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EDITORIAL
TOOLS FOR THE KNOWLEDGE OF THE BUILT HERITAGE

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The contributions in this volume deal with the topic of the tools of knowledge for the built heritage following two different research lines.

The first one, belonging to the disciplinary field of Construction History, deals with the study of unique cases in order to investigate the relations established between architectural outcomes and construction solutions, with the aim of clarifying the importance that technical knowledge plays in translating a design idea into a built product. Within this framework lie the contributions that deal with some masterpieces designed by leading figures in Italian architectural production of the second half of the twentieth century, such as Renzo Zavanella, Ignazio Gardella, and Pier Luigi Nervi. Another contribution presents two significant examples of steel buildings in Milan that underwent an interesting renovation project. Finally, the contribution focusing on industrialization systems for building prefabricated thin vaults in Latin America in the second half of the twentieth century concerns the relationship between the know-how based on the construction practice and the one based on innovation through the use of standardized methods and processes.

The second line, on the other hand, focuses on the use of digital tools and processes that enable the showcase of different levels of information, ranging from the methods of surveying and representing a built object to those that identify its performance and conditions of use.

In this polarity, the scientific contributions presented here must be evaluated between the hermeneutic dimension of historical investigation and the analytical-instrumental dimension of the engineering kind. They all provide interpretative keys and operational methodologies useful for understanding the heterogeneity condition that defines the built heritage. For this very reason, this field is a fruitful harbinger of multiple research interests.

STEEL ARCHITECTURE AVAILABLE FOR ALL. RENZO ZAVANELLA'S WORK BETWEEN DESIGN AND PRODUCTION (1946-1958)

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Laura Greco, Francesco Spada

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Abstract

Renzo Zavanella stood out in the Italian framework for the research of architectural and construction solutions, which, taking advantage of steel construction, aimed at the mass production of buildings using prefabricated, demountable, reusable elements. Zavanella's efforts to collaborate with the manufacturing sector, which was oriented toward the massive diffusion of steel architecture in the 1950s, are not well known. Through the analysis of key buildings, this study aims to highlight this collaboration.
Between 1946 and 1958, there were two phases of the architect's work: the first one concerned the construction of OM temporary exhibition pavilions (1946-1953); the second one, linked to the collaboration with UISAA and CECA, concerned prototypes for the assembly production of buildings. The steel structure service station (1954) represented the first project for the mass production of buildings, but the prototype was not built. The acme of this phase coincided with Expo 1958 when Zavanella developed a steel structure house project for UISAA, involved in the construction of the CECA pavilion. Budget problems forced the reduction of work; Zavanella reviewed the project for the exhibition, but the weakness of the context in which he worked manifested itself again.
The contemporary Italian construction developments confirmed the obstacles that affected Zavanella's work. Mass-produced buildings and the idea of a steel construction available for all remained largely unimplemented.

Keywords

Italian construction history, Steel construction, Exhibition, Industrialization, Mass production building.

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1. INTRODUCTION

In the 1950s, Italian steel construction developments were marked by the effects of the activity of the European Coal and Steel Community (CECA), founded in 1951 to create a common market for coal and steel. Belgium, France, the Federal Republic of Germany, Italy, Luxembourg, and the Netherlands became members. In Italy, in the field of building construction, CECA's work was conducted by the Italian Steel Applications Development Office (UISAA), by the Association of Steel Builders (ACAI), and by the College of Steel Technicians (CTA). Renzo Zavanella (1900-1988), an architect from Mantua interested in the relationship between project and industrial production on the scale of objects and architectural design, participated in these events. The results of the steel construction promotion program in the national context were conditioned by the Italian designers and builders' lack of familiarity with the technique and by the caution of users towards steel architecture. The frequent application of this option was favored in extra-residential fields (i.e., offices, factories), thanks, above all, to large public and private clients, such as Eni, Rai, La Rinascente, and Olivetti [1].

These cases concerned unique buildings, in which the use of the metal components corresponded with a proto-industrialized phase far from the mass production of construction systems and standardized buildings. It was more oriented towards the construction of iconic tall buildings, large roofs and curtain walls. In fact, the Italian experimentation on the steel house, which began in the interwar years – pilot cases were the houses of the 1933 Triennale – struggled to restart after the war. Building industrialization remained a theoretical question with sporadic applications in the debate on construction techniques for reconstruction. The slow post-war conversion of the steel industry and the hegemony of masonry and reinforced concrete techniques, supported by public programs, consigned steel construction to the margins of the reconstruction phase and expansion period of the 1950s. There were many reasons for this: the predilection of masonry and reinforced concrete techniques in public programs; the predominant structural research on reinforced concrete by the masters of Italian engineering; the consequent development of investments in the Italian manufacturing sector, as a consequence of the circumstances mentioned above, towards reinforced concrete, with a limited repertoire of wall components and finishings for steel structures buildings; the artisan organization of the manufacturing sector and of the design process that slowed down the industrialization of the building process; the slow diffusion of the prefabrication in the housing field and starting from reinforced concrete systems. Indeed, it was only in the early1960s that the *Prà Italsider* district in Genoa (1960-1961) documented the attempt to relaunch experimentation on the steel house for large projects, which nevertheless remained a niche solution on the national scene and was rarely characterized as an option for mass housing [2]. The use of metal components associated with a concrete structure was more frequent, as happened in tall buildings with the spread of the curtain wall, a sign of the slow adaptation of the construction sector to the industrialization of the building site. The work of Renzo Zavanella stood out in this framework for the research of architectural and construction solutions, which, taking advantage of steel construction principles, was aimed at the mass production of buildings using prefabricated, demountable, reusable elements. The most recent studies conducted on Renzo Zavanella, based on readings developed in the 1980s [3], have highlighted the relationship between the architectural design process and the aesthetics of the industrial components in his work [4]. Studies done in the early 2000s in the field of construction history have indicated the designer's contribution to the development of suspended cable roofs in Italy in the 1940s-1950s [5]. Zavanella interpreted this type of roof, synthesizing the aesthetic values of the "poetics of the filiform" of a rationalist matrix [6] with the mastery of steel construction.

However, Zavanella's efforts to collaborate between design and manufacturing sectors, oriented at the massive diffusion of steel architecture in the daily life of the Italian 1950s society, are less known. Through the analysis of relevant buildings designed by Zavanella, dating back to the period 1946-1958, and of some emerging features of his approach to steel construction, this study aims to highlight this collaboration to enrich the knowledge of the steel construction history in Italy in the second half of the twentieth century.

2. RENZO ZAVANELLA AND THE ITALIAN STEEL BUILDING CONSTRUCTION INDUSTRY

Renzo Zavanella trained in Milan, where, in the 1930s, he participated in the development of advertising and exhibition architecture. The agreement established with Officine Meccaniche (OM) in 1946 marked a turning point in Zavanella's career and in the events of the Italian steel construction of that moment. After the war, his participation in the *Movimento per gli Studi di Architettura* (MSA) (Architectural Studies Movement) introduced Zavanella to the unification and standardization issues debated in the years of building reconstruction, training him to explore the aesthetics of the *civilization of machines* in domestic and working spaces.

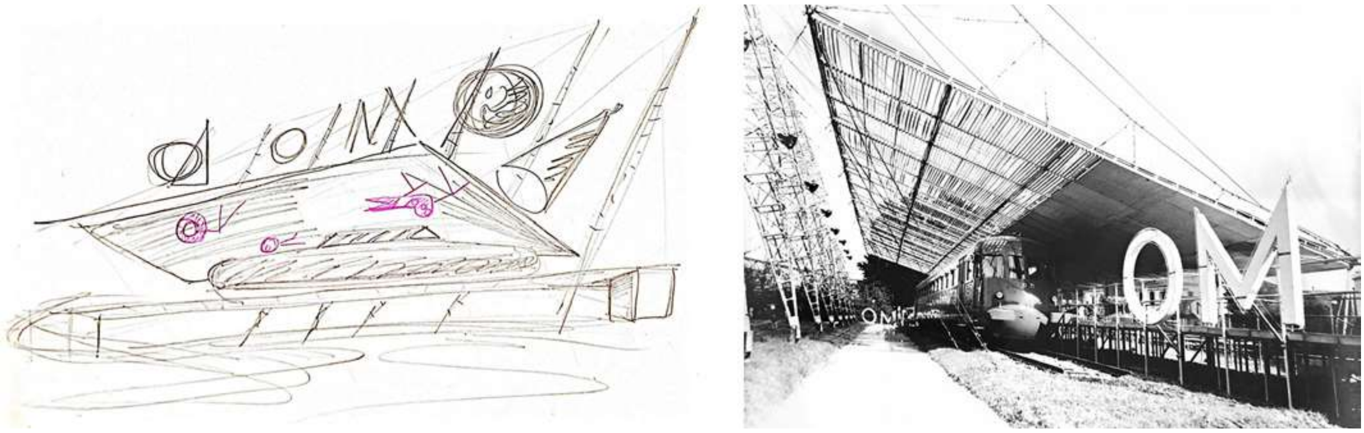

Fig. 1. *The OM shelter at the Fiera Campionaria of Milan, 1950. Preliminary sketch and the built stand. Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

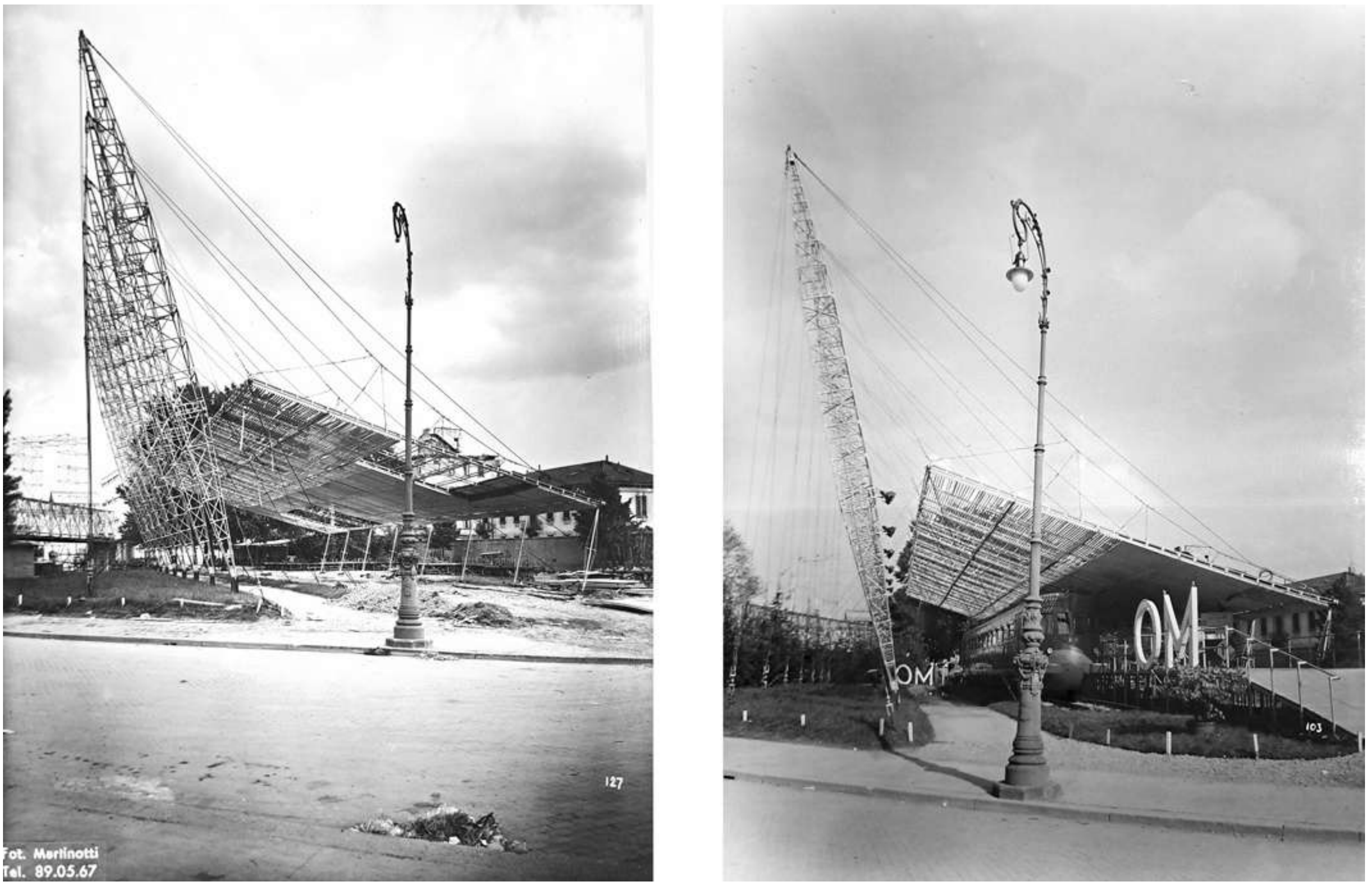

Fig. 2. *The OM shelter at the Fiera Campionaria of Milan, 1950: the canopy under construction (left) and the realized building with the suspended cable roof (right). Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

Zavanella's investigation started with the inventive exhibition structures for OM at the Milan Fair (1946, 1948, 1950, 1953) and continued with the Finmeccanica pavilion for the X Triennale (1954), the project for the Dalmine motorway service station (1954), and then the Steel House for the 1958 Expo in Brussels. The use of steel, the exaltation of static flows, of connections, of the filiform silhouettes of the rods, forged the language of these works, in which Zavanella managed the code of steel construction with enthusiastic optimism as a «direct interpreter and creator of particular living conditions of Man» [7], that is those of modernity, to which he looked with convinced trust in technology. Therefore, Zavanella aimed to achieve mass diffusion of metal construction. However, he urgently needed to overcome the difficulties that inhibited this trend in Italy. Among the problems that affected the Italian context, he identified the still immature relationship between designers and manufacturers in the coordination of resources in the optimization of design and construction processes as one of the weak points of the Italian background. Zavanella's ten-year work with privileged interlocutors such as the UISAA, with companies such as Dalmine and, finally, with the CECA represented an attempt to counter this weakness.

Zavanella's tenacity supported his work as a privileged designer, accredited by clients-promoters of steel architecture, which recognized him as a precious ally for the development of consistent policies on metal construction, as well as a designer skilled in making the technique a spectacular matter. The development trajectory coincided with the series of stands and prototypes he curated for the exhibitions. The analysis of the buildings helps to clarify the experience and to place Zavanella's work in the Italian context of those years, highlighting – according to this study – two phases in the architect's work between 1946 and 1958. The first, linked to the collaboration with OM, concerned the construction of temporary exhibition pavilions and the spectacular use of steel construction. The stands and pavilions were a springboard for Zavanella's research into a broad use of steel, not limited to elite experiences and the iconic construction sites of large clients. The Fiera Campionaria in Milan constituted a decisive testing ground. The resonance of the event put the public in contact with the stands designed by Zavanella and fed public interest in these new architectures. At the same time, the Milanese successes did the groundwork for accrediting Zavanella at organizations such as UISAA and CECA as a skilled metal construction designer and helped him strengthen his relationship with industrial clients. The second phase of Zavanella's work, linked to his collaboration with UISAA and CECA and to a mass diffusion of steel construction, concerned the design of prototypes for the assembly production of buildings.

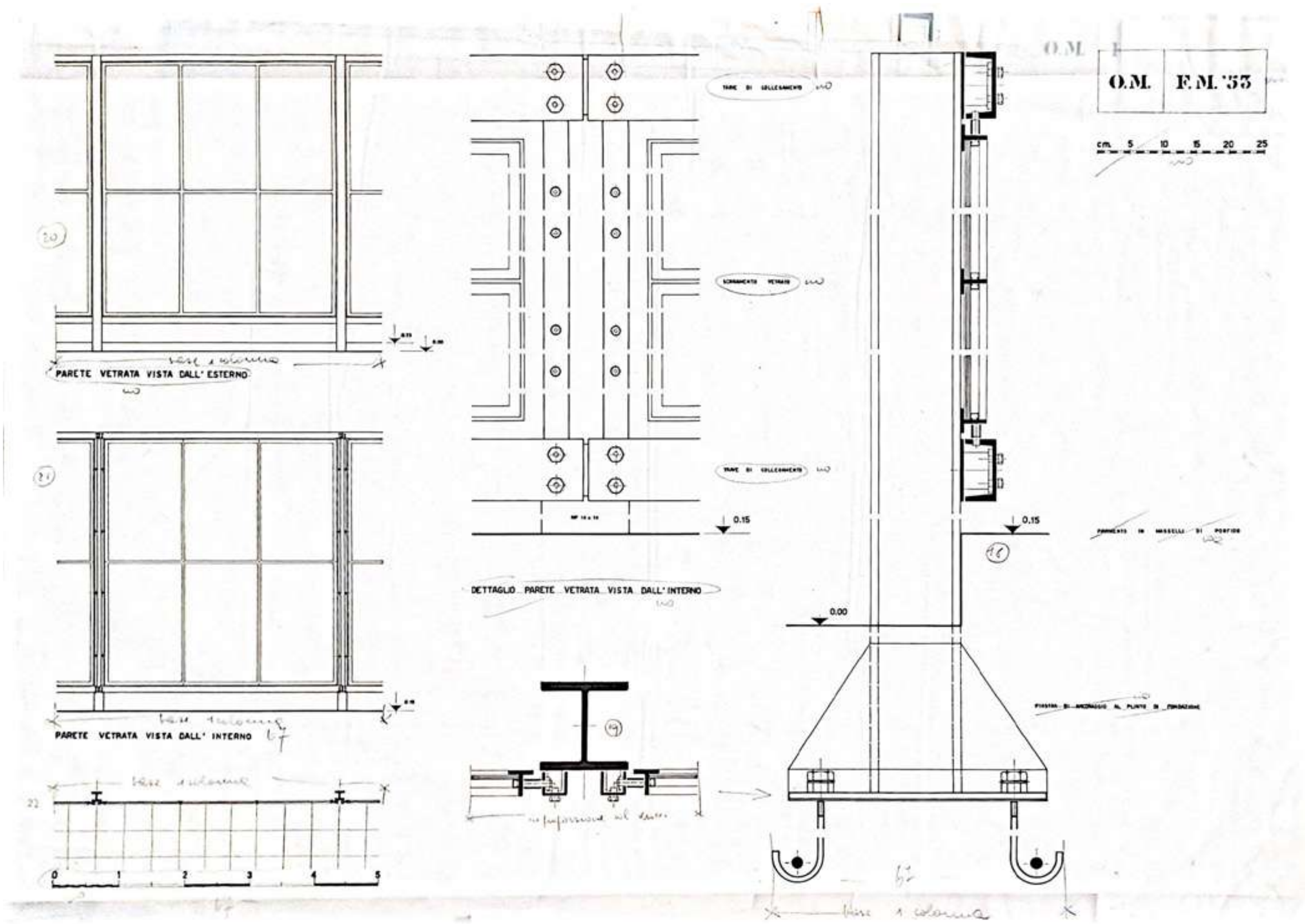

Fig. 3. *The OM pavilion at Fiera Campionaria of Milan, 1953: construction details of the façade by Renzo Zavanella, highlighting the connection between the steel pillars and the glass façade. Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

The project for the steel structure service station for the X Triennale marked the transition to this new phase of Zavanella's program. It represented, in fact, the first project for the mass production of buildings. For Zavanella, it was a demonstration of the possibility of impacting the construction market with cheap, standardized, demountable solutions. On this occasion, Zavanella exhibited his idea of a building to be mass-produced, then reformulated a few years later at the UISSA and the CECA with the participation of the Steel Community at the Brussels Exhibition of 1958. In the 1954 exhibition, Zavanella was also very attracted to service buildings for transport systems as a field of experimentation for mass production. He considered this type of building «one of the liveliest and most current aspects of the needs of modern man» and positively evaluated the realization of typical elements for motels or service stations. He believed that «typical constructions such as these could be resolved on the level of a highly studied integral prefabrication to be able to be saved after the exhibition and then assembled even at a great distance» [8]. The acme of this second phase coincided with the 1958 Expo in Brussels. Zavanella was a member of the UISAA working group for the design of the CECA pavilion. His goal remained the effective collaboration with a client, promoting the development of an aesthetic of steel in the spaces and objects of daily use. The occasion was a steel structure house project with prefabricated and demountable elements. With this project, he intended to demonstrate how «a steel house can solve the housing problem both functionally and economically given its possibility of being mass-assembly production» [9].

3. THE EXHIBITION PAVILIONS: SPECTACULAR STRUCTURES

After WWII, in the Fiera Campionaria of Milan, which reopened with the reconstruction of the fair district, metal construction had prominence, with Gino Covre's large roofs, such as the two exhibition halls for the 1950 edition and the Meccanica Pesante pavilion for the 1951 exhibition (100 m of span). In addition to these examples of large roofs, the fair also stood out for its developments in small temporary constructions, such as the Guest House (1949) and the tower built for Fiat 1950, using tubular-section mullions, U-section cross-bands, and lattice elements. Pavilions marked the character of the exhibition, in the construction of which Zavanella's work emerged for the spectacularity of the roofs, as proved by the 1946 OM stand. Two years later, the first case linked to the large metal roofs that marked Zavanella's involvement at the Fiera of Milan advanced. The 1948 OM shelter was one of the first Italian examples of suspended cable roofs, which was resolved with the composition of a large, inclined flat surface (30 m x 5.50 m) and six lattice trees (14.50 m high) with a tubular section to which the cable system was anchored. In 1950, Zavanella presented a variant of the 1948 stand at the Milanese fair: it was the shelter for the exhibition of the OM ALN 990 railcar. It was a pavilion consisting of a 1-metre raised walkway and a 35-metre-long canopy, with a maximum height of 18 m. The structure of the shelter was as essential as it was spectacular. Zavanella studied the shelter in numerous preliminary sketches, considering the incidence of the sun's rays and the geometrical composition given by the combination of the flat surface and the inclined supports (Fig. 1). The result was, as Zavanella wrote, a canopy "entirely hovering in space", suspended from a network of rods anchored to eight spindle-shaped supports, arranged at a distance of 5 m (Fig. 2). In 1953, Zavanella was once again the protagonist of the Milanese fair with a new OM pavilion, 45 m long, 8.40 m wide and 6.50 m high, on which a lattice roof was arranged. The plan of the building was organized on a 125 cm x 120 cm grid. The longer side of the module regulated the composition of the front, made up of 125 cm panels, and the arrangement of the pillars, placed at a distance of 3.75 m.

The structure of the building consisted of pillars connected to the crosspieces, arranged 45 cm from the ground and in correspondence with the roof structure. The beams had a section consisting of a C profile (100 mm) and a flat iron, while the roof consisted of trusses (primary and secondary) 10.80 m long and arranged at a span of 1.25 m. The sections of the bars of the trusses consisted of channel section, T-bar, and angle-bar profiles (Fig. 3). The intrados of the roof was clad by wooden matchboarding, while the external cladding was

Fig. 4. *The OM pavilion of 1953 under construction. Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

made of corrugated aluminum sheets (Fig. 4). The ceiling of the pavilion consisted of modular panels of steel grids (Keller type), which shaded and diffused the light (Fig. 5).

