing structures concerning the 'hidden' construction details, the building process, and the maintenance intervention that occurred during their service life.

The relevance of Construction History is clear since «we are what we build and how we build; thus, the study of Construction History is now more than ever at the centre of current debates as to the shape of a sustainable future for humankind»[3]. Its role is more and more clear since it aims to understand the ways in which everyday building activities shaped the built environment according different cultures, times and places. The Construction History is a wide-ranging knowledge field that comprehends all of the actors involved in the building activity, both collective (contractors, materials producers and suppliers, schools, associations, and institutions) and individual (engineers, architects, entrepreneurs, craftsmen). All these actors used specific technics, tools, materials, norms and rules that define the "technological horizon" in each places and historical period. The analysis of this "horizon"

1 University of Padua, Department of Civil, Architectural and Environmental Engineering.
2 University of Rome Tor Vergata, Department of Civil Engineering and Computer Science Engineering.
3 Mascarenhas-Mateus J. and Pires A. P., "Introduction". In *History of Construction Cultures*, edited by Mascarenhas-Mateus J. and Pires A. P., 11-12. Leiden: CRC Press/Balkema, 2021.

allows not only the understanding the particular socio-economic context and cultural models, but also the identification of the technical solutions set for every single built object.

Beside that the digitalization process gives an important tool to collect, structure and query the data of the building or the infrastructure. This approach requires the BIM (Building Information Modelling) methodology that it's mandatory in Italy for the management of public works[4]. This issue remains very challenging specially in existing buildings and infrastructure since in Italy there are nearly one million public buildings, approximately 10% of which are of architectural value, and one and a half million of active bridges and viaducts, where maintenance and management issues have significant consequences for safety.

The chapter presents the first results of an ogoing research projecet aiming to develop innovative methodologies for the digital management of public buildings, by a specic focus on bridges, conceived as complex structures involving structural, construction, and architectural features. At the same time, techniques and protocols for the control and monitoring of bridge structures are being defined and tested[5]. The methodology is developed within a joined scientific collaboration between the ICEA Department of the University of Padua, the Department ICII of the University of Rome Tor Vergata concerning the knowledge, protection, management and enhancement of the built heritage. This research framework combines the archival data mining and construction analysis together the digitalization process trought HBIM models in order to enhance and mage the built heritage of the Nineteenth and Twentieth centuries. Within "I_BRIDGE" project different bridges in Verona were studied: a 1970s Gerber-beam bridge (*Ponte Unità d'Italia*), a reconstructed Roman mansonry arch bridge (*Ponte Pietra*) and a 1950s reinforced concrete arch bridge (*Ponte della Vittoria*). The latter is an interesting case study since it was built in the 1920s, nearly completely destroyed at the end of Second World War and reconstructed in the 1950s; the analysis conducted within the Construction History discipline provided important data useful to the digitalizations process of the bridge.

4 The BIM model is required by Ministerial Decree 321 of August 2nd, 2021, which makes the use of Building Information Modelling mandatory for public procurement contracts with a value of €1 million or more starting in 2025.

5 The research project "I_BRIDGE. Innovative methodologies for the digital management of bridges and public buildings" is co-funded by the University of Padua and the Municipality of Verona. The goal is to enable public administrations, in this case the Technical Offices of the Municipality of Verona, to develop both the skills and knowledge for the management of civil infrastructure and to appropriately approach the process of digitalizing buildings for their effective management over time.

1. The Reinforced Concrete Bridges in Verona: a Twentieth century Construction History

In Italy at the end of Nineteenth century the use of reinforced concrete within the bridge construction became quickly an alternative to the iron and steel since the country depended on foreign imports of raw materials (i.e. coal and minerals). The new material was introduced at first thought foreign patents like the French patent Hennebique (1892 and 1897) regarding linear structural elements (beams and pillars) and the German patent Wayss and Koenen (1892 and 1895) regarding flat elements (ribbed floor slabs and beams)[6]. The traditional practice of masonry building techniques and the consolidated use of hydraulic concrete (both to lay foundation floors and to set the core of abutments and decks) allowed the success of the new technology and sustained the economic competitiveness thanks to its limited use of iron. Resorting to reinforced concrete was moreover more suitable for local building companies, still employing traditional manpower that could easily be trained to use the new material; on the other hand, using iron when building required a highly-specialised manpower, able to perform particular and complex tasks both in workshops and in building yards[7]. Reinforced concrete was mainly used and tested in Italy in industrial buildings or infrastructures, above all bridges and viaducts. First the Conte textile factory at Schio (1906), the Genoa harbour silo (1898-1901), the Bagnoli ILVA plant (1908-1909), the Turin Fiat Lingotto factory (1916-1922), the bridges over the Tagliamento at Pinzano (1902-1906), over the Stura at Fossano (1910) over the Isonzo at Gorizia (1920-1921). These works witness the scientific, entrepreneurial and technological development reached by Italy as regards building large reinforced concrete structures, filling the gap with other European countries[8]. These first building yards were the field of research and testing for many engineers and builders, e.g. Arturo Danusso, Enrico Giay,

6 In Italy both the Hennebique and the Wayss and Koenen patents were highly successful thanks to their being promoted and marketed the former by Turin firm Porcheddu and the latter by Rome Ferrobeton that were for a long time the only authorized dealers. They were followed by several further minor patents, such as Coignet (1892), Melan (1892), Moeller (1893), Matrai (1896), Walser-Gerard (1898). Iori T., *Il cemento armato in Italia, dalle origini alla seconda guerra mondiale*. Roma: Edilstampa, 2001, 59-62; Mochi G. and Predari G., *La costruzione moderna a Bologna (1875-1915). Ragione scientifica e sapere tecnico nella pratica del costruire in cemento armato*. Milano-Torino: Bruno Mondadori, 2012, 45-54.

7 Poretti S., "Struttura e architettura nel modernismo italiano". *Rassegna di Architettura e Urbanistica* 121-122 (2007): 9-33.

8 Nelva R. and Signorelli B., *Avvento ed evoluzione del calcestruzzo armato in Italia: il sistema Hennebique*. Milano: Edizioni Scienza e Tecnica, 1990, 90-98.

Giuseppe Vacchelli, Luigi Santarella, Attilio Muggia and Giuseppe Albenga. Reinforced concrete being used in outstanding works furthered the scientific enquiries regarding the plastic behaviour of concrete, in this way overcoming the traditional limitation of elastic behaviour, and this evolutionary process was to become technique and practice after many years[9].

After the pioneering phase of reinforced concrete use in Italy the new material started being employed also in Verona, though at a slower rate, since the local traditional masonry techniques hindered its success. After being first employed in the Camuzzoni canal[10] and in industrial buildings (i.e. the Tiberghien textile mill, where the Baroni-Lüling patent was used), reinforced concrete was widely resorted to from the 1920s onwards when achieving those sections of the buildings that required the new material for large spans, such as the vaults of Porta Nuova railway station and the dome of the "Rotonda" at Magazzini Generali (built by *Ferrobeton*)[11], as well as in all those buildings in which it proved more economical; moreover, it could withstand fire hazards better than metal structures.

The economic and demographic growth of the city after the First World War was accompanied by the increase of the traffic, which required a comprehensive transformation of the system of bridges crossing the Adige, leading a quick rebuilding of the exiting bridges and the construction of new ones[12]. Starting from the late 1920s, the new *San Francesco* bridge (1927-29) was built; together with *Catena* bridge (1928-29) it provided a ring connection between the southern and eastern and western districts; the historical centre and the *Borgo Trento* district were to be doubly connected: thanks, either to *Vittoria* bridge (1926-1930), or to the one linking "*la Campagnola*" and *San Zeno* district, which, however, was never built. However, in the 30s, because of the problems caused by traffic, the following bridges were rebuilt: *Garibaldi* (1933-36), Navi (1934-36) and *Umberto* (1935-39) bridge, while

9 Brenchich A., *Il Cemento Armato dagli albori alla modernità*. Milano: Mc Graw Hill, 2025, 115-118.

10 Morgante M., "I cementi a Verona nella loro fase pionieristica". In *L'arte del costruire a Verona. Studi e ricerche su materiali e tecniche dell'edilizia storica*, edited by Castiglioni G., 69-86. Verona: Scripta, Verona, 2012.

11 Bertolazzi A., Turrini U. and Croatto G., "Una cupola per la Modernità (1929-1930). Materiali e tecniche nella Centrale Frigorifera Specializzata di Verona". In *Stati Generali del Patrimonio Industriale 2022*, edited by Currà E., Docci M., Menichelli C., Russo M., and Severi L. 1792-1806. Venezia: Marsilio, 2022.

12 Mulazzani M., "Il piano regolatore del 1931-1932". In *Urbanistica a Verona (1880-1960)*, editet by Brugnoli P., 213-247. Verona: Ordine degli Architetti, 1996; Bertolazzi A. and Segala I., "Verona Novecento: la città, la macchina e l'uomo". In Bertolazzi A., Bossum E., De Mori M., Segala I. and Xamo S., *Verona in cantiere*, 12-13. Verona: Edizioni ZeroTre, Verona, 2017.

during the war the building yard of *Aleardi* bridge, opened in 1939, was stopped and abandoned during the Second World War[13].

Building – or rebuilding – bridges in Verona meant the first massive resort to reinforced concrete, a material that had been widely employed in Italy since late Nineteenth century. The bridges built from the early 1930s onwards provide a sort of case study that also traces their evolution towards increasingly efficient and economical structures: for *Catena* and *San Francesco* bridges the structure was a three-arch structure where the three reinforced concrete variously-thick arches had reinforcing decks made up of longitudinal and transverse trusses connected to the arches by means of several square-section concrete pilasters. Since the structures needed to be protected from water erosion, the gables of the two bridges were filled up, so that they ended up looking like traditional masonry structures. For the *Vittoria* bridge the cell-like structure was employed, which resulted in a moderately-thick keystone as well as a sturdy – though at the same time light-weight – bridge[14].

The reinforced concrete structure of the bridges (particularly city bridges) was to be clad by stone slabs, according to the restrictive regulation issued by *Soprintendenza ai Monumenti*. *San Francesco* and *Catena* bridges were in fact simply plastered by concrete, to which some unpretentious details were added to make them look like masonry structures. On the other hand, as regards *Vittoria*, *Garibaldi*, *Umberto*, *Navi* and *Aleardi* bridges, a cladding made by Verona stone slabs and "*bolognini*" was explicitly required on all vertical and horizontal structures; moreover, as regards *Navi* and *Umberto* bridges it was also required to modify the outline of the decks. The cell-like structures of *Vittoria*, *Garibaldi* and *Aleardi* bridges allowed the additional permanent loads of stone cladding to be withstood. *Navi* and *Umberto* bridges were instead equipped with continuous truss systems consisting in a cribwork of longitudinal inter-chained trusses[15]. The set of problems raised by the required alteration of the outline of bridges and by their stone cladding was particularly outstanding as regards the two last-mentioned ones: new calculations had in fact to be made of the width of the river to be spanned, of the level of the springers and of the connections with access ramps.

13 Bertolazzi A. and Savoia R., *I ponti in cemento armato a Verona nel Novecento*. Verona: Edizioni ZeroTre, 2022, 31-32.

14 The same solution was adopted for *Garibaldi* and *Aleardi* bridges; whereas for *Navi* and *Umberto* bridges had a simpler reinforced concrete truss (the second one by using the Melan patent for the iron bars) leaning onto the existing abutments to avoid as much as possible the destruction of Nineteenth century massive banks. *Ivi*, 163.

15 As regards *Umberto* bridge, the Melan-type iron frame was specifically necessary for the deck trusses, to support the increased permanent loads caused by the heavy (between 4 and 9cm.-thick) stone cladding. *Ibidem*.

The construction (or reconstruction) of the new bridges revealed also how the entrepreneurial class in Verona reacted to the new material. As many as six of the seven bridges completed in Verona in the 1920s and 1930s were built by the Turin-Roma-and-Verona-based *S.A. Bertelé* company that boasted of a noteworthy experience in employing reinforced concrete in large structures; only *Vittoria* bridge was built by a local company, *Tosadori*. This proves as in Verona – like in other small Italian towns – during the 1930s the reinforced concrete techniques were held by few firms that we able to play a sort of monopoly in this field[16].

This situation changed after the Secon World War when the reconstruction of the Verona bridges started. In the night between the 24th and the 25th April (or the following day, according to other sources) German mines blasted all the bridges in Verona, a vain attempt of halting the northwards advance of the allied troops. All of them were more or less seriously ripped and made useless: the blast crumbled down *San Francesco* bridge; the trusses of *Navi* and *Umberto* bridges fell into the river, together with one of the pillars; *Garibaldi* bridge lost its right arch completely, whereas the left arch was seriously crippled. *Catena* bridge was also seriously hit: only the central arch was lost, and the keystone of the left one lowered nearly 30 cm; *Vittoria* bridge kept its right archway, but the central and left ones were lost; *Aleardi* bridge, which had not been completed because of the start of the war, was only affected by the destruction of its left pillar[17].

The rebuilding of the city bridges started in January 1946 with the opening of *Catena* bridge yard and ended with the unveiling of *Vittoria* bridge in November 1953; the fastest yard was the *Navi* bridge one: opened in January 1949, it was closed the same year, in August; the slowest the *San Francesco* bridge one: opened in February 1949, it was closed only in January 1952, due to the 1950 bankruptcy of the *Getto* company from Padua. As regards *Vittoria* bridge, instead, notwithstanding the wary task of grafting the new arch onto the old one, the works started in May 1952 and were completed in August 1953.

The structural types chosen were the same as the ones of the 1930s: *Vittoria*, *Garibaldi* and *Aleardi* bridges kept cell-like structures; *San Francesco* and *Catena* bridges were rebuilt resorting to structures with arches strengthened by the decks; as regards *Navi* and *Umberto* bridges – the latter changed its name in 1946, becoming *Ponte Nuovo del Popolo* – reinforced concrete continuous trusses with lowered-arch intrados were resorted to[18].

16 Morgante M.. "I cementi a Verona nella loro fase pionieristica", op. cit., 69-86.

17 Bertolazzi Angelo and Savoia Renzo. *I ponti in cemento armato a Verona nel Novecento*, op. cit., 34-36.

18 These choices were mainly prompted by the need as far as possible to preserve either

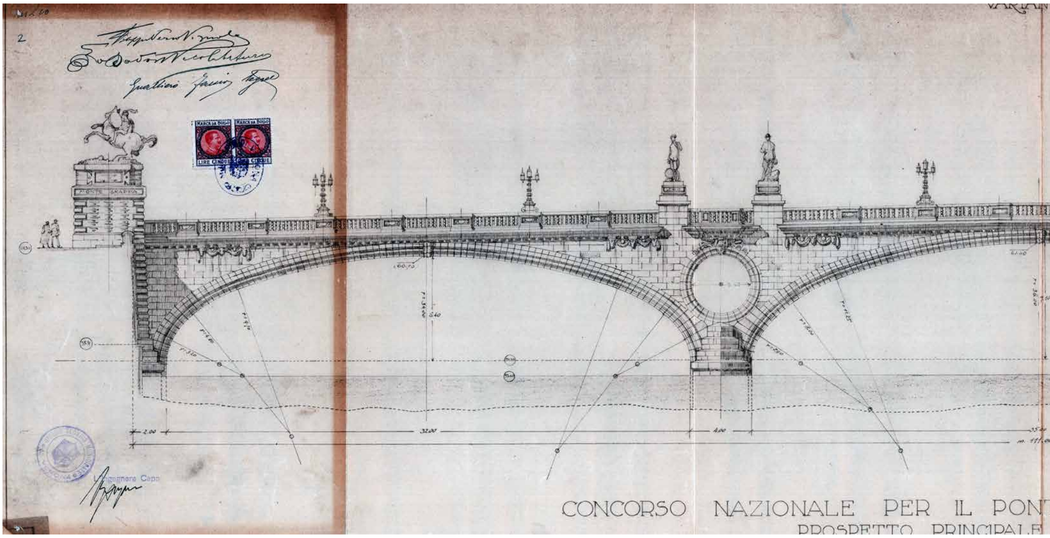
Reconstruction times largely depended on the various technical problems that had to be faced, both from a hydraulic and a structural, construction-related point of view; however, they also revealed how companies worked in those times: in the 1920s and 1930s few were the companies capable of building a reinforced concrete bridge, in the 40s instead, things had changed: up to 6 or 7 companies could take part in a tender on a national scale. The *S.A. Bertelè* company, which after the war had become *Impresa di Costruzioni in Cemento Armato* (I.C.C.A.), was the winner only on two occasions: in the *Catena* bridge tender (for which it was directly appointed) and in the *Vittoria* bridge tender; the same firm then took over the *San Francesco* bridge yard when the *Getto* company went bankrupt. The remaining bridges were built by Milan companies, such as *Bruno Chiesa* (Garibaldi and Umberto bridges) and *Ragazzi* (Cavaion bridge) and by Rome-based *Ferrobeton* (Albaredo bridge), Padua-based *Getto* and Verona-based *Lonardi* won the contracts respectively for *San Francesco* and *Navi* bridges. The large number of companies that participated in the reconstruction testifies how reinforced concrete, over the course of approximately 15 years, become a developed technique and a shared knowledge in the Verona engineering and building sector.

2. The Case Study: *Ponte della Vittoria*

The bridge named *Ponte della Vittoria* is located in Verona and it crosses the Adige river linking the city centre and the Borgo Trento district. The historical documents concerning the case study were collected from two main Archives: the first is the *Archivio Generale del Comune di Verona* that preserves the documentary heritage of the Verona Municipal Archives mainly from the Twentieth century and preserves the legal-administrative and technical documentation produced by the different municipal offices (public works, urban planning, school buildings, etc.). The Archive holds the *Carteggi* (since 1931) and the *Contratti* (since 1881), which, through their technical documentation (drawings, reports and photographs), accurately outlines the main transformations of the city – urban, architectural and building – since the end of the Nineteenth century to the Twentieth century. The second one is the *Fondo del Genio Civile dello Stato*, preserved in the *Archivio di Stato di Verona*[19]. By crossing the technical-administrative data stored in the *Archivio*

the foundation structures of the existing abutments, or a pillar (as it was the case in *Umberto* or *Aleardi* bridges), or even the whole arch, as it was possible in *Vittoria* bridge. *Ivi*, 37-38.

19 The *Fondo del Genio Civile dello Stato* archive consists of 2,586 folders, 466 registers and more than 6,000 photographs, for a total of 520 linear meters This archive preserves the



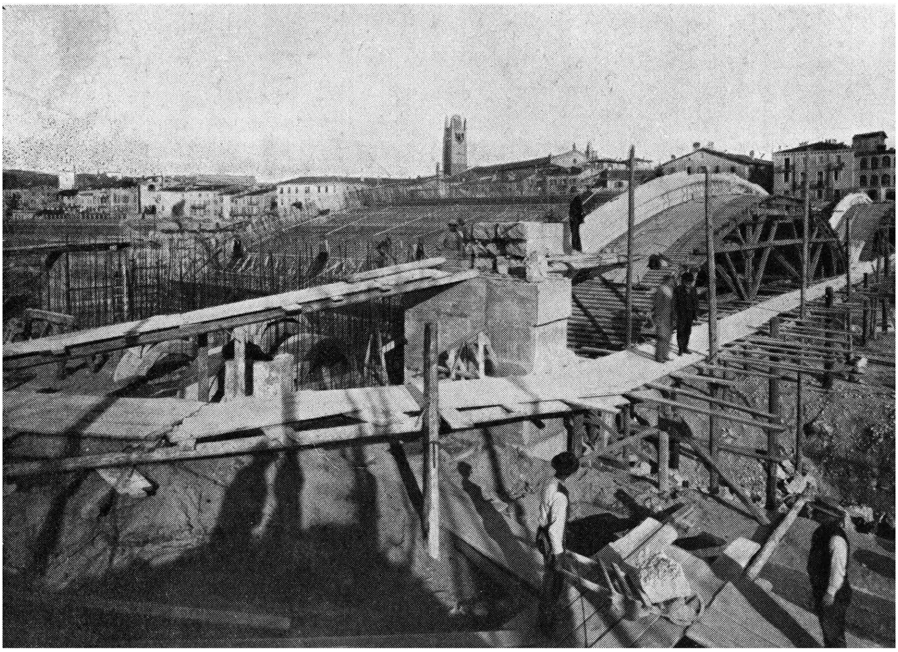
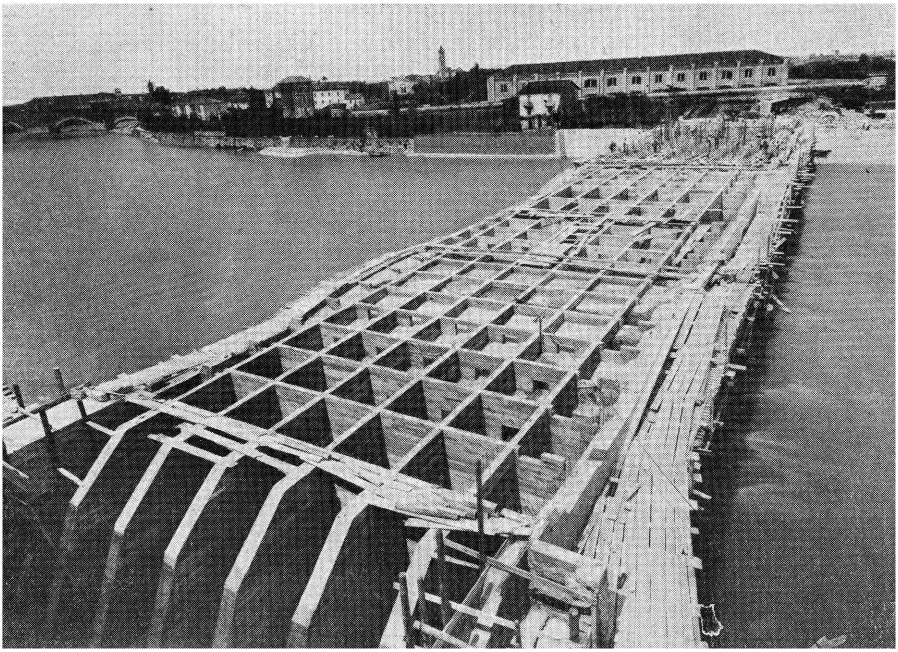
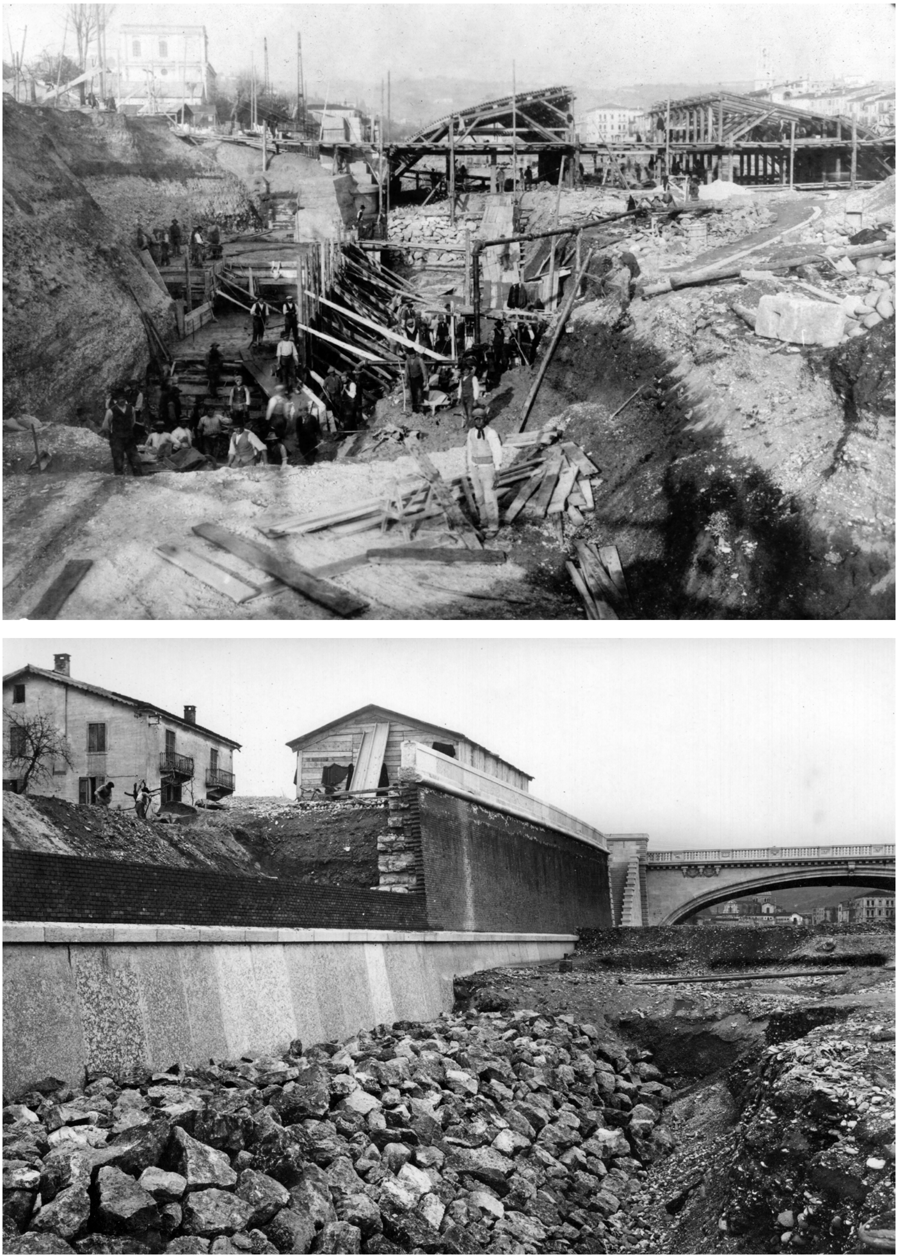


Fig. 1 – *Ponte della Vittoria (1926-29): elevation drawing of the executive project (top) by Arch. Ettore Fagiuoli and Eng. Umberto Fasanotto. Since the choice for a cell-type r.c. structure the contractor –* Tosadori *company – asked the consultancy of Eng. Arturo Danusso, who worked for the structure of* Risorgimento *bridge (1910-11) in Rome. [ACVr, Contratti, b. 134; Rep.: 14258].*

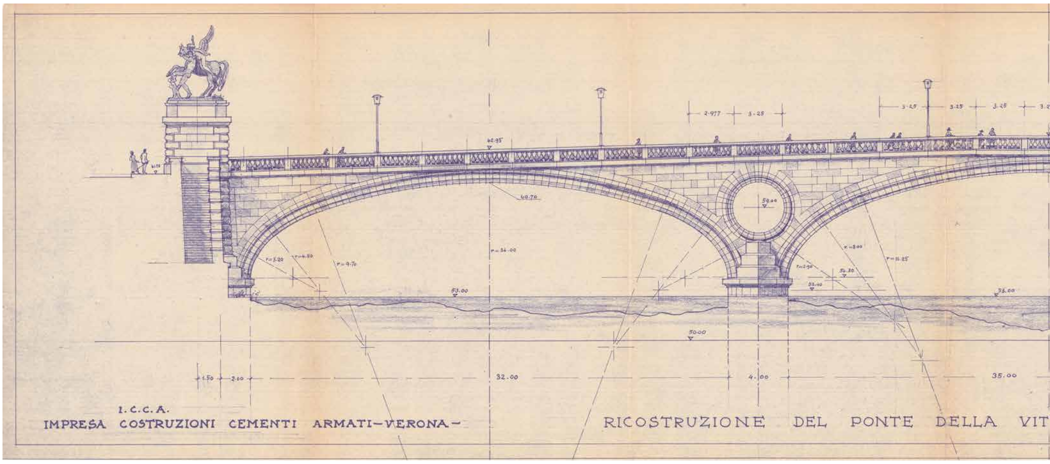


Figg. 2-3 – Ponte della Vittoria *(1926-29): some pictures from the photographic survey made by the* Ufficio del Genio Civile *were published also by Eng. Luigi Santarella in his volumes* Ponti in Cemento Armato *published in 1930. The survey testifies the main steps like the construction of the centering for the bridge arches (bottom left) and the building of the cellular structure (bottom right). [Santarella and Miozzi, 1930].*



Figg. 4-5 – Ponte della Vittoria *(1926-29): during the works for the new embankments alongside the "*la Campagnola*" the photographic survey made by the* Ufficio del Genio Civile *shows also the bridge yard, like the centering (top) and at the end of the building works (bottom). The pictures explain the strong connection between the hydraulic works and the bridge construction. [ASVr, Fondo Genio Civile, scatola 9 and 10].*

Figg. 6-7 – Ponte della Vittoria *(1926-29): the picture just before the opening (top) shows the ongoing transformation in the* Borgo Trento *district. At the end of the Second World War the Vittoria bridge blasted away leaving only the right arch (bottom); over the damaged structure the US Army posed a Bailey-type military bridge that served until the 1951. [ACVr, Contratti, Cat. X.5- 1; N° Prot. 30481; ACVr, Carteggi, f. CA.X.510].*


I.C.C.A.
IMPRESA COSTRUZIONI CEMENTI ARMATI–VERONA–
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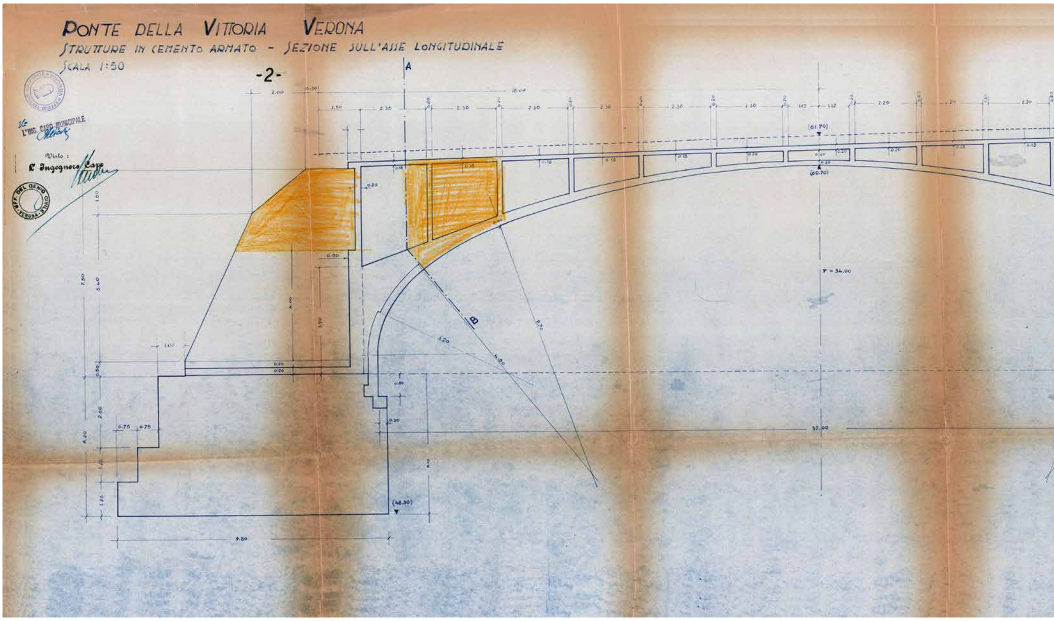
PONTE DELLA VITTORIA VERONA
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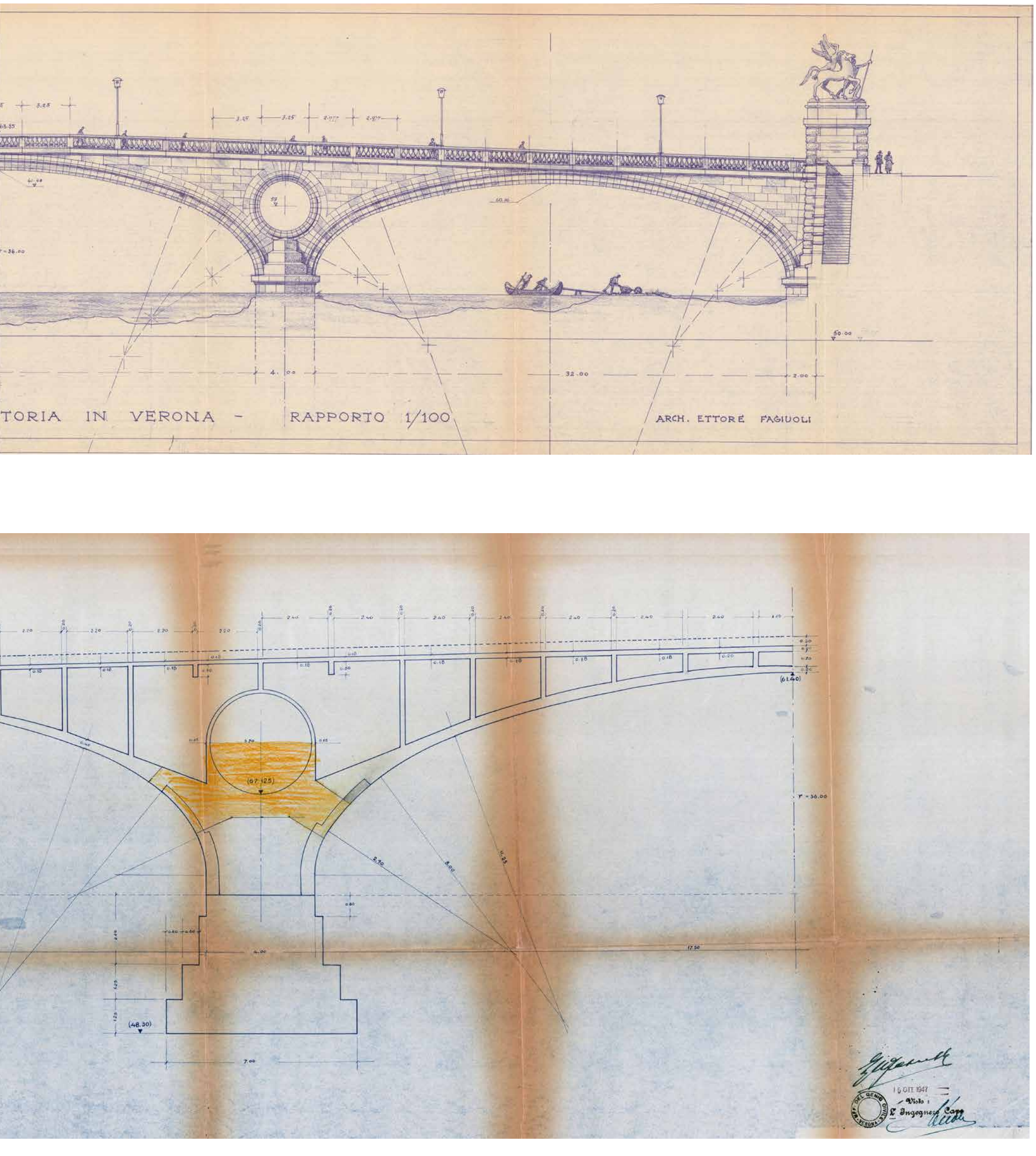


Figg. 8-9 – Ponte della Vittoria *(1949-53): elevation drawing of the executive project (top) by Arch. Ettore Fagiuoli and Eng. Umberto Fasanotto. The connecting among the two new arches and the old one required a specific structural project (bottom) by Eng. Giuseppe Albenga. [ACVr, Contratti, Cat. X.5- 1; N° Prot. 30481].*

Figg. 10-11 – Ponte della Vittoria *(1949-53): the construction of two new arches similar to the older ones involved the use of the same tools like the wooden centering used in the 1920s (top); when the bridge was finished it looked like the old one even if without the complex decoration of the 1920s; Borgo Trento shows great changes ater the growing up building activity of the 1950s. [ACVr, Contratti, Cat. X.5- 1; N° Prot. 30481].*

Generale with the technical-design data from the *Fondo del Genio Civile dello Stato* allowed to outline the historical events of the *Ponte della Vittoria*.

The bridge was built at first in the 1920s since in 1921 Verona War Veterans expressed the wish to build a bridge over the Adige in order to celebrate World War I victory. The city Council undertook the commitment to build the memorial bridge during its meeting on June 14th 1923; the following year, on May 22nd, the bid for tender for the new bridge that was to connect the historical centre with the newly-developing "*la Campagnola*" district was published: 14 out of the 40 projects entered were selected: on June 30th 1925, the commission (Arch. Gaetano Moretti, Eng. Camillo Guidi and Prof. Corrado Ricci), named the winner: it was the Arch. Ettore Fagiuoli and Eng. Ferruccio Cipriani`s project. On 13th October 1925 the works were committed to the *Tosadori Nicola* company, who proposed Eng. Umberto Fasanotto as director of the works; on behalf of the council Eng. Adolfo Zorzan and Eng. Gino Pomini were appointed. The final structural project was drawn up by Eng. Arturo Danusso on behalf of *Tosadori* company and the city Council[20]. The works started between February and March 1926; the main structures were tested in December 1927; finally – ornaments included – the bridge was finished in January 1930; the bronze groups by Verona-based sculptors Mario Salazzaro and Angelo Biancini were added in 1931, even though the bridge had been inaugurated on November 4th 1929; the total cost was 4,125,000 lire[21].

As all the bridges in Verona, it was blasted by German mines at the end of the war: the explosion ripped the central arch, whose collapse pulled down the left arch; the left pile and the right arch, instead, were left standing. On top of them, the American Army cast a "Bailey-type" military bridge in order to let military vehicles drive through; it was later shifted from its original site and used for ordinary traffic until 1953, as the city council requested.

It was decided that the bridge was to be rebuilt starting from 1950, and that its original features were to be kept. Arch. Ettore Fagiuoli and Eng. Umberto Fasanotto were charged with drawing up a new project, providing to

activities, albeit partially, from 1920 to 1987; The photographs, drawings and technical documents, delineate the urban, building and infrastructural transformations of Verona and its territory during the Twentieth century. Bertolazzi A. and Stendardo L., "Dagli archivi in rete al museo diffuso dell'ingegneria: il fondo del Genio Civile di Verona e la sua valorizzazione". In *Atti dell'8° Convegno Nazionale Storia dell'Ingegneria*, edited by D'Agostino S. and d'Ambrosio Alfano F. R., 137-146. Napoli: Cuzzolin, 2020.

20 Archivio Generale del Comune di Verona (ACVr), Contratti, Busta: 9671; Repertorio: 14298; Date: 4/03/1926; Bertolazzi A. and Savoia R., *I ponti in cemento armato a Verona nel Novecento*. op. cit., 106-108.

21 Archivio Generale del Comune di Verona (ACVr), Contratti, Busta: 134; Repertorio: 14258; Date: 26/03/1926.

preserve the still standing arch and to reduce the ornaments. The project was submitted to the *Ufficio dei Lavori Pubblici* on 5th April 1951 for approval. Even the cell-type structures were to be kept; however, the need to fit in the new structures with the old ones and to strengthen the existing arch, suggested that the calculations were to be verified further: to that end, Milan Polytechnic Eng. Giuseppe Albenga was called in as a consultant[22].

The bid for tender in 1951 was won by I.C.C.A. company that had already rebuilt *Catena* bridge and that provided for the dismantling and remounting of the Bailey metal bridge. The works started on 12th May 1952 and were ended on 29th August 1953 by the *Ufficio del Genio Civile* Eng. Bruno Baldin, and – on behalf of the I.C.C.A. company – by Eng. Federico Albert and Eng. Giuseppe Biasioli and Arch. Ettore Fagiuoli.

The official inauguration took place on 4th November 1953. The replacement of the bronze groups on stone blocks at the bridgeheads was delayed as a consequence of a controversy triggered by Mayor Giovanni Uberti: not only was the traffic impaired (so it was argued) but also the style of the statues proved morally objectionable; as a result, the works were suspended in July 1953. Only after the report issued by a council-appointed commission that advised to modify the blocks of the bridgeheads and to evaluate the repositioning of the bronze groups, and after the strong intervention of Verona War veterans, were they replaced, though on more streamlined blocks. The reconstruction of the bridge cost 87,000,000 lire[23].

The first bridge and the second one had the same features and structural typology. The structure consists in three polycentric arches, the lateral ones with 32.00 m clear spans and the central one a 35.00 m span; the total length amounted to 111.00 m and the width to 16.00 m. Both bridges had the same r.c. cell-type structure by Hennebique patent[24]; the arches consisted

22 Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.4; Date: 16/09/1949.

23 Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.25; Date: 15/07/1954.

24 The cell-type r.c. structure was patented by *Maison Hennebique* in Paris in 1905 and, after, the Italian company *Porcheddu* acquired the French patent by which designed and built the *Risorgimento* bridge in Rome (1909-11). This was at the same time the first 100 m single-span r.c. bridge in the world and a model for further structure in Italy and abroad, i.e. the bridges over the Boate at Rapallo (1911), over the Dora in Turin (1912-1913), and the railway bridge over the Stura at Pessinetto (1915-1916). The so-called '*Risorgimento*' type consists in a quite lowered wedged arch, with a deflection amounting to 1/10 of its span; the reinforced concrete structure is made up of "cells" or of "tapered-section elements" where the extrados of the arch was made up of a thin vault reinforced with vertical load-bearing walls (i.e. ribs and gables) crossed by a network of connecting transverse ribs integral with the base of the deck. The longitudinal load-bearing walls rested on huge abutments that provided efficient

in intrados (ranging between 0.20 and 1.60 m-thick) slabs and in 0.38-metre-thick horizontal slabs supporting the deck, connected by means of reinforced concrete longitudinal supporting walls joined together by means of transverse slurry walls. The foundations of the abutments consisted in 10 self-sinking wells embedded as far down as 6.00 m below the riverbed; the piles were supported by differently-sized wells that reached the same depth. This structural typology allowed the bridge to be light and sturdy, which was essential, since the choice had been made to clad the bridge with Verona Nembro marble slabs and block, even if the reconstructed bridge had a simplified decoration[25].

3. Research Methodology: Symplified HBIM Models

Today's workflow is based on creating BIM models from point clouds obtained with laser scanners. This increases the effort required for operators to translate the point cloud into the model, while the latter becomes very heavy and difficult to handle. The ongoing research set a specific methodology focusing on the use of the HBIM as a tool to collect, organize, classify, and support the broad access to technical data derived for historical and current archives. The proposed HBIM follows a traditional philological approach, using the model itself as both investigation and representation tool, supporting the organization, the classification, and the display of the documents derived data. This approach allows an easy reading of the archival documents, and the embedded technical data framework, supported by the visual correlation with the 3D reconstruction of the bridges.

The huge number of bridges across Italy – approximately 1,000,000 structures – requires a review of approaches and methodologies to be managed since the urgent social need for safety. The first innovative aspect of I_BRIDGE project is methodological and foresees the synergy by which different skills will contribute to data creation, its subsequent implementation in the BIM model, and its operative restitution. This requires multidiscipli-

constraint wedges. At its highest point the structure was relatively thin, so as to evince a structural configuration presenting two rigid slabs wedged at the outer ends on the abutments and connected at the top my means of plastic joints. The result obtained was not only a quite light and sturdy, but even fairly-easy-to-build structure, as witnessed by the short time (16 months) it took. Società Anonima Porcheddu, *Il ponte del Risorgimento attraverso il Tevere in Roma*, 1912; Nelva R. and Signorelli B., *Avvento ed evoluzione del calcestruzzo armato in Italia: il sistema Hennebique*, op cit., 81-84.

25 Archivio di Stato di Verona (ASVr), Fondo del Genio Civile dello Stato, Busta: P.25; Date: 15/07/1954.

nary collaboration between the disciplines involved in the various research activities, from data acquisition to digitalization and on-field verification through direct testing. Currently, the digitalization of buildings primarily involves the acquisition (scanning and archiving) of technical documentation leading to a simple three-dimensional model. The research instead aims to create interoperable models (BIM), implemented, as a demonstration of the digital process, within a platform capable of implementing, in addition to three-dimensional data visualization, an organized and queryable database helpful to multiple user levels for the informative repre-sentation of the built heritage (historical evolution, geometric, material, construction, and structural aspects)[26].

It is deemed necessary to approach the topic starting from a set of case studies – the bridges in Verona – that are homogeneous in terms of function and challenges, yet broad enough to investigate the various aspects involved (materials, construction, and structural). The case studies represented by the two types of bridge structures identified (masonry, reinforced and concrete) allow for a comprehensive study of digitalization aspects in relation to the various structural and construction aspects of bridges. This allows for an innovative connection between digitalization aspects from the archive data to numerical modelling of the structure (static and dynamic analysis, in situ testing)[27] .