In the same decade, Zavanella contributed to the cultural laboratory of the Triennale with research on buildings related to the diffusion of mass motorization in Italy [10]. In 1954 (X edition), he was curator of the *Architetture in Movimento* section and designed, with Giulio Minoletti and Mario Tevarotto, the Finmare-Finmeccanica pavilion, created to house an exhibition of drawings, photographs and components of naval buildings and furnishings. The building was part of the exhibition, destined, as Zavanella wrote, to host «those constructions which should be understood as real cinematic architectures» [11]. The pavilion was conceived as a promenade on the water, developed on a walkway that extended from one side of the lake to the other in the Triennale park. In the middle part of the path, the walkway was protected by a flat roof arranged on a series of pillars organized on

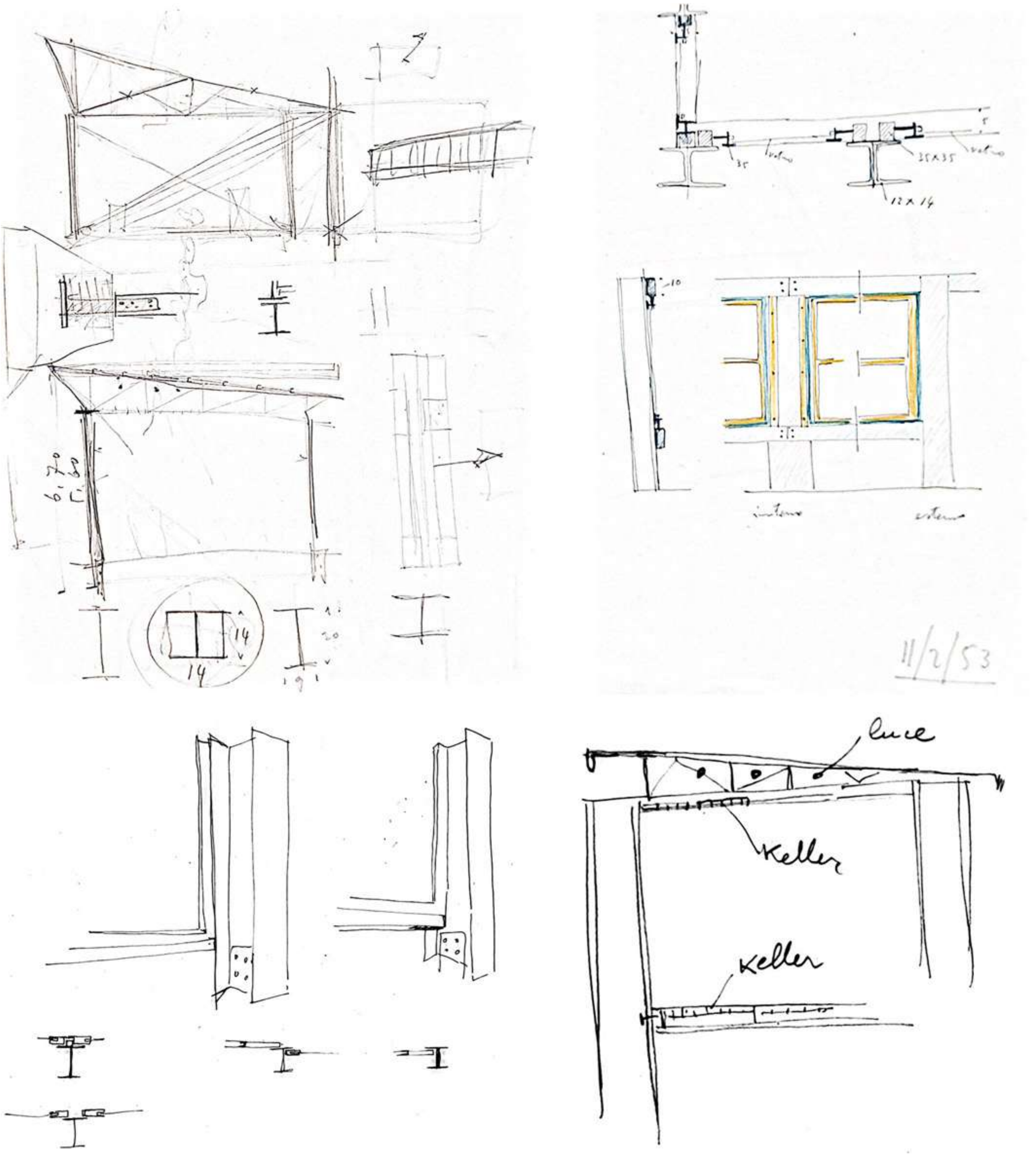

Fig. 5. *The OM pavilion in 1953: preliminary sketches by Zavanella concerning the typical pavilion section, the joints between pillars and beams, and pillars and glass façade. Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

a modular grid with a square base (2.80 m x 2.80 m). This central part of the path was the actual pavilion made up of demountable steel elements (Fig. 6). The structure consisted of 36 columns, whose base was placed at the bottom of the pond. Their section comprised four angle bars welded together and spaced by metal blocks (Fig. 7). These 36 pillars were connected to each other by beams with a section composed of a U-profile and flat iron. The beams were arranged at the level of the walkway and in correspondence with the roof structure. Purlins were

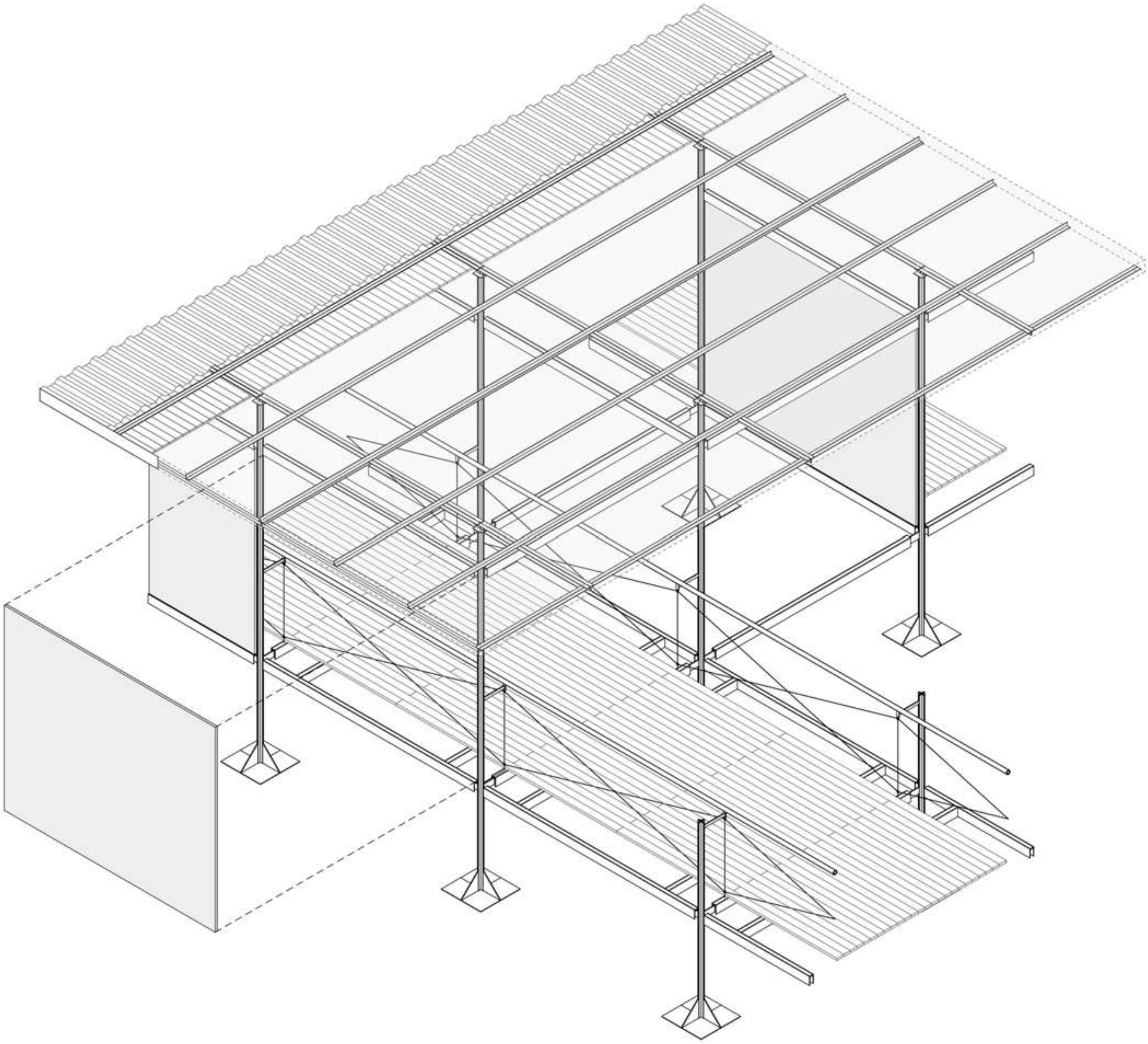

Fig. 6. *Scheme of the construction system implemented for the Finmare pavilion at X Triennale of Milan, 1954: steel beams connected pillars under and above bracing panels (also used for exhibitions); lower beams supported the wooden floor of the walkway; purlins (L section) were placed on the steel structure to support the folded roofing sheet panels and the wooden ceiling. Source: image elaborated by Francesco Spada, 2024.*

placed on the main steel structure to support the corrugated galvanized steel sheet panels.

4. THE DALMINE SERVICE STATION. THE FIRST PROJECT FOR MASS PRODUCTION

In the 1940s-1950s, the design of service stations was based on metal construction. Consider, for example, the work of Andrea Marchetti, which focused on the use of elements that could be combined in configurations for small, medium and large stations for urban areas, and the series of urban service boxes developed by Agip. Marchetti started with typological studies on the new motorway service buildings and used metal construction as an effective option for prefabricated stations. Zavanella participated in this framework, albeit following a different path, taking steel as a material and technique effective to express various modern architectural typologies, including stations. Marchetti and Zavanella shared an interest in canopy design, which was considered a key element of the station's aesthetic and construction system [12]. In Zavanella's project, it became an iconic sign, exploiting the potential of technology to give spectacular features to the architecture of the small object in continuity with the pavilion roofs. Comparing the steel station project with the following service station designed by Zavanella for Motta in the 1960s-1970s, it is noticeable a different aesthetical language of the metal construction, in which he merged the vernacular approach required from Motta with the insertion of industrial components such as HE and IPE profiles, and sandwich panels [13]. The architect evolved his approach from the spectacular dimension of the large canopy to the domestic scale of the Motta restaurants, preserving the key role of the steel components in the representation of modern spaces. Zavanella's work was a particular expression in this field, comparable to the use of steel – even if his realizations were few – with the series of Pavesi and Motta highway bridge-restaurants. Steel service station for 1954 Triennale testified his first contribution to highway architecture.

In December 1953, the first documented contact between Zavanella and the UISAA took place to agree on the institution's participation in the X Triennale of Milan. The architect demanded that the UISAA management create a prototype of a single-family house or a portion of an apartment building with an all-steel structure, finishes and furnishings. The architect also introduced the option of a highway service building, such as a service station or motel.

In a letter dated December 1953, Zavanella specified the objectives of the project, which, beyond the typology of the prototype, had to have «a technical, construction and economic form and substance whose features can affect the wider problem of the house steel structure» [14], thus highlighting the issue of the diffusion of steel in the housing sector, going against of the Italian construction mainstream of those years.

Ultimately, Zavanella's project focused on a motorway service station. It included a box (6.50 m x 4.20 m) for assistance and sales services to travelers and a sunshade canopy extending over the service area. The element of great interest in the project was the shelter, 7.90

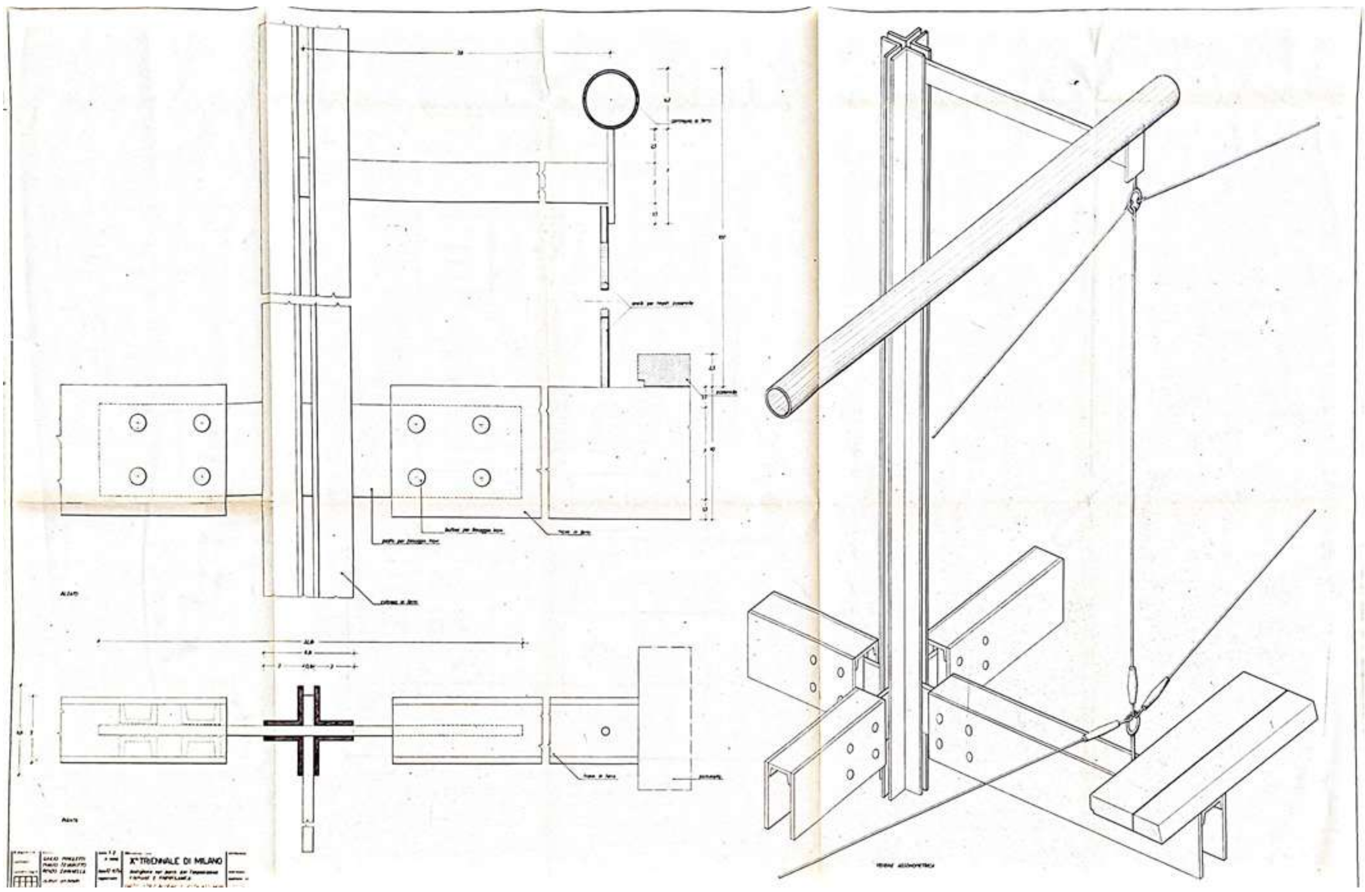

Fig. 7. *The Finmare pavilion at X Triennale of Milan, 1954: construction details by Zavanella. The section of the steel columns is noteworthy, made up of four angle bars welded together and spaced by metal blocks. Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

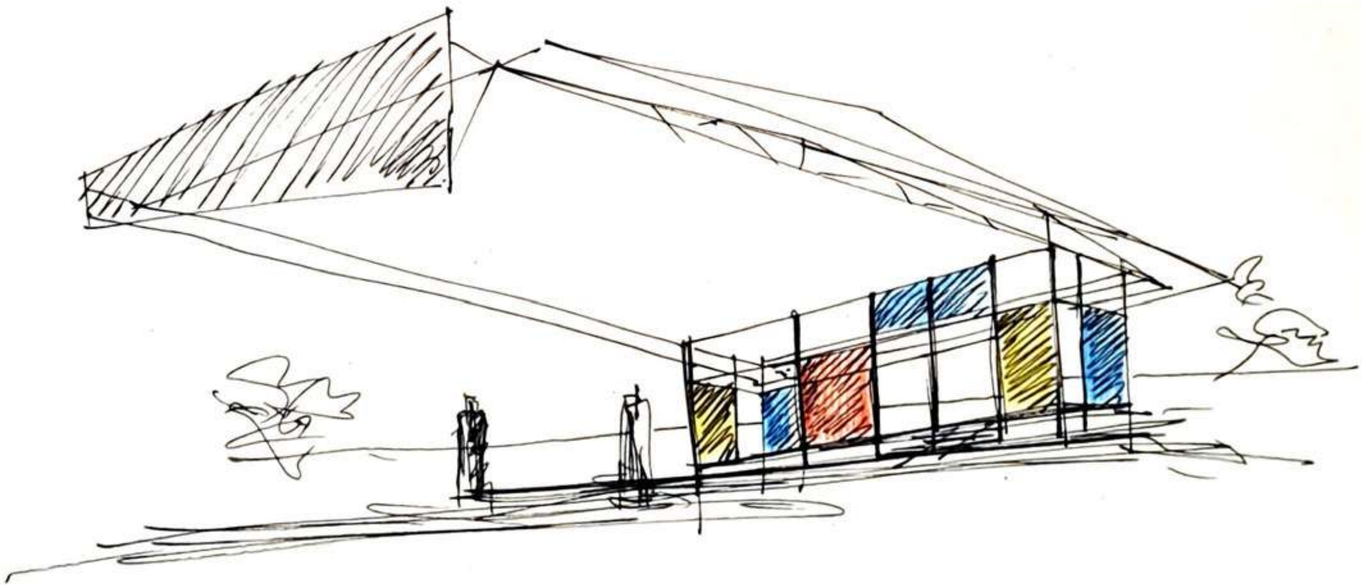

Fig. 8. Dalmine Station *at X Triennale of Milan, 1954: preliminary sketch by Zavanella. Noteworthy are the great canopy and the use of different colors for the modular panels of the box. Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

m long and supported by metal lattice beams arranged on uprights placed on the perimeter of the box (Fig. 8). The cladding of the steel structure was made up of aluminum sheet panels on the extrados and of plastic material panels on the intrados. The structure of the cabin and the shelter were completely prefabricated and could be disassembled. The external walls consisted of components with a metal frame and glazing panels. Some parts of the walls were made up of opaque panels of insulating material with a brightly colored plastic coating. During the winter of 1954, contacts with the UISAA management continued, but the institution could not support the prototype's creation. In the spring of 1954, the Società Dalmine took over, giving a favorable opinion on Zavanella's preliminary drawings and developing one by its technical department dating to 6 April 1954. The Dalmine station was based on a 1.125 cm module and a typical planimetric unit of 4.50 m x 2.25 m [15], updated in a second version with a canopy (17.50 m long) [16]. Zavanella wrote to the UISAA manager Eng. Del Grosso informed him in June 1954 that the station would be built by the Società Dalmine. After a few days, it was Del Grosso himself who congratulated Dalmine and recommended the involvement in the project of the National Research Council (CNR) that was interested in promoting «productivity in building construction», establishing the presentation of the project as "Dalmine construction on the initiative of UISAA" as a condition of the agreement [17]. At this point, the contacts established by Zavanella between promoters and producers in the steel sector around the project of a steel prototype for the X Triennale seemed to translate into a decisive test for the diffusion of the material and technique in the Italian construction scene. However, the weakness of the context in which Zavanella worked did not take long to manifest itself. In early July, Dalmine wrote to the Mantuan architect to acknowledge that the station project had stopped [18]. So, nothing was done. The Dalmine station project did not reach the X Triennale, and the test of the steel mass diffusion program was postponed.