Finally, the main scientific contribution to advancing knowledge of the different activities lies in the sharing of historical and technical documentation – digitized, structured, and organized – for the morphological, constructional, and structural characterization of bridges, at the scale of the individual structure, throughout their historical evolution. This will consequently increase the knowledge of active stakeholders – public administration responsible for managing the structures and documentary heritage and clusters of the international scientific community operating in the construction sector. The dialogue between the different areas – digital data creation and field verification – is another innovative aspect of the research. Its most tangible

26 A specificinnovative aspect, where the ICEA (University of Padua) and ICII (University of Rome "Tor Vergata") Departments have already developed expertise, is the ability to connect archival data with simplified models to collect geometric and degradation survey data, as well as data from long-term monitoring of the structures or buildings.

27 Within I_BRIDGE project also were studied *Ponte Unità d'Italia* and *Ponte Pietra*; the first one is modelled in order to collect in an HBIM model both the historic data and the contemporary data following the dynaic tests and material characterization; the second one was used to explore the digitalization isssues in a specific case study with different and disomogeneous typologies of masonry (bricks and stone blocks) that was reconstructed after the Second World War.

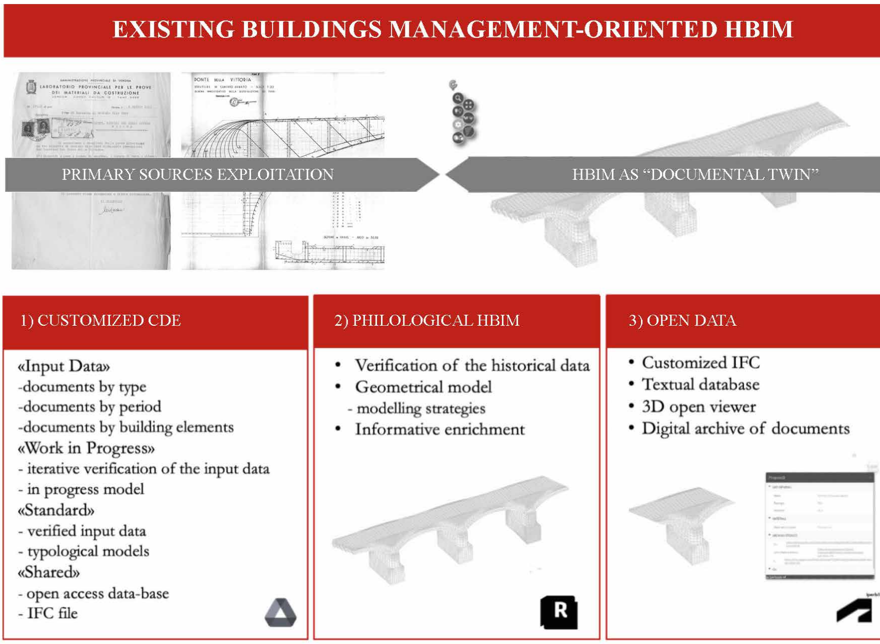


Fig. 12 – Ponte della Vittoria *HBIM: methodology workflow of the HBIM digitalization process. [© 2025, Giannetti, Bertolazzi].*

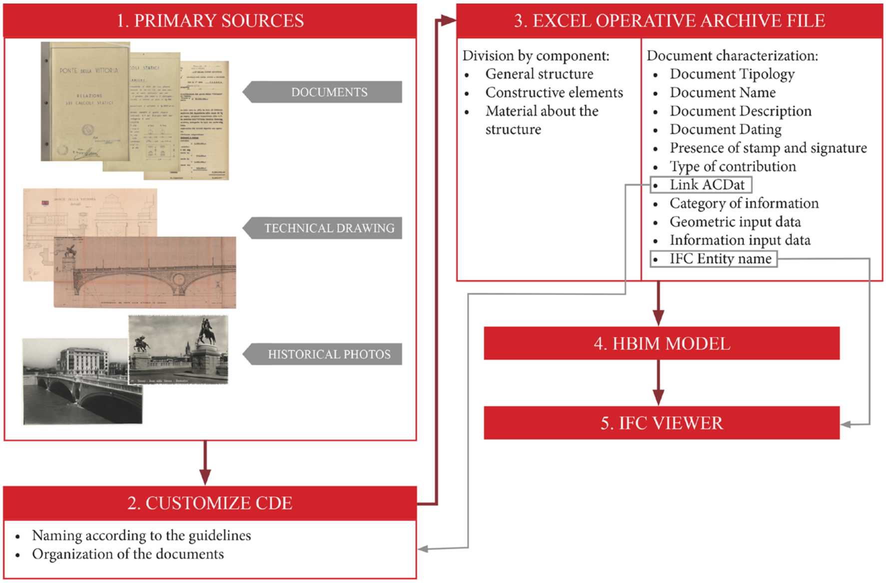


Fig. 13 – Ponte della Vittoria *HBIM: the database structure and the process to collect the primary sources. [© 2025, Giannetti, Bertolazzi, Sartore].*

result will be the development of a sound methodology for the digitalization of built environments. Its main strength lies in its replicability across other structures (buildings and infrastructure) at various scales (construction and urban) managed by the Public Administration.

The proposed methodological framework focused the use of the HBIM as a tool to collect, organize and visualize the archival documents and the historical survey related data for the knowledge of the buildings in management-oriented process. The methodology is based on the application of the philological approach for the realization of models with a high level of detail (LOD E, F,), as defined by the Italian UNI 11337 standard the built environment conservation[28], taking advantage of the native functionalities of the Autodesk Revit platform[29] for the extraction of tabular data and the production of Industry Foundation Classes (IFC)[30]. The choice of a commercial BIM Authoring platform to elaborate the models rely on the aim to extend the application of the proposed ap-proach in professional practices. At the same time the extraction of tabular data and the production of the model according to IFC standards guarantee the production of open access data, supporting interoperability.

The methodology, schematically shown in Figure 1, features three main phases corresponding to the three roles that the model assumes- knowledge, systematization, and representation too along site the historical-technical analysis. In detail:

1. During the documentary collection, HBIM functions to classify and system-atize documentary sources.
2. During the documentation analysis phase, HBIM supports the cross-reference and verify data contained in different documental sources.
3. During the restitution phase of the history, technical and constructive solutions of the infrastructure, HBIM provided structured 3D-informative representation
4. During the extraction data phase, the HBIM produces interoperable tabular and IFC format data framework, embedding structured historical and technical data.

28 UNI 11337:2017, Parte 4: *Gestione digitale dei processi informativi delle costruzioni: requisiti di conoscenza, abilità e competenza delle figure coinvolte nella gestione e modellazione informativa* (2017).

29 Autodesk Revit (2024): https://help.autodesk.com/view/RVT/2023/ITA/?guid=RevitRelease_Notes_2023release_html [Accessed on: 30/05/2025].

30 Buildingsmart (2024): https://standards.buildingsmart.org/IFC/DEV/IFC4_2/FINAL/HTML/, [Accessed on: 30/05/2025].

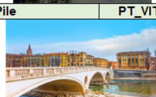
In the first stage, constructing a customized Common Data Environment (CDE)-or Data Sharing Environment (AcDAT)-enables the classification of documents by type and the selection of key documents that constitute the input data for modelling. In the second stage, geometric and informative modelling, following the philological method, allows for "verification" of the reliability of the data contained in the documents considering the geometric and technological characters of the works. In the third stage, the model is developed for 3D-informative representation of the geometry associated with the documentary sources. At this stage, the production of the model in IFC format, through the development of specific "Property Sets," allows the selection of the geometric data and information parameters for knowledge and management. In this way, the produced model can thus move from a proprietary system to a web accessible system without the need for dedicated software or special digital skills, offering, on the one hand, the possibility of potentially showing different configuration scenarios and integrating information from external databases.

4. The HBIM Model for *Ponte della Vittoria*

The I_BRIDGE project focused on the implementation of simplified HBIM model of the *Ponte della Vittoria*[31]. This is developed by the proposed methodology within the scope of this study, adapting its roles – knowledge, systematization, and representation of the data for the infrastructure management – in the elaboration of a model that represent the 1953 bridge, even if it collects the data also the previous one dated 1931. The workflow develops in three phases (figure 12), which, previously described, characterize the proposed methodology:

I. construction of the customized CDE, or AcDAT, cataloguing of historical documentation, preparation of input data for modelling;
II. three-dimensional philological modelling, verification of input data, informational enhancement of the model;
III. filtering of parameters, interactive visualization of the three-dimensional and informational model, with complete links to the documentary database on open access platform.

31 The research task concerning Ponte della Wittoria within I_BRIDGE project was held in 2025 by prof. Angelo Bertolazzi (P.I.), arch. Michele De Mori, eng. Francesco Sartore and arch. Francesco Albarelli, il collaboration with prof. Ilaria Giannetti and eng. Kilian Bruckner from University of Rome "Tor Vergata".

Struttura	ID Progetto	Documenti		
Ponte della Vittoria	PT_VITTORIA_VR	Tipologia di documento	Nome documento	
		Libro	/	/
		Relazione tecnica	PT_VITTORIA_VR-VV-A-1926-CONTRATTO_APPALTO	contratto d'appalto
			PT_VITTORIA_VR-VV-A-1926-CAPITOLATO_SPECIALE_DAPPALTO	capitolato speciale
			PT_VITTORIA_VR-VV-A-1926-PROCESSO_VERBALE	processo verbale
			PT_VITTORIA_VR-VV-A-1950-PROGETTO_DI_RICOSTRUZIONE	progetto di ricostru
			PT_VITTORIA_VR-VV-R-1950-RELAZIONE_ACCOMPAGNANTE_IL_PROGETTO	relazione accompa
			PT_VITTORIA_VR-VV-RT-1950-ANALISI_DEI_PREZZI	analisi prezzi
			PT_VITTORIA_VR-VV-RT-1950-CAPITOLATO_SPECIALE_APPALTO	capitolato speciale
			PT_VITTORIA_VR-VV-RT-1950-COMPUTO_METRICO	computo metrico
			PT_VITTORIA_VR-VV-RT-1950-STIMA_DEI_LAVORI	stima dei lavori
			PT_VITTORIA_VR-VV-R-1947-PROGETTO_RICOSTRUZIONE	proposta pogetto d
			PT_VITTORIA_VR-VV-A-1949_55-CORRISPONDENZA	corrispondenza
			PT_VITTORIA_VR-VV-A-1956_58-RISERVE	riserve
			PT_VITTORIA_VR-VV-RT-1947-49_PROGETTO_RICOSTRUZIONE	progetto per la rico
		Fotografie di cantiere		
		Fotografie stato di fatto	PT_VITTORIA_VR-VV-F-192X-FOTO_DEPOCA-01	foto stato di fatto
			PT_VITTORIA_VR-VV-F-192X-FOTO_DEPOCA-02	foto stato di fatto
			PT_VITTORIA_VR-VV-F-192X-FOTO_DEPOCA-03	foto stato di fatto
			PT_VITTORIA_VR-VV-F-195X-FOTO_DEPOCA	foto stato di fatto
		Disegno tecnico	PT_VITTORIA_VR-VV-D-1947-SEZIONE_LONGITUDINALE	sezione longitudina
			PT_VITTORIA_VR-VV-D-1947-SEZIONE_TRASVERSALE	sezione trasversal
			PT_VITTORIA_VR-VV-D-1947-PROSPETTO	prospetto generale
			PT_VITTORIA_VR-VV-D-1947-PLANIMETRIA_E_PROIEZIONE_ORIZZONTALE_	planimetria e proie
			PT_VITTORIA_VR-VV-D-1926-PROSPETTO_GENERALE	prospetto generale
			PT_VITTORIA_VR-VV-D-1926-SEZIONE_LONGITUDINALE_E_DETTAGLI	sezione longitudina
			PT_VITTORIA_VR-VV-D-1947-DISTRIBUZIONE_FERRI	distribuzione ferri
			PT_VITTORIA_VR-VV-D-1952-VERIFICA_DELLE_SEZIONI	verifica delle sezio
			PT_VITTORIA_VR-VV-D-1952-VERIFICHE_SEZIONI_ALVEO	lavori di urgenza p
			PT_VITTORIA_VR-VV-D-1926-PIANTE_LINEA_IMPSOSTA_E_PARAPETTO	pianta sulla linea d
				WIP
Elemento costruttivo	**ID Elemento**	**Documenti**		
Spalle	PT_VITTORIA_VR-S	Tipologia di documento	Nome documento	
		Relazione tecnica	PT_VITTORIA_VR-S-R-1954-OPERE_RIPRISTINO	computo metrico
			PT_VITTORIA_VR-S-R-1955-BLOCCHI_LISTA_MENSILE_OPERAI_E_MATERIA	dati statistici mens
			PT_VITTORIA_VR-S-R-1954-RIPARAZIONE_E_RICOSTRUZIONE_ BLOCCHI_A	perizia demolizione
			PT_VITTORIA_VR-S-A-1955-BLOCCHI_CONCESSIONE DI PROROGA	concessione di pro
			PT_VITTORIA_VR-S-A-1954-BLOCCHI_PROCESSO_VERBALE	processo verbale
			PT_VITTORIA_VR-S-A-1954-BLOCCHI_ELENCO_DEGLI_ATTI	elenco degli atti
			PT_VITTORIA_VR-S-A-1954-BLOCCHI_CAPITOLATO_SPECIALE_DI_APPALTO	capitolato speciale
			PT_VITTORIA_VR-S-A-1954-BLOCCHI_ATTO_DI_COTTIMO	atti di cottimo
			PT_VITTORIA_VR-S-A-1954_55-BLOCCHI_ATTI_FINE_LAVORI	atti di fine lavori
			PT_VITTORIA_VR-S-A-195X-RICOSTRUZIONE_ BLOCCHI_DI_SOSTEGNO_E_	ricostruzione blocc
			PT_VITTORIA_VR-S-A-195X-BLOCCHI_ORDINE_DI_SERVIZIO_N.1	ordine di servizio n
		Fotografie di cantiere		
		Fotografie stato di fatto	PT_VITTORIA_VR-S-F-192X-BLOCCHI	foto bocchi alle tes
			PT_VITTORIA_VR-S-F-192X-DECORAZIONI_BLOCCHI-01	foto bocchi alle tes
			PT_VITTORIA_VR-S-F-192X-DECORAZIONI_BLOCCHI-02	foto bocchi alle tes
			PT_VITTORIA_VR-S-F-192X-DECORAZIONI_BLOCCHI-03	foto bocchi alle tes
			PT_VITTORIA_VR-S-F-192X-DECORAZIONI_BLOCCHI-04	foto bocchi alle tes
			PT_VITTORIA_VR-S-F-192X-DECORAZIONI_BLOCCHI-05	foto bocchi alle tes
			PT_VITTORIA_VR-S-F-192X-DECORAZIONI_BLOCCHI-06	foto bocchi alle tes
			PT_VITTORIA_VR-S-F-192X-GESSO_DECORAZIONI_BLOCCHI-01	gessi delle statue
			PT_VITTORIA_VR-S-F-192X-GESSO_DECORAZIONI_BLOCCHI-02	gessi delle statue
		Disegno tecnico	PT_VITTORIA_VR-S-D-1954-BLOCCHI_OPERE_RIPRISTINO	prospetti
			PT_VITTORIA_VR-S-D-1952-NUOVI_BLOCCHI_DETTAGLI_ORNAMENTALI_PR	dettagli ornamento
			PT_VITTORIA_VR-S-D-195X-BLOCCHI_DISEGNI_TECNICI	prospetti e sezioni
		Prove in situ	WIP	
			/	/
Collegamento (appoggio)	PT_VITTORIA_VR_C	Tipologia di documento	Nome documento	
		Relazione tecnica		
		Fotografie di cantiere		/
		Fotografie stato di fatto		
		Disegno tecnico		
		Prove in situ	WIP	
			/	/
Pile	PT_VITTORIA_VR_P	Tipologia di documento	Nome documento	
		Relazione tecnica		
		Fotografie di cantiere		
		Fotografie stato di fatto		
		Disegno tecnico	PT_VITTORIA_VR-VV-D-1926-DETTAGLI_PILE	dettagli parapetti e
		Prove in situ	WIP	
			/	/
Arco	PT_VITTORIA_VR_A	Tipologia di documento	Nome documento	
		Relazione tecnica		
		Fotografie di cantiere		
		Fotografie stato di fatto		
		Disegno tecnico	PT_VITTORIA_VR-A-D-1947-CENTINA_PER_ARCO	centine per arco
			PT_VITTORIA_VR-A-D-1947-VERIFICHE_STRUTTURALI	verifica delle sezio
			PT_VITTORIA_VR-A-D-1947-VERIFICA_SEZIONI	verifiche strutturali
		Prove in situ	WIP	
			/	/

				Link ACDat	Categoria di informazioni
Descrizione documento	Datazione	rma e timbr	Contributo		
	/			/	
	1926	Sì	Valorizzazione culturale	02 04 00 01 01 01-RELAZIONI	Datazione (data progetto/costruzione)
e d'appalto	1926	Sì	Valorizzazione culturale	02 04 00 01 01 01-RELAZIONI PT V	Datazione (data progetto/costruzione)
	1926	Sì	Valorizzazione culturale	02 04 00 01 01 01-RELAZIONI PT V	Dati sui materiali
uzione	1950	Sì	Manutenzione	02 04 00 01 01 01-RELAZIONI	Interventi di ripristino
agnante il progetto	1950	Sì	Manutenzione	02 04 00 01 01 01-RELAZIONI PT V	Dati sul sistema costruttivo
	1950	Sì	Valorizzazione culturale	02 04 00 01 01 01-RELAZIONI PT V	Importo
e appalto	1950	Sì	Valorizzazione culturale	02 04 00 01 01 01-RELAZIONI PT V	Datazione (data progetto/costruzione)
	1950	Sì	Manutenzione	02 04 00 01 01 01-RELAZIONI PT V	Importo
	1950	Sì	Valorizzazione culturale	02 04 00 01 01 01-RELAZIONI PT V	Importo
i ricostruzione, analisi struttura, materiali e sti	1949	Sì	Valorizzazione culturale	02 04 00 01 01 01-RELAZIONI	Dati sul sistema costruttivo
	1949-54		Manutenzione	02 04 00 01 01 01-RELAZIONI	\
	1956-58			02 04 00 01 01 01-RELAZIONI	\
ostruzione	1947-49			02 04 00 01 01 01-RELAZIONI	Dati sul sistema costruttivo
	192X	No	Manutenzione	02 04 00 01 02 02-GENERALI	Datazione (data progetto/costruzione)
	192X	No	Manutenzione	02 04 00 01 02 02-GENERALI	Datazione (data progetto/costruzione)
	192X	No	Manutenzione	02 04 00 01 02 02-GENERALI	Datazione (data progetto/costruzione)
	195X	No	Manutenzione	02 04 00 01 02 02-GENERALI	Datazione (data progetto/costruzione)
ale	1947	Sì	Manutenzione	02 04 00 01 01 04-SEZIONI	Dati geometrici di progetto
e	1947	Sì	Manutenzione	02 04 00 01 01 04-SEZIONI	Dati geometrici di progetto
e	1947	Sì	Manutenzione	02 04 00 01 01 03-PROSPETTI	Dati geometrici di progetto
zione orizzontale dell'impalcato	1947	Sì	Manutenzione	02 04 00 01 01 02-PIANTE	Dati geometrici di progetto
e	1926	Sì	Manutenzione	02 04 00 01 01 03-PROSPETTI	Dati geometrici di progetto
ale e dettagli	1926	Sì	Manutenzione	02 04 00 01 01 04-SEZIONI	Dati geometrici di progetto
	1947	Sì	Manutenzione	02 04 00 01 01 04-SEZIONI	Dati geometrici di progetto
ni e altro	1952	Sì	Manutenzione	02 04 00 01 01 04-SEZIONI	Dati geometrici di progetto
er il ripristino di difese spondali ed espurgo alv	1952	Sì	Manutenzione	02 04 00 01 01 04-SEZIONI	Dati geometrici di progetto
'impota e all'altezza del parapetto	1926	Sì	Manutenzione	02 04 00 01 01 02-PIANTE	Dati geometrici di progetto
					/
				Link ACDat	Categoria di informazioni
Descrizione documento					
	1954	No	Manutenzione	02 04 00 01 01 06 03-SPALLE	Dati sul sistema costruttivo
sili sull'andamento delle opere desunti dal giorr	1955	Sì	Manutenzione	02 04 00 01 01 06 03-SPALLE	Importo
e e ricostruzione blohci alle testate	1954	Sì	Manutenzione	02 04 00 01 01 06 03-SPALLE	Importo perizie suppletive
oroga	1955	Sì	Valorizzazione culturale	02 04 00 01 01 06 03-SPALLE	Atti amministrativi
	1954	Sì	Valorizzazione culturale	02 04 00 01 01 06 03-SPALLE	Atti amministrativi
	1954	Sì	Valorizzazione culturale	02 04 00 01 01 06 03-SPALLE	Atti amministrativi
e d'appalto	1954	Sì	Manutenzione	02 04 00 01 01 06 03-SPALLE	Datazione (data progetto/costruzione)
	1954	No	Valorizzazione culturale	02 04 00 01 01 06 03-SPALLE	Atti amministrativi
	1954-55	Sì	Manutenzione	02 04 00 01 01 06 03-SPALLE	Atti amministrativi
chi di sostegno e ornamenti	195X	No	Manutenzione	02 04 00 01 01 06 03-SPALLE	Interventi di ripristino
.1	195X	Sì	Manutenzione	02 04 00 01 01 06 03-SPALLE	Atti amministrativi
state	192X	No	Manutenzione	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
state con statue	192X	No	Valorizzazione culturale	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
state con statue	192X	No	Valorizzazione culturale	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
state con statue	192X	No	Valorizzazione culturale	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
state con statue	192X	No	Valorizzazione culturale	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
state con statue	192X	No	Valorizzazione culturale	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
state con statue	192X	No	Valorizzazione culturale	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
decorative dei blocchi alle testate	192X	No	Valorizzazione culturale	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
decorative dei blocchi alle testate	192X	No	Valorizzazione culturale	02 04 00 01 02 03 03-SPALLE	Datazione (data progetto/costruzione)
	1954	No	Manutenzione	02 04 00 01 01 06 03-SPALLE	Datazione (data progetto/costruzione)
	1952	No	Manutenzione	02 04 00 01 01 06 03-SPALLE	Datazione (data progetto/costruzione)
dei blocchi alle testate	195X	No	Manutenzione	02 04 00 01 01 06 03-SPALLE	Datazione (data progetto/costruzione)
				/	
Descrizione documento					
				/	
				/	
Descrizione documento					
pile	1926	Sì	Manutenzione	02 04 00 01 01 06 02-PILE	Dati geometrici di progetto
				/	
Descrizione documento					
	1947	Sì	Manutenzione	02 04 00 01 04-SEZIONI	Dati sul sistema costruttivo
ni	1947	Sì	Manutenzione	02 04 00 01 01 04-ARCO	Dati sul sistema costruttivo
	1947	Sì	Manutenzione	02 04 00 01 01 06-ARCO	Dati sul sistema costruttivo
				/	

Fig. 14 – Ponte della Vittoria *HBIM: the Excel database collects all informations and data, to manage and to valorize the bridge [© 2025, Sartore, Albarelli].*

The CDE, built in the first phase of work, is divided into four areas: "Input Data," "Work in Process", "Standards," and "Shared". The first area contains the documentary sources properly catalogued, according to the date and type of documents (reports, drawings, photographs), and systematized, following an associative criterion between the data contained in the documents and the individual constituent elements of the bridge. The catalogued documents in the input area are subsequently linked to the final model present in the "Shared" area. The "Work in Process" area contains the model input data and intermediate modelling steps related to the various verification assumptions of the data contained in the documents. The "Standards" area contains "verified" input data and the model related to individual building elements (user families) of the bridge. Finally, the "Shared" area contains the final model and interoperable database in IFC and text format; model contained in the "Shared" area is simultaneously shared on the APS viewer.

After an indepth analysis of the archival documents and understanding how to organize them, one of the first steps was dividing the material between the main components of the bridge. Once divided for topic, documents were named by following the guidelines for digital model's management. Such methodology by defining the documents' name aims to easily organize and classified them: starting with the name of the project, it is composed by adding the component of the bridge that the document referred to, the typology of the document (i.e. technical drawing, or a technical report, etc.), the year, a short description of the content of the document and the number of its variant, if there are (figure 13).

To organize the documents in components, we referred to the nomenclature of the Verona municipality, so all the documents were included in "shoulder" (S), "connection" (C), Cpier" (P) and "arch" (A). Since there is not yet how to define the general documents, that doesn't fit in the previous categories, it was decided to create another one, called "VV" (which stands for "various") through which the documents that comprehends many types of information can be classified. For some documents arose the problem of not having a defined date, but for many of them it was possible to identify the possible timeline; so, the solution to classify them was to use the letter "X" in the date, to approximate the decade (for example: 195X) [32].

32 The huge amount archive data of this case study are very interesting by a methodological point of view. Compared to others bridges *Ponte della Vittoria* present many copies of the same technical drawings and documents, moreover the 1920s and 1930s drawings were used for the reconstruction of the bridge, many of them without signature and/or date. This led to a great confusion to understand the design process and the construction steps; the Excel database allowed to manage the data by checking and validating the documents and drawings according the relevance for the maintenance or cultural valorization purposes.

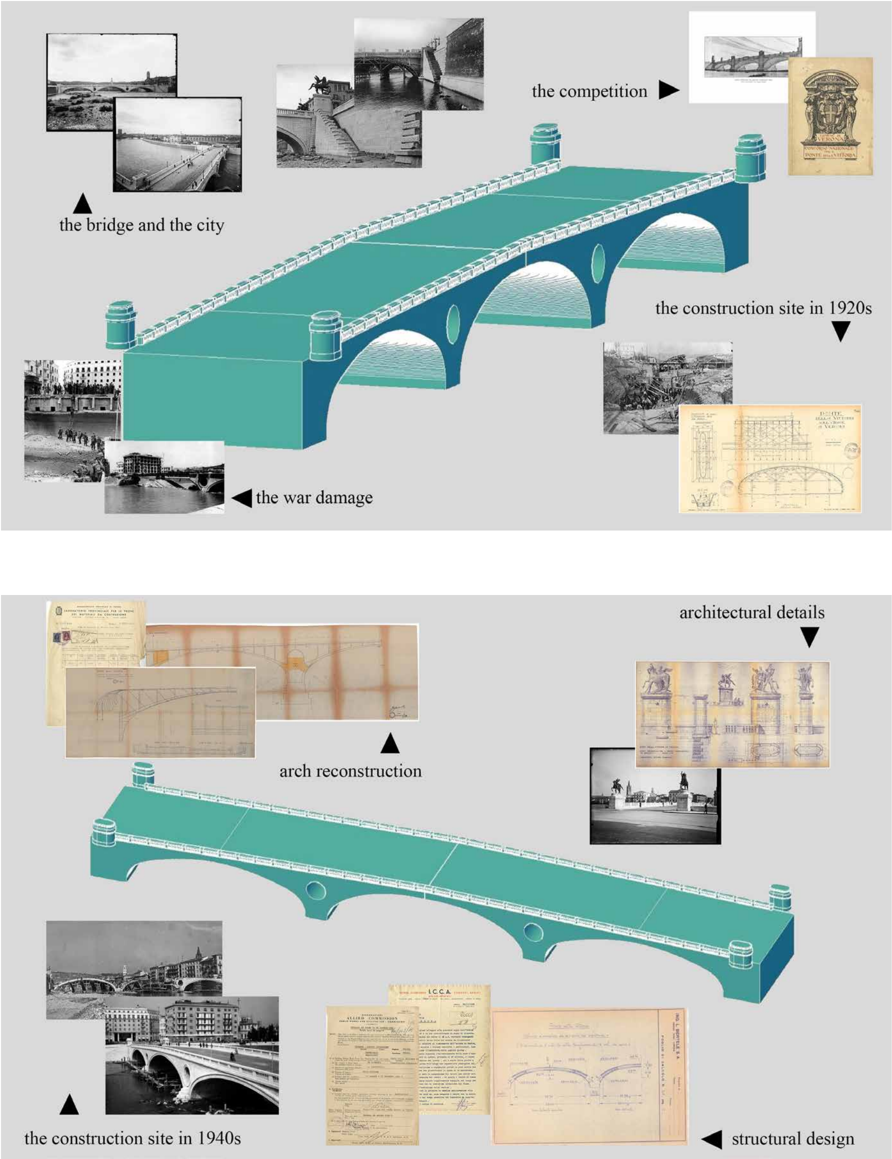


Fig. 15 – *The HBIM model as data collector: since the 3D model is a simplified tool to collect, organize, classify, and access the data it can be used to valorize and enhance (top) the history of the bridge (i.e the competion in the 1920s, the building site ant the link between the bridge and the surrounding environment or its destruction during the war). At the same time it can be used today to manage (bottom) the bridge and collecting the "operative" data (i.e. structural design and calculation, reconstruction drawings and material test). [© 2025, Bertolazzi, Sartore].*

The organization of the vast amount of information started with the division in the Drive folders, as pointed before. This part of the work was defined in two main steps: first the documentation was grouped into general folders, to organize the more precisely by component, in subfolders, in a second moment. It was essential during this process to be able to see the preview of the .pdf documents through the Drive visualization, to have a smooth workflow. Some technical drawings were too heavy to be seen through the Drive visualization, so they were compressed until they were able to be visualized. During this part of the process there was also a question arose as to whether to merge into a single document the different scans that composed a document or keeping them separated. It was de-cided that to keep them separated, organizing them in subfolders when needed, to be more versatile in the use of them and to avoid the creation of files too big[33].

To organize and simplify the filing process, an Excel file was created to gather all the information (figure 14). The aim of this file is to create an operative digital archive that is the link to the archive documents to the HBIM. Both the Drive and the Excel file are planned to be open and upgradable by the municipality so that every new information (such as structural tests or restoration interventions) can be imported, ensuring that it remains up to date.

The file is organized starting with first part concerning the bridge in general, that is followed by the documents subdivided into the structural components named previously. The Excel file provides all the most important information for each document, such as, the name of it, the typology, the year and a description of the content. It is also indicated if the documents give information input or geometric input, use-ful for the creation of the model. There is also a space to indicate the IFC entity that will link the document's information to the BIM model (figures 15-16). Through the link CDE and the file path in the Excel it will be possible to go back to the official document in the Drive, to easily verify any critical issue[34].

33 As explained before, the bridge was blasted during the Second World War, and in the documents, there were some concerning the debris removal or the temporary walkway built while the bridge was under construction. These documents were considered not directly relevant for the purpose of the building management, but for the aim of creating a complete digital archive they couldn't be deleted; so, a folder was created to group all these types of information and store them.

34 As pointed before, many documents were devoid of not only of the year, but also of signature and stamp; to easily understand if they were provided with them or not it was put a specific tag in the Excel to highlight the feature. The indication is to use first the documents with the signature and, only if there is a lack of information, to use the ones that are not provided with it. It was also added to the Excel sheet a tag about the contribution that the documents provide, to understand if it is useful for maintenance or for cultural valorisation.

5. Conclusions

This work presented a methodology for the use of HBIM processes for the purposes of knowledge, management and valorisation of the bridges, and the infrastructures as whole, exploiting the archival documents and the historical survey-derived data, the today monitoring of the structural behaviour.

The procedure supported the technical knowledge and the management of the existing building stock, focusing on the novel use of the HBIM as a tool to collect, organize, classify, and access the archival documents data. Exploiting a traditional philologic approach, the model itself is used as both investigation and representation tool, allowing the final display of the documents-derived data, supported by the visual correlation with the 3D reconstruction of the buildings.

The methodology concerns three phases, following the different HBIM roles as a knowledge, systematization, and representation tool, within the historical-technical analyses, and it is demonstrated through the case study of *Ponte della Vittoria* in Verona. The case study is considered paradigmatic and demonstrated the capability of the proposed methodology, with specific reference to the sector of the existing bridge, even if they present a high complexity (in this case the cell-type structure together the stone massive cladding and the decoration). Regarding the application of the proposed methodology to the broad heritage of the existing buildings, the study remarked the efficiency of the proposed HBIM approach. In particular, the philological approach proves to be particularly efficient for the construction "documental twins", features by a structured data organization frame, supporting management and maintenance interventions. On the operational level of the modelling processes, the application of the customized strategies, developed for the case study, demonstrates the possibility of applying the original documents from the archives, fully exploiting the native functions of commercial BIM Authoring platform, with comparable results in terms of model-ling time-consuming to the established "SCAN to BIM" workflow. Furthermore, the combined use of BIM Authoring platform and the IFC open standard supported the effective production of open access data and simplified online viewer. Another step will be the implementation of specific database parts to allow the data customization from on site monitoring; this will make the simplified model a tool for an effective bridge management from archival to contemporary data.

Automation in 3DGIS Models for Satellite Data-based Structural Monitoring: the Building Block in Testaccio*, Rome*

Kilian Bruckner[1], *Fabio Di Carlo*[1]*, Ilaria Giannetti*[1]

3DGIS platforms and semantic 3D city models are increasingly required to support tasks that go beyond visualization: asset inventories, maintenance planning, diagnostics, simulation and multi-source integration[2]. Image-based 3D reconstruction is attractive in this context because it can be deployed quickly, with limited field instrumentation, and it yields geometry that is directly tied to the visual appearance of the built environment. However, photogrammetric outputs are usually delivered as dense point clouds or textured meshes[3]. These representations are well suited for inspection and measurement, but they remain difficult to use for object-level analyses because they lack explicit elements (e.g., windows, doors, balconies) and their associated attributes, as required by semantic city-model representations (e.g., CityGML)[4]. They are, in other words, geometrically rich but lacking semantic enrichment.

Conversely, computer vision can extract semantic information from images, including architectural elements on façades[5]. Yet 2D inference results remain tied to the viewpoint and to the pixel grid. Without a robust spatial anchoring to 3D geometry via camera poses and reconstructed surfaces, they cannot be queried in a GIS, aggregated across façades, or connected to other datasets. The practical challenge is therefore to connect

1 University of Rome Tor Vergata, Department of Civil Engineering and Computer Science Engineering.

2 Biljecki F., Stoter J., Ledoux H., Zlatanova S. and Çöltekin A., "Applications of 3D City Models: State of the Art Review". ISPRS I*nternational Journal of Geo-Information* 4/4 (2015): 2842-2889. https://doi.org/10.3390/ijgi4042842.

3 Remondino F. and El-Hakim S., "Image-based 3D Modelling: A Review". *The Photogrammetric Record* 21/115 (2006): 269-291. https://doi.org/10.1111/j.1477-9730.2006.00383.x.

4 Open Geospatial Consortium (OGC). "CityGML Standard": https://www.ogc.org/publications/standard/citygml/ [Accessed on 2/01/2026].

5 He K., Gkioxari G., Dollár P. and Girshick R., "Mask R-CNN". In *2017 IEEE International Conference on Computer Vision (ICCV)* (Venice, 22-29 October 2017), 2980-2988. https://doi.org/10.1109/ICCV.2017.322.

2D semantic inference with 3D geometry in a way that is robust, reproducible and scalable.

1. Methodology and Case Study

This chapter presents the methodological backbone to bridge image-based inference and 3D geometry in support of an automated workflow for producing 3D semantic city models compliant with the CityGML standard. We propose a pipeline to build a semantically enriched 3D representation of an urban building block using two input sources: a fast close-range image survey for façade reconstruction and element extraction, and satellite imagery for roof delineation. The close-range branch combines photogrammetric reconstruction with instance segmentation of visible façade building elements (e.g., windows, doors, architectural details) and 2D↔3D semantic transfer to generate GIS-ready features. In parallel, roof surfaces are extracted from satellite images and integrated as a complementary semantic layer at block scale.

The pipeline is divided into the following steps: (i) reconstructs calibrated cameras and dense geometry from a close-range fast image survey[6]; (ii) performs YOLOv8-Seg instance segmentation of façade building elements on the close-range survey images and roof-surface patches on satellite imagery[7]; (iii) transfers building façades elements (e.g., windows) instances to 3D via a 2D↔3D mapping strategy based on camera calibration to create a semantic-georeferenced point cloud; (iv) construction of the CityGML representations of the previously obtained semantic-point cloud[8].

Figure 1 provides an overview of the pipeline and its main data products. The pipeline is applied to a building block in *Testaccio* district in Rome. The area is representative of compact European urban fabrics where streets restrict viewpoints and produce limited parallax between viewpoints, façade elements repeat across floors, lighting varies along short paths, and occlusions from trees and street furniture are common. These conditions affect both photogrammetric alignment and instance segmentation accuracy, making the case study a realistic benchmark for an automation-oriented workflow.

6 Schönberger J. L. and Frahm J.-M., "Structure-from-Motion Revisited". In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (CVPR) (2016): 4104-4113. DOI:. https://doi.org/10.1109/CVPR.2016.445.

7 Ultralytics. "YOLOv8": https://docs.ultralytics.com/models/yolov8/ [Accessed on 02/01/2026].

8 Open Geospatial Consortium (OGC). "CityGML Standard": https://www.ogc.org/publications/standard/citygml/ [Accessed on 2/01/2026].

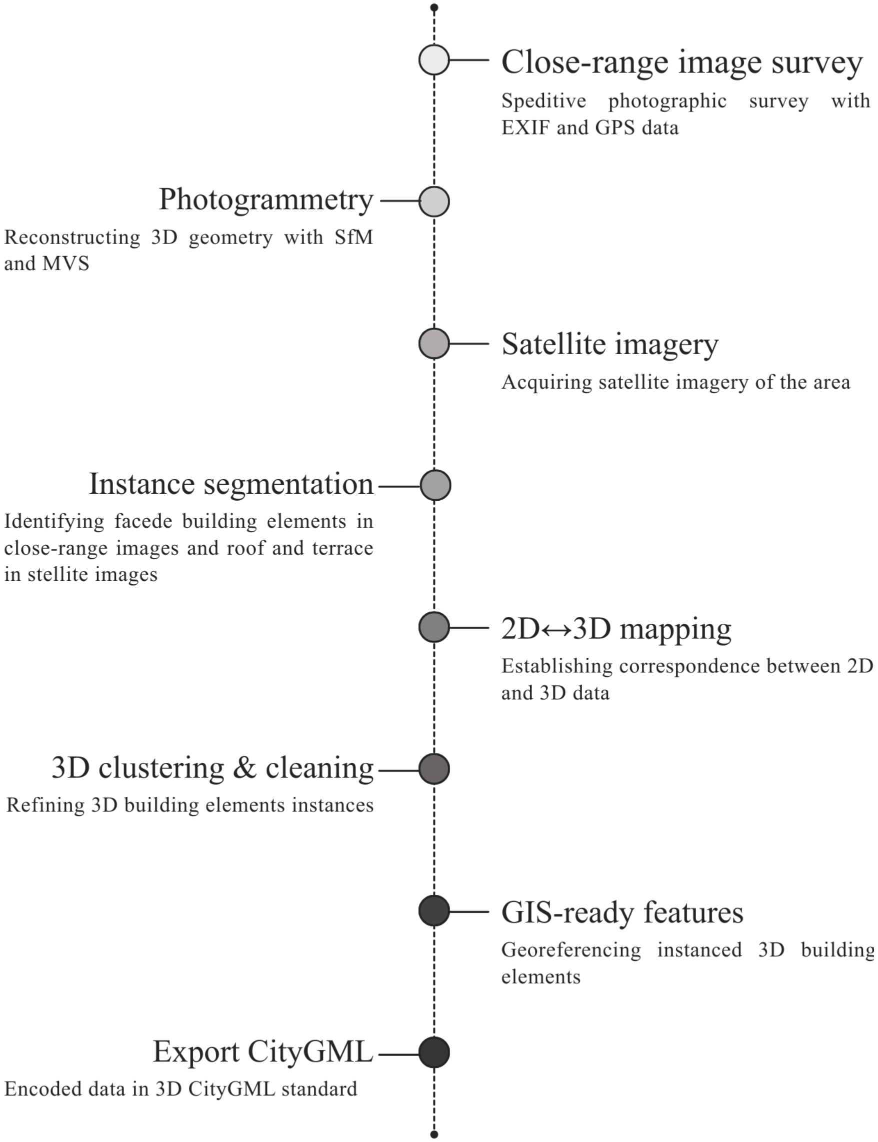


Fig. 1 – *An overview of the workflow and its main data products.*

Fig. 2 – *Study area in the* Testaccio *district (Rome): urban block extent and surrounding street network used for the close-range image survey [basemap: Google Earth, accessed January 2, 2026].*

Fig. 3 – *Dense façade point cloud reconstructed with OpenDroneMap (ODM): close-range SfM processing produces a high-density 3D point sampling of the visible façade surfaces, capturing the overall volume and the main architectural components (openings, cornices, and façade texture) as a metric geometric representation.*

The study area consists of an urban block within the *Testaccio* district in Rome (figure 2); buildings are characterized by mid-rise volumes and articulated façades featuring regular window rhythms, balconies and shading elements. For image-based reconstruction, the scenario provides abundant texture on plaster, masonry and window frames, but it also introduces geometric challenges: long planar façades can be reconstructed accurately in isolation, yet they can be weakly constrained with respect to each other if corners are not sufficiently observed. Moreover, repeated façade patterns can lead to ambiguous matches, and street canyons reduce the range of camera baselines that can be achieved without crossing the road or changing elevation.

2. 3D-Semantic Building Model

Regarding the first block of the pipeline, the primary dataset is a set of close-range photographs acquired, with a smartphone camera, by walking around the block and capturing all four façades.

The acquisition strategy follows three principles that directly support the downstream pipeline. First, intra-façade overlap: consecutive images along each façade are acquired with high overlap to stabilize feature matching and bundle adjustment. Second, cross-façade connectivity: corner images and oblique views are deliberately included so that tie points link adjacent façades and avoid disconnected components. Third, parallax diversity: the survey introduces moderate variations in height and viewing direction rather than strictly frontal shots at constant height. These variations improve depth estimation and reduce the risk of planar degeneracies[9].

Where present, EXIF metadata (time, focal length and GNSS tags) are used as a soft prior for organizing the dataset and for checking gross inconsistencies. Embedded GNSS is not assumed to be accurate enough for metric georeferencing on its own, but it can help in two practical ways: it can provide an approximate scale and orientation for the initial reconstruction, and it can support later alignment checks when the model is brought into a GIS coordinate reference system (CRS)[10].

Before starting the pipeline, the acquired dataset is inspected and cleaned manually. Blurred images and severely over/underexposed frames are removed because they can introduce unstable matches and increase reprojection residuals during bundle adjustment. When wide-angle lenses are used, radial

9 Szeliski R., *Computer Vision: Algorithms and Applications*. New York: Springer, 2010.
10 Remondino F. and El-Hakim S.,"Image-based 3D Modelling: A Review", op. cit.

distortion can create systematic geometric bias across the image frame. In those cases, an undistortion step is applied to generate an "undistorted" image set exploiting the native function of OpenDroneMap[11]. This improves the geometric consistency of key points, especially near image borders, and it simplifies later reprojection because the intrinsics used by the SfM solution become closer to a pinhole model[12].

The pre-processing stage also enforces a stable naming convention and maintains a consistent mapping between original images and undistorted derivatives. This is essential for automation: inference outputs, camera poses and reprojection results must remain traceable to the source image ID across processing steps, and any transformation applied to geometry must be propagated consistently to the corresponding camera parameters[13].

In our workflow, Structure-from-Motion alignment is performed using OpenDroneMap (ODM)[14] and its underlying OpenSfM reconstruction engine. Reconstruction starts by extracting key points and descriptors for each image and matching them across image pairs. Robust geometric filtering based on epipolar constraints reduces mismatches before camera poses are estimated. A global bundle adjustment then refines camera intrinsics and extrinsic, as well as sparse 3D points, by minimizing reprojection error across all observations. The bundle adjustment stage is crucial because it produces calibrated cameras that are later reused for 2D-3D reprojection; in the proposed workflow, camera calibration is not a by-product but a prerequisite for semantic transfer. Figure 3 illustrates cloud point export.

In close-range urban façade surveys, two aspects are especially relevant. The first is repetitiveness: window grids and similar architectural details can generate similar local features across different floors, increasing the likelihood of incorrect matches. The second is planarity: when the acquisition is strongly frontal and baselines are small, large portions of the scene approximate a dominant plane, weakening depth cues and making it difficult to constrain the relative orientation between different façades[15]. For this reason, the acquisition strategy emphasizes corner imagery and oblique views that create tie points spanning multiple façades.