5. THE STEEL HOUSE FOR THE 1958 BRUSSELS UNIVERSAL EXHIBITION. THE EUROPEAN CONTEXT

The opportunity for Zavanella reoccurred a few years later. On 6 December 1955, a meeting of the CECA working group was held in Paris to discuss the institution's participation in the 1958 Brussels Universal Exhibition. It was decided to entrust the development of the various program points to be treated in the sections of the CECA pavilion to the Information Centers of the member countries [19]. Each Information Center (for Italy, the UISAA) was required to indicate an architect expert in the field of exhibitions. Zavanella participated in the first steps of the UISAA work. In a document dated 2 April 1956, the architect summarized his vision of the project, noting that the intent would be to «make known the importance assumed by steel understood not as a means of production, but as a product protagonist of direct and immediate relationship with the life of Man in his most diverse and distant needs, humble or important» [20]. The complex coordination between the various CECA countries determined constant changes to the pavilion's program. In the end, UISAA would be entrusted, among other things, with constructing a pilot single-family steel house designed by Zavanella. The Brussels project was part of the repertoire of prefabricated single-family houses developed in Italy starting from the 1933 Triennale and enriched with the prototypes of the 1954 exhibition, including the mountain house by Baldessari and Grisotti, the B24 house by Ravegnani and Vincenti, and the single-family house by Ponti, Rosselli and Fornaroli. In these buildings and other subsequent ones, such as the Minolina series designed by Minoletti for Holiday, all conceived as holiday homes, the metal structure was combined with wall and floor components of various types and, as in the prototype by Ravegnani and Vincenti, it was exhibited as an essential part of the aesthetical system of the house [21]. In Zavanella's prototype, on the other hand, steel was the basic material used for the structure and for the finishing and furnishing elements,

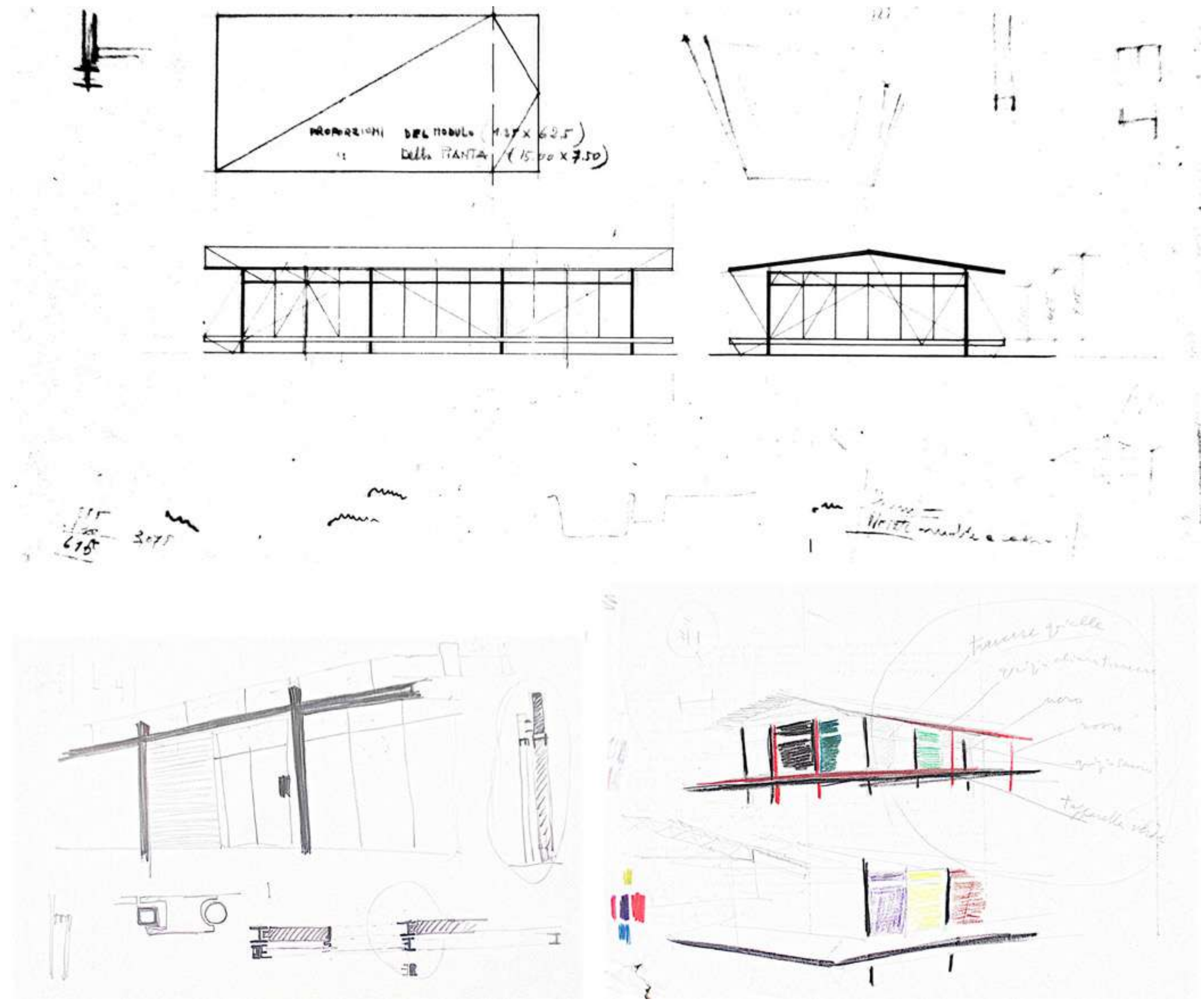

Fig. 9. *Steel house at the CECA pavilion, Expo 1958 in Brussels. Preliminary sketches by Renzo Zavanella. Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

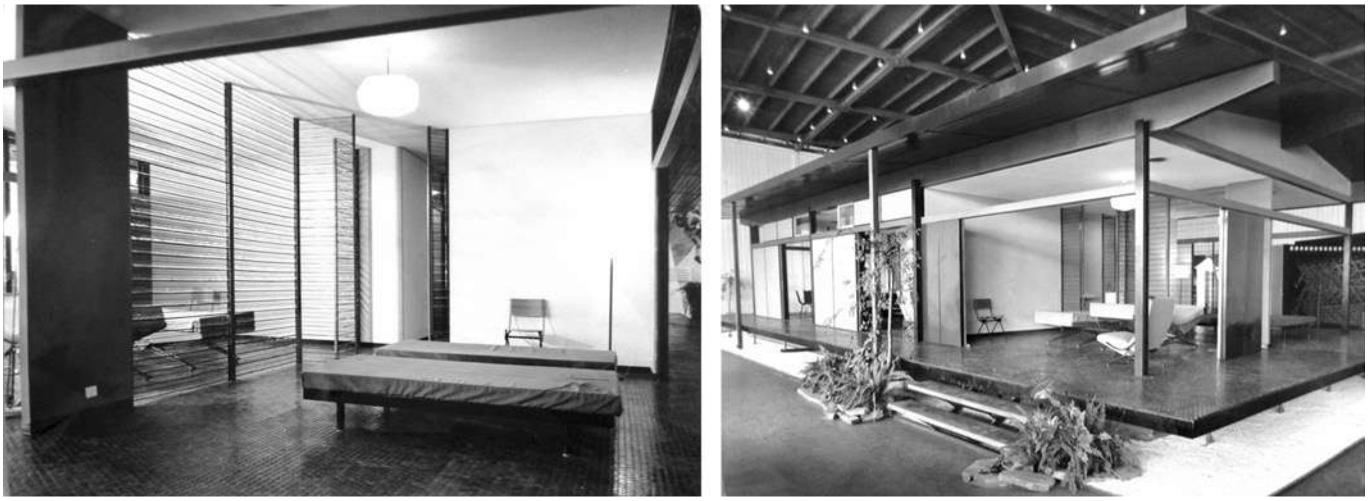

Fig. 10. *Steel house at the CECA pavilion, Expo 1958 in Brussels. View of the prototype. Source: CSAC, Università di Parma, Renzo Zavanella Collection.*

an expression of the aesthetical and construction system of the building. We can note that it was the application of a promotion program similar to the campaign on the use of steel developed in the 1930s, which can be summed up in the call launched by *Casabella*, "Built in steel" [22], and that Zavanella revised, aiming at the diffusion of a catalogue of small buildings. The house was designed to be assembled, disassembled, and reassembled, thanks to the modular nature of the elements, constituting a proving example of a catalogue house. Furthermore, if in the exhibition pavilions, the disassembly of the construction was ordered by the planned use of the buildings, in this case, the temporariness and lightness of the construction were a new and courageously antithetical issue of the domestic space, built on the values of permanence and mass typical of the masonry technique, to which the Italian tradition was anchored. Concerning the concept of temporariness related to demountable buildings, Zavanella pointed out that «the house thus prefabricated does not denounce the weakness and temporariness associated with other similar constructions. Even though it is fully advanced in its conception, taste, materials, and construction systems, it assimilates the tradition of the home understood in its essential and eternal values: solid, protective, durable, welcoming, and intimate, small, and yet large, a true sign of peace and civilization» [23].

The volume of the building is essential and corresponds to the principles of steel construction. Only in the design of the roof did Zavanella renounce the correspondence between the modernity of technique and innovation of architectural language, preferring the profile of the pitched roof to make the prefabricated object more similar to traditional housing models.

In the preliminary project, the structure of the house included uprights with a square, rectangular or T-section and connecting beams arranged to support the guides of the external doors and windows and the perimeter walls and, on the fronts of the building, to support the roof structure (Fig. 9). In the built prototype, the structure of the house consisted of 8 pillars set on a reinforced concrete foundation plinth. In contrast, the structure of the floor, confirmed in the built version, was made up of T-section profiles (Fig. 10). The perimeter walls were planned and built of demountable modular elements, made up of panels with external cladding in enameled sheet metal, internal finish in gypsum plaster laid on a "Nervometal" support mesh obtained from cold-rolled steel strips, and interposed thermal insulating layer.

The events related to the assembly of the house document the troubled transition from the design phase to production and the construction site, highlighting the difficulties encountered by Zavanella in coordinating the specific issues of the prototype with the complex bureaucratic machine of the CECA and in transporting the components produced in Italy by Officine Bruno Cavaglieri to Belgium. Budget problems forced a decisive reduction of the work. Zavanella reviewed the project for the exhibition. The entire structure of the house was built, and the living room area was completed, while the other rooms were delimited only by the floors and ceilings. At the end of the exhibition, in the absence of specific drawings, the disassembly of the prototype was difficult, distressing one of the assumptions of Zavanella's program [24].

6. CONCLUSIONS

The analysis of Zavanella's work in the two phases – the exhibition pavilions and the projects for mass construction – highlights some predominant and invariant features in the architect's approach.

First, with reference to the use of the technique, we can observe that Zavanella conquered its avant-garde position in steel construction thanks to the research on the adjustability and disassembly of the construction system and to the ambition of the aesthetics of steel that he developed from the 1950s projects to the following realizations of the 1960s, such as the BPM offices and facilities. The 1950s buildings were fundamental in the definition of this path. The bolted unions between beams and pillars and the use of dry-assembled floors (in the OM pavilion of 1953 and the Finmare pavilion) match the issue of the demountable construction system, which he developed beyond the temporary nature of the exhibition buildings. Likewise, the study of the construction details, testified by the preliminary sketches of the nodes of the various structures, is a sign of the control of the technique, which moves towards the definition of an architectural language of steel construction, articulated through the colors used to highlight the static and construction relationships between the elements.

Secondly, as we consider his program for promoting steel as a technique available for all, some remarks can be raised. According to early studies on the Italian architect, he developed his ability to use mass industrial production as a «tool of language rather than of functional organization and economic rationality» [25]. However, it is possible to outline a further contribution, suggesting a wider role of the Italian architect in the steel construction background. In the 1940s-1950s, Zavanella's clients were agencies in charge of the industrialization of building production; they were responsible for the diffusion of steel construction in technological, aesthetic, functional and economic terms. This is the feature of Zavanella's work and a substantial sign of his thought that moves behind the evolution of architectural language. The architect aspired to affect the cultural approach to steel architecture, starting from the relationship between production and design. He shared with his clients the aim of introducing the industrial product in a cultural and social background that was still skeptical of the subject, emphasizing typical features of steel construction: functional, economic, and social. His attention to the disassembly and reuse of the parts of the buildings, suggested by economic reasons, is extremely current and underlines his approach to the critical aspects of the technique. In Zavanella's works, disassembly and reuse issues were dictated by construction correctness, using the technique according to its characteristics and with respect to the construction economy, compatible with the idea of the modern technology available for all. Nevertheless, Zavanella's vision was affected by tools that were still being pioneered. The architect implemented his strategy by starting with his artisan atelier. The companies with which he collaborated to develop his projects to be mass-produced were factories such as Bruno Cavaglieri of Lecco, which worked according to an advanced craftsmanship approach. In this view, Zavanella's work was part of the prefabrication of small buildings, such as service stations, single-family houses, and exhibition pavilions, whose essential functional and construction systems allowed, in the 1950s, designers and manufacturers to experiment with the technique and create prototypes. However, this effort was not matched by commercial diffusion. The trend in contemporary Italian construction developments confirmed the obstacles that affected Zavanella's work. Mass-produced buildings and the idea of a steel construction available for all remained largely unimplemented.

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THE IMPORTANCE OF "THE CONTINUITY OF HISTORY": IGNAZIO GARDELLA'S MONUMENT TO THE VICTIMS OF THE PARTISAN STRUGGLE AND THE VICTIMS OF PIAZZA LOGGIA

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Abstract

"The continuity of history" appears in the project report written by Ignazio Gardella for the monument built in 1984 at the Vantiniano cemetery in Brescia. The Vantiniano stands out as the first monumental cemetery in Italy (1815). The architectural layout, the relationship it establishes with the city and the unified composition of the project by Rodolfo Vantini will constitute a model for many 19th-century Italian cemeteries, such as the one designed by G. Barbieri in Verona (1829).

The paper traces the research in progress about the Vantiniano site from the historical-architectural and symbolic point of view, focusing on Gardella's Monument to the Fallen of the Partisan Struggle and the Victims of Piazza Loggia, and introducing a study of its architectural features and symbolic aspects.

We propose to consider the cemetery not as a set of buildings and monuments placed within a perimeter (the city of memory separated from the city of the living people) but as a spatial system which must have a relationship with the city. This relationship is applied in Gardella's project. The analysis and the survey of the monument demonstrate this link and highlight this architecture as a "continuity of history" symbol. Gardella's monument embodies the theme of the external envelope and the relationship with the context. Its geometry and the brick façades give a modern touch to the cemetery and create an intense dialogue with the roughness of the brick walls of neighboring industrial sites.

Keywords

Cemetery, Ignazio Gardella, Monument to the Victims of Piazza Loggia, Architectural survey, Cultural heritage.

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1. INTRODUCTION

The Vantiniano Cemetery is located west of Brescia along one of the main historic routes, the one from the west to the *Brixia Romana* [1]. The area was chosen outside the city center following the Napoleonic Edict issued in St. Cloud on 12 June 1804. It became, over the years, an area of industrial development: the monumental cemetery was besieged to the east and south by factories of which, up to date, remain testimonies of industrial archaeology as evocative as they are loaded with questions about the choices to be made.

Bishop Nava consecrated the Cemetery on 10 January 1810. It did not initially have its current appearance and size; architect Rodolfo Vantini sketched the orderly, almost metaphysical layout that distinguishes it today. Algid

Fig. 1. *Vantiniano Cemetery. Detail of the NE area with Gardella monument. Source: BAMSphoto-Rodella, flight 03/12/2021, photograph taken by helicopter flight.*

in its lines and the color of Botticino stone, enlivened by monumental trees, it spreads out in a rectangular shape. It is slightly rotated with respect to the north/south orientation, standing with a short side to the south of Via Milano (Fig. 1). The laying of the foundation stone took place in November 1815, while the construction of the different buildings would continue for more than a century.

Due to its monumental characteristics, it can provide space for cultural initiatives aimed at the knowledge and appreciation of the site as a whole and of the historical-artistic heritage it holds. Above all, it can provide an opportunity to reflect on the historical, cultural and social value that a "city of memory" represents for the "city of the living people". Reflecting does not only mean thinking about new strategies to broaden the horizons of knowledge but also looking in the mirror and extracting the founding characteristics from the reflected image. Cultural and social references consolidate self-awareness as a community and civil society, helping to focus on the objectives most consistent with one's history.

Suppose it is true that civilization begins when a population needs to bury its dead. In that case, it is necessary to initiate a process of awareness-raising aimed at the knowledge and enhancement of this place, which is a garden of collective/individual memory as well as a very important architectural complex.

The Vantiniano is the first example of a monumental cemetery where a constant order and space – a real module – is given to the various individual burials, avoiding the competition between different families for the wealthiest and most impressive monument.

In this sense, the architectural layout, the relationship it establishes with the city and the conscious and unified composition of the project make it the reference and model for other cemeteries built in Italian cities during the 19th century: in Parma, the Villetta monumental cemetery is designed by Giuseppe Cicconcelli in 1817, in Verona Giuseppe Barbieri designed the monumental cemetery in 1829 while the cemetery in Genoa-Staglieno began in 1835, designed by Carlo Barabino. Costanza Fattori highlights the cultural *koinè* in the Lombardo-Veneto area and in particular in Brescia and Verona, where the poets Ugo Foscolo, Cesare Arici and Ippolito Pindemonte started the Romanticism movement [2]. Rodolfo Vantini breathes this atmosphere [3]. In some cemeteries of northern Italy, beginning from Vantiniano, the theme of the "holy fence" – a high wall as a boundary – prevails [4]. Inside it, orthogonal axes organize the burial fields.

2. CASE STUDY DESCRIPTION

2.1. THE CITY WITHIN THE CITY

The cemetery layout is articulated according to a succession of two rectangular areas that are very different from each other and are divided by an axis avenue. At the ends of it, two twin buildings stand. The layout has an orthogonal matrix that quotes the one of the *cardo* and the *decumano* of the Roman *civis*. The geometry takes up the *cardo* and the *decumano* scattered by buildings that are not always passable.

A fundamental axis is a long avenue lined with rows of cypress trees that starts from the entrance and ends with the monumental architectural backdrop: the church of neoclassical matrix [5], the first building designed by Vantini (1815-1824) together with the two porticoed side wings.

The historic core of the cemetery is located in the second half of the cemetery layout. It was built in several phases according to a quadrangular plan with perspective axes reminiscent of the layout of the Roman *castrum*. Here, the space is densely occupied by buildings in the neoclassical style [6]. They emphasize the Vantini concept of alternating full elevations and high porticoes, connected by compact volumes: chapels with a square or circular base or large halls.

The various signs traced on the ground (avenues, paths), the rows of trees, and the different architectural elements are part of the settlement language and render the cemetery a city within a city. The presence of the surrounding wall, a physical and symbolic boundary between the two settlements, constitutes a warning to those who cross it at the entrance. It triggers the visitor's perception of entering a place where individual and collective memory is celebrated. Just as in the city of the living, historical figures and events are remembered through toponyms and monuments, so in a cemetery, every single tombstone, every memorial stone and every building tells the individual story as a sort of resonance chamber for the celebration of the collective one. Half pilasters rhythmically punctuate the wall and maintain a visual relationship with the city on the Via Milano side: large openings with wrought iron window bars allow for a visual exchange between the two cities, made even more effective by the perfect axiality of the windows with the main internal pedestrian avenues [7] (Fig. 2).

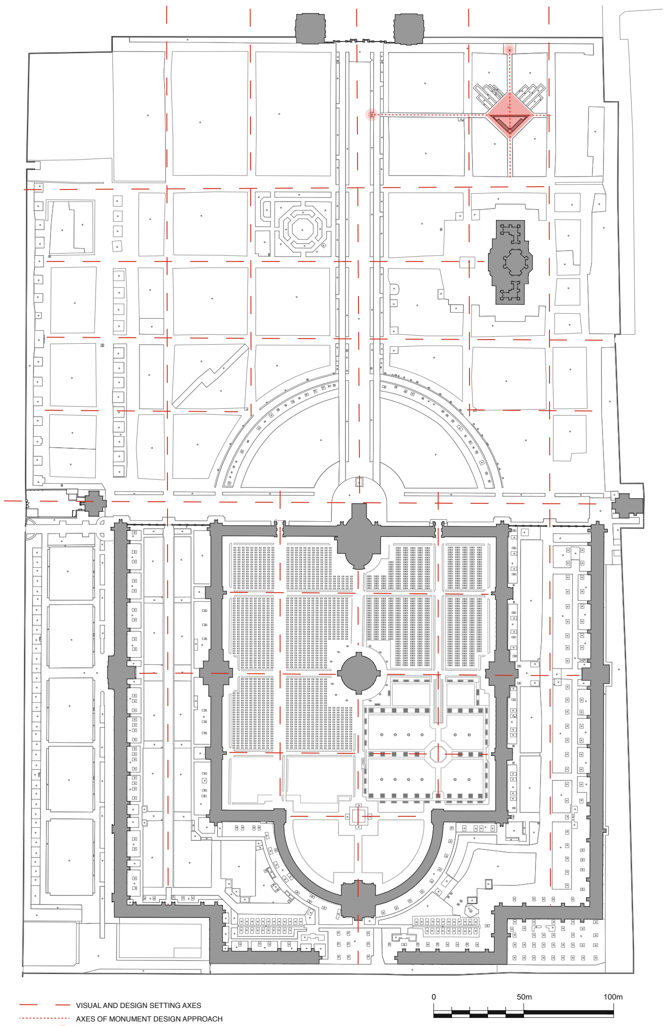

Fig. 2. *Vantiniano survey plan and visual axes.*

2.2. THE FOCUS: THE CELEBRATION OF COLLECTIVE MEMORY AND THE DOUBLE DEDICATION TO THE PARTISANS AND THE FALLEN OF PIAZZA LOGGIA

The first quadrangular sector of the cemetery is a large green park composed of evergreen trees, mainly conifers. Few architectures are placed in this area, hidden in the dense vegetation. On the right, there are garden tombs arranged in a large octagon, and, in the background, family chapels are placed in two neat rows. On the left, one can barely catch a glimpse of a single building chromatically and materially different from the homogeneous character of the Vantiniano: the Monumento ai Caduti di Piazza Loggia e alla Lotta Partigiana, designed by Ignazio Gardella in 1980. South stands the massive Monumento ai Caduti, designed by Oscar Prati in the 1930s to honor Brescia's fallen soldiers in the First World War. In this area of the cemetery, the architectural language of the Twentieth Century becomes the bearer of collective memory. Here, men who fought for a common cause or, in the case of the Fallen in the terrorist attack in Piazza Loggia, demonstrated for a common cause are celebrated chorally.

On 28 May 1974, during a demonstration against neo-fascist terrorism, a bomb was detonated: 8 people died and 102 were injured. One of the most severe attacks of the *Anni di Piombo* era left an indelible mark on the population. In 1980, the Municipality of Brescia launched a call for ideas to design a commemorative monument. The site indicated is where the Memorial designed by Gardella now stands.

Considering the distance and diversity of the events represented, it may seem unusual that a monument should be conceived with a double dedication. The first dedication is for the partisans of the Second World War, and the second is for the fallen in Piazza Loggia in 1974. The unification of the remembrance was, indeed, a controversial and much-debated issue in 1978, as several archive documents testify.

Fig. 3. *Gardella's Monument, north façade, 2023.*

The solution proposal identifies «not a single monument, but a common area appropriately arranged by an artist or an architect or the collaboration of both, which would include the separate signs referring to the partisans and the fallen of Piazza Loggia» [8]. This approach is taken up in the text of the Notice of Competition, which indicates as the site «the tree-lined area to the left of the driveway adjacent to the war dead ossuary» and in Article 3 where it states that the monument «shall express the high ideal and unitary value of the events to be commemorated, but at the same time bring out their distinct specific meanings». As will be seen later, these indications were realized in Gardella's project (Fig. 3).

2.3. HISTORY, STARTING FROM THE COMPETITION

The *Bando di concorso per il Monumento ai caduti della lotta partigiana e alle vittime di Piazza della Loggia* was announced on 20 November 1979 by the Mayor Trebeschi, whose father Andrea died deported to the Gusen concentration camp in 1945. The notice is a text divided into 13 articles as concise as it was clear in its objectives. The first article states: «In order to jointly celebrate the ideal motives that animated the struggle for the liberation from Fascism and for civil and national freedom, and those that nourish the democratic and anti-fascist conscience of Italy born of the Resistance, still and always firm against any cowardly attack, the Municipality of Brescia announces a national competition for a monument to be erected in honor of those who died in the partisan struggle and the victims of the Piazza Loggia attack on 28 May 1974». Thus, a single architectural gesture is entrusted with the complex task of remembering the victims of two different and distant events as a warning to future generations. Article three specifies: «It shall express the high ideal and unitary value of the events to be commemorated, but at the same time bring out their distinct specific meanings». This is the starting point for reading Gardella's monument in its symmetry, which simultaneously unites and separates the two facts. The inscriptions look at each other, autonomous but related by the vertical split in the wall on which they are placed.

The competition has a mixed formula: open to all Italian artists, architects and engineers and by invitation. The invited sculptors were: Cascella, Consagra, Guerrini, Giò Pomodoro, and Spagnulo. The invited architects were: Baldessari, Gardella, Gregotti, Sottsass, and Valle.