Given the calibrated cameras from SfM, Multi-View Stereo estimates depth from multiple viewpoints and fuses it into a dense point cloud.

11 "OpenDroneMap": https://www.opendronemap.org/ [Accessed on 2/01/2026].

12 Hartley R. and Zisserman A., *Multiple View Geometry in Computer Vision* (2nd ed.). Cambridge: Cambridge University Press, 2004.

13 Schönberger J. L. and Frahm J.-M., "Structure-from-Motion Revisited", op. cit.

14 "OpenDroneMap": https://www.opendronemap.org/ [Accessed on 2/01/2026].

15 Hartley R. and Zisserman A., *Multiple View Geometry in Computer Vision*, op. cit.

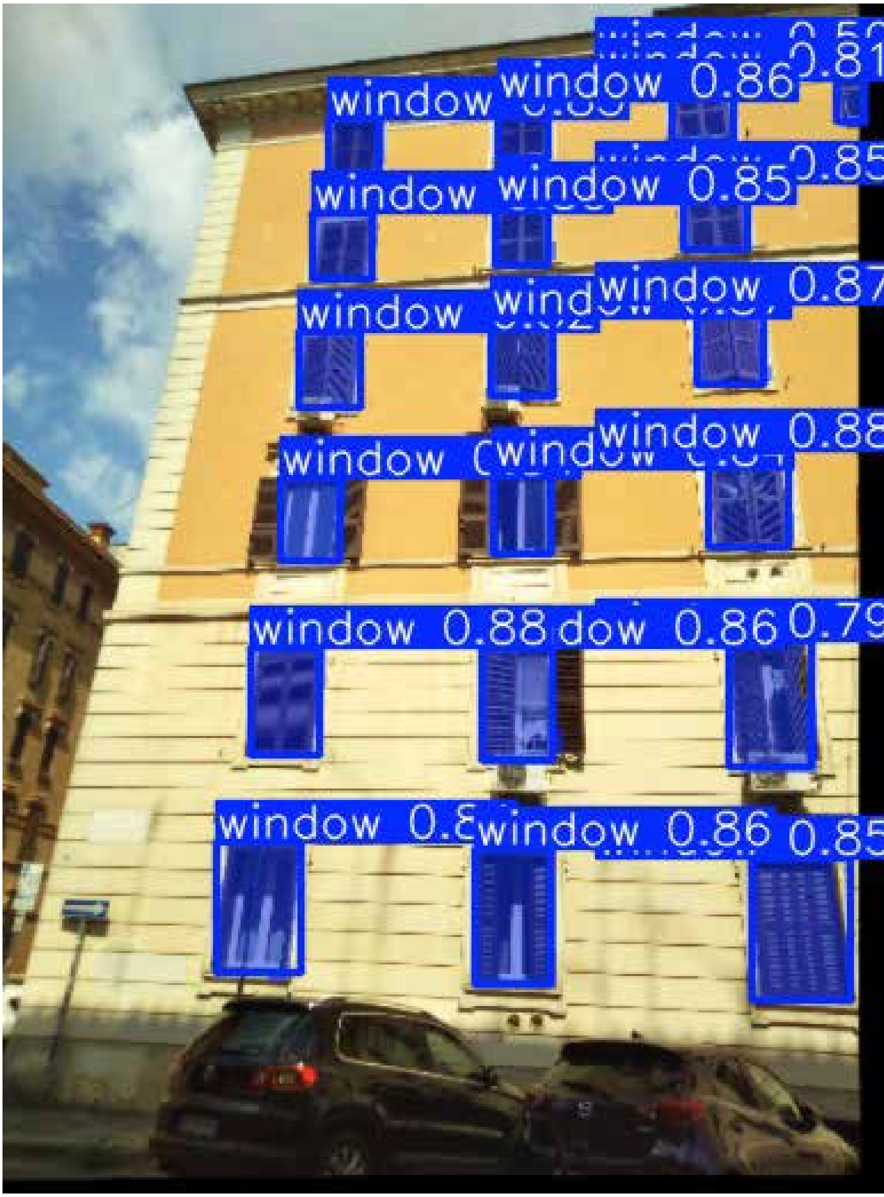


Fig. 4 – *Example of YOLOv8-Seg instance segmentation on a façade image: detected window instances with masks, bounding boxes and confidence scores.*

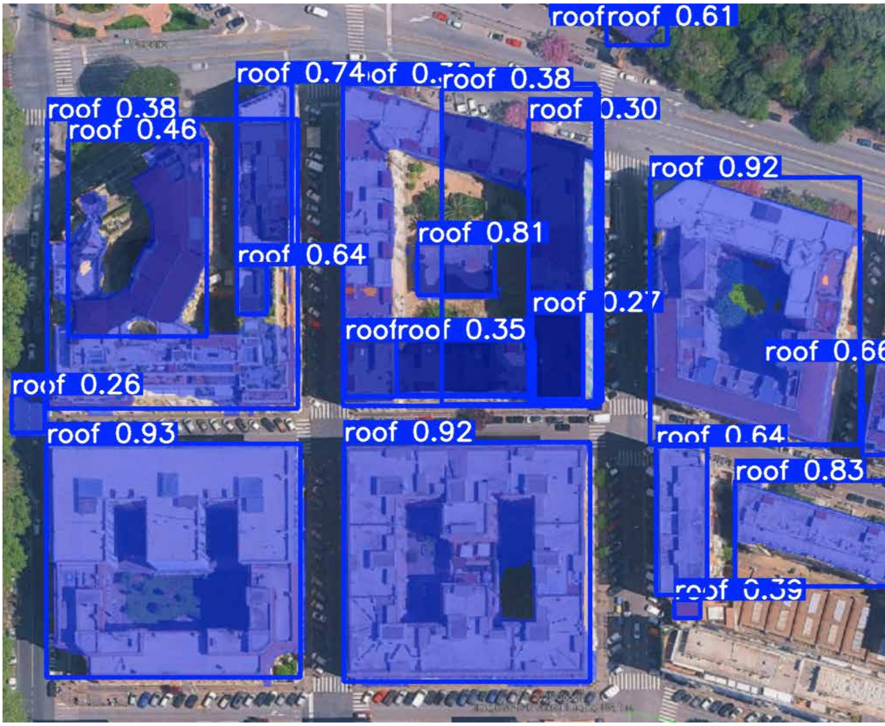


Fig. 5 – *Example of YOLOv8-Seg roof instance detection on satellite imagery: predicted roof-surface are highlighted with instance masks, bounding boxes and each instance is reported with its confidence score.*

Densification is sensitive to texture richness and viewpoint diversity. Repetitive patterns and specular elements can produce noise, while occlusions can create holes or floating artifacts[16]. Because the goal is semantic transfer rather than purely photorealistic visualization, we prioritize reliability over maximum density. Conservative filtering settings reduce the presence of outliers, which improves the stability of later reprojection and clustering steps.

Quality control is performed at both local and global levels. Locally, each façade is inspected for completeness and noise: missing zones indicate insufficient coverage or occlusions, while floating artifacts suggest depth ambiguity. Globally, the reconstruction is inspected for connectivity. A common failure pattern in compact urban blocks is fragmentation: the SfM pipeline yields multiple disconnected components, often corresponding to individual façades. Each component can be internally consistent yet

16 Szeliski I., *Computer Vision: Algorithms and Applications*, op. cit.

arbitrarily rotated and translated with respect to the others. This outcome is problematic for integration because it breaks the assumption of a single coherent reference frame[17].

Fragmentation is diagnosed by analysing connected components in the sparse cloud, inspecting clusters of camera poses, and checking whether corner images successfully register across adjacent façades. In practice, the primary mitigation is to strengthen connectivity through acquisition and image selection (favouring corner and oblique views and removing weak images that introduce ambiguity). When fragmentation persists, the workflow remains usable by focusing downstream 2D↔3D mapping on the target façade/component, while explicit similarity transformations are managed to ensure that geometry and semantic layers remain coherent when exported to a target CRS. Automatic consolidation of disconnected components into a single block-scale model is treated as a future extension of the pipeline.

The 2D↔3D mapping step uses calibrated cameras to relate image-space detections to 3D geometry. Any operation that changes geometry without updating the corresponding camera parameters breaks this relationship. Likewise, if semantic labels are computed in a local frame and later the point cloud is rotated or scaled for GIS integration, labels must be transformed identically. In practice, quick visualization-oriented adjustments often rotate point clouds while leaving camera parameters unchanged; the model may look correct, but subsequent 2D↔3D operations fail. To prevent this, the workflow treats transformations as explicit objects and enforces their consistent propagation to geometry and semantic layers—and to camera parameters when further 2D↔3D operations are required in the transformed frame.

In practice, we apply transformations in a controlled order. First, semantic transfer is computed in the native SfM reconstruction frame, using the calibrated cameras to map between image space and 3D geometry. Second, a similarity transform T is estimated and stored as an explicit artifact whenever alignment to a target CRS is required for export and 3D GIS integration. Third, T is propagated to dense geometry and all semantic layers (façade, labeled points, window features) to ensure spatial consistency in the target CRS[18]; camera parameters are updated only if further 2D↔3D mapping is required after the transformation.

17 Schönberger M. and Frahm S., "Structure-from-Motion Revisited", op. cit.

18 International Organization for Standardization, ISO 19111:2019. Geographic information – Referencing by coordinates, 3rd ed. (Geneva: ISO, 2019), https://www.iso.org/standard/74039.html.

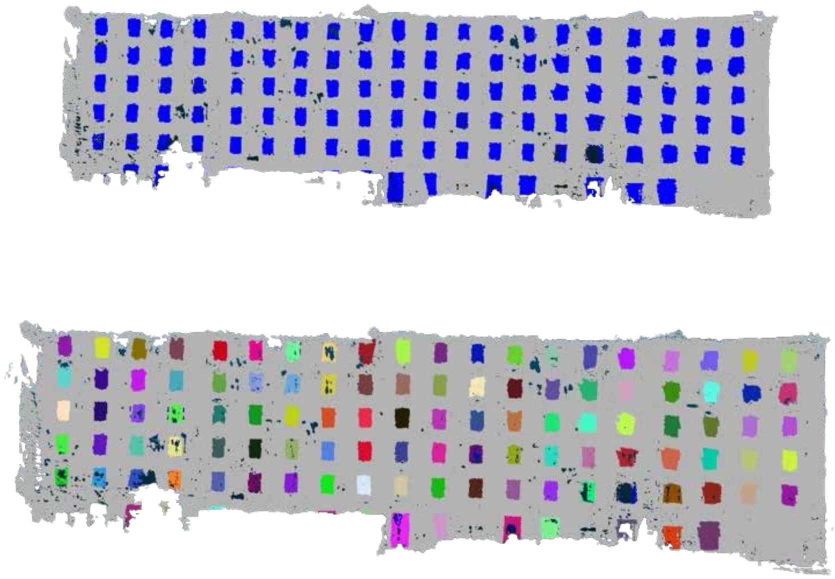
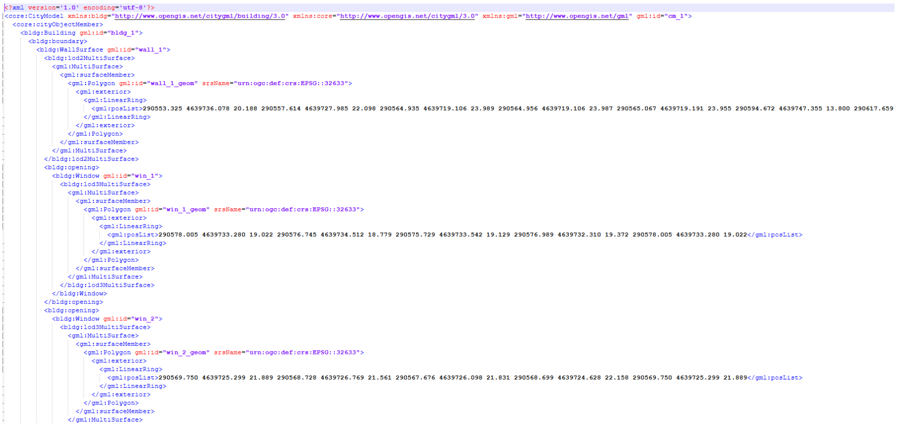


Fig. 6 – *2D↔3D semantic transfer results on the façade point cloud: (a) labeled 3D points projected from the window masks and the derived GIS-ready window features (per-instance centroids and oriented bounding rectangles on the façade plane); (b) clustered window instances after 3D consolidation, showing the cleaned and grouped window points used to derive stable per-instance features.*




```xml
<?xml version='1.0' encoding='utf-8'?>
<core:CityModel xmlns:bldg="http://www.opengis.net/citygml/building/3.0" xmlns:core="http://www.opengis.net/citygml/3.0" xmlns:gml="http://www.opengis.net/gml" gml:id="cm_1">
  <core:cityObjectMember>
    <bldg:Building gml:id="bldg_1">
      <bldg:boundary>
        <bldg:WallSurface gml:id="wall_1">
          <bldg:lod2MultiSurface>
            <gml:MultiSurface>
              <gml:surfaceMember>
                <gml:Polygon gml:id="wall_1_geom" srsName="urn:ogc:def:crs:EPSG::32633">
                  <gml:exterior>
                    <gml:LinearRing>
                      <gml:posList>290553.325 4639736.078 20.188 290557.614 4639727.985 22.098 290564.935 4639719.106 23.989 290564.956 4639719.106 23.987 290565.067 4639719.191 23.955 290594.672 4639747.355 13.800 290617.659
                    </gml:LinearRing>
                  </gml:exterior>
                </gml:Polygon>
              </gml:surfaceMember>
            </gml:MultiSurface>
          </bldg:lod2MultiSurface>
          <bldg:opening>
            <bldg:Window gml:id="win_1">
              <bldg:lod3MultiSurface>
                <gml:MultiSurface>
                  <gml:surfaceMember>
                    <gml:Polygon gml:id="win_1_geom" srsName="urn:ogc:def:crs:EPSG::32633">
                      <gml:exterior>
                        <gml:LinearRing>
                          <gml:posList>290578.005 4639733.280 19.022 290576.745 4639734.512 18.779 290575.729 4639733.542 19.129 290576.989 4639732.310 19.372 290578.005 4639733.280 19.022</gml:posList>
                        </gml:LinearRing>
                      </gml:exterior>
                    </gml:Polygon>
                  </gml:surfaceMember>
                </gml:MultiSurface>
              </bldg:lod3MultiSurface>
            </bldg:Window>
          </bldg:opening>
          <bldg:opening>
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              <bldg:lod3MultiSurface>
                <gml:MultiSurface>
                  <gml:surfaceMember>
                    <gml:Polygon gml:id="win_2_geom" srsName="urn:ogc:def:crs:EPSG::32633">
                      <gml:exterior>
                        <gml:LinearRing>
                          <gml:posList>290569.750 4639725.299 21.889 290568.728 4639726.769 21.561 290567.676 4639726.098 21.831 290568.699 4639724.628 22.158 290569.750 4639725.299 21.889</gml:posList>
                        </gml:LinearRing>
                      </gml:exterior>
                    </gml:Polygon>
                  </gml:surfaceMember>
                </gml:MultiSurface>
```


Fig. 7 – *Example of CityGML 3.0 export: excerpt of the generated XML showing a building element with façade geometry and associated window openings encoded as CityGML features in a georeferenced coordinate reference system.*

We adopt a similarity transformation model consisting of a rotation R, a translation t, and a uniform scale s. In homogeneous coordinates, the transform is represented by a 4×4 matrix T such that $X'=TX$, where X and X' are 3D points in homogeneous form. In our implementation, this model is used to estimate the transformation $T_{obj \rightarrow UTM}$ and to propagate it to façade and window semantic layers before export to the target GIS CRS. Similarity transforms preserve shape while allowing global orientation and scale adjustment[19]; in this chapter they are used primarily for CRS-consistent export, while consolidation of disconnected SfM components is treated as a future extension.

The estimation of T depends on available constraints. In the absence of ground control, correspondences between components can be identified by selecting homologous points (e.g., corner edges, façade features) and solving for the transform that best aligns them. In our workflow, $T_{obj \rightarrow UTM}$ is estimated through cloud-to-cloud registration between the local reconstruction and the georeferenced point cloud produced by ODM. When distances or reference landmarks are available, T can be estimated by minimizing residuals between reconstructed and reference coordinates[20]. Regardless of the method, the key design choice is to store T as an explicit artifact (e.g., a .json record of the 4×4 matrix with metadata describing source and target frames). This makes transformations inspectable and reusable, and it allows the entire dataset to be re-exported consistently.

Once computed, T is applied to the derived outputs that must remain spatially consistent: reconstructed geometry (dense point cloud coordinates and, when available, mesh vertices) and semantic layers (labeled points, façade outline, and window features). By transforming geometry and semantics with the same T, the workflow preserves the spatial attachment of labels to the corresponding façade structures after CRS alignment. Camera extrinsics are updated only when additional 2D↔3D mapping is performed in the transformed frame; in that case, camera centers are transformed by T, while camera orientations are updated by the rotational component.

After applying a transformation, practical checks verify coherence. When further 2D↔3D operations are performed in the transformed frame, projected camera frusta should visually "look at" the reconstructed façades, and reprojecting a small set of image points should intersect the expected surface

19 Umeyama S., "Least-Squares Estimation of Transformation Parameters Between Two Point Patterns". *IEEE Transactions on Pattern Analysis and Machine Intelligence* 13/4 (1991): 376-380. DOI: https://doi.org/10.1109/34.88573.

20 Besl Paul J. and McKay Neil D., "A Method for Registration of 3-D Shapes". *IEEE Transactions on Pattern Analysis and Machine Intelligence* 14/2 (1992): 239-256. DOI: https://doi.org/10.1109/34.121791.

regions. Independently of camera availability, semantic consistency can be validated by checking that window labels supported by multiple views converge on the same 3D areas and by inspecting the overlay of façade/window layers in the target GIS CRS. These checks are simple but effective, and they can be automated to flag inconsistent transformations before exporting to GIS.

2.1 AI-based Instance Segmentation (YOLOv8-Seg)

We treat both window and roof extraction as instance segmentation tasks and implement them with a YOLOv8-Seg model[21]. In semantic segmentation, each pixel is assigned to a class (e.g., "window"), but individual openings are not separated; in instance segmentation, each detected object receives its own mask and instance ID, enabling window-level measurements and queries. The instance formulation therefore supports object-level GIS operations (counts, locations, clustering) rather than only class-level pixel coverage. Each window instance receives an ID that can be propagated to 3D via 2D↔3D mapping and used to build GIS features with attributes, supporting later aggregation per façade, building, or urban block. In this chapter, roof instances correspond to distinct roof-surface patches (roof pitches/terraces) as delineated in the image annotations.

2.1.1 Training, inference and outputs

Window training data consist of close-range façade images where each window is annotated in XML format[22]. Annotations are converted into YOLOv8-Seg format, which represents each instance mask as a polygon in normalized image coordinates. The dataset is split into training and validation sets to preserve variability across façades and acquisition conditions (lighting changes, occlusions, and different window typologies).

Training is performed within a dedicated, reproducible Conda environment by fine-tuning a pretrained YOLOv8-Seg model[23]. The procedure is executed twice, producing two single-class models trained separately for "window" and "roof". The window model is trained and applied on the close-range façade survey images, whereas the roof model is trained and applied on satellite imagery. For each run, the selected model corresponds to the checkpoint with the best va-

21 Ultralytics. "YOLOv8": https://docs.ultralytics.com/models/yolov8/ [Accessed on 02/01/2026].

22 Roboflow. "What is Roboflow Universe?": https://docs.roboflow.com/universe/what-is-roboflow-universe [Accessed on 02/01/2026].

23 Ultralytics. "YOLOv8": https://docs.ultralytics.com/models/yolov8/ [Accessed on 02/01/2026]..

lidation performance ("best" weights), and outputs include the learned weights and associated logs.

To ensure traceability and repeatability, the workflow records the dataset version, class definition, and key execution parameters. A dedicated Conda environment is used to pin library versions and ensure reproducibility; the environment specification is stored together with the model weights and logs to support later reruns and auditing. In particular, inference settings that directly affect predictions (image size, confidence threshold, and non-maximum suppression) are saved together with the per-image output artifacts, so that each mask can be traced back to the source image ID and to the downstream 3D and GIS products

Inference is performed in two separate runs: on the survey images with the window model, and on satellite imagery with the roof model. In both cases, outputs include per-instance masks, bounding boxes, confidence scores and instance IDs, stored as per-image artifacts linked to the source image identifiers and downstream GIS products. Results stored as per-image artifacts that retain a stable link to the image identifier and to downstream 3D and GIS products. This separation is important: it allows the 2D↔3D mapping stage to be rerun with different thresholds or after applying transformations to derived layers, without repeating inference. Basic filtering is applied to remove very low-confidence detections, but most validation is deferred to the 3D consolidation stage where geometric consistency acts as an additional constraint. Figure 4 shows an example of instance segmentation output on a façade image. The same training strategy is applied to the roof model on satellite imagery as reported in figure 5.

In this scenario, typical false positives occur on doors, balcony openings, and reflective or shadowed regions that mimic window boundaries; false negatives occur under vegetation occlusions, strong backlighting, or partial visibility. The workflow mitigates these errors by preserving confidence scores, enabling threshold tuning, and using 3D multi-view consolidation on the labeled geometry: detections that are not spatially consistent across views tend to be filtered out in later stages.

2.2 2D-3D Reprojection: From Inferred Pixels to 3D Labels

The 2D↔3D mapping described in this section is applied to façade building elements (eg. windows) instances detected on close-range images, because it relies on camera calibration from the photogrammetric reconstruction. Given calibrated cameras, 2D↔3D mapping can be performed by projecting reconstructed 3D points into the survey images and transferring labels from image space to geometry. In our workflow, each 3D point is reprojected onto multiple images using the estimated intrinsics and extrinsic; if its projected pixel falls inside a

YOLOv8-Seg window mask, the point inherits the corresponding semantic label (and instance information), together with the detection confidence. Aggregating this test across views yields a labelled (semantic) point cloud that can be consolidated and exported to GIS.