On 28 May 1980, an exhibition of the projects was inaugurated in the halls of the Associazione Artisti Bresciani. This way, a participatory architectural action was activated: citizens were invited to view the design proposals and express their opinions. The judging committee met for the final examination of the projects, and the first prize was awarded to Gardella. The monument was unveiled four years later on the tenth anniversary of the massacre (28 May 1984) and completed between 1988 and 1989 with the addition of two memorial stones at the end of the paths leading to the monument and with the project for the burial of the partisans' remains on the ground facing the entrance to the monument.

Gardella's project was significantly published in 1980 in the *Controspazio* magazine special issue dedicated to *The presence of the past*, the 1st International Architecture Exhibition of the Venice Biennale edited by Francesco Cellini and Claudio D'Amato. The issue opened with the article *The re-emergence of archetypes* by the curator of the exhibition and editor of the magazine Paolo Portoghesi [9].

3. METHODS: ARCHITECTURAL SURVEY VERSUS PROJECT DRAWINGS

The monument stands out for its dual capacity to configure a space of both recollection and sharing. The architecture is set along the natural continuation of the visual axes designed by Vantini but constitutes an outpost of modernity. The campaign to survey the monument, which used direct and indirect surveying instruments, therefore aimed to bring out the relationships that Gardella's project intertwines with Vantini's project (Fig. 2) and restore the geometric instances generating the monument. 1,500 measurements were taken from 50 separate topographic stations at the cemetery's site. In particular, 3 topographic stations surrounding Gardella's monument were identified to take all the measurements of the building (Fig. 4).

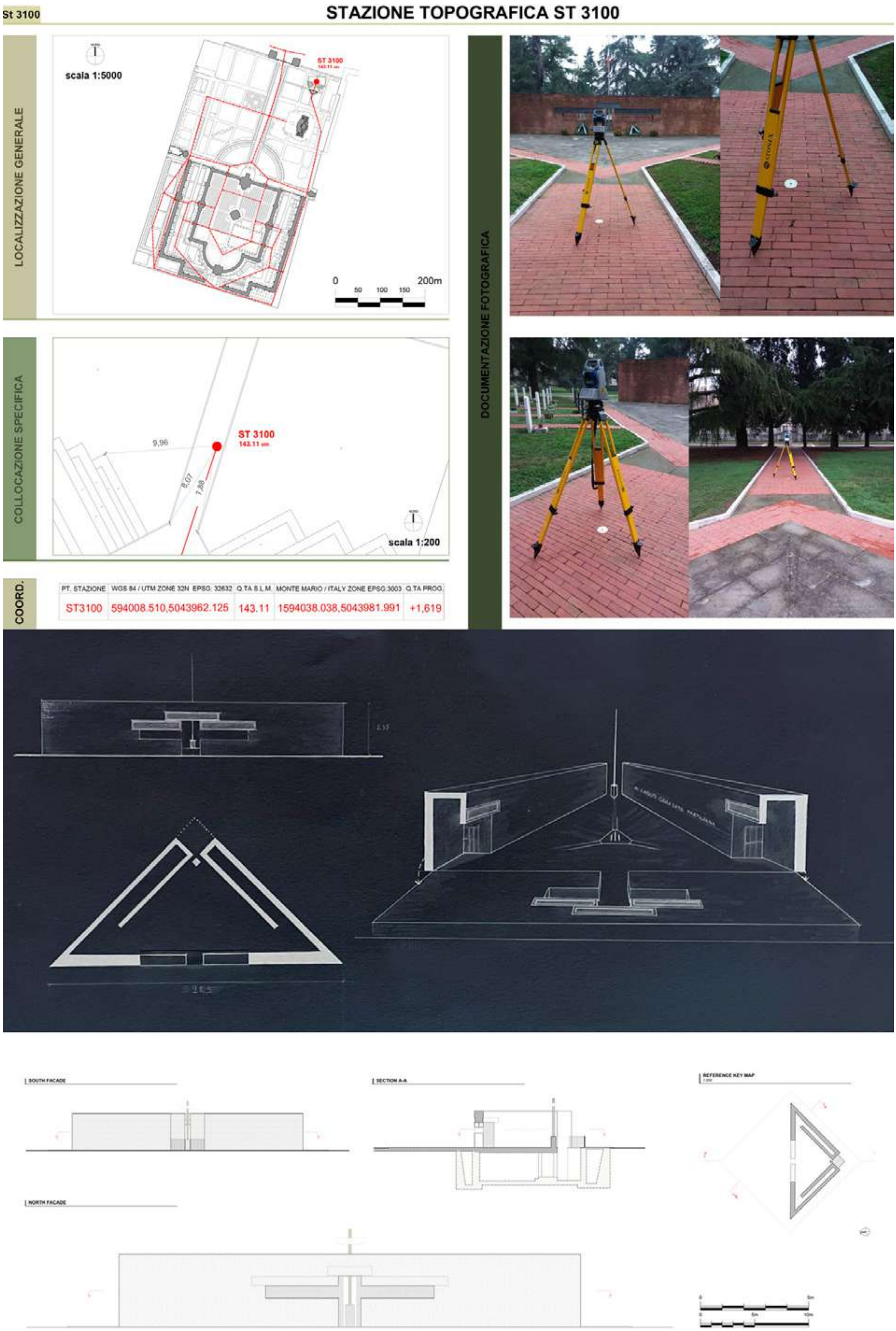

Fig. 4. *Gardella's Monument. Top: topographic survey, datasheet of station point n. 3100. In the middle: sketches. Down: architectural survey, 2023.*

The project report states: «The system of orthogonal axes underlying Vantini's design is thus resumed, while the inner space of the enclosure, whose closure is intended to invite a moment of recollection, meditation and memory, is also perceived by passers-by without stopping, and flows and interpenetrates with the outer space of the cemetery as if to emphasize that those commemorated are not isolated facts but facts that are part of the continuity of the history of yesterday, today and tomorrow» [10]. The survey confirmed a respectful and coherent insertion with Vantini's structure. It is fascinating to compare both survey and project drawings.

Dramatic use of shadows emerges in Gardella's drawings, enriching the plan representations with three-dimensionality. The elevations are recounted in their most material aspect (the survey had the same attention rendering brick walls), allocating to the use of solid face brick the emphases of the horizontal lines that mark the dynamism of the wall partitions. The use of representations such as bird's-eye views and airy perspective views clarifies the relationships between new and old architecture. These drawings make perceivable those invisible threads that link the focal points on which the built space of the cemetery is articulated (easy to see comparing Fig. 2, Figs. 5 and 6). The boundary stones placed at the entrance to the paths prop up like cardinal points the axes of the paths that coincide with the visual axes, and only at their intersection does the monument take shape (Figs. 5 and 6).

In Gardella's drawings, from views that suggestively outline the context, we move on to framing boards where the monument, thanks to a full and decisive stroke, is defined in all its sharp geometry and then to detail boards, where details are rendered with executive exactitude. In these latter drawings, great attention is paid to the definition of the materials and the construction techniques for laying the tombstones and the foundations.

The project was then also rendered three-dimensionally, as required by the competition, with a wooden maquette carefully photographed from various viewpoints. The choice of wooden slats and framing emphasizes the sharpness of the figure of the triangle that pivots the entire project.

4. INTERPRETATION

4.1. GARDELLA'S MONUMENT AND ITS RELATIONSHIP WITH THE CONTEXT

As often in his architectural production, also in this project, Gardella resorts to the elementary form of the quadrilateral cut along the diagonal; the main compositional axes connect with the main axes of the cemetery and also establish a strong visual relationship with the outside space and with the city. To do this, Gardella exploits one of the openings in the boundary wall on Via Milano. The two main axes coincide with the two pedestrian access paths to the monument. Two driveways, one orthogonal to the other, start from the cemetery's avenues, marked by two square-based memorial stones with pyramidal tops, a contemporary interpretation of the funeral memorial stones found in large numbers and models at Vantiniano. The memorial stones are placed exactly in the center of the paved access paths. As anticipatory signs of the monument, they are simultaneously impediments to the path's entrance, concrete obstacles that impose a moment of reflection on the visitor, accentuated by the fatigue of continuing the walk.

In harmony with the orthogonal grid of the site, the design layout proposes two different viewpoints. The first has a north-south direction. It is possible both from the urban space outside the cemetery (Fig. 5), through the opening in the surrounding wall from which anyone can see the main front of the monument and catch a glimpse of the shrine, and in the opposite direction, to connect the interior space with the space of the city. The second one unravels in the west-east direction and interacts with the monument in a tangential way, highlighting its acute spike that accentuates the monument's dynamism and drama.

The expressive meaning of Gardella's project is also subtly linked to the peculiarities of the site. The monument takes up, in a contemporary key, the theme of the wall with inscriptions (only the material changes, here it is brick) that delimits «the enclosure of remembrance» [11], isolating a commemorative and sacred area. Contradicting the very meaning of the enclosure, Gardella leaves the triangular shape open so that the view from the

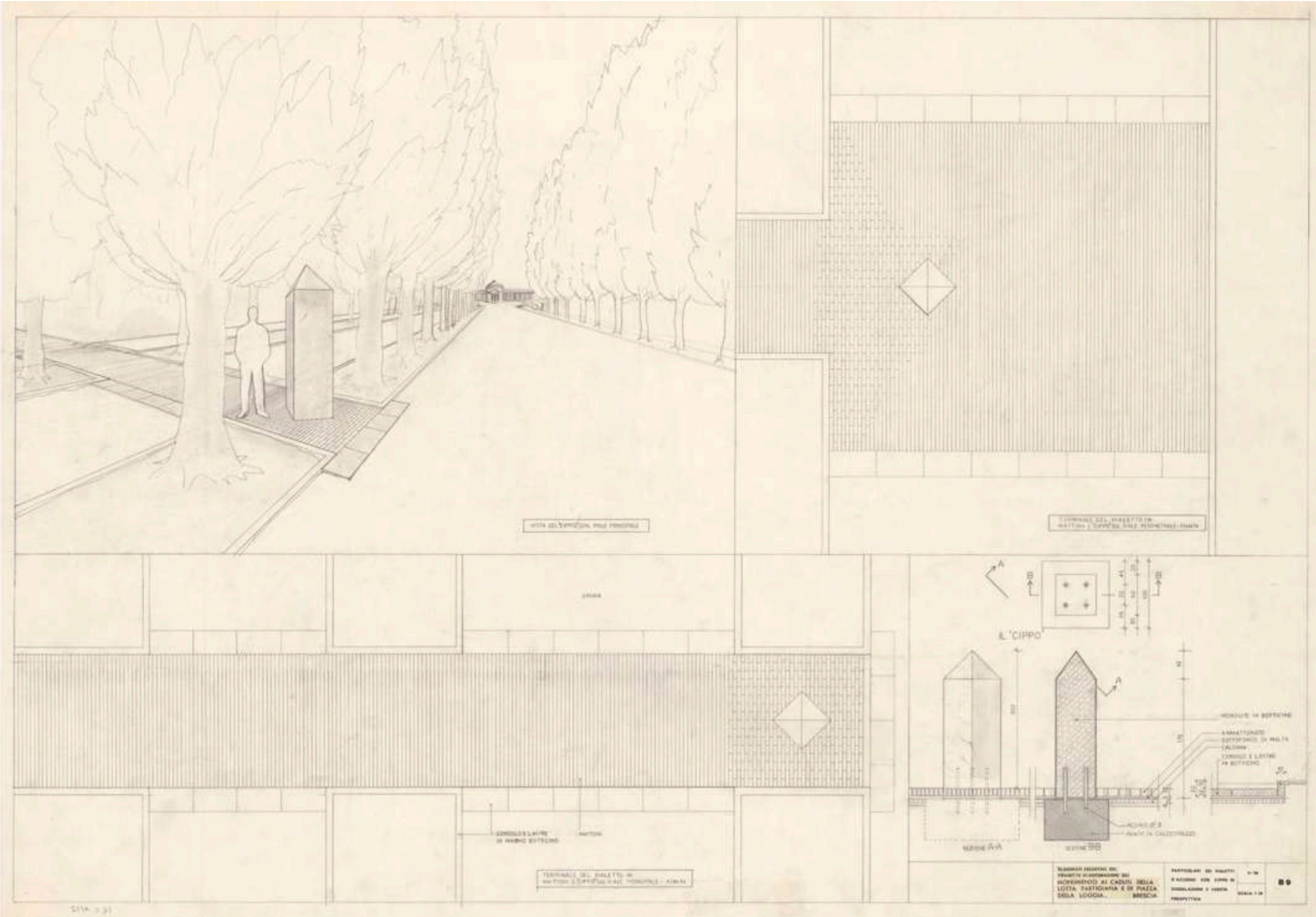

Fig. 5. *I. Gardella, visual axis and marker stone, Balerna. Source: Archivio del Moderno, Fondo Ignazio Gardella - Monumento ai caduti di Brescia.*

outside is fluid and guarantees a visual connection with the war memorial charnel house.

The plan drawing consists of a square rotated by 45° with respect to the orthogonal axes that order Vantini's project [12] (Fig. 6). Gardella's architecture is thus generated by diagonal geometries that leave half of the square untouched and half of the walls emerge to form an isosceles triangle. Therefore, the project's layout informs the visual and geometric relations it entertains with the site in which it is located and attaches itself while affirming its own lineage and autonomy. The monument stands as an enclosure within the larger enclosure designed by Vantini.

The architecture is substantiated by clear lines that take on depth where they accommodate a function that is no longer only symbolic but also practical: along the hypotenuse – the diagonal of the starting square, the access passage to the monument opens up, while along the two cathexes of the triangle are housed two staircases leading underground to the ossuary, one for descent, one for ascent, thus tracing the univocal direction of a ritual path. The square continues to be perceived in its unity thanks to the design of the paving that maintains the same finish between the inside of the monument's enclosure and the outside, like a large carpet that abstracts from the pavement of the Vantini cemetery and leads to another dimension.

The accent between interior and exterior space is also emphasized by the choice of maintaining the pre-existing trees whose thick, vast foliage becomes the natural cover of the Monument.

The grey trachyte paving, the red bricks, and the steel beams are humble materials that speak of simplicity and dignity. Gardella writes in the project report: «I think that the two different facts to be commemorated can find the substantial unity of their ideal value in the rigorous unity of architecture, even more than in symbolic figurations […] I believe that the monument must be easy for the people to read» [13].

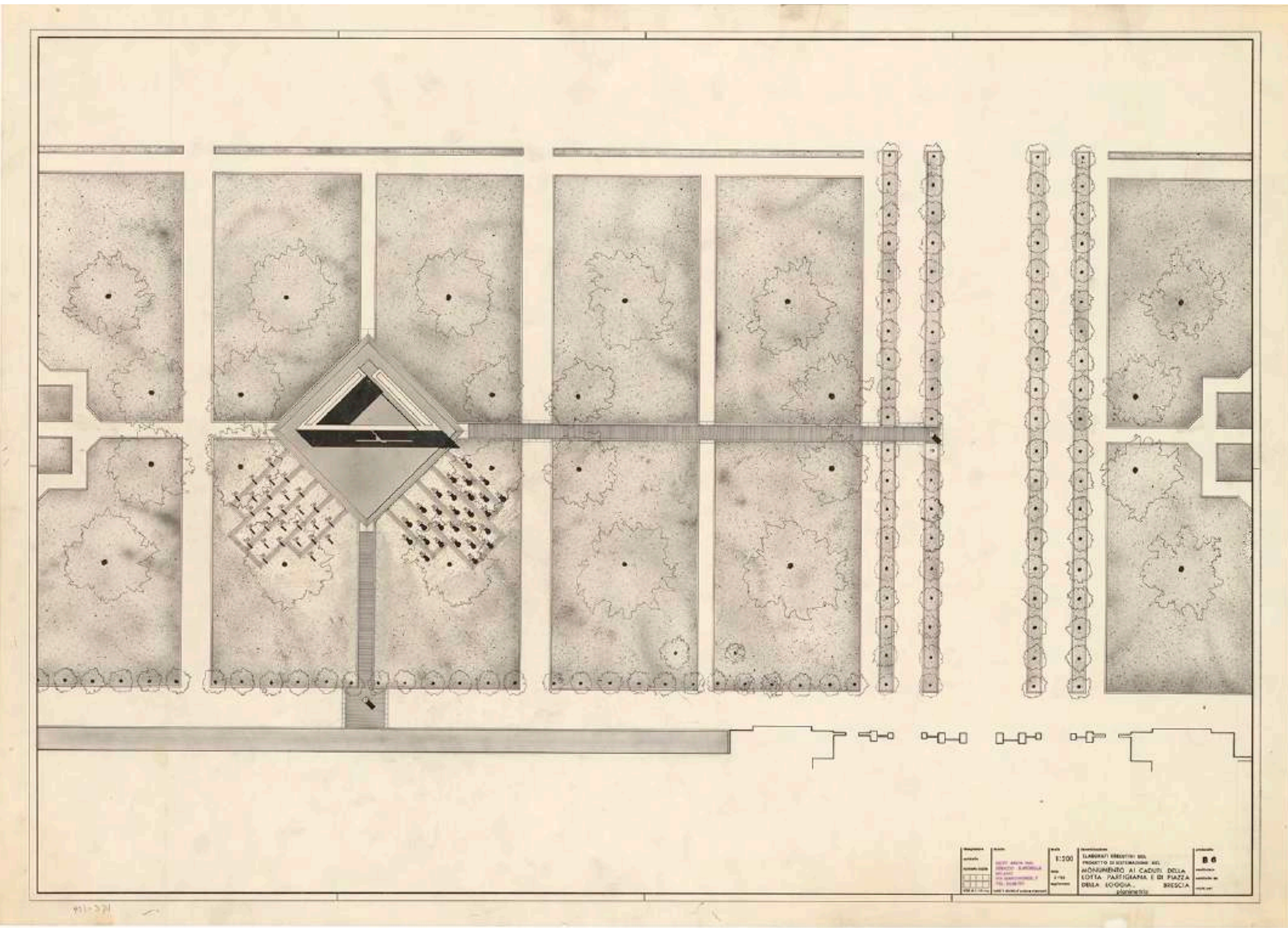

Fig. 6. *I. Gardella, plan with shadows, Balerna. Source: Archivio del Moderno, Fondo Ignazio Gardella - Monumento ai caduti di Brescia.*

The entablature is adorned only by the grooves of the "corten-a" steel architrave, which breaks and rises by a module at the entrance space threshold. A horizontal cut opens up below the beams, framing and making the two commemorative epigraphs readable from the outside. The two walls – on which the dedications to the victims of the two historical events are placed – converge towards a flagstone that embraces the two tragic events of Italian history in the tricolor. The two walls unfold like two pages of a history book united by a gap: a slit opens between the two walls and places them in direct dialogue with the Memorial to the Fallen of the First World War by Oscar Prati, which can be glimpsed just beyond the split. «In this way, the wall is restored to its original task of dividing, of separating two open spaces; at the same time, these walls become two great epigraphs, in memory of those who died» [14].

4.2. SYMBOLIC ARCHITECTURE

Article 3 of the Competition brief states that the monument must «harmoniously fit into the valuable landscape and monumental context of the Vantini complex».

Gardella adheres to these indications by resorting to the basic elementary forms of the quadrilateral cut along the diagonal. The design adopts diagonal geometries where the entrance axis divides the square into two triangular segments; one is left open and untouched, while the other emerges to form an isosceles triangle (Figs. 6 and 8). One of the triangular spaces encloses the sacred and memorial area, while additional triangular space is created by planes on the two short cathexes housing access stairs to the ossuary.

Nevertheless, the unity of the square is maintained through the paving design that keeps the same finish between the inside of the monument's enclosure and the

Fig. 7. *Gardella's Monument compared with the texture of the nearby brick wall of the former industrial area, Brescia 2023.*

outside, like a large tapestry abstracted from the pavement of the Vantini cemetery.

In the abstract design of the Memorial, architecture outgrows historicism and pushes towards formal typologies, where geometry plays a crucial role not only as a symbol for the manifestation of the sacred but also as a limitless framework for the simple design, which it strives for. The simple geometry is the ultimate testimony of the artificial striving for rationality and universality within the irrationality and locality of nature.

To quote Tadao Ando, «Creation by geometry is always accompanied by the struggle between abstraction and representation. Rational and irrational. Whole and part. Artificial and natural. These dualistic propositions surface one after the other to torment the mind of the creator. […] The deeper and more intense the opposition between pure abstraction and diverse representation, the more the creation comes alive. There, beautiful, robust and rich geometrical expressions emerge» [15].

Gardella created a mix of modern and traditional architecture. On the interior, the walls establish a serene zone that encloses a more private space, sacred and personal, that counters the dynamics of the surrounding nature. On the exterior, the walls shield the surrounding nature. This sculptural geometric form goes beyond its pragmatic function and becomes the Yorishiro-object in which a spirit is drawn, which symbolizes the unity of the living and the souls of the dead.

The design places much importance on nature, light, and material, and the walls shield and allow nature into the structure. The enclosed space created by means of the two cathexes creates both a place for the individual, a zone for oneself within nature, and a sacred space for the dead. As it is a holy space, the walls are without openings, thus isolating the interior space from the forces of the environment, yet through material use, it creates an interior that is full and satisfying.

The cross is the only sign designating the Memorial as formally Christian. Nevertheless, the cross is not physically present; it is present as absence because it is cut out of the wall. The design of the cross as an *Aperture* denies the symbolic character of the cross in classical architecture in favor of a more expressive dimension; the cross becomes a non-object, pure expression that serves more to express, that is, to make present, than to represent. Its presence is dramatized by the light passing through the Aperture, thus defining the emptiness as sacred. Furthermore, as an Aperture cut in the roof looking towards the sky, the cross brings together nature and the sacred, earth and sky, and exteriority and interiority.