Although pixel-to-surface ray casting is possible when a high-quality mesh is available, in compact urban façade surveys the mesh is often incomplete or noisy due to occlusions and limited parallax. For this reason, our implementation prioritizes the point-labelling strategy (3D→2D reprojection), which is more robust for producing GIS-ready window features.

Efficient 2D↔3D mapping requires avoiding exhaustive evaluations of all points against all images. In our implementation, labelling is performed by reprojecting 3D points into candidate images and testing mask membership in image space. Points are first filtered using inexpensive checks (positive depth and image bounds) so that only visible projections are evaluated. Window masks are represented as polygons, and a point-in-polygon test assigns the "window" label (and instance information) when the projected pixel falls inside a mask. Key parameters controlling this step (e.g., image selection strategy and confidence thresholding of masks) are recorded to ensure reproducibility. To reduce computation, the current implementation applies an early-exit strategy: once a 3D point is classified as belonging to a window in at least one view, no further images are evaluated for that point. Robustness is then enforced in the subsequent 3D consolidation stage, where spatial consistency and cluster-level filtering suppress most single-view noise.

Starting from the labelled point subset, the workflow consolidates detections into stable 3D window candidates. Consolidation is performed through density-based clustering on the labelled points to separate individual openings and suppress scattered noise. To improve geometric stability, clustering and validation are carried out in a façade-aligned reference frame derived from the estimated façade plane: points are evaluated for coherence with the plane model and out-of-plane artifacts are rejected. Each resulting cluster is treated as a candidate window instance and is further regularized downstream (e.g., by computing a hull and a robust rectangular approximation), which turns noisy point sets into GIS-ready window features.

To support GIS integration, we derive compact, stable features for each window instance from the clustered labeled points. The primary representation is a centroid point enriched with attributes such as instance ID and aggregated confidence (and, where available, quality indicators derived from the 3D cluster). When a façade plane is available, we additionally compute an oriented bounding rectangle on the façade plane to approximate the window extent; this provides a footprint that is easy to query and visualize in GIS. Optionally, simplified poly-

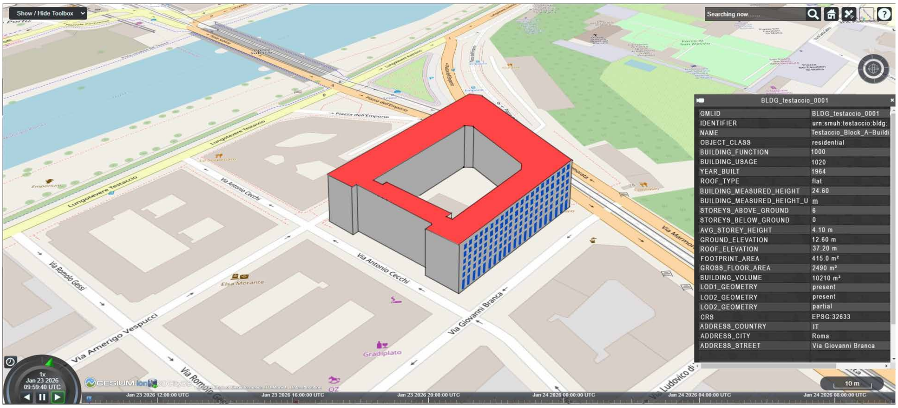


Fig. 8 – *CityGML visualization in 3DCityDB Web Map (Cesium-based): the building model is rendered on top of a web basemap, and selecting an object opens an attribute panel showing its CityGML identifier (gml:id) and associated attributes. This interactive view supports query, inspection, and comparison of semantic city-model features.*

gons can be generated from the convex hull of the clustered points and then regularized. These representations intentionally trade geometric detail for stability and queryability, which is typically the correct choice for GIS. Figure 6 illustrates the labelled points on the dense cloud and the derived window features.

2D↔3D semantic transfer is sensitive to several sources of uncertainty: residual camera pose and calibration errors, imperfect geometry reconstruction (noise, holes, and misaligned components), and segmentation uncertainty at object boundaries. In the point-labelling strategy adopted here, these uncertainties manifest as small reprojection shifts that can move a projected 3D point across a mask boundary or into visually similar regions. The workflow therefore relies on practical, robust thresholds rather than brittle exact decisions: low-confidence detections can be filtered, façade-plane coherence can be used to reject out-of-plane artifacts, and clustering parameters (e.g., minimum cluster size and density) can be tuned to suppress scattered noise. Failure cases are handled explicitly: projections outside image bounds or in invalid camera configurations are ignored, and candidate window instances that remain weakly supported in 3D (e.g., too sparse or fragmented clusters) are flagged as incomplete so they are not exported as reliable GIS features.

3. The 3D-Semantic Model According to CityGML Standard

After the completion of the 2D↔3D semantic transfer, the last step of the pipeline supports the construction of the CityGML-oriented representations of the 3D-semantic model. The CityGML is generated using a Phyton script dedicate to alignment of the 3D-semantic data to the CityGML data model via standard ".json" format. In the first step, standard ".json" format is used to transfer the geometric features of the building elements coupled with their semantic labels extracted from the labelled point-cloud. For the "windows" elements, the ".json" reports the geometric features – as the coordinates of the vertex of the boundary-polygon of each window– coupled with an alphanumeric ID code of each instance (label). In a second step, the ".json" is aligned with the geographic coordinates using on the previously introduced T Matrix. In the third step, the transformed ".json" is encoded according to the CityGML standard as reported in figure 7. Once building elements instances are represented as CityGML features, the geometric and semantic feature of the model can be easily visualized in a 3D GIS environment as shown in figure 8.

4. Discussion and Future Perspectives

The case study highlights that semantic automation is only as reliable as the geometric backbone supporting it. When camera poses and geometry are fragmented, the pipeline can still operate on a selected façade/component, but it loses its capacity for seamless block-scale integration. Explicit transformation management remains essential because it preserves the consistency required by 2D↔3D mapping and ensures that geometry and semantic layers remain coherent when aligned to a target CRS for export. In practical terms, this means that transformations must be computed, stored, and propagated with the same discipline used for semantic outputs.

A practical implication of fragmentation is that façade components may be internally correct yet mutually misoriented, preventing a single, continuous block-scale model. In the current workflow this is handled operationally by strengthening cross-façade connectivity during acquisition and, when needed, by focusing semantic transfer on a target component while maintaining CRS consistency at export. A key direction for future work is to automate the consolidation of disconnected components by estimating similarity transforms between components (using geometric cues such as façade planes, corner constraints, and robust 3D registration) and validating the result through consistency checks before downstream semantic processing.

Some limitations remain and are worth stating explicitly. First, the pipeline's reliability depends on sufficient cross-façade connectivity; acquisition that treats façades as independent planar sequences increases fragmentation risk and can limit block-scale integration. Second, 2D↔3D semantic transfer benefits from a dense reconstruction with limited holes and from clear image evidence: when large occlusions remove geometry or when windows are partially hidden in the images, point labeling becomes sparse and the resulting 3D window candidates can be incomplete. Third, repetitive façades can still induce occasional mis-associations during clustering; geometric constraints such as façade-plane coherence, expected window size ranges, and robust regularization reduce but do not fully eliminate this risk. In operational use, we recommend designing acquisition with corner images, performing a fast connectivity check before densification, and validating the transformation stage with small 2D↔3D mapping tests before exporting.

A second lesson concerns the relationship between 2D inference and 3D consolidation. Instance segmentation alone can produce false positives due to shadows, reflections, and repetitive façade patterns. By transferring detections to 3D through 2D↔3D mapping and then validating them with geometric constraints, the workflow introduces a strong filter for errors. In practice, façade-plane coherence, 3D clustering, and robust regularization constrain which detections are plausible in space and suppress many scattered single-view artifacts. This suggests that, for façade elements, a combined 2D–3D pipeline can be more robust than trying to perfect 2D post-processing in isolation.

Finally, automation requires disciplined data management. Camera parameters, transformation matrices, and semantic outputs must be stored in stable formats and versioned together with the configuration used to produce them. Without this discipline, manual adjustments become unreproducible and inconsistencies can propagate silently into exports. The workflow therefore treats metadata and transformations as first-class outputs rather than temporary internal variables. This approach is particularly important when results are consumed by a 3D GIS, where coordinate reference systems, provenance, and repeatability are essential.

Future work will focus on strengthening cross-façade connectivity during acquisition, refining façade and roof-surface regularization to produce cleaner 3D polygons and improving the robustness of 2D↔3D semantic transfer. A stricter alternative, to be evaluated in future work, is to require multi-view support (e.g., at least two consistent supporting views among a set of candidate images) before accepting a label at point level. Additional directions include extending the semantic vocabulary beyond the current window and roof-surface case studies to further façade elements (doors, balconies, shutters) and improving export mapping toward standardized city-model encodings. The modular design of the pipeline is intended to scale to larger areas by repeating the same sequence while preserving transformation and metadata management.

Scenarios for the City and the Landscape. Data as a Factor in the Project Evolution

Luigi Siviero[1]

In the digital age, the relationship between information, city and landscape project has become increasingly crucial. Technological evolution has radically transformed the way we collect, analyze, and use data in the project.

The advent of big data and information collection and processing technologies has provided the various stakeholders engaged in the transformation of cities and landscapes with an unprecedented amount of information, often confusing and, even more often, difficult to interpret. As data increases, so do the overlaps and conflicts between the meanings attributable to surveys and analyses, often with an effect contrary to the possibilities they are supposed to offer. From traffic patterns to citizen preferences, from environmental to socioeconomic data, to the increasingly detailed and precise representation of space, this information offers a different, and not always clearer, vision of the human environment.

One of the most significant features of this early twentieth century is a pervasive, sometimes contradictory and problematic, relationship between society – and the several related activities and expressions – and data. This relationship has changed in parallel with technological development, which supports the increasingly rapid and efficient collection, storage, and representation of information. This peculiarity extends to countless aspects of society and its expressions, from the physical to the more abstract, from the most complex decision-making processes, to the most common behaviors. The collection, management, and use of data appear to be a central and decisive issue, underlying the most revolutionary innovations of recent decades.

Over the past twenty years, with the exponential acceleration, typical of the information age, through the systematic collection and use of data, the people modified their system of orientation and movement trough the space, their communication and social behavior, their procurement of goods and services, and their method of acquisition of information. More generally,

1 University of Padua, Department of Civil, Architectural and Environmental Engineering.

they have significantly altered their problems approach, equipping themselves with tools capable of supporting decisions more effectively – at least apparently, certainly more quickly. The theme of information, consequently, has opened up a complex framework of issues, some of which is open and subject to debate, despite certain habits having now profoundly impacted our approach to information services. One of these themes is the changing relationship between the information – the "data" – and the "project".

To better understand the dimension of the problem, we can consider the term "project" in a general and etymological sense, as a structured method for predicting changes from a pre-existing to a subsequent state: not only a technical project, such as a that related to a building or an urban area, but also a general forecast, such as an electoral program, a corporate strategy, or the safety mesures for an inhabited area; or, more commonly, a simple prediction, such as that of a trip or a route, a purchase, a daily choice: where information was once gathered through archival research, or with the advice of an expert (in more complex cases), or verbally, or even through a limited number of dissemination channels (newspapers, television, radio, texts, etc.) in a unidirectional system, today the tools for receiving information are several, with widespread, transversal effects across the recipients, and highly interactive. Applications, IT portals, databases, and now even chatbots integrated with artificial intelligence technologies, constitute a complex and articulated system for the use of information in various forms: maps, images, places, photographs, drawings, written and acoustically reproduced texts are the product of computer-generated data extrapolation, which in turn is collected with technological tools once accessible to a small circle of people (primarily governments and large companies), but now much more widespread and precise.

More specifically, this framework includes the project as a tool for transforming space (for example, architectural, urban, or landscape project) and the information that influences choices, or describes the characteristics of the designed subject in an accumulation of knowledge useful at different times.

The project is influenced, sometimes conditioned or entirely managed, by the data. Information can be diverse in nature and represented in several ways; they can have many origins, either because they come from heterogeneous sources or because they were gathered at different times, and therefore varies in reliability, accuracy, or complexity. Topographical, architectural, and geographical surveys; analyses and investigations of structures, architectural elements, and terrain; historical, anthropological, and environmental documents and studies... they are starting points of any design process. Following an ideal trajectory (to put it simply: the trajectory is often less linear

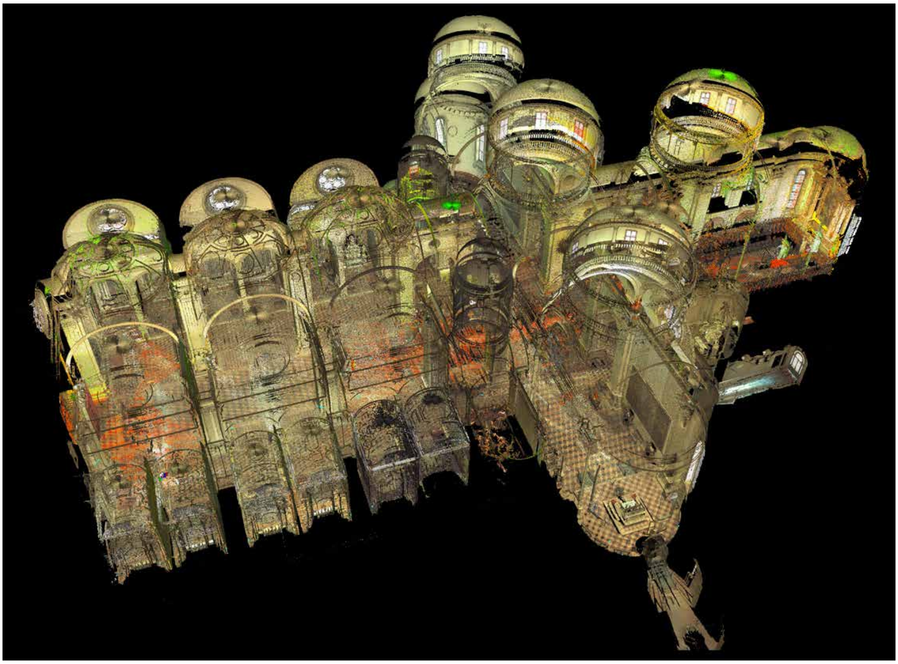


Fig. 1 – *Tu-Cult Research. Point cloud produced throug the laser scanner survey of the church od Santa* Giustina *(Padova, 2016).*

than desired), it develops from information that defines its direction.

Compared to the last century – when it was relatively difficult to find data then what is available today – the information potentially relevant to a project have increased exponentially. The precision and resolution of this information is so detailed that it is sometimes redundant with respect to the targets. With negligible effort, we can determine the exact number of farms, for example, in the Lagarina Valley, or the footprint of the Brennero highway in the section that crosses the Veneto region; or, on an architectural scale, quickly produce a survey of the church of *Santa Giustina* in Padua with a resolution of one point per square centimeter as shown in figure 1[2].

A first consideration therefore revolves around the overabundance of infor-

2 The data cited here for illustrative purposes only can be obtained through public access from the Veneto region geo-portal (https://idt2.regione.veneto.it/), just as similar data can be publicly accessed from other web sites or databases. The survey of the church of Santa Giustina in Padua was conducted as part of the Tu-Cult research project (University of Padua), described below, but is cited here as one of many examples of the overabundance of geometric information in instrumental surveys, as for example the laser scanner technology, which is nowaday widely used.

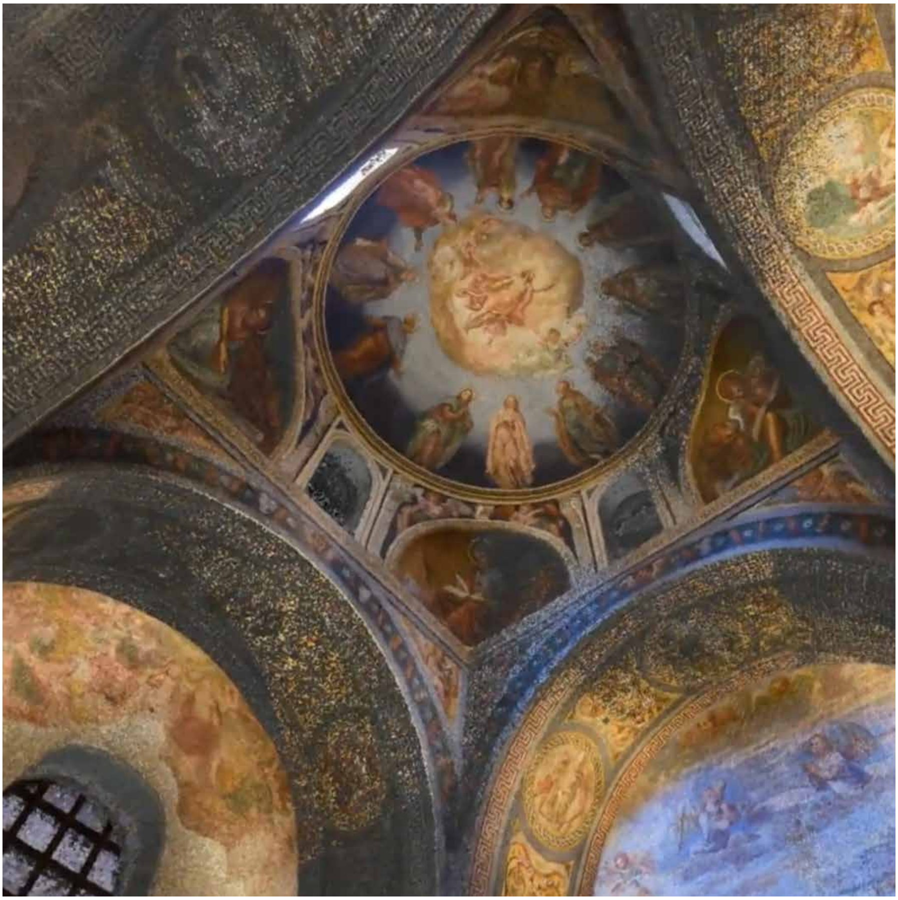


Fig. 2 – *Tu-Cult Research. Point cloud produced throug the laser scanner survey of the church of* Santa Giustina *(Padova, 2016).*

mation, which undermines and challenges the traditional relationship between project and data: in operating conditions characterized by a relative scarcity of data, with a substantial inability to access specific information, the project tends to be based on a naturally simplified framework, with fewer conflicts between different pieces of information and reduced complexity, despite although in this case it inevitably generates a deficiency in some areas of knowledge; on the contrary, an overabundance of information, while offering a much more precise framework of knowledge, increases the complexity, generating the need for a guidance system capable of selecting information, highlighting conflicts, structuring a hierarchical order, eliminating redundancies, and consequently defining a more clear strategic project line.

A second issue concerns the possibility of integrating information throughout the project. This possibility is provided, in part, by the enormous availability of data mentioned above, and by the difficulty of providing a unified and complete logical structure to the information: the knowledge framework, as well as the project guidelines, may become open and provisional, evolving through progressive approximations, as the project development process evolves. However, it is also a consequence of the ease of integrating data where it is missing. A survey of a building, for example, may be available in form of a paper and incomplete because it is the result of a survey conducted long ago, manually, with approximations acceptable for tath time: LIDAR, laser scanner, and photogrammetric surveys, as in figure 2, which integrate the missing information, are today easy to obtain and quick to process, thus providing previously inaccessible information, making the design process gradually more precise.

The topic of the integration raises then the issue of the information archiving, subject today of extensive reflection[3], which is now more than ever subject to the problem of data inconsistency. The need to preserve project-related information and documents – either because they form their basis, or because they are the product of post-design processing – appears fundamental today. Information is contained in several media, both physical (maps, plans, drawings, documents, reports, photographs) and digital (computer files are subject to a very rapid process of obsolescence, partly due to the disappearance of physical reading tools and partly to the constant obsolescence of formats, subject to a constant progress). Archives must therefore be divided, use different media, and find a structure capable of highlighting each document, and more generally adopt strategies[4] to contrast the data obsolescence[5].

1. Automatisms

Information overabundance, ease of data retrieval and construction, and difficulty archiving information are just some of the many challenges that define the new operating conditions of contemporary project. However, they are sufficient, at least here, to identify and raise other important questions.

3 Peters J. D., "Proliferation and Obsolescence of the Historical Record in the Digital Era". In *Cultures of Obsolescence. History, Materiality, and the Digital Age*, edited by Tischleder B. and Wasserman S., New York: Palgrave Macmillan, 2015.

4 In Italy, the archiving of digital materials in public administration is the subject of Presidential Decree 03.12.2013, which attempts to address an issue that appears essential to regulation, despite the limitations of the legislative instrument and the complexity of public archives.

5 Chuqiu L., "Debunking the Myth of Obsolescence: Strategies for Digital Heritage Conservation." *Advances in Social Behavior Research* 8/5 (2024).

One of these can be identified, schematically, with the term "automation", or the ability to achieve a design result not only through the direct interpretation of the information – in a process of data reception and immediate and linear interpretation, through the direct production of drawings, diagrams, descriptions, and ultimately, documents, without any IT mediation – but also by using software and technologies that select and interpret the data, and automatically transform them into a design product.

The technological evolution of the graphic tools supporting architectural design helps us better understand how a certain degree of automation in design processes has been achieved.

The invention of Computer-Aided Design dates back to the 1960s, but CAD software began to be extensively used in the 1990s. Some tools integrated into the software are automation principles revolutionary in some respects: the ability to retrace a list of previously issued commands and undo choices; the ability to copy parts of a drawing in a potentially infinite way, without the need to redraw them; the automatic production of series of objects in space, using parameters such as dimensions, distances, angles, etc. These are some of the possibilities offered by computer-aided design, compared to the previous analog system of drawing on a sheet of tracing paper, traced with ink. The most significant, in terms of project, is perhaps the automation of the use of layers, or drawing levels (previously obtained through the overlapping of semi-transparent sheets), which not only made simpler and more immediate the understanding of the project during the drawing phase, but in a more extensive sense contributed to influencing subsequent architectural culture.

Computer-aided design will bring about significant changes in design methodology and representation: with the use of 3D models, which have enabled the automated production of drawings, once drawn line by line (plans, sections, elevations, axonometric views, and perspectives), and global control of the project geometry; and subsequently, once achieved the computing power required to produce them, with the introduction of animations and renderings.

With the introduction of CAD, it is clear that design is beginning to undergo a progressive transformation, affecting not only the production phase but also the substantial phase, that is the very result of the design process, the underlying principle. The influence of CAD can be perceived starting from the projects of Bernard Tchumi and Rem Koolhaas, for example, for the park La Villette in Paris (1982), or in the early works of Zaha Hadid, again for the La Villette or for The Peak in Hong Kong (1981-83), and increasingly in several other subsequent works, which have influenced, and still influence, the culture of architectural, city and landscape design.

The studies of the city defined through "parts", which in the 1980s took as their synthesis and model the analytical-design principles contained in The *Architettura della città* by Aldo Rossi[6], were accompanied by a different interpretation, perhaps influenced by the new methods of design offered by the computer aided design, as well as by a more general cultural evolution. Architecture, the city, and the landscape began to resemble, in many projects, more stratified and complex organisms, made up of overlapping layers, not in an archaeological sequence, where each layer finds its place within a vertical progression, but rather in a system of layers in mutual relation, which can be analyzed and constructed piece by piece, but which finds completion only as a whole[7].

This story, so schematically and incompletely described, deserves reflection also in light of the subsequent evolution of automation in design. Indeed, in the context we are addressing, automation takes on a dual role. On the one hand, it has become a system for quickly and seemingly simply producing projects that previously required effort and time, changing the mechanical production tool rather than the result or production process. On the other, it has begun to take on a more complex and nuanced, and also substantially more impactful, meaning. The principle of this can be traced back to the origins of CAD[8], which consisted of providing a tool that provides a universal language and shares common methodologies and practices, thus laying the foundation for the project to be the product of multiple authors, thus losing some of its subjectivity.

This second meaning fits more precisely into the theme of the relationship between data and project. Subsequent developments in IT design tools have followed at least two approaches, which overlap each other, but wich is useful here to analize separately, because they express two different interpretations.

The first approach to automation involves the parameter as a system for defining space, supported by software capable of producing geometries based on inputs that allow automation to operate freely within parameters defined by a designer. From a practical standpoint, the advantage is in the possibility to introduce information into the model, progressively increasing its complexity while maintaining the possibility to modify it even in the most fundamental factors. In this sense, parametric architecture shifts the design

6 Rossi A., *L'architettura della città*. Milano: Clup, 1987.

7 Stendardo L., "Dalla città per parti alla città per layers". In *Forme a venire*, edited by Rispoli.F. Roma: Gangemi Editore, 2013.

8 Cardoso Llach D., *Builders of the vision. Software and the imagination of Design*. New York: Routledge, 2015.

process from a "cascade" approach, where each detail is gradually added in a crescendo of complexity, difficult to reverse, to an "accumulation" approach, where the model is constituted by a set of variable geometric relationships, and where new information does not prevent even substantial modifications to the structure at any point during the design phases. In this sense, parametric software addresses the problem of continuous data addition, which we described above, by providing a more flexible tool.

The information that defines the parameters of the model are not only geometric, but of a several natures, and produces a project strongly characterized by the production of different layers. For this reason too, parametric architecture, which over the years has gone beyond the practical aspect of software to become a field of research, can be extended, according to some of its exponents[9], to different aspects and scales of spatial design, such as urban, territorial, and landscape project. Several works by Zaha Hadid, Peter Eisenman, Coop Himmelb(l)au, and other prolific architects at the beginning of the Twenty-first century, display the common characters of parametrically controlled architecture, in an attempt to go beyond the formal characteristics of the international style, with the fluidification[10], even metaphorical, of space and architecture. Beyond the debate on the actual sustainability and representativeness of these works in a social context strongly characterized by inequalities, and whether parametric architecture is actually a new style characterizing the Twenty-first century[11], it is interesting to note here that parametric architecture addresses the need to introduce increasingly layered and complex data into the design process as an intrinsic characteristic of contemporary design, and consequently attempts to represent this necessity through an architectural form that is the consequence of partial automation, capable of managing information without completely losing control of the design principle.

9 Schumacher P., "Design Parameters to Parametric Design". In *The Routledge Companion for Architecture Design and Practice*, edited by Kanaani M. and Kopec D., New York: Routledge, 2015.

10 The term "fluidification" refers to the description by Bauman of contemporary society (Bauman Z., *Liquid Modernity*. Cambridge: Polity Press, in association with Blackwell Publishing, 2000). Parametric architecture, through curved, elusive space, folded (Deleuze G. *Le pli. Leibnitz et le Baroque*. Parigi: Les Éditions de Minuit, 1988) on itself, metaphorically reproduces the characteristics of a contemporary society, defining itself as the style of its staging. – see. Al-Azzawi Tahseen, Al-Majidi Zainab., "Parametric architecture: the second international style." *IOP Conference Series. Materials Science and Engineering*, n. 1067 (jan. 2021).

11 Mokhles Youns A. and Grchev K., "A Historical and Critical Assessment of Parametricism as an Architectural Style in the 21st Century". *Buildings* 14 (2024).

The second approach to automation, in which the first is integrated at least in its technological and pragmatic aspects, consists of a more direct association between data and model, where the latter, or parts of it, are attributed with information not necessarily geometric. This logical structure, which we have described schematically than the real, is primarily represented by the Geographical Information System (GIS) and Building Information Modeling (BIM), which today are the standard for project management in all phases of the design process, respectively for the territorial and architectural scales.

GIS and BIM allow the metric information of a model to be directly combined with an infinite variety of information – synthetic, analytical, or interactive – and to extract further information through their mutual interaction and following the introduction of queries.

Over time, GIS and BIM have become operational tools, just as previous computer-aided design software was, and still partially is. In this sense, the approach to these systems is, from the perspective of design professionals, a necessity. On the one hand, this ensures the ongoing technological development of the related software, and therefore the continuous improvement of the system. On the other, it makes them subject to commercial strategies, that are not always conducive to dialogue in an open system, in which different information technologies integrate and interact with one another.

What is of interest here, however, is the cultural change these systems have introduced and fostered, represented by the increased level of automation in the design process and the trust in data, as a product of computer processing. The use of automated computer procedures in design has become frequent and natural, with the risk that the results of the processes, which are in turn further information, are assumed uncritically, and that their logical origin, the principle, is lost, as happens in a famous story by Isaac Asimov[12].

The problem of losing the principle indirectly refers to the relationship between architecture (ἀρχή = principle, origin, foundation) and automation. The design phase of architecture, in fact, involves principles that are difficult to automate, which often draw on artistic experiences, or are themselves configured as such, only to be condensed later into a project, and only in some cases into a construction. Automation, therefore, although decisive in project management and implementation phases, cannot support the initial phases, i.e. the concept, which needs to be fuelled by perceptual experiences, artistic culture, in situ observations, interpretations and intuitions that cannot be replicated by

12 In "Feeling of power", a short story by Isaac Asimov written in 1958 for the science fiction magazine «If», in a future where all activities are automated, humanity has placed such trust in computers that it has completely forgotten the mathematical principles underlying calculation, which are rediscovered by chance as the plot develops.

a machine because they are subjective – the result of cultures acquired through individual experiences and intertwined in a non-mathematical, non-progressive path, sometimes characterised by unplanned events – to synthesise the design principle that structures it.

2. Selection, Archives and Projects

The increase in the quantity and availability of data seems to be ultimately related to automation mechanisms in design production, which in turn generate further information. In this proliferation of project-related data, which already implies a complex situation in which issues and problems overlap, generating conflicts and confusion, the issue of information archiving appears to be central and raises a number of questions.

Over the years, following the transformation of the type of information and technological developments – primarily that of computer databases – archives have undergone changes. The contemporary archive is not so much a collection of materials as a device capable of collecting and simultaneously providing infinite possible selections of different materials.

We have seen how archives are capable – and in some ways necessary – of collecting materials and information that differ in nature, format and age of production in a single or multiple logical structure. An archive contains both paper and digital materials. While it is easy to understand that the first are diverse (books, documents, maps, drawings, prints, etc.), it is perhaps less clear how diverse digital materials can be. Alongside scanned documents, contemporary digital archives may contain, for example, point clouds, three-dimensional models, GIS databases or BIM files... a multitude of objects, each of which requires specific software to be viewed and modified. In this sense, the problem of the conditioning of software development becomes clearer, as for commercial reasons, software is often incompatible with each other, as are file formats (which are often subject to copyright), which are also subject to obsolescence[13].

Ultimately, the problem is not just one of information overload or archive capacity, but of efficiency in the way information is catalogued and, in particular, extracted from the whole. Given a multitude of physical and digital objects, differing in terms of age, origin and medium, and often incompatible in various respects (reading, comparison, overlapping), the is-

13 Pearson D. and Webb C. "Defining File Format Obsolescence". *The International Journal of Digital Curation* 3/7 (2008).

sue of data selection appears central, and is even more so in terms of the relationship between data and the project. In a system already strongly characterised by automation, it seems that the archive must be able not only to provide information extracted from a database, but also to cross-reference it, to make it interact with each other, and ultimately to create a number of interpretative possibilities.

Part of the research has therefore focused in recent years on studying the potential of digital archives, which have consequences for the relationship between data and design. Contemporary archives are not limited to the collection, study and cataloguing of information and materials, but are able to superimpose them, geo-reference them and make them interact within a relatively versatile platform. Platforms are often able to receive different types of data and standardise them in a cross-sectional reading and selection system, open to subsequent modifications or additions.

Among these studies, it is worth mentioning four attempts made in the context of four studies conducted at the University of Padua between 2014 and 2020, which can be grouped together in terms of aspects relating to the relationship between data and design. The researches are: *Metodologie per l'acquisizione e la comunicazione dei dati relativi ai beni culturali e per il progetto architettonico e tecnologico di interventi atti alla relativa conservazione e al miglioramento della fruizione turistico-culturale*; *Tu-CULT - Il turismo culturale non conosce crisi: strategie innovative di recupero, conservazione e accessibilità multilivello del bene artistico architettonico per il miglioramento della fruizione intelligente*; *DATA - Development of Abandoned Transurban Areas; iWrecks – Industrial Wrecks: Reusing Enhancing aCKnowledging Sheds*[14].

14 The research was funded under the POR-FSE 2007-2014 and POR-FSE 2014-2020 Veneto Region programmes. The professors and researches involved, in addition and support to the various operational and network partners who actively participated in the projects, are: *Metodologie per l'acquisizione e la comunicazione dei dati relativi ai beni culturali e per il progetto architettonico e tecnologico di interventi atti alla relativa conservazione e al miglioramento della fruizione turistico-culturale*. Research team: prof. A. De Rosa, prof. A. Giordano, prof. L. Stendardo (P.I.), prof. S. Zaggia. Fellow Researchers: A. Bertolazzi, P. Borin, M. R. Cundari, F. Gasperuzzo, F. Panarotto, R. Spera, S. Zoerle. *Tu-CULT - Il turismo culturale non conosce crisi: strategie innovative di recupero, conservazione e accessibilità multilivello del bene artistico architettonico per il miglioramento della fruizione intelligente*. Research team: prof. G. Croatto, prof. A. De Rosa, prof. A. Giordano, prof. C. Monteleone, prof. R. Paparella, prof. L. Stendardo (P.I.), prof. S. Zaggia. Fellow researchers: A. Bortot, C. Boscaro, C. Cecchini, F. Condorelli, M. R. Cundari, V. Palma, F. Panarotto, L. Siviero. *DATA - Development of Abandoned Transurban Areas*. Research team: prof. M. De Marchi, prof. A. Giordano, prof. M. C. Lavagnolo, prof. M. Savino, prof. L. Stendardo (P.I.). Ricercatori: S. Antoniadis, D. Barbato, R. Malesani, G. Pettoello, G. Pristeri, E. Redetti. *iWrecks – Industrial*

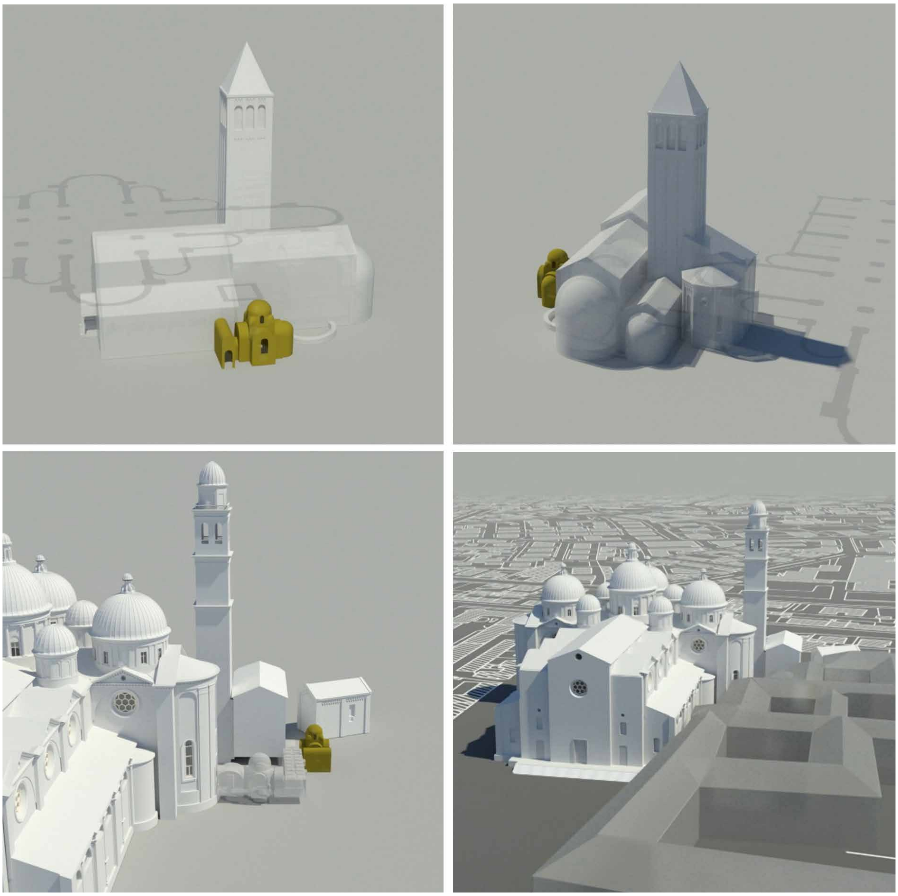


Fig. 3 – *Tu-Cult Research. Digital processing of the historical phases of the building development of the church of* Santa Giustina *(Padova), based on archive documents (2016).*

The first two focus on cultural architectural heritage (the *Eremitani* church and the two churches of *Santa Maria dei Servi* and *Santa Giustina* in Padua), while the second two address the issue of decommissioning, focusing in particular on abandoned industrial areas and buildings. The research involved various subjects, including researchers from different disciplinary areas and operational and network partners, thus providing a sufficiently representative cross-section of the complexity that characterises the issues we are addressing.

Wrecks: Reusing Enhancing aCKnowledging Sheds. Research team: prof. C. Dias Coelho (Universidade de Lisboa), prof. G. D'Acunto (IUAV), prof. M.C. Lavagnolo, prof. M. Savino, prof. L. Stendardo (coordinatore scientifico). Fellow researchers: S. Antoniadis, R. Bernardello, R. Malesani, E. De Stefani, E. Redetti.

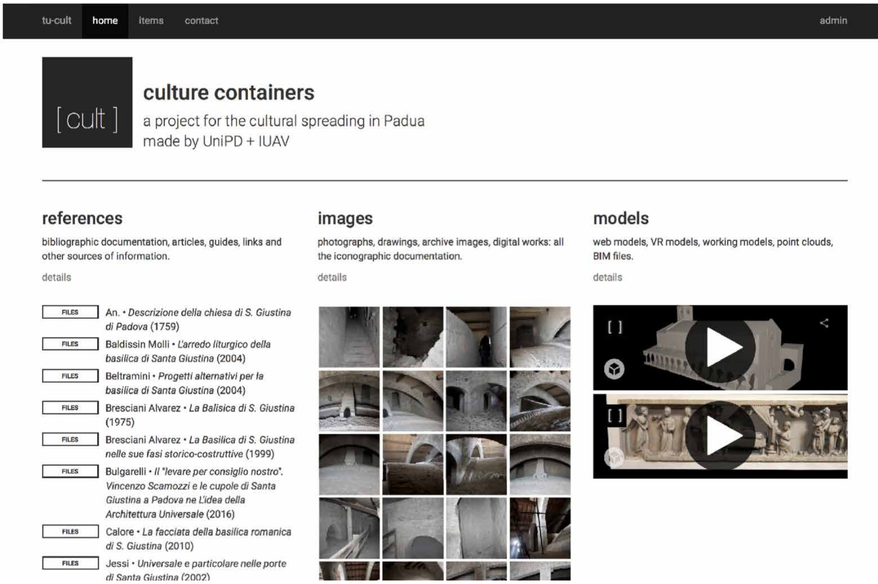
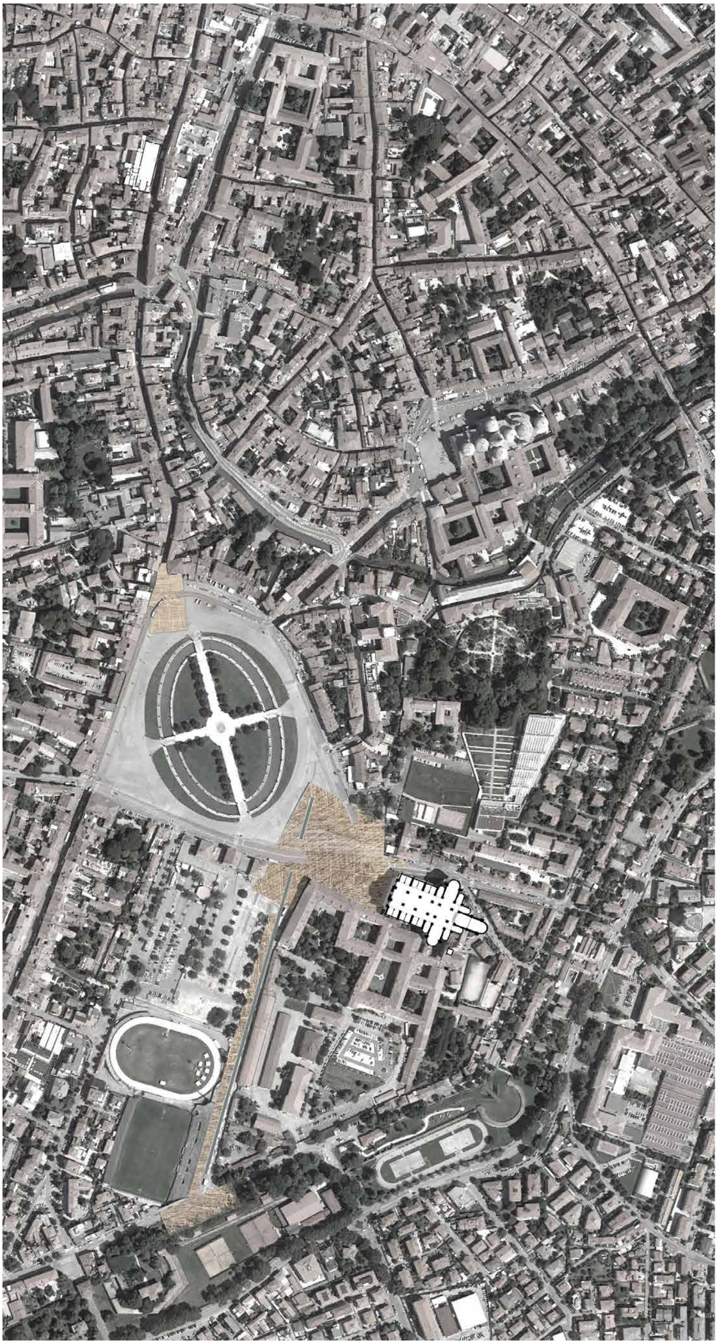
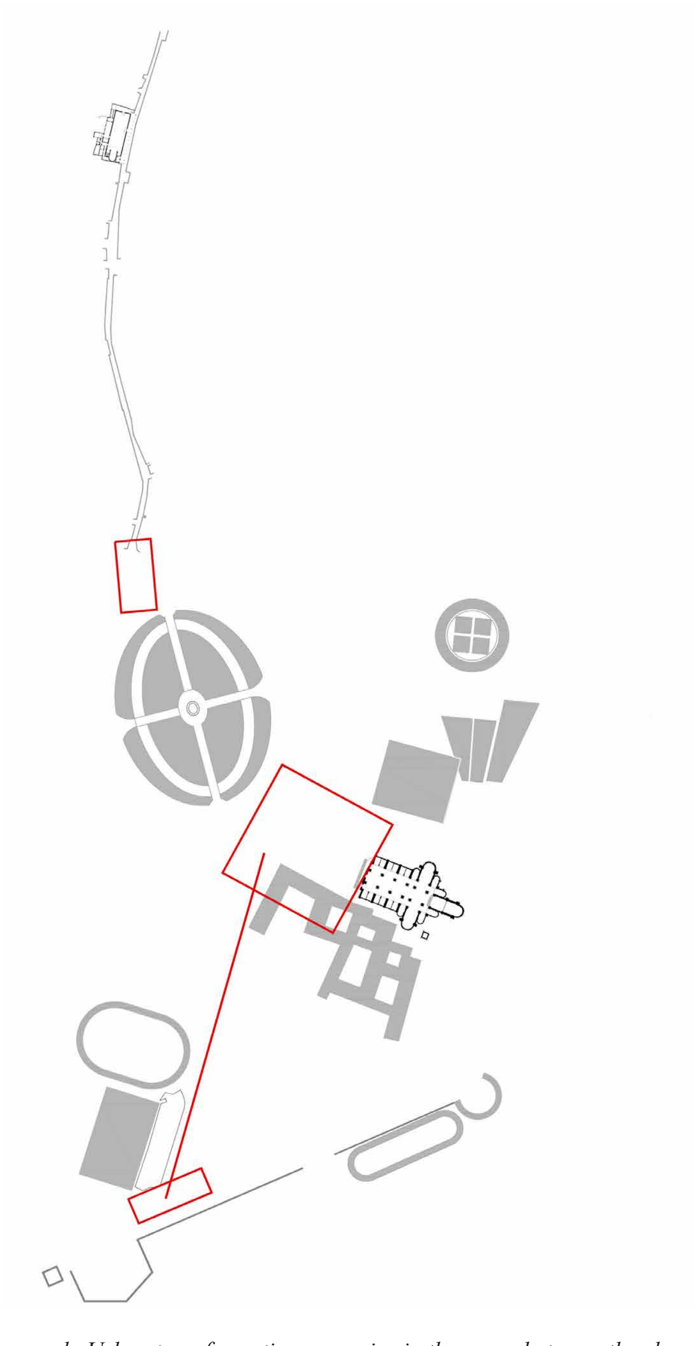


Fig. 4 – *Tu-Cult Research. Screenshot of the web interface of the interactive platform containing the archive (processing by Valerio Palma, 2016).*

Fig. 5 – *Tu-Cult research. Interactive outputs: unrealized designs for the perspect of the church of* Santa Giustina *(Padova) reproduced using augmented reality. (2016).*





Figg. 6-7 – *Tu-Cult research. Urban transformation scenarios in the space between the churches of* Santa Maria dei Servi *and* Santa Giustina *(Padova, 2016). Diagram of the urban elements. [Luigi Siviero, 2016].*

Fig. 8 – *Tu-Cult research. Urban transformation scenarios in the space between the churches of* Santa Maria dei Servi *and* Santa Giustina *(Padova, 2016). [Luigi Siviero, 2016].*

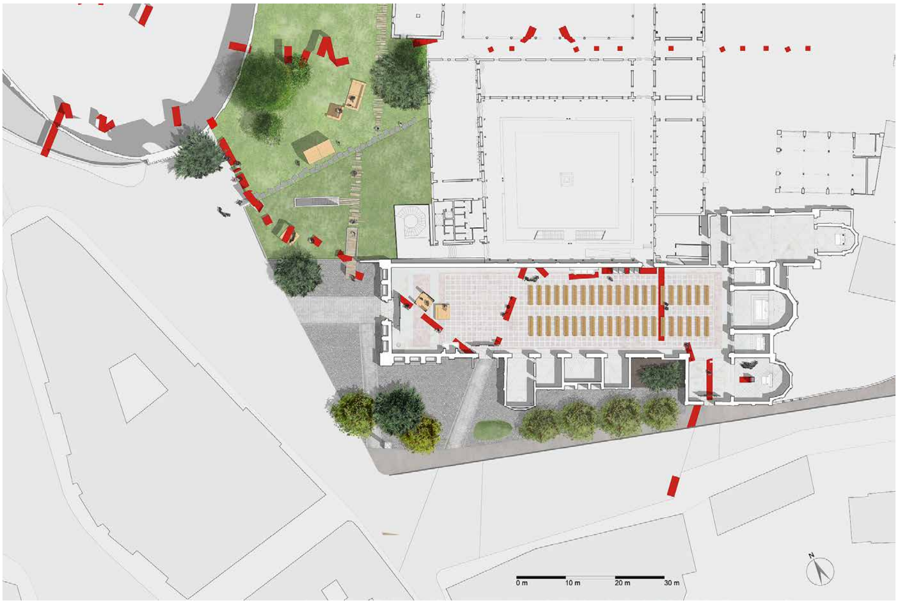


Fig. 9 – *Eremitani Research. Project for a new path for the* Eremitani *church in Padova. Plan view. [Raffaele Spera, 2015].*

Fig. 10 – *Eremitani Research. Project for a new path for the* Eremitani *church in Padova. Plan view. [Raffaele Spera, 2016]..*

Beyond the topics investigated in the individual research projects, what they have in common is a “growing” interest in the system of data archiving and dissemination, which has been developed in parallel with the project both in the operational phases and in the research output phases as shown in figure 3.