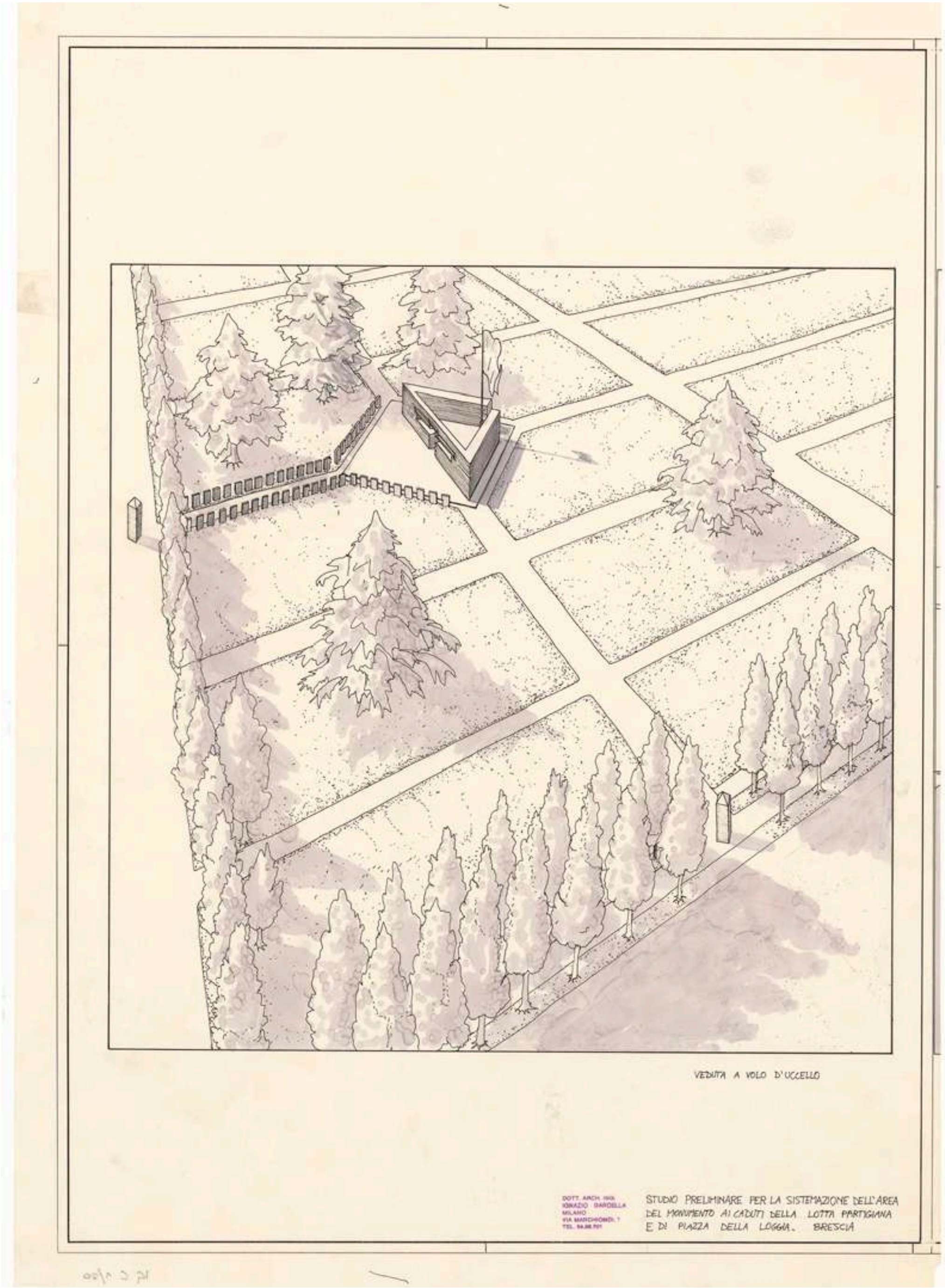

Fig. 8. *I. Gardella, bird's eye view, Balerna. Source: Archivio del Moderno, Fondo Ignazio Gardella - Monumento ai caduti di Brescia.*

The monument's design resembles Ando's architecture in creating a haiku effect, emphasizing serene nothingness and empty space to represent sacred and simple beauty. Nevertheless, the simplicity of the architecture emphasizes sensation and physical experiences as one walks through the path and reaches the monument.

Gardella has done more to create a space for gathering; he has created moments for contemplation. The walls of the simple geometry became instruments for inwardness, stillness and prayer. Placing the walls, a strange element in the landscape creates a camera frame effect where a specific part of nature is created, generating vistas and transformative spaces. As one walks through the main axis towards the Memorial, one is transformed from observer to participant; the entrance places one in the comfortable position of a distant observer, but gradually, one is gently taken in by a fascinating architectural event that opens itself and oneself to greater things (Fig. 8).

As a final note, the triangular spaces within the square make a metaphoric link to the number three, which has several high symbolisms across ages. Three is the first number to which the meaning "all" was given. Three denotes divine perfection; Seven denotes spiritual perfection; Ten denotes ordinal perfection; and twelve means governmental perfection.

The ancient Greek philosopher Pythagoras postulated that the meaning behind numbers was deeply significant. In their eyes, the number 3 was considered the perfect number, the number of harmony, wisdom, and understanding. It is The Triad. It was also the number of times – past, present, future; birth, life, death; beginning, middle, end; heaven, earth, waters. It is human as body, soul and spirit – it was the number of the divine. Hence, the number three points us to what is real, essential, perfect, substantial, complete, and Divine. This symbolizes a triad or trinity. It is a symbol of the unity of body, mind and spirit.

5. CONCLUSION

The research leads to the updated survey of the entire Vantiniano Cemetery, which is interpreted as a system of complex relationships involving both the built part and the open spaces. This survey that looks at the Vantiniano cemetery from a systemic point of view has paid particular attention to the restitution and enhancement of the visual and sense relations that link the Cemetery to the City. The research work at the archive [16], the survey and photographic campaigns led to an overall restitution of the Vantiniano. We set an integrated survey, where the drone and direct surveys, with traditional instrumentations, flanked the topographical measurements using the total station.

The survey investigated both the built part and the "trees architecture", from the contextualization of the cemetery at the urban scale with the inclusion of a new topographical reference network to the detailed survey at a scale of 1:20. These graphic, photographic and textual materials now constitute a reservoir of up-to-date technical and historical information, usable for future maintenance and restoration work on the monuments, but above all useful for a renewed collective awareness of historical and cultural heritage.

The phase following the survey campaigns includes a series of proposals for the possible use or adaptation of some free spaces available for temporary uses (exhibitions, events, performances – recalling the theatrical use since the Middle Ages) that would allow the transmission of the culture of this place while respecting the value of memory. To this end, five thematic routes have been prepared [17, 18], proposed at various levels of complexity to meet the most diverse cultural and educational needs. Gardella's Monument has been included in the "Historical Events and Eminent Personalities" path. In fact, it represents the most emblematic case of

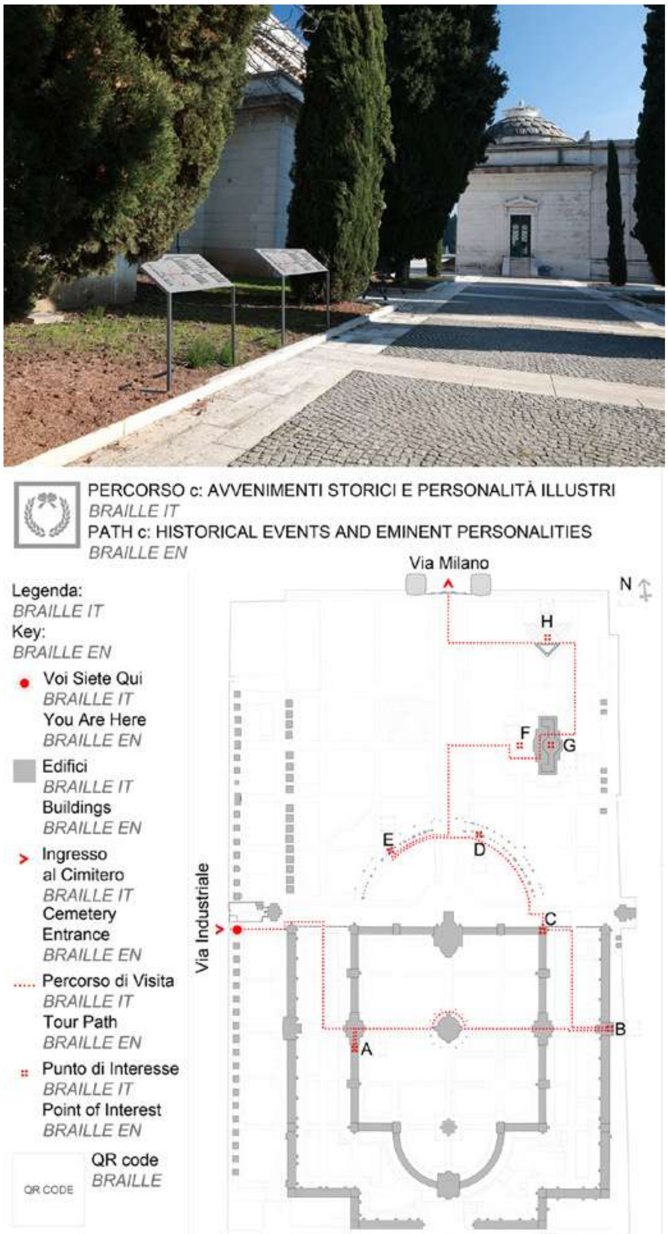

Fig. 9. *Top: tactile maps placing. Down: Path C "Historical Events and Eminent Personalities": Gardella Monuments (H point), 2023.*

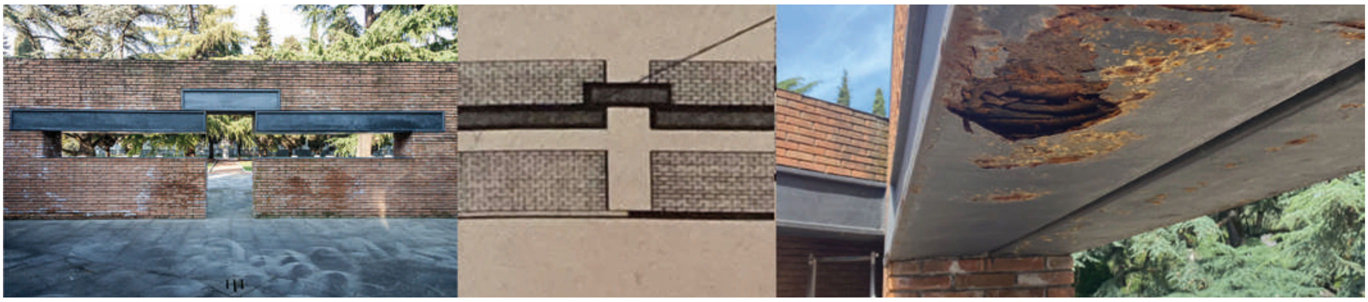

Fig. 10. *Photographic image of the front of the monument compared with Gardella's original design panel, highlighting the current state of conservation of the beam.*

modern architecture in the cemetery and one of the most significant examples of Italian authorial architecture of the 1980s for the city of Brescia.

An app is also being developed to make the exploration of the Vantiniano more interactive and dynamic. At the same time, a new wayfinding system is being studied for visually impaired persons, with the aim of making the visit to this place increasingly comprehensive and inclusive (Fig. 9).

The survey analysis revealed a medium state of conservation of the monument. The most compromised part concerns the corten steel entablature of the entrance portal. Its deterioration led to the investigation of Gardella's early drawings, where this threshold appears very different. The curtain wall, in fact, breaks at the portal, leaving a void above the architrave. This idea of suspension is later modified by Gardella, who will continue the wall septum along the lintel. On the one hand, the idea of suspension and lightness of the first proposal is lost; on the other hand, the monument gains in compactness and compositional unity (Fig. 10).

The solution adopted here is reminiscent of the degree of abstraction and geometric solidity of works such as those by Gianugo Polesello (in particular, the analogy with the triangular plan proposed for the Competition for the Offices for the Chamber of Deputies in Rome, 1966) or Gino Valle (Monumento alla Resistenza in Udine, 1969, where the idea of architecture as enclosure recurs) [19, 20].

Furthermore, when comparing the realized project with Gardella's drawings, it emerged that the dedicatory epigraphs were initially intended to be placed in the recess of the beam and not in the cut below where they were later inserted. This location would have certainly improved their legibility and visual impact. Gardella had also planned a front gate that was to give the possibility of closing the monument. This gate was not realized, leaving the work more open to visitors and rooting it more to the always open perimeters of the Vantini monuments [21].

In conclusion, the research is not yet complete, but it has reached two important milestones: the book *Rilevare e valorizzare la memoria. Analisi e proposte per il cimitero Vantiniano* [22], with the reference to the chapter concerning Gardella [23], and the exhibition *La città della memoria nella Capitale della Cultura: Conoscenza e valorizzazione del cimitero Vantiniano di Brescia* [24].

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Authors contribution

Despite having shared objectives, methodologies and results of the research, it is highlighted that I.P. is the author of paragraphs 1, 2.1, 2.2, 3, 5; C.S.R. of paragraphs 2.3, 4.1; A.M.A.G. of paragraph 4.2.

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A PRELIMINARY STUDY FOR THE KNOWLEDGE PROCESS: PIER LUIGI NERVI'S TAORMINA STADIUM

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Abstract

The article highlights the fragilities of a specific category of 20th-century heritage, namely football stadiums. These architectures are even more vulnerable as they are subject to continuous regulatory and performance adjustments that clash with the building's cultural, historical and technical values. Therefore, there is a need to raise awareness of the protection of these architectural works so that interventions can be carried out that combine technical innovation and heritage conservation.
The paper provides a synthesis of the research conducted on football stadiums designed and built by Pier Luigi Nervi, in collaboration with his son Antonio, in Italy's second half of the 20th century. The analysis was carried out on various levels to grasp their specificities, understand their current state, and make the necessary comparisons to identify a case study for further evaluation. The Taormina stadium is a unicum concerning the others considered, both for its compositional and structural components and for additional vulnerabilities that denote it and, at the same time, constitute an exceptional example. Archive research and field investigations outline this architecture's original characteristics and current state of conservation. This process of anamnesis shows how awareness-raising assumes a fundamental role in assisting the different competencies involved in preserving these assets.

Keywords

Architectural fragility, Concrete degradation, Football stadium, Modern architectural heritage, Pier Luigi Nervi.

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1. INTRODUCTION

The various epistemological discussions seem not to deal with the complexity of the very essence of heritage and the most appropriate methodologies for their protection. Cultural heritage appears not to be considered unambiguously, as if there were a dividing line between monuments belonging to Antiquity, which are universally acknowledged and therefore to be protected, and the "other" monuments, which, due to the absence of historical distance and to interpretative difficulties, are subject to judgments of merit on the quality or integrity of being heritage. The need for more safeguarding and the critical issues arising from the buildings' complexity and, consequently, the actions to be taken are added to the discrepancy in the value recognition [1]. Furthermore, it is evident how the mutation of terminology and the indiscriminate use of terms, such as transformation, recycling, and reuse, elude the very meaning of the words conservation and restoration [2] and generate confusion in the purposes of protection and in the tools for identifying and protecting heritage values. Thus, it is noticeable that interventions on existing built heritage are complex actions whose governability is directly proportional to the degree of knowledge and the ability to read the built environment to reunite the asset with the values it carries.

In twentieth-century architecture, the close distance between the authors of the work and the authors of the intervention allows for design possibilities that also presuppose, in some cases, the posthumous execution of incomplete parts or the restoration to their original form for those parts that have deteriorated. This fragility is directly related to the material, making the interventions in architectures realized through technological innovation particularly complicated. Their experimental character has often been betrayed by time, leading to the rapid deterioration of these new materials. This heritage has been «neglected by Italian legislation» [3] and is treated in the same way as coeval buildings, for which interventions are carried out to meet firstly current conformity requirements. In addition, the amendments to the Codice dei Beni Culturali e del Paesaggio with the Italian Decree Law 70/2011 shifted the time constraint from fifty years to seventy years, exposing much of the heritage of the Modern to compromise further. The fragmentation of the unity of heritage is also evident in the case of sports facilities. The ratification of Article 55 bis of the Italian Law Decree 76/2020 – known as the "sblocca-stadi" amendment – acts as a backlash to many of the articles of the Italian Legislative Decree 42/2004 and Article 9 of the Constitution itself, allowing exceptions to the safeguard procedures. What emerges is the lack of a total and general vision of the national cultural heritage and the dangers to which it may be subjected, admitting exceptions to the basic principles of protection with consequent threats of widespread demolition and denaturalization.

The emblematic incident of the Artemio Franchi stadium – formerly Giovanni Berta – in Florence highlights the fragilities that characterize the specific category of sports facilities. Since 2020, the stadium has been, and still is, the protagonist of a controversy that began with the hypothesis of its transformation – with the possibility of extensive demolition – raising the alarm on how cultural heritage should be managed. The function of these architectures is crucial in their survival and risk of compromising their testimonial value. Constantly updated compliance requirements often justify intervening with radical transformations or decommissioning iconic structures that can no longer meet economic and management needs. When abandonment occurs, the size of these structures makes it even more challenging to identify functions other than the original ones, inevitably leading to demolition or abandonment and, thus, degradation. In Florence's case, the recognition of this architecture as a masterpiece and the authorship of Pier Luigi Nervi's project do not imply greater attention to protection; on the contrary, the administrations have entirely ignored these values. The same happened with the Fla-

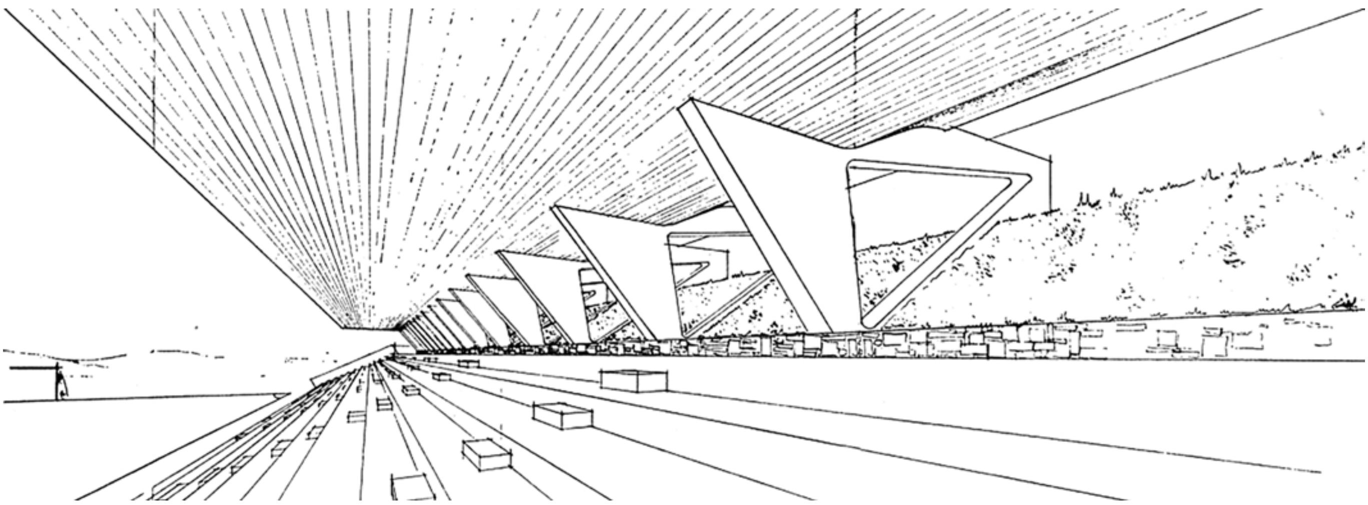

Fig. 1. *Sketch of the Taormina Stadium. Source: © 1958, Architectural Record 12.*

minio stadium in Rome, decommissioned between 2011 and 2012 and still awaiting a valid restoration project. In 2017, a Conservation Plan was drawn up and financed by the Getty Foundation as part of the “Keeping It Modern” program [4]. This also led to its preservation and revealed the severe state of decay in which the stadium finds itself due to the improper interventions carried out on some parts of its structures. Concerning the other stadiums designed and built by Pier Luigi Nervi in Novara and Taormina (Fig. 1), the paternity of the former has been attributed exclusively to his son Antonio, while the latter is often not considered among Nervi’s works and also for this reason almost entirely unknown.

2. METHOD

The research focuses on stadiums designed by Pier Luigi Nervi. The stadiums were built during the post-World War II period in the context of the Italian engineering sector, which was characterized by a new architectural language made of innovation and experimentation on reinforced concrete systems. The construction manifested the constraints from the previous autarkic period when the choice of materials was linked to the need to use only national products. Steel had to be used moderately, making it necessary to optimize the structures. The reduction of reinforcing bars, structural weights, and resistant sections, as well as the use of the arch to realize large spans persisted even later, representing the architecture of the years of the Italian economic miracle.

The Italian engineering sector assumed a leading role due to Pier Luigi Nervi, who could perceive the correspondence between structure and form through its manifestation in reinforced concrete. His first internationally acclaimed work, the Berta Stadium in Florence, represented a curved structure shaped by the masterly use of its material. In the second half of the century, Nervi conceived a new way of building that would later become an authentic style, a system capable of being aesthetically, economically, and temporally practical simultaneously. Eliminating the wooden formwork and reducing the thickness of the elements to limit the use of material, the originality of Nervi’s system is expressed in the organization of the construction area divided into parts on-site where the skeleton of the architecture – excavations, foundations, pillars – is built. Another characteristic of prefabrication is that it creates all the elements that, when assembled, recompose the structure into a monolithic structure. In football stadiums, Nervi applies his way of «building correctly» [5], bringing out his *modus operandi* in synthesizing technique and aesthetics. Giuseppe Perugini defined this binomial as «form-structure» [6], where the term structure is identified and associated with the concept of functionality [5]. This binomial finds a practical application in sports facilities as buildings determined by the decisive role of design. Form, technique, and function are interconnected and discovered through the construction possibilities offered by reinforced concrete.

The analysis was conducted starting from the protection and preservation systems inherent in the designs of three stadiums signed by Nervi (Fig. 2): the sports center stadium in Taormina (1955-1960), the Flaminio stadium in Rome (1956-1959) and the municipal stadium in Novara (1964-1976). After the famous Berta municipal stadium in Florence, these stadiums resulted from the collaboration with his son Antonio, with whom he founded the Studio Nervi in 1954 to join the Nervi & Bartolini design studio. These are typologically innovative sports facilities, where a significant role is taken by technical and structural achievement and with particular attention to aesthetic expression [7]. The Florence Stadium, even if it was mentioned at the starting point for the discussion, is not included in the study as it is: chronologically earlier, designed by Pier Luigi Nervi without the collaboration of Antonio, and extensively covered with the discussions on the dangers of demolition.

The three stadiums have been investigated by defining categories of analysis, which are necessary to understand the complexity of the individual architectures and compare them. For example, in addition to the year of construction and the authors, the following are also considered: the competition announcement and the constraints imposed by the client; the project and the location; the planimetric configuration, including the capacity and the compositional characteristics; the structural choices, embracing the prefabricated elements designed; the development of the construction site; and the current state of conservation and degradation. In the case of the Flami-

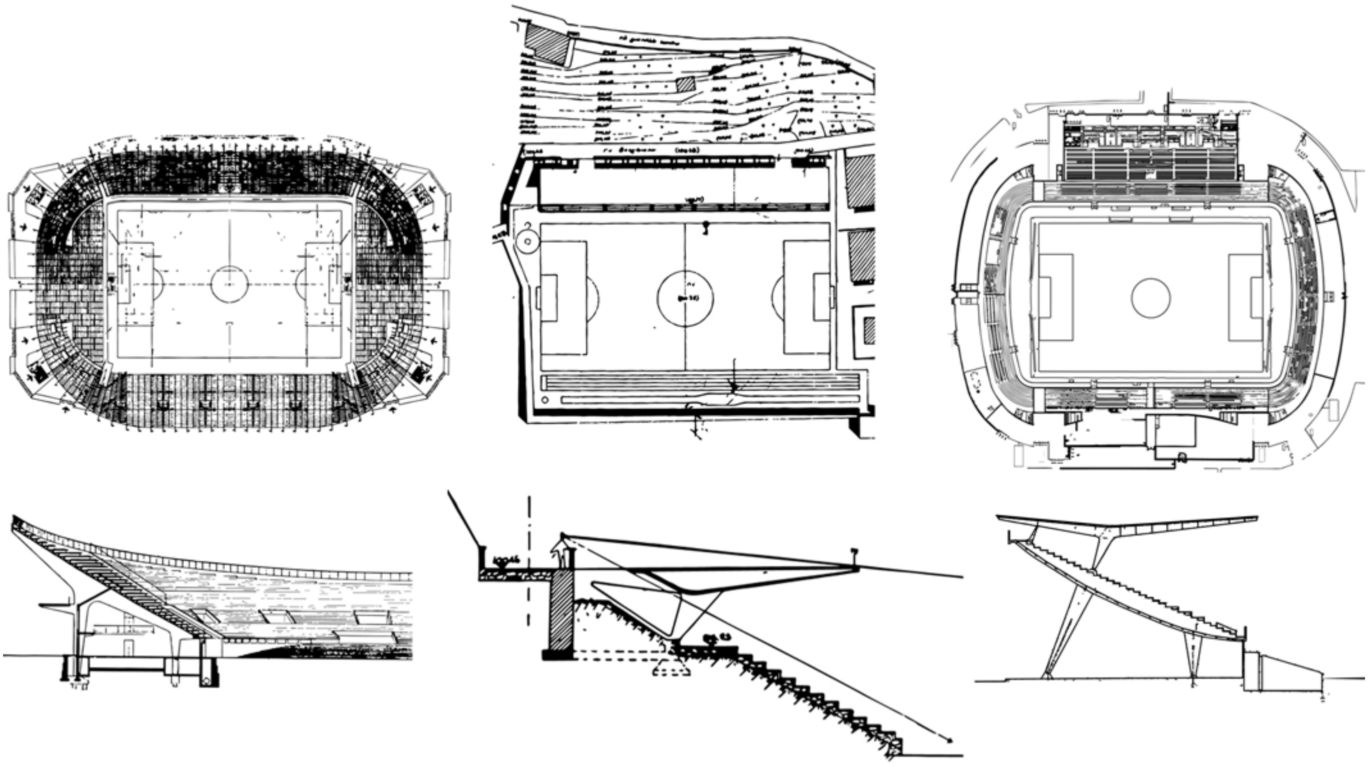

Fig. 2. *Sketch of plans and sections of the three Nervi stadiums in Rome (left), Taormina (center), and Novara (right). Source: © 2024, drawing by the Authors.*

nio stadium in Rome, the characteristics of the asset were recognized and protected thanks to the joint action between the Municipality of Rome, Sapienza Università di Roma, Pier Luigi Nervi Project Foundation and Do.Co.Mo.Mo. Italia with the support of the Getty Foundation. To date, the stadium is in a state of neglect. It is particularly subject to degradation – due to decommissioning and the physiological aging of materials and equipment – although a conservation plan and restoration project have been drawn up, which still need to be implemented. In the case of Novara, the football club announced a competition to construct a new multi-purpose stadium; the Andra Maffei Architects studio, the competition's winner, proposed an *ex novo* project, keeping the west part standing as the only original element. The Taormina stadium is still partly used by the local football club. It is in a limited state of decay and has not been subjected to any interventions, so it was chosen as the object of the following investigation. The case study analysis was conducted through an anamnesis of the archival documentation and an on-site inspection based on Coppola and Buoso's methodology. In particular, this methodology identifies the objectives to be pursued when undertaking maintenance work on reinforced concrete structures. These are general objectives regarding restoring structural safety, use function, and aesthetics, and specific objectives regarding degradation mechanisms [8].

2.1. PRELIMINARY ANALYSIS

The Flaminio stadium represents the first outcome of the change in Pier Luigi Nervi's professional activity. The stadium was built for the 1960 Rome Olympics, replacing Marcello Piacentini's previous National Stadium (1911). The pre-existence became a condition of constraint in the call for tenders: to fit into the tight time schedule – given by the demolition time of the pre-existence (between July 1957 and December 1958) and the construction site (within the following 18 months) – and to preserve the playing field and not to move out of the original area, it was unfeasible to adopt a totally "crescent" shape [9]. Thus, Nervi designed a ring-shaped grandstand surrounding the playing field to centralize the considerable number of seats on the straights corresponding to the field's length. The seats are standing and seating, the latter uncovered and covered. In particular, the covered seats are protected by a cantilever roof to the west. A further constraint of the competition notice was the realization of autonomous services. The swimming pool and gyms for boxing, weightlifting, and heavy athletics were built on the lower level of the west straight; gyms for gymnastics and fencing were constructed below the east straight [10]. The public's accessibility to the grandstands is guaranteed by two pincer staircases that disengage the café and toilets and the cantilevered external galleries: the last ones were built to provide easier distribution of spectators to the various *vomitoria*. Independent entrances are designed to welcome the authorities. From a structural point of view, Nervi proposed a solution with ninety-two reinforced concrete frames with two hinges and a center-to-center distance of 5.70 m, whose section has a constant shape and adapts to the various multi-purpose areas, varying in height and width over the entire curvilinear field. In addition, innovative technical experimentation allowed for the construction of the bleachers and the cantilever roof of the west stand with prefabricated reinforced concrete elements. The frame of the stadium's load-bearing structure, which has no cladding or plaster and is realized through wooden formwork composed of planed and tapped staves, is connected by secondary ribs and the prefabricated structures of the bleachers. The site was developed in two autonomous, parallel locations: in the first, *in situ*, the foundations in Frankie piles (length: 10 m; ϕ: 55 and 35 with load-bearing capacities of 90 and 55 tonnes), and the structural frames were cast; in the second, in a neighboring area, the prefabricated elements were built and then gradually assembled on-site. This process synthesizes technical solutions capable of building quickly and economically, thanks to the elimination of the wooden formwork for the prefabricated elements and the reduction of the thickness of the resistant aspects, permitting the containment of material costs [11].

Simultaneously, in those years, Nervi designed and supervised the construction of the Taormina stadium. Smaller in size than the Flaminio, it was a facility resulting from the administration's need to build a new stadium in the area of the old playing field. The main constraints were related to the small total surface area and the inclusion of the facility within a highly characterizing historical landscape context. In this regard, Nervi combines respect for the existing context with structural components with innovation, and this integration represents a distinctive expression of Nervi's innovative vision in architecture and engineering. From a compositional point of view, the football pitch is flanked to the north and north-east (seaside) by the athletics track and a tiered seating area cantilevered from the retaining wall. Two covered bleachers above the south grandstand have been placed on the opposite side (street side), accommodating both standing and seating. These seats were designed below street level to create a viewing terrace above the canopy, providing additional space for the overflow spectators. It was designed and built to open up the view of the playing field and the surrounding landscape for spectators while sheltering under the covering – thanks to the reduced size of the front grandstand – and for anyone standing on the viewing terrace. The sports facility adapts to the terrain, and the bleachers on the side opposite the sea make the landscape a theatrical backdrop [12]. Finally, the respect for the context was also manifested by the choice to use local materials – grey stone – for the cladding [13]. From a structural point of view, this cantilevered square was created using the technical and technological innovation applied to the reinforced concrete canopy. The section has a curved slab resting on eighteen triangular cantilevered brackets of 8.50 m (placed with a 5.7 m spacing) resting on pillars that intersect in the ground, where each frame is connected at the rear to the retaining wall. Thus, it provided for the creation of a balanced system, avoiding tipping over towards the valley. The ceiling is an overall volume consisting of two parts: an upper part in reinforced concrete and bricks that extend over a large part of the carport and a remaining part built only in reinforced concrete. The canopy is 3.5 m away from the rear wall. In 1955, the Nervi studio integrated an expansion joint in the structural part and four shelf beams inserted in the curvilinear part of the interpreted slab to interrupt the critical length of the long side, avoiding modifying the frame section and the original design [14].

The last stadium, dating back to the 1970s, is in Novara. The contract was awarded by Nervi & Bartolini design studio through an invitation-only tender. Studio Nervi & Bartolini designed the project to replace

Fig. 3. *The Nervi's skills emerges between fragility and degradation. Source: © 2021, Authors.*

the existing stadium to maximize the available space. The plan was more linear and pragmatic to permit the possible expansions, as was in the Rome stadium: the non-use of the crescent solution allowed for additional grandstands positioned above the existing ones, offering greater flexibility in the design and expansion of the stadium [15]. This sports facility has a symmetrical rectangular plan with two straights along the length, housing the covered and uncovered stands, and two curves along the width with the remaining seats. Nervi designed the structure with economy and compositional harmony, placing the curves on a gravel layer and ensuring the contrast between the turf and the reinforced concrete walls was attractive. Above the straights made of a concrete slab, the inclined grandstands were located at the highest point (10.50 m). These consist of a repetition of reinforced concrete trestle frames lying on an inclined beam, curved in the intrados and with steps cast *in situ* on the extrados, where the seats rest. Both the inclined beams and the seats are made of prefabricated elements. Two pillars support the beam, an inner one on the field side and an outer one at the highest point. Thanks to prefabricated elements, the configuration of these frames, determined by static requirements, is easily repeatable. As in the Flaminio stadium case, there are dedicated spaces below the stands – changing rooms, toilets, and two gyms – and external pincer staircases and walkways to access the rooms. A grit finish was planned for the cladding, which was not realized because it was considered redundant.

The three stadiums analyzed represent architectural *unicum*, where Nervi's signature is evident in all structures. As illustrated in the following table, the comparison between the three stadiums highlights how the Taormina stadium is an isolated case compared to the other two: in fact, the design of the Novara stadium is more easily comparable with the Flaminio in terms of design choices, such as the presence of a similar subdivision between the grandstand and the parterre, but also for some of the technical solutions mentioned above. The substantial difference is noticeable not only from a compositional point of view – with a plan that is more rectangular than ring-shaped – but also from a structural point of view, evident in the compositions of beams, pillars and frames.

3. RESULTS

In the case of Taormina, there are further specific vulnerabilities (Fig. 3) characteristic of football stadiums, in addition to the criticalities typical of the Modern heritage. Several reasons lead to assimilating the stadium into a minor work [16]. The first is that, compared to the stadiums in Rome and Novara, it is smaller in size, designed to hold up to a maximum of 3,900 spectators (Tab. 1). The second is that this stadium has been little studied and, at times, excluded from the scientific literature, being the subject of interest only of authors Antonino Marino and Laura Marino [14]. A third reason is the lack of interest in heritage protection from organizations and associations.

	Stadium of Rome	*Stadium of Taormina*	*Stadium of Novara*
Year of construction	1959	1960	1976
Authors	Pier Luigi e Antonio Nervi	Pier Luigi e Antonio Nervi	Pier Luigi e Antonio Nervi
Project constraints imposed	- Preserving the field - Respect the area of occupation of the previous stadium - Tight deadlines for the demolition of the old stadium (18 months) and the closure of the construction site (18 months)	- Respect the area of occupation of the previous stadium - Respect the landscape	- Respect the area of occupation of the previous stadium
Projected seats	42000	3900	25000
Planimetry (Fig. 2)	Ring implant without *crescent* shape, athletics tracks and possible expansions	Two-straight track associated with a theatre with athletics tracks (on the long north-north-east side) and grandstand (on the opposite side)	Rectangular layout based on two straights and two curves without *crescent* shape
Compositional characteristics	Presence under the stands of a lower floor with swimming pool, gyms (boxing, weightlifting, heavy athletics, gymnastics and fencing) and service rooms	- Openness to the landscape - Rooftop open square in case of surplus - Dual view for spectators (panoramic and field view)	Presence under the stands of a lower floor with two gymnasiums and service rooms
Structural section	92 frames with non-repeatable 2 hinges (constant shape, variation in height and width)	18 triangular brackets on which the curved floor of the canopy rests	Repeatable gantry frames
Shelter	Cantilevered roof positioned on the grandstand	Cantilevered roof positioned on the grandstand and square open to the landscape	Cantilevered roof positioned on the grandstand
Stairs	Pincer exteriors with cantilevered balconies	Integrated into the grandstand	Pincer exteriors with cantilevered balconies
Main finishing	Exposed concrete	Exposed concrete	Exposed concrete
Prefabricated elements	- Roof - Stands	- Roof	- Seats - Soffit inclined beam of structural frames
Construction site	Developed in two parts	Developed in one part	Developed in two parts
Actual state (2024)	Abandoned and subject to severe degradation	Partially functional and prone to degradation	New project in progress

Tab. 1. *Comparison of the three Italian stadiums analyzed by Pier Luigi and Antonio Nervi. Source: © 2024, Authors.*

Among them, it's worth mentioning the absence of this stadium on the portal of the Pier Luigi Nervi Project Foundation, dealing with preserving the patrimonial memory of Nervi's works. This knowledge gap also impacts the local community, which needs to be aware of its values and recognize it as heritage. The stadium cannot be visited and is not indicated on any itinerary. Moreover, its use for sporting purposes is restricted to the local amateur football club, whose limited availability of funds does not guarantee its adequate management and maintenance. The only project concerning the stadium's maintenance was in 2023, funded by the National Recovery and Resilience Plan, for resurfacing synthetic turf and the energy efficiency of the facilities (Unique Project Code: E84H22000500001). Also, the Taormina stadium must still reach the seventy-year Legislative Decree 42/2004 protection bond requirement. The area where it stands – classified as an "F3 Sports Zone" – has hydrogeological, geomorphological, and seismic risk level 2 restrictions. The absence of constraints or protection can be dangerous, especially when considering an intervention that does not take the form of restoration since any action is left to the sole sensitivity of the designers. Consequently, the stadium is subject to potential risks of alterations that could compromise its value transmission. Nervi was aware that the architecture of the time would not withstand five hundred years [17] and therefore questioned the durability of materials, particularly the resistance of reinforced concrete to thermal expansion. Aware of the critical issues related to the construction system, the engineer put in place solutions – for example, the need to keep the steel of the concrete

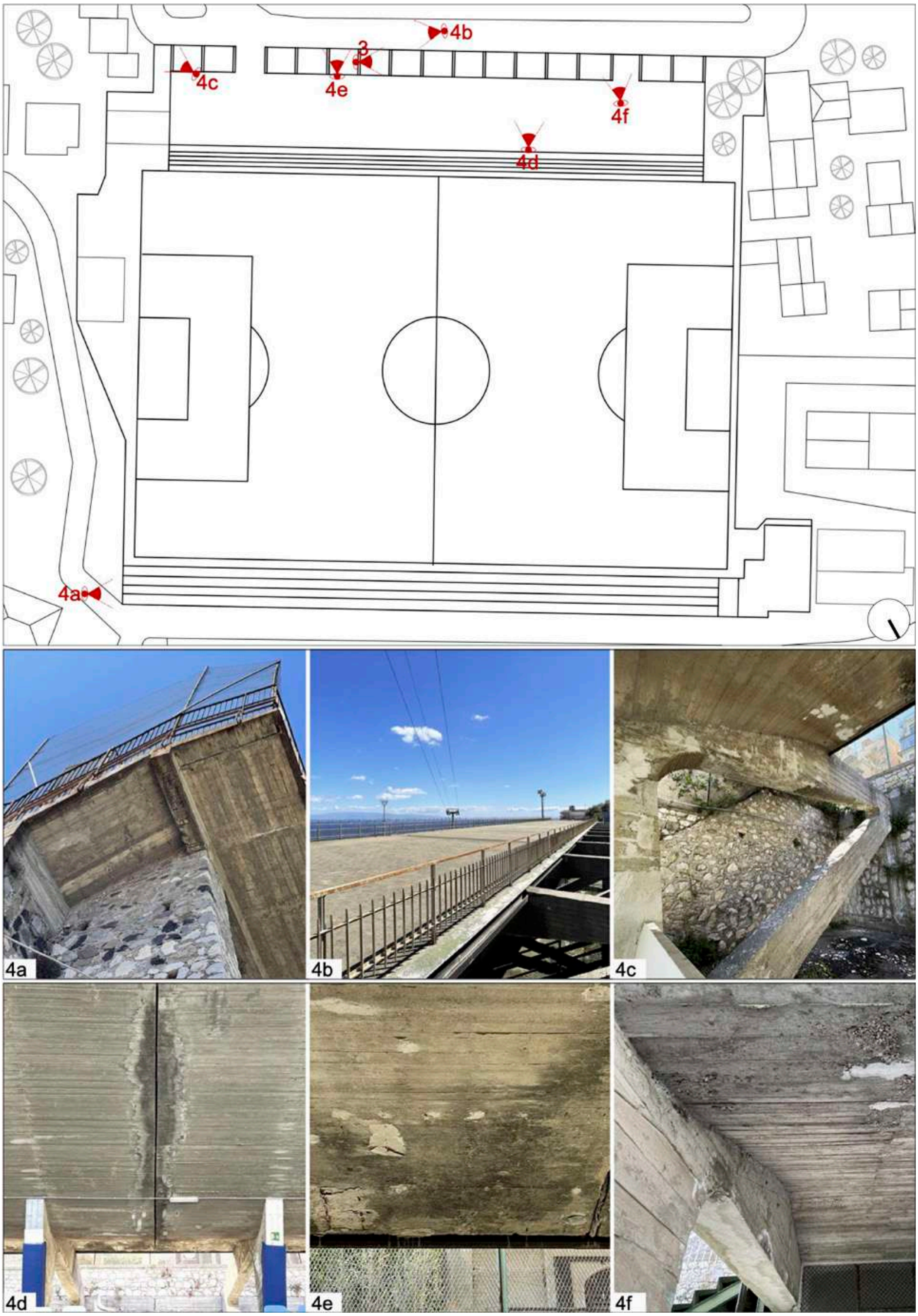

Fig. 4. *Details of the degradation and location in the floor plan: (a) the north stand in structural decay, (b) the abandoned terrace, (c) aesthetic degradation from incorrect patching and vegetation, (d) degradation at the structural joint, (e) lack of concrete and spalling, (f) construction defects such as honeycombs. Source: © 2021, Authors.*

reinforcements away from the external surface – which kept the Taormina stadium in a reasonable state of preservation, beyond the widespread degradation due to aging and lack of maintenance plans.

In April 2021, an on-site inspection was conducted to study the actual state of the stadium, and it appeared to be in good condition from a structural point of view. However, it presented criticalities that prevented its use during the survey. The following description of the detected pathologies is referred to the Italian standard UNI 11182:2006 Beni Culturali (former Normal 1/88 ICR-CNR).

The north stand is cantilevered and has reduced thickness (Fig. 4a), which shows damage due to pull-out phenomena that expose the reinforcement bars and have caused cracks and localized corrosion decay. In addition, it shows significant degradation due to increased exposure to weathering. The south grandstand presents problems that also impact the functional aspect: the terrace above the roof cannot be used for the heavily degraded flooring and the corroded metal parapets (Fig. 4b). Other problems are related to poor or inadequate maintenance, such as weed vegetation and inconsistent patching with cement mortars (Fig. 4c). Problems related to water exposure have caused efflorescence, discoloration, delamination, and cracking, particularly at the three structural joints of the south stand roof (Fig. 4d). In several places, material *lacunae* and small localized spalling phenomena are also evident where the ceiling reinforcement cover is thinner (Fig. 4e). Finally, sporadic honeycombs are evident (Fig. 4f). All of these elements contribute to an evolving cracking and degradation process that, over time, could alter the very stability of the structure. The sports facility generally does not meet regulatory requirements regarding fire prevention and removing architectural barriers.

This study aimed to highlight an architecture largely unknown to date that reveals features of patrimonial value that are not manifest. The anamnesis of the building's history was possible thanks to the consultation of archive material kept at the technical office of the municipality of Taormina. The comparison between the current state of the stadium and the executive drawings in the archives, the technical reports, the sheets of materials used, and the correspondence between those in charge of the project made it possible to reconstruct an accurate knowledge of the property. The inspection allowed a preliminary mapping of the degradation present and is configured as a first step for a future detailed survey, through which non-destructive testing (NDT) will be carried out to assess the residual helpful life [18]. Subsequently, collecting all the data will permit the evaluation of suitable interventions within the framework of conservative restoration.

4. CONCLUSIONS

The Taormina case is emblematic as it illustrates the many fragilities that can characterize sports facilities. To this day, the Sicilian stadium partially maintains its function. Despite this, it highlights problems, offering the possibility to reflect on feasible restoration projects that can emphasize the work's valuable qualities and allow for adequate maintenance work. Knowledge of conservation also assumes an understanding of the concept of heritage and its recognition. Therefore, it is essential to contemplate further the performance adjustment defined in the current regulations when dealing with components that lack the initial evaluation phase, as discussed by Bardelli [19]. Design interventions should be guided by greater attention to the phase of historical-material knowledge of the building. This guarantees an understanding of the cultural heritage and leads to value recognition and, therefore, to subsequent protection, even when not linked to a binding regime. The Taormina stadium shows fragility, which is evident in the widespread lack of recognition of Pier Luigi Nervi's work. In the case of Novara, this oversight extends to the misattribution of the project's authorship solely to his son Antonio, with no mention of Pier Luigi Nervi. Conversely, the definitive identification of the designer behind the Flaminio stadium has significantly contributed to the building's recent protected status. However, there are still many challenges related to its restoration. This study aimed to initiate a knowledge process that could be the base for future interventions concerning the Taormina stadium. Identifying additional vulnerabilities resulted in its classification as minor work, leaving the Sicilian sports facility even more susceptible to risk than the others under consideration. In this context, the words of Dezzi Bardeschi, «not only to know to conserve but also to conserve to know» [20], are highly pertinent for the preservation of this architectural typology. These words aimed to raise awareness among public administrations and the community by exploring viable solutions through scientific research. By acknowledging the value of the work, scholars can initiate processes that increase consciousness within the local community. This plays a crucial role in addressing the challenges associated with restoring the most fragile buildings, which are still unresolved today. It emphasizes the necessity for a "case-by-case" approach to intervene based on the specificities of each of these architectural structures. Collaboration among experts is essential to uncover all relevant characteristics through research and harmonize strategies with stakeholders to preserve and transmit the heritage to future generations.

Authors contribution

Conceptualization, F.V.; Methodology, A.R.; Investigation, G.D.M.; Writing – Original Draft Preparation, G.D.M.; Writing – Review & Editing, F.V. and A.R.; Visualization, G.D.M. and A.R.