Growing because, over the years and with each new experience, the theme of the relationship between data and design has become increasingly central, to the point of aligning the archiving technologies envisaged in the four research projects with the design process. The research projects have produced interactive platforms, as in figure 4, capable of consolidating heterogeneous information into an interoperable system, i.e. of using different systems such as BIM and GIS in a single IT environment, but also of providing tools for the production of new information from existing data. Each programme included work packages dedicated to the interaction between data and users, with the development of interactive systems and data representation systems that made use of immersive forms of visualisation, see figure 5, as well as images and videos.

The four research projects, in their complexity and diversity, produced heterogeneous results. However, it is worth highlighting the emergence in these studies, thanks also to the contribution of the partners and the attempt at collective dialogue that was attempted around the various topics addressed, of a change in the role of the project, closely related to the possibilities offered by a new relationship with information. The project gradually took the form of a scenario, with the primary role of “generating visions” and acting as a basis for discussion between different subjects, often with conflicting interests as reported in figures 6 to 10.

In this sense, the project is defined through a process that differs from the one commonly understood. Freed from the need to produce the immediate creation or transformation of a space or object (a building, an area, infrastructure or any other possible subject), it becomes a more open and flexible starting point, perhaps less precise, but capable of conveying the idea of the potential of a place or architecture, and consequently catalysing the interest of diverse subjects.

Furthermore, a vision project, represented through open scenarios, takes on the task of selecting the data upstream of the process, identifying which are necessary and fundamental, and providing a hierarchy with the definition of objectives expressed through images, converting the traditional logical sequence that leads from data to project into a system in which intuition, interpretation, experience or the different cultural experiences that are condensed in the project return to the centre of a data system that has the function of supporting them, rather than replacing them.

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Authors' Biographies

Luisa Berto received the Laurea degree in Civil Engineering with specialization in Structures (*summa cum laude and special mention for the curriculum studiorum*) from the University of Padua and her Ph.D. in Structural Mechanics from the University of Bologna. She is currently an Associate Professor of Structural Analysis and Design at the University IUAV of Venice. She is a member of the Doctoral School Faculty Board at the University IUAV of Venice. Her research interests mainly focus on the development and implementation of numerical models for the analysis of reinforced concrete and masonry structures including mechanical-environmental damage models for reinforced concrete, the seismic vulnerability assessment of existing structures and cultural heritage and the risk mitigation for art objects.

Angelo Bertolazzi received the Laurea degree in Building Engineering at the University of Padua and his Ph.D in Architecture the Ecole Doctorale Villes Transportes et Territories of the University of Paris-Est and at the University of Bologna (2013). He trained at the Department of Architecture, Urban Planning and Surveying (DAUR) of the University of Padua, and at the Department of Geometries, Structure and Architecture (EN-SA Paris Malaquais) within the "Histoire et Construction" research group. He is Associate Professor of Architectural Engineering at the Department of Civil, Building, and Environmental Engineering (DICEA) of the University of Padua. His research interests focus on the history of construction and the valorization of built heritage through digitalization.

Manuela Bonano received the Laurea degree *(summa cum laude*) in Environmental Engineering from the University of Cagliari in 2004 and the Ph.D. degree in Infrastructures and Transportation from the University of Roma La Sapienza in 2012. Since 2007, she has been with the IREA-CNR of Napoli, Italy, where she is currently a Senior Researcher working in SAR interferometry. Her main interests concern the development of multi-pass algorithms for full-resolution DInSAR applications, to investigate localized displacements affecting single buildings and infrastructures in anthropogenic hazard scenarios. Recently, she has been involved in developing innovative, parallel, and scalable multi-temporal processing chains to process large full-resolution DInSAR data stacks, by exploiting distributed HPC capabilities, CC environments, and GPU devices.

Kilian Bruckner received the Laurea degree (*summa cum laude*) in Building Engineering from the University of Rome Tor Vergata in 2022. He is Ph.D. candidate in Civil Engineering from University of Rome Tor Vergata. His research interest focus on advanced digital tools for the management of the build environment, including parametric modelling, 3D semantic city models, image recognition and semantic segmentation techniques. He has collaborated in research projects conducted by the University of Rome Tor Vergata and University of Padua.

Federica Casamento received the Laurea degree at Environmental Engineering from the University of Palermo, Sicily, Italy, in 2021. She is currently working toward the Ph.D. degree in the "Information and Communication Technology and Engineering" programme with the University of Naples "Parthenope",Naples, Italy. Since 2021, she is with the Institute for Electromagnetic Sensing of the Environment (IREA)-National Research Council (CNR), Naples, as a Research Fellow. Her research interests include the DInSAR applications, specifically on developing algorithms to filter out atmospheric phase screen from DInSAR products, using external auxiliary data.

Carlo Del Gaudio received the Laurea degree in Civil Engineering in 2011 and his PhD in Structural Engineering, Geotechnical and Seismic Risk in 2015, at the University of Naples Federico II. He is Assistant Professor in Structural Engineering at Department of Structures for Engineering and Architecture of University of Napoli Federico II. His research focused on seismic behaviour of elements/structures and seismic vulnerability and risk assessment of buildings at large scale. He participated to the activities of Extended Partnership RETURN Multi-risk science for resilient communities under a changing climate for what concerns the Spoke Metropolitan and Urban Settlement, where is member of Scientific Council. He participated to the working group ito support the Italian Department of Civil Protection in the derivation of the "National Risk Assessment 2018" (EU decision 1313/2013). He is member of Academic Senate of University of Napoli Federico II since 2025.

Fabio Di Carlo received the Laurea degree (*summa cum laude*) in Civil Engineering in 2009 and his PhD in Civil Engineering in 2015 from the University of Rome Tor Vergata. He is Associate Professor of Structural Engineering at the Department of Civil Engineering and Computer Science Engineering of the University of Rome Tor Vergata. He is Professor of "Existing RC structures" and "Seismic design". He is member of the fib CEB-FIP TG3.2 "Modeling of structural performance of existing concrete structures". He is member of the CNR working group "Valutazione della sicurezza di opere in c.a. e c.a.p. soggette a corrosione".His research activity mainly focuses on degradation phenomena affecting reinforced concrete and prestressed concrete structures, use of fiber reinforced concrete for structural applications, and structural assessment and health monitoring of the built-up environment with digital image correlation methods and satellite radar interferometry.

Francesca D'Uffizi, building engineer, graduated *cum laude* in Building Engineering-Architecture, served as a Research Fellow at the University of Rome Tor Vergata (Department of Civil Engineering and Computer Science) for the project "Tiber'S – Embankment structures of the urban Tiber: HBIM and webGIS integration" (2022-23); she was Research Fellow for the project "SMUH – Safeguard of Modern Urban Heritage" (2024-25) at the same department. Since 2018, she has been a Founding Partner and Technical Manager at Iperboole srl, a specialized consultancy firm providing support and assistance to companies in the application of BIM procedures. Her work focuses on enhancing and accelerating internal workflows through visual scripting, coding, visualization, and online model sharing.

Ilaria Giannetti received her Laurea degree in Architecture (*summa cum laude*) from the Sapienza University of Rome and her Ph.D. degree in Civil Engineering from University of Rome Tor Vergata. She is Associate Professor of Architectural Engineering at the Department of Civil and Computer Science Engineering (DICII) of the University of Rome Tor Vergata. Her research interests focus on the history of construction, history of engineering and the safeguard and valorization of the 20th Century building heritage via advanced digital tools, including parametric 3D and informative modelling and extended reality environment. She is editor of the

Scientific Journals “Patrimonio Industriale” and “Tema: Technologies, Engineering, Materials, Architecture”. She is responsible for national research projects and research agreements with public and private bodies charged of the safeguard and valorization of the 20^{th} building heritage.

Giacomo Iovane received the Laurea degree (*summa cum laude*) in Building Engineering from the University of Naples Federico II (UNINA) in 2014 and the Ph.D. degree in Structural Engineering, Geotechnical and Seismic Risk from UNINA in 2020. He is Assistant Professor in Structural Engineering at UNINA. Memberships: national scientific committee Timber of ICOMOS (International Council of Monuments and Sites - IIWC); international technical committee IABMAS (International Association for Bridge Maintenance and Safety); international technical-scientific committee ITA (International Tunnelling and Underground Space Association); international technical committee ECCS (European Convention for Constructional Steelwork), TC11 “Composite Structures”, Working Group 6 “Steel-Timber Composite Structures”; international technical-scientific committee Fib Task Group 1.2 - WP 1.2.4 “Submerged/Floating Bridges in Seismic Areas”. His research focused on timber, steel and hybrid structures, seismic engineering, vulnerability of existing buildings against exceptional actions, Submerged Floating Tunnel.

Riccardo Lanari received his Laurea degree in Electronic Engineering (s*umma cum laude*) from the University of Napoli Federico II in 1989. He joined the CNR that same year, working at IRECE and later at IREA, where he was the Director (2010-2021) and is currently Director of Research. He was Visiting Scientist at DLR (Germany), ISAS (Japan), and JPL (USA). He was Adjunct Professor at the University of Sannio and main Lecturer at the Institute of Geomatics in Barcelona (2000–2008). He holds national habilitation as a Full Professor of telecommunications and of geophysics. He is a GRSS IEEE Distinguished Speaker, and has contributed to numerous scientific committees and advisory groups for major space missions. With over 30 years of experience, he holds two patents, coauthored a book, and published more than 600 papers. His awards include NASA recognitions, the Dorso Prize, the Huygens Medal, the Ulaby Award, and the title of Knight of the Order of Merit of the Italian Republic.

Michele Manunta received the Laurea degree in Electronic Engineering and the Ph.D. degree in informatics and electronic engineering from the University of Cagliari, Cagliari, Italy, in 2001 and 2009, respectively. Since 2002, he has been with the IREA-CNR of Napoli, Italy, where he is currently a Director of Research. He was a Visiting Scientist with the Institut Cartografic de Catalunya, Spain, in 2004 and with the Rosenstiel School of Marine and Atmospheric Science of the University of Miami, USA, in 2006. His research interests include high- resolution SAR and DInSAR data processing. More specifically, he works on developing SAR/DInSAR algorithms and techniques for studying deformation affecting surface and man-made structures. More recently, he focused on Cloud and GRID computing exploitation for SAR interferometry applications. He has contributed to various national and international initiatives to exploit satellite SAR techniques.

Francesco Mauro received the Laurea degree in Building Engineering and Architecture from the University of Padua in 2023. He is a PhD candidate at the ICEA Department of the University of Padua. His research focus on integrating technical expertise with GIS and WebGIS tools. Within the FSE-funded SchoolNET project, he contributed to research and outreach activities and developed a digital tool for managing and evaluating school building assets. He also collaborated on projects such as SMUH (Safeguard of Modern Urban Heritage) and LINUS (Living the University City), supporting mapping, data collection, and communication. He is currently involved as teaching assistant in the Urban Planning Techniques and Lab course of the Master of Building Engineering and Architecture at University of Padua.

Alberto Meda received the Laurea degree in Civil Engineering from the Politecnico di Milano in 1994. He is Full Professor of Construction Techniques at the Department of Civil Engineering and Computer Science Engineering. He is Professor of Bridge Construction Engineering and Supplementary Techniques. He is the Coordinator of the TERC Research Centre (Tunnelling Engineering Research Centre) at the University of Rome "Tor Vergata". He is Deputy Chair of the fib (federation international du beton) Technica Council, Chairman of the fib Commission 1 "structures" and Convener of the fib Task Group 1.4 "Tunnels. He is member of the Editorial Board of the Journal "Tunnelling and Underground Space Technology".

Andrea Miano received the Laurea degree in Structural and Geotechnical Engineering in 2014 and his PhD in Structural, Geotechnical and Seismic Risk Engineering in 2018 from the University of Naples Federico II. He is currently an Associate Professor at Pegaso Digital University in Naples (Italy). His main research interests can be summarized in: structural health monitoring of existing constructions (buildings and infrastructures); combined use of remote sensing techniques and artificial intelligence for large-scale monitoring of urban environments; safety assessment of existing structures; performance-based approaches and derivation of fragility curves for existing constructions. He is involved in numerous international collaborations and participates in several research projects coordinated by national or international institutions or private companies. He is the author of numerous publications in international journals focusing on his research topics.

Stefania Mornati, architect, is Full Professor for the ICAR 10 (Technical Architecture) at the Department of Civil Engineering and Computer Engineering (DICII) at the University of Rome "Tor Vergata". She teaches Integrated Design and Projects for Building Renovation and Rehabilitation; she is on the teaching staff of the Doctorate in Civil Engineering "Architecture and Construction". She has taught at the Department of Structures at the University of Calabria and in postgraduate and master's courses (University of Rome "Tor Vergata", University of Cagliari) on the topics of the restoration and conservation of modern architecture. Her research focuses primarily on twentieth-century Italian construction, with particular reference to the history of construction techniques, the relationship between design and construction, and the restoration of modern architecture. Since 2010, she has directed the editorial series "Architecture and Construction of the Project" at Gangemi Editore International.

Zila Rinaldi received the Laurea degree in Civil and Building Engineering from the University of Naples Federico II in 1994 and obtained her PhD at the University of Rome Tor Vergata. She is Co-Convener of the fib Task Group 1.1.7 ": Performance Evaluation and Service Life Extension of Existing Bridges". She is member of the CNR working group "Valutazione della sicurezza di opere in c.a. e c.a.p. soggette a corrosione". Her research activity mainly focuses on the following topics: modelling and analysis of RC structural elements; evaluation of the behaviour of FRC elements; retrofitting interventions of RC and masonry structures with innovative materials (FRP, FRC); residual life of structures affected by corrosion of the steel reinforcement; RC structures subjected to fire action; behaviour of RC and FRC tunnel segments.

Francesco Sartore received the Laurea degree in Building Engineering and Architecture (UniPD) in 2024. He is PhD candidate at the ICEA Department of the University of Padua. His doctoral research focuses on the possible uses of game engine software on the analysis, visualization and design assessments of built environment. He participated to the Erasmus+ project at "Ion Mincu" University in Bucharest and he did his master thesis in collaboration with Duke University Department of Art, Art History & Visual Studies. After graduation, he started his research activity on the T.E.A.C. Project (iNEST founded) where, through an interdisciplinary approach, he helped to develop a methodology for data interpretation and relate them to the urban representation of pre-Alpine area. He is also currently working on I_BRIDGE and SMUH projects in ICEA Department and Verona Municipality for the digitalization of documentary heritage using BIM tools.

Luigi Siviero received the Laurea degree in Architecture at the University IUAV of Venice and PhD at the Trento University. He is a Researcher at the Department of Civil, Architectural, and Environmental Engineering at the University of Padua, where he taught Architectural and Urban Design (Master's Degree in Architectural Engineering) and teaches Landscape Protection and Design (Master's Degree in Environmental Engineering). A member of the UniPD-ReLOAD – REsearch Lab of Architecturban Design laboratory, he focuses his research on strategies and scenarios for transformation of cities and landscapes, particularly those characterized by the presence of mobility infrastructure, investigating potential related intervention and regeneration actions. He approaches this topic at all project scales, experimenting and validating theoretical experiences during many workshops, seminars, and conferences, and participating in national and international research groups.

Pasquale Striano received the Laurea degrees in Telecommunications Engineering from the University of Naples Federico II, Naples, Italy, in 2011 and 2014, respectively, and the Ph.D. degree in signal processing from the University of Strathclyde, Glasgow, U.K., in 2021. Since 2021, he has been with the IREA-CNR, Naples, Italy, where he is currently a Research Scientist. His main research interests include the development of methodologies for synthetic aperture radar (SAR) signal and data processing, as well as advanced differential SAR interferometry (DInSAR) algorithms for monitoring surface displacements associated with natural and anthropogenic hazard phenomena. He has also been involved in the development of automatic tools and parallel processing chains for efficiently generating advanced DInSAR products by exploiting a huge amount of SAR data acquired by multi-frequency SAR constellations.

Diego Alejandro Talledo received the Laurea degree in Civil Engineering from the University of Padua in 2009, and in 2013 he obtained his PhD in "Mitigation of Risk Due to Natural Hazards on Structures and Infrastructures" as part of the joint PhD program between the University of Florence and Technische Universität Braunschweig. He is Associate Professor of Structural Analysis and Design at IUAV University of Venice. He was a member of the CNR (National Research Council) working group for Guidelines for Assessing Structural Robustness. His research interests mainly focus on: coupled mechanical-environmental damage models for reinforced concrete structures, seismic analysis of reinforced concrete and masonry structures, vulnerability of historical buildings, behavior of wooden building, study of the biaxial behavior of connections and walls, robustness of buildings, and the use of satellite data for structural monitoring.

Ivana Zinno received the Laurea degree (*summa cum laude*) in Telecommunication Engineering and the Ph.D. degree in electronic and telecommunication engineering from the University of Naples Federico II, Naples, in 2008 and 2011, respectively. In 2011, she received a grant from the University of Naples for research in the Department of Electronic and Telecommunication Engineering. Since 2012, she has been with the IREA-CNR of Napoli, where she is currently a Senior Researcher. In 2017, she was a Visiting Scientist with the Jet Propulsion Laboratory, USA. Her work is mainly focused on the development of advanced DInSAR techniques for the generation of time series of surface displacement aimed at monitoring Earth surface deformation due to both natural and anthropic phenomena.

ILARIA GIANNETTI, Architect, Associate Professor of *Architettura Tecnica* at the Department of Civil Engineering and Computer Engineering (DICII) of the University of Rome Tor Vergata.

ANGELO BERTOLAZZI, Engineer, Associate Professor of *Architettura Tecnica* at the Department of Civil, Architectural and Environmental Engineering (DICEA) of the University of Padua.

ANDREA MIANO, Engineer, Associate Professor of *Tecnica delle Costruzioni* at the Pegaso Digital University of Naples.

MANUELA BONANO, Engineer, Researcher working on SAR interferometry at IREA-CNR (Consiglio Nazionale delle Ricerche) of Naples.

LUISA BERTO, Engineer, Associate Professor of *Tecnica delle Costruzioni* at the University IUAV of Venice.

This volume collects the results of the multidisciplinary research project funded by the PRIN 2022 grant, "SMUH – Safeguard of Modern Urban Heritage: a cross-disciplinary webGIS for knowledge, monitoring and risk analysis", presented at the conference held on December 16th, 2025, at the University of Rome Tor Vergata.
The research aims to develop, test, and share a multidisciplinary method for safeguarding the built heritage in urban areas of the twentieth-century city. This method is based on a combination of a historical-technical framework derived from extensive documentary research, large-scale structural vulnerability assessments, and satellite radar interferometry techniques for measuring surface displacement phenomena. To support analysis and dissemination, the research relied on the construction of a customized webGIS platform, featuring three-dimensional representations and governed by conceptual models of informational data.
The method was tested on exemplary case studies within the twentieth-century districts of Verona: this area, overlooking the Adige River, presents a diverse range of building typologies and construction techniques, as well as complex environmental conditions. Alongside the research results, the book gathers a collection of further case studies to test the scalability, disciplinary potential, and future research trajectories opened by the application of this method.

FrancoAngeli
La passione per le conoscenze