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THE REWRITING OF THE URBAN PALIMPSEST THROUGH AN "EVOCATIVE BUILDING RENEWAL" OF TWO MILANESE ARCHITECTURES

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Abstract

The topic of urban regeneration consistently involves a reflection on the relationship between pre-existence and transformation, between permanence and the research for an image renovation of the buildings that participate in the construction of the urban palimpsest. A contemporary architectural narrative cannot overlook the fundamental coherence between what it was – and now what is lost – and what remains. That point is symbolic of what happened in some industrial districts, which were subject to a functional conversion that is still in progress. As a result, these industrial archaeologies appear as silent buildings without any function. Otherwise, a building could still be used and play a leading role in the urban setting as an integral part of the contemporary urban story. In this instance, the conservation requests frequently prevail over the transformation requirements. However, this does not preclude design strategies that can also encompass the partial or complete renovation of the building, solely focusing on the functional and technological enhancement of the exterior envelope or even the reorganization of the interior spaces. Two significant examples of these directions – namely the first pertaining to the recuperation of industrial archaeology heritage that has been incorporated into the urban fabric, and the second aimed at reshaping buildings that necessitate urgent technological and formal renovation – were executed by Park Associati in the past decade.

Keywords

Urban palimpsest, Building renewal, Envelope retrofitting, Milan, 20th-Century architectural heritage.

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1. INTRODUCTION

Paul Ricoeur believes that «to build coherent temporal sets» means, in the very activity of the story, taking the form of «configuring time» [1]. However, the selection of a temporal whole and the research of a coherence – which can be internal if it is solely related to the events already included or external if it crosses multiple sets – are not straightforward actions and cannot always be attributed to objective criteria. They are the outcome of a critical-interpretive process that cannot abstain from the fundamental moment of selecting the data of each set. This selection phase appears to be even more essential in projects involving existing buildings, namely "to build on the built". Indeed, the determination to proceed with a contemporary architectural narrative that does not overlook the essential coherence between what was – and what is now lost – and what remains, can only be derived from a meticulous examination of past fragments and traces, of relationships and rules in each structure. All this information can translate the nature of the built heritage into a comprehensible and interpretable whole, as a prerequisite for the ability to work on it. The process of transcoding the signs' inheritance which in this way is transferred by the existing heritage leads to the identification of some features of permanence that allow to establish in a new story the diachronic coherence between before and after, between yesterday, which could be more or less far, and tomorrow, closer as envisaged by the project [2]. Therefore, these characteristics constitute the essential temporal connection required to establish continuity between diverse ages, which can be expressed in various manners. At times, it manifests itself as the mere preservation of the built heritage, encompassing the complete or partial preservation of its material consistency; other times, it corresponds to the rediscovery of a system of architectural rules and signs that belong to the existing buildings and are adopted by the designers charged with the renovation to give life to seemingly new buildings; other times, it is the outcome of a balanced process that acts as a mediator between the aforementioned topics. Consequently, the design style exhibits varying degrees of coherence with the original structure and the associated transformation phases. They progress from meticulous precision to the urban palimpsest, wherein the building engages in a more explicit freedom of expression, with the aim of presenting a renewed image of the existing building. However, this relationship recovers the system of rules that guide it or takes from the alphabet of signs that defines it.

Different modulations of the operational style cannot be entrusted to a mere arbitrary choice of designers. Nevertheless, it must be measured based on the nature of the urban palimpsests and the relationship the selected building establishes with them. With this perspective, it is imperative to comprehend its significance in the urban setting and its pivotal role in the narrative [3]. It is even more important if a state of abandonment of the existing buildings has led to a substantial loss of meaning, considering the inevitable and evolutionary process that the palimpsest faces. Moreover, it is noteworthy that certain industrial districts have undergone a transformation that is still in progress, even though it has already resulted in a profoundly altered urban landscape, wherein the vestiges of industrial archaeology appear to be "silent" buildings, devoid of any function. In this case, the building stands as a historical testimony, but it has now lost its character as an urban living space. The renovation project aims to reclaim the abandoned spaces and reclaim their "voice", transforming them from "mutes" to "singers" through distinctive solutions that, depending on the circumstances, act as a mediator between conservation and transformation [4].

Otherwise, a building can still be used and play a leading role in the urban set and in such cases, the conservation request typically prevails over the transformation one. However, this distinction does not exclude design strategies that can also consider the renovation of the entire building or only a portion of it, with a focus on the theme of the functional and technological updating of the envelope, as an essential element of the contemporary urban story, or even the new arrangement of the interior spaces.

Among the most significant examples of the operational strategies are two works developed in Milan in the last decade by the Milanese studio Park Associati: the renovation of the former General Electric factory, which hosts offices and laboratories of an important company, and Palazzo Campari, a building built in the 1960s. The first one aims at renovating the heritage of industrial archaeology now included in the urban texture, and the second one is aimed at restyling buildings that need an urgent and undelayable technological and figurative renewal. Following two distinct strategies, the designers adopted the same approach for both interventions, which could be described as an «evocative building renewal» [5].

2. THE REDEVELOPMENT OF AN INDUSTRIAL AREA: THE LUXOTTICA DIGITAL FACTORY

The renovation project of the former General Electric factory entails the search for rules that could be able to affect, according to a different story of what it acquires as a narrative trace, the palimpsest of the Milanese industrial area flourished near Porta Genova in the middle of the 19th century. The related building texture, organized on a road grid parallel to the railway line and characterized by the large industrial blocks, is originally over-

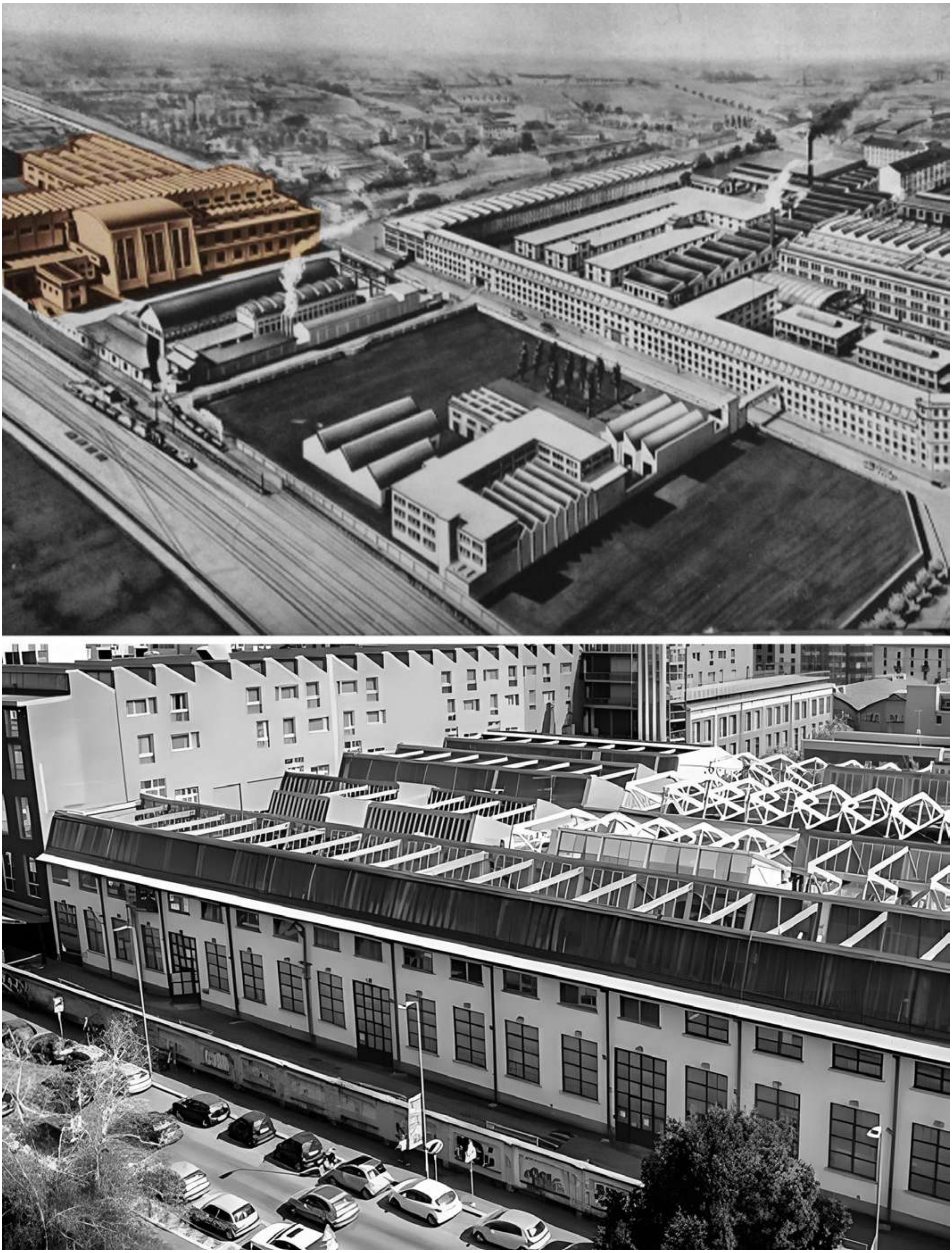

Fig. 1. *The former General Electric factory in the industrial district close to the railway station of Porta Genova and the factory before the renovation design. Source: © MUMI Ecomuseo MilanoSud.*

Fig. 2. *The façade along Via Tortona and the interior space of the GE factory placed next to the building block redesigned by Alfredo Beretta and Matteo Thun. Source: © Park Associati.*

written on the rural layouts and the agricultural partitions determined by irrigation infrastructures and crops. The defining elements of the agricultural landscape, such as farmsteads, irrigation ditches, borders, and fences, establish the boundaries for the designation of district blocks. These blocks, since the initial urban development, have been shaped by regular forms of large size with a singular function, soon occupied by both Italian and foreign industrial companies, as well as the initial workers housing and, gradually, schools and services [6].

In Via Tortona, at number 35, the factory of the Compagnia Generale di Elettricità S.p.A. – an associate of the multinational General Electric – was built in the 1920s to set up a plant for turbine production in an area of 30,000 m^2 (Fig. 1). After the lively economic development of the 1960s, the industrial site was affected by a phase of decline due to the transformation of production systems and the energy crises. Many factories were decommissioned and, in a few years, either abandoned or subject to easy resettlement processes of other productive activities. After the phase of decommissioning and disuse of the plant, at the end of the 1990s, an American group settled in the former General Electric area, using the building for television production and as a data centre [7].

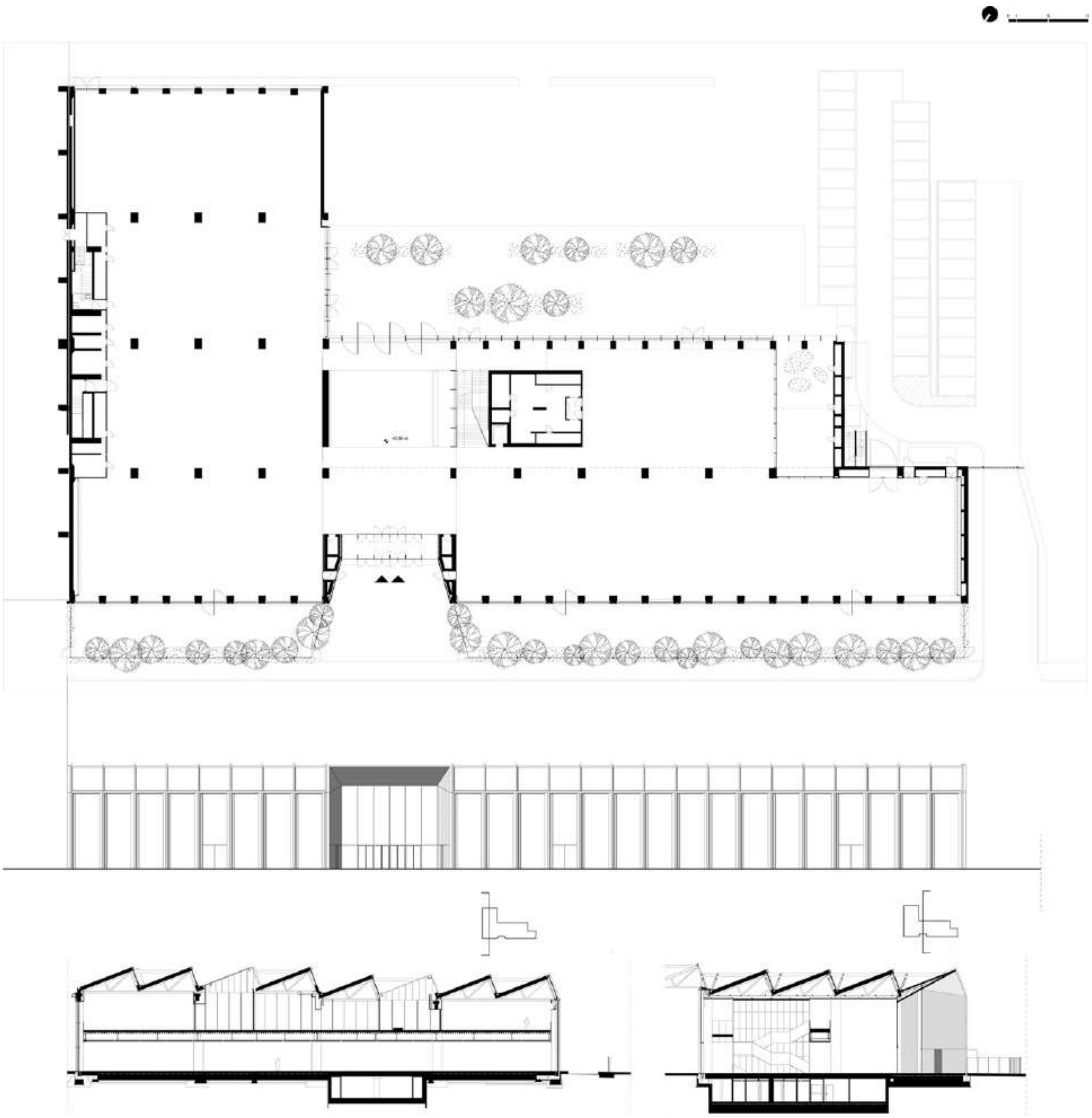

Fig. 3. *The layout of the building designed by Park Associati that replaces the former GE factory. Source: © Park Associati.*

In 1983 a process of transformation and regeneration of the industrial quartier began: the first example, the creation of Flavio Lucchini's Superstudio in the locomotives' garages of the Porta Genova station and a bicycle factory, was followed starting from the 1990s by the redevelopment of the Ansaldo area, the establishment of the Domus Academy in Via Savona, the Armani Theater in the Nestlè factory, the Arnaldo Pomodoro Foundation, etc.

This process of regeneration continued with additional significant private interventions, which were subsequently supplemented by public initiatives that significantly altered the role and image of the district [8]. In this scenario, the area of the former GE industry was also interested in 2006 by the renovation of the tall block located on the edge of the production site to host the Nhow Hotel designed by Alfredo Beretta and Matteo Thun and by an architectural competition call for the design of the Luxottica Digital Factory (Fig. 2). The winning project, which was developed by Park Associati in collaboration with MSC Associati, best exemplifies the identity principles of the client, which include utmost care for quality and technological innovation of materials, exploration of avant-garde architectural solutions, and acknowledgement of the unique values of the location, taking into account the social composition of the neighborhood that will host the new functions [9].

The project area has a depth of 64 m and a length of 113 m, wherein the shed pavilions are arranged side-by-side. Additionally, the continuity of the front, which is 13 m high, is clearly visible on Via Tortona. The structural typology of the original building – a large single or dou-

Fig. 4. *The transparent façade on Via Tortona with the upper part shaped as the backward roof of the previous industrial building. Source: © Park Associati.*

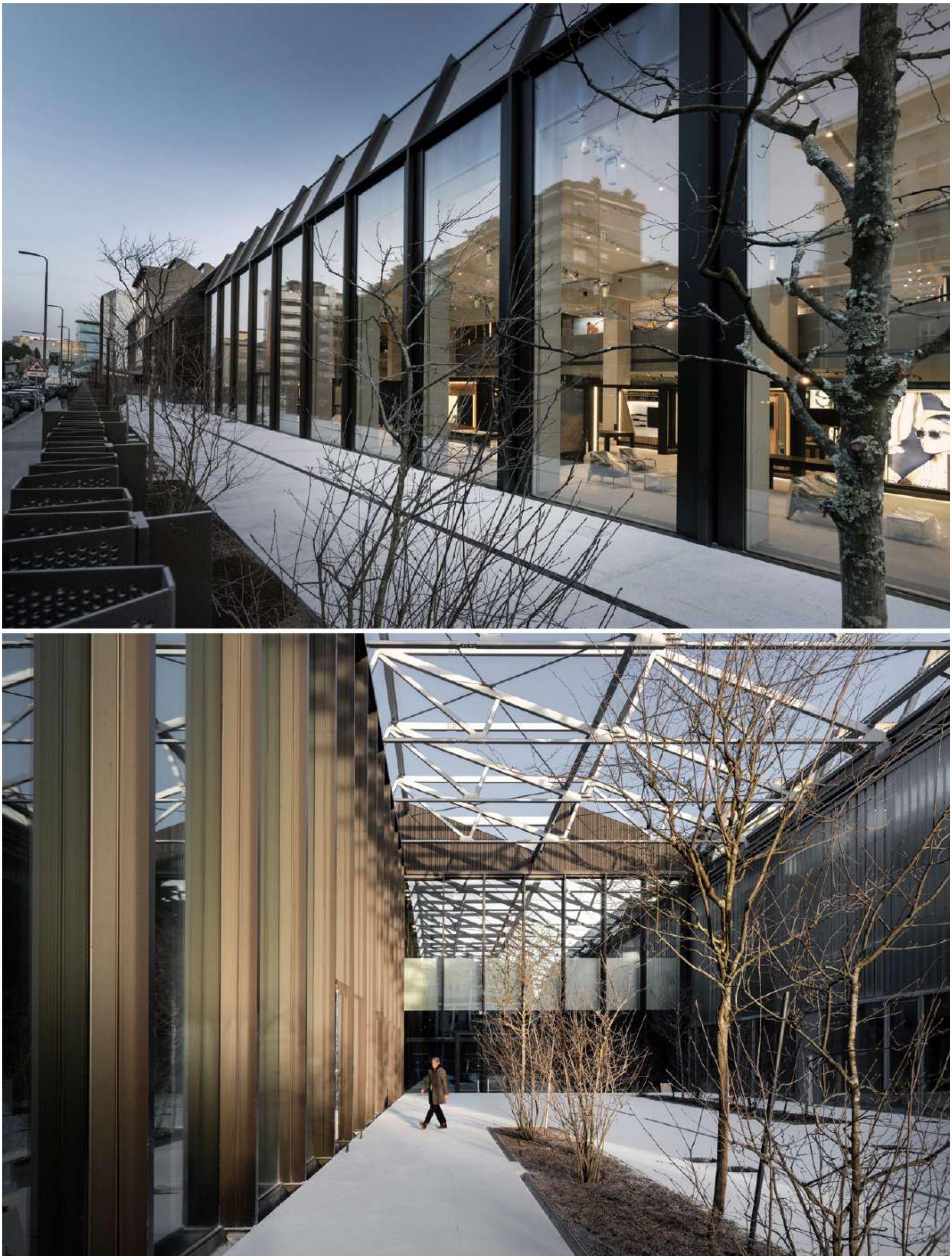

Fig. 5. *The façade on Via Tortona treated as a continuous shop window and the internal courtyard with the permeable roof built of steel trusses. Source: © Andrea Martiradonna.*

ble-span block – characterized by reinforced concrete frames and a roof built of truss beams to facilitate the movement of bridge cranes, was strongly compromised by the refurbishment works of the 1990s.

The interior space of the pavilions was divided, with the construction of several floors catering to the functional requirements of the new television broadcasting. This also influenced the darkening of the skylights and the new arrangement of the window system, resulting in a significant reduction of the symbolic identity of the former industrial plant and the assumption of the anonymous character of a service building situated in the outskirts.

The objective of the project was to identify and restore, through a careful critical and interpreting process, all those elements that were capable of ensuring a comprehensible re-reading of its past, even recent, and to identify those that were capable of advancing in the narration of a contemporary tale through fresh and coherent episodes to reinterpret traces, logics and intentions. Two rewriting keys were used: an "introverted" one, which concerned the return of the original free internal space, and the "extroverted" one, which involved the maintenance of the original shape on which the episodes of the contemporary project were grafted (Fig. 3). The strategy of preserving the external volume shape and re-reading the structural elements of the building resulted in precise design choices that primarily focused on the front of Via Tortona. The compact shape of the old factory was underlined and emphasized by the opaque envelope that marks the head profile and the depth and height of the two walls, forming the large and squared fornix to mark a different relationship between the building and the city. The façade, which is shaped by full-height windows and separated by dark, slender columns constructed from bronzed metal, reinterprets the metric of the previous structure. It accentuates its verticality by doubling the structural elements and following the rhythm of the shed beams, which propose the same shape as the pre-existing reinforced concrete elements with a steel frame (Fig. 4).

The building's exterior envelope was the result of technological and structural research, which resulted in maximum transparency and brightness; the same transparency applied to the interior spaces, made with precious materials that emphasize the monumental character of the internal naves facing the enclosed courtyards, designed by the landscape architect Marco Bay (Fig. 5).

Regarding the correlation between material preservation and novel functional requirements, a reconstruction of the structure was anticipated, preserving a portion of the original pillars that were appropriately reinforced. In the latest functional layout, the incorporation of an intermediate floor aimed at supporting high overloads necessitated the incorporation of essential steel structures of the deck. Relevant interventions were undertaken on the ground floor to underlie the existing foundation plinths and construct the basement. With an overall and integral retrofitting project, the building is then suitable for the parameters of safety and sustainable living with the adoption of the LEED protocol and the attempt at a GOLD class certification [10].

The factory hosts a meeting place for production and use, showrooms with commercial spaces on the ground floor and the Digital lab with the high-tech innovation centre on the upper floor, according to a distribution model that foresees two cores of lift systems and stairs covered in burnished brass. Around them, the whole internal space is organized. It remains possible to establish novel and unexpected visual connections by precisely defining transparency gradients between the wings of the internal courtyard, the surfaces and textures of the steel roof beams, and the metric of the glazing of the new façade with the city.

3. THE NEW BUILDING DRESS IN THE CITY CENTRE: THE PALAZZO LA SERENISSIMA

The Palazzo La Serenissima restyling project was mainly aimed at renewing the ambitious urban concept of the "Gran Milano". The building overlooks the Via Filippo Turati, which connects Piazza della Repubblica with Piazza Cavour. The current layout of the road axis is due to the provisions of the City Plan, which was drawn up in 1863 by engineer Garavaglia. A long series of following changes starting from the mid-nineteenth century, well describe the process of transformation of the historic city and, consequently, the overwriting of the urban palimpsest according to the rules and methods of a "modern" language [11]. The district that arose around Via Turati

Fig. 6. *The original office building La Serenissima placed on Via Turati and designed by Ermenegildo and Eugenio Soncini. Sources: © Park Associati; Archivio Soncini – © Comune di Milano – CASVA; © General Planning.*

mainly developed during the kingdom of Umberto I of Italy. The residential buildings and the headquarters of the Society for Fine Arts and the Permanent Exhibition filled the area's capacity in the early 20th century.

In the first years after the First World War, three significant architectures changed the configuration of Via Turati. The first one, in 1922, was the Ca' Brutta, designed by Giovanni Muzio, a singular building in terms of size, height, and eclectic style of the façades [12], followed in 1931 by the new monumental Central Station designed by Ulisse Stacchini according to "Teutonic typological models" [13], and completed in 1936, by the Palazzo Montecatini by Studio Ponti-Fornaroli-Soncini with its smooth and compact façades, clad by marble slabs and marked by the rhythm of the flush-to-wall windows [14].

Fig. 7. *The façade, the porch and the internal courtyard of the building La Serenissima. Source: Archivio Soncini – © Comune di Milano – CASVA.*

The transformations of the 1920s were followed by those of the 1950s and 1960s, favoured by the building replacement with volumetric increase foreseen first by the 1949 Reconstruction Plan and then by the 1953 City Plan. Some of the transformations concerned the building of well-known architectures in the Milanese scenario: the thirteen-storey tower of Montecatini, designed by the Ponti-Fornaroli-Soncini studio and inaugurated in 1951; the two towers at the entrance to Via Turati, designed by Giovanni Muzio and his pupil Luigi

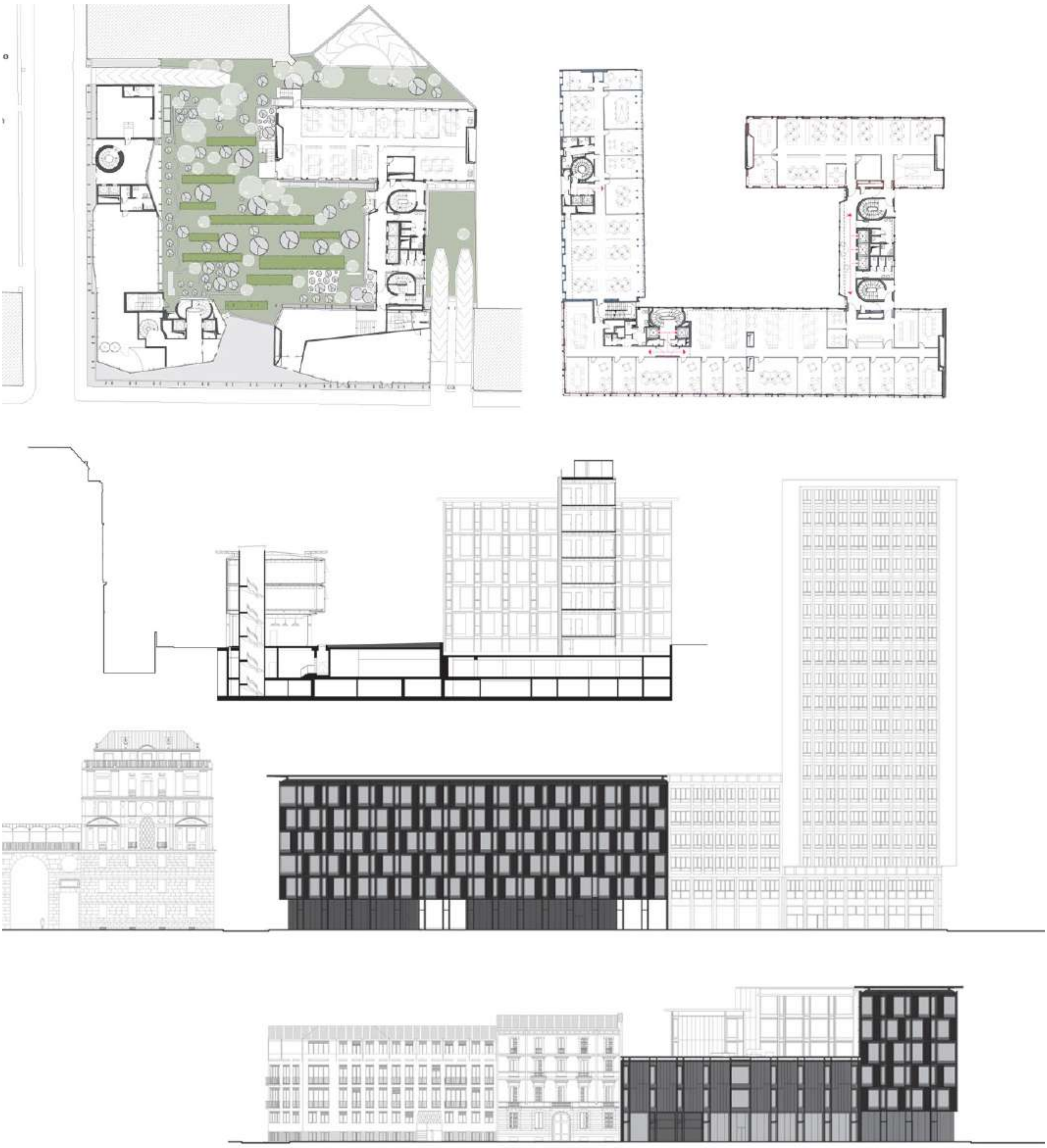

Fig. 8. *The new layout of the offices and the project of the two main façades showing the relationship with the other buildings of the urban context. Source: © Park Associati.*

Mattioni. Another important building, the Palazzo La Serenissima, played a significant role in the dynamics of the transformation process of this late 19th-century Milanese district (Fig. 6). The building, conceived by the brothers Eugenio and Ermenegildo Soncini, who had previously worked in the same urban area, initially acquired its name from the real estate firm that promoted its construction to replace two residential structures situated adjacent to the Turati Tower [15]. It was completed in 1969 and it hosted apartments and office spaces of some international companies (Fig. 7) – including Campari, indeed it was also known as the "Campari building" – until its recent purchase by a foreign real estate fund, which favoured the refurbishment.

In 2008, the building complex was incorporated into the real estate portfolio of Morgan Stanley Sgr, prompting the announcement of a design competition for a comprehensive renovation that included both structural and energy retrofitting. The restricted competition process concluded in January of the ensuing year with the triumph of the Milanese studio Park Associati. The management of building works and the structural and plant design was entrusted to the engineering company General Planning [16].

The Park project was focused on the redesign of the façades. Between the extremes of conservation and modernization, the designers sought a third way capable of preserving the complex of symbolic and characterizing values of the building, without renunciation with respect to use and market values.

The building is, in fact, based on the replacement of the original envelope; its texture is reinterpreted in the project to create a "new architectural dress" that fits the dimensional and proportional metrics of the Soncini building and, in particular, of its structural layout. For the new envelope, the designers selected non-standardized solutions based on distinct schemes on the street fronts of Via Turati and Via Cavalieri, as well as the internal courtyard.

A preparatory phase for the transformation of the curtain wall was the recognition of the "regulatory" value of the steel structure, designed by the Soncini brothers with the company Società Anonima Elettrificazione di Lecco and characterized by the repetition of an exposed structural pattern, which consists of single span frames oriented in the short side of the building facing Via Turati [17]. This "regulatory weft" was entirely preserved, with the exception of limited reinforcements and remediation for asbestos. It was exposed with the removal of the curtain wall to serve as a syntactic rule, thereby guaranteeing continuity between the old and new narration by overwriting the urban palimpsest.

The steel weft was transformed on Via Turati into an exposed lattice with a glass surface placed backwards, characterized by an updated composition of vertical and horizontal elements to reconfigure a contrasting image with the stereotomic rules of the close Ca' Brutta and to achieve a renewed analogy with the tectonic principles followed by the adjacent buildings. The structure established the design modularity of the new façade, which was interrupted and arranged by incorporating a perforated aluminium panel that was appropriately proportioned to the coupled columns and variedly repeated, introducing asymmetry and dissonance with novel formal guidelines. The addition of new steel elements provided further flexibility for the partition walls, and the integration of an LED lighting system allowed the building to transform into a large "lantern" during the night.

A similar arrangement of the façade was proposed for all fronts of the courtyard, but it was based on a different position of the glass, which was shaped as a flat surface with all coplanar components. This strategy ensured maximum penetration of light and enhanced the visual relationship with the garden (Fig. 8). It was designed with the advice of landscape architect Marco Bay and made visible from the outside by a large atrium shaped in the covered walkway of the porch [18, 19]. A different strategy was adopted for the building envelope located in Via dei Cavalieri, originally designed for residential use and characterized by a prevalent opaque front to guarantee the necessary privacy. A distinct arrangement of the ground floor resulted in a more seamless connection with the principal structure and a modification of the porch height. Moreover, a novel reflecting and flat glass façade proposed a direct dialogue with the side of Ca' Brutta. Even in the new façade arrangement, the choice of coupled columns was confirmed as a regulatory pattern for

Fig. 9. *The two façades respectively conceived for the blocks of Via Turati and Via Cavalieri with a different relationship between steel frame and glazing. Sources: © Park Associati; © Andrea Martiradonna.*

the window module (Fig. 9), which was repeated according to different rules [20].

The renovation design involved a new definition of the crowning element, which was proportioned to the new volumetric arrangement. The biggest overhang of the projecting roof allowed the integration of the glass cleaning system, and the different façade sides were marked with a deep shadow line (Fig. 10).

The retrofitted façade enhanced the energy efficiency of the envelope by combining an opaque and transparent module, resulting in a reduction in heat dispersion and superior acoustic insulation. The containment of energy resources was confirmed with the achievement of LEED Gold certification and the transition from G to B energy class with a halving of specific building consumption [21].

The revised functional layout of the La Serenissima building resulted in an available area of approximately 15,000 m^2 for the underground floor and about 8,000 m^2 for the upper floors which were distinguished by open space offices.

4. CONCLUSIONS

The project on existing buildings appears to be a valuable practice that could regenerate a story aimed at continuing and representing the architectural heritage in a coherent temporal configuration. The new narrative must establish a *fil rouge* between urban dimensions, arranged in chronological order, referring to distinct moments in the creation of the palimpsest.

The two case studies illustrate the dynamic character of the "Gran Milano" entrepreneurial spirit, which tries to preserve its roots without renouncing them to promote its image through a contemporary architectural narrative. As per the definition of an "evocative building renewal", the project adheres to the development of a dual design register that can be tailored to the functional and technological update in accordance with the principle of control and sustainable management. Furthermore, it also collaborates in the rewriting of the urban palimpsest, particularly expressed through formal codes of the façade elements, restoring a distinct narrative of the public space inherited from the "dusty" industrial districts or the elegant quarters of the late 19th century.

The city's regeneration is, in fact, a practice that involves the awareness of updated assessments of needs and spaces and the definition of vulnerability and potentiality aimed at its sustainable management. It is also linked to the opportunity to reactivate the transformation process that, with the persistence of certain conditions, spontaneously generated the «enormous deposit of signs and practices» of the palimpsest, which «stratifying, overlapping, deforming and sometimes contradicting itself, has produced surprising and often barely interpretable results» [22]. In an unpredictable time frame, the evolution and transformation of the palimpsest transpired in accordance with a natural chronology, acquiring the characteristics of a self-regulating process. Taking into account the actual complexity of the problems and the variation speed of the urban dynamics, the work on the urban palimpsest should involve the character and methods of «an active process that reports an effective and constant suitability to experiment and to explore the various plots of relationships compatible with what can be called the "edge of the possible transformation", namely the ability to vary and the suitability to change without compromising the continuity of which any notion of identity, even the weakest, cannot fail to feed on» [23].

Therefore, «to design for the existing buildings» can identify the perspective overturning in which the choice or indeed the need for one or more categories of the design work – restoration, refurbishment, reuse, redevelopment, etc. – represents the coherence of a methodological approach with the dimension of foreseen operations that must be chosen case-by-case. The interpretation, namely «to say of the saying» which «has remembrance as its own dimension, as a factor that is able every time to raise the hidden potentiality in the primitive object reached by memory», shapes a different and possible condition of the pre-existence according to a «faithful and free project at the same time: it has to be faithful because it is compliant with what has already been said and free because it gradually adds that much which is recognizable as virtually included in the original saying» [24].

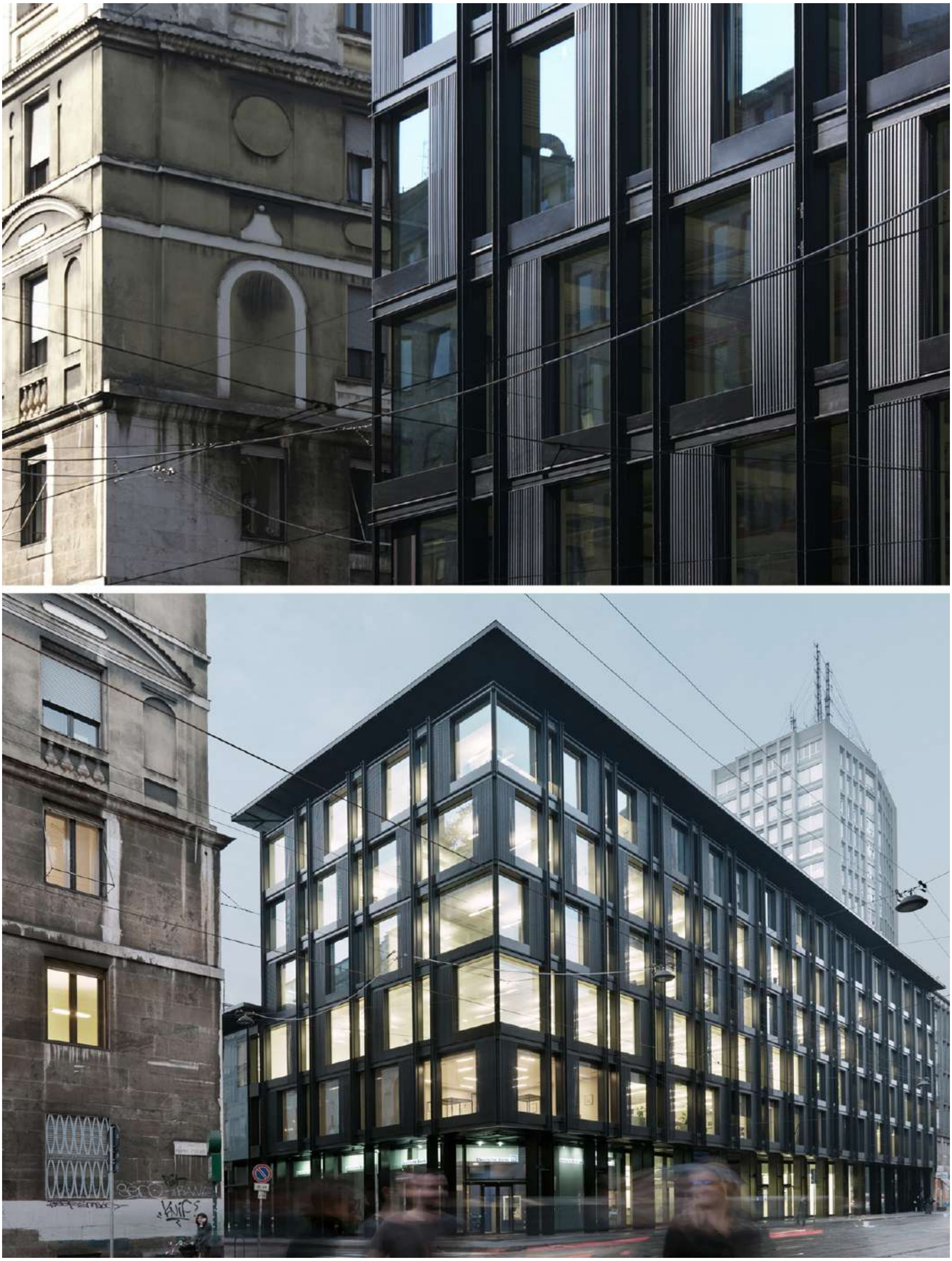

Fig. 10. *The new configuration of the steel building that reaffirms the contrast with the ecleptic façades of the Ca' Brutta. Source: © Andrea Martiradonna.*

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INDUSTRIALIZATION AND PREFABRICATION OF THIN VAULTS AND SHELLS IN LATIN AMERICA DURING THE SECOND HALF OF THE 20TH CENTURY

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Abstract

After World War II, the socio-economic difficulties in some Latin American countries often led to political instability conditions. In this complex context, solutions were adopted by some designers to meet looming needs: housing for populations reduced to poverty and the construction of strategic infrastructures.

In these countries, starting from the 1940s, the introduction of new techniques and materials – such as concrete and steel – enabled the industrialization of building processes. This also allowed the experimentation of standardized models of thin vaults and shells using the traditional thin vaults, whose technique was imported from the Iberian Peninsula as a reference.

The solution of "thin" vaults is one of the most interesting, given the peculiarities that distinguish it from other systems. The small thickness of such vaults derives from the consideration that their strength is determined by their shape and cohesive behavior, following the theories of R. Guastavino Moreno.

Based on these assumptions, this paper aims to review some solutions developed for the prefabrication of thin vaults and the construction of some remarkable buildings. Based on the principles of prefabrication and reinterpretation of the traditional construction technique, the solutions adopted in some emblematic buildings can be useful for suggesting the development of new technical solutions to put in place shells and thin vaults in the second millennium.

Keywords

Thin vaults, Thin shells, Latin America, Prefabrication, Industrialization.

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1. INTRODUCTION

This paper shows the solutions adopted after World War II in several Latin American countries for prefabricated elements for constructing shells and thin vaults. In these countries, the use of brick elements was predominant over other building materials due to the high import cost of the latter. Prefabrication techniques for such thin-layered structures led to a reduction in construction time, and even today, they can be used as a model for the construction of modern prefabricated thin vaults/shells, where ribbing can be reduced or eliminated.

Uruguay, Mexico, Argentina, and Colombia are the Latin American countries where the work of designers such as Eladio Dieste, Carlos González Lobo, or Mario Kalemkerian took shape, significantly contributing to the development of the thin-shell technique. The circumstances in which these designers worked were marked by political instability and unfavorable economic conditions. This prompted them to think of vaulted systems in which they could combine their knowledge of building history with the possibilities obtained from the use of techniques and materials that were becoming preferred in those years (steel and reinforced concrete, among all).

The thin-tile vaulting technique has been altered throughout history. Designers/builders have been able to adapt them more and more effectively to the varying dimensions of the spaces as well as to the types of buildings in which they were being built.

On the origin of the construction technique related to thin vaults, many debates still take place and there are many hypotheses suggested to identify where it would derive from: from the timbrel vault found in the Campbell chamber inside the Great Pyramid of Giza (ca. 2550 BC) [1] to the *bipedales* brick vaults (sized 60 cm x 60 cm x 7 cm) of Roman times [2], to the hypothesis of an Arab architectural inspiration [3]. The oldest written evidence of the brick-and-gypsum mortar setting system dates from an early 15th-century document concerning the construction of a vault for a votive chapel in Valencia, Spain [4]. In the Spanish regions of Catalonia and Extremadura, some excellent examples of the so-called *bóvedas tabicadas* (bricked-up vaults) are still visible [5]. More examples, in addition to the Iberian area, can be found in Portugal in the Alentejo region (hence the name *abobadilhas alentejanas*, Alentejo vaults) [6], and in France, in Languedoc-Roussillon, where *combles briquetes* (bricked roofs) can be observed [7]. In Italy, they are known as *in folio* vaults [8] or, in relation to the areas where they are built, as *volterrana* vaults (in central Italy) [3] or *realine* vaults (in Sicily) [9] (Fig. 1, left).

The traditional construction technique for thin vaults consists of thin clay masonry tiles (no greater than 3 cm thick and weighing 1.6 kg) joined with gypsum mortar (in many cases combined with various materials or, more recently, substituted by cement mortar) [10]. The lightness of the tiles and the rapid setting of the mortar used to build them offer several advantages, such as the ease and rapidity of installation and the absence of any ribbing systems. These features remained nearly unchanged until the end of the nineteenth century. Afterward, the advent of materials that were no longer associated with local culture, such as concrete and steel, enabled the testing of new geometries distinguished by their "free" shapes. As a result, an increase in the plan size of the elements (vaults or shells) corresponds proportionally to an increase in their thickness, albeit in a considerably smaller percentage when compared to typical vaults. In general, the capacity of shells to resist loads is dependent on their resistance by shape, namely their structural form (a unity of function, material, and statical principles) [11]. In this sense, Rafael Guastavino Moreno (1842-1908) is considered a pioneer in designing and constructing thin vaults. Thus, between the 19th and 20th centuries, he was able to rethink and readapt the *tabicada* technique, even registering several patents [1], exporting it to the United States of America, and carrying it to a level of excellence and audacity until then unexplored. He is also the first theorist of the structural behavior of thin vaults, defined as "cohesive structures", that is, structures in which the composing materials cannot be separated without destroying the entire element [12].

There is one distinction to be made between "carrying shells" and "carried shells". While these two varieties may appear to be similar from an architectural point of view, the distinction is primarily structural. In fact, in a carrying shell, subtracting a portion leads to a redistribution of internal tensile states. On the other hand, in a carried shell, the stress states remain unchanged. This is because, while stresses are distributed in a continuous pattern in the carrying shell, they are distributed linearly along the shell's surface in the carried shell, which behaves similarly to grid-shells. Otherwise, carrying shells must be modeled for planar continuous elements, whereas carried shells can be modeled for linear elements. Therefore, because of their conformation and structural behavior, shells and vaults shown in this paper can be considered carrying shells.

The earliest example of a proper thin shell is Robert Maillart's Cement Hall, built for the 1939 Swiss National Exhibition in Zurich and later demolished (Fig. 1, right) [13]. It was built using reinforced concrete, consisting of a parabolic shell connected to two large central arches. One of its remarkable characteristics was the lack of gaps between the roof and the vertical walls (a common characteristic of all thin shells).

Fig. 1. *Left: view of the extrados of a realina vault in Partinico, Sicily. Source: © C. Di Maggio 2019. Right: Cement Hall by Robert Maillart. Source: [13].*

2. EVOLUTION OF THE CONSTRUCTION TECHNIQUE IN LATIN AMERICA

In Latin American countries, the earliest examples of thin vaults can be dated back to the work of the Valencian missionary Fray Domingo de Petres. Between 1759 and 1811, the missionary employed the traditional technique of *tabicade* vaults in Colombia in the buildings he built [14]. This technique, which soon spread to other countries [15], remained almost unchanged until the second half of the 20th century. During those years, each state's complex and unique socio-economic context provided fertile ground for experimenting with various vault and thin shell construction methods. In particular, these solutions were related to the specific area and used for the roofing of social housing as well as large strategic and public buildings. In this sense, the limited availability of economic resources and the consequent reduced import of cement and steel from abroad led designers to adopt building solutions using the raw materials available, including bricks largely used in traditional construction.

Since the second part of the 20th century, different types of shells and thin vaults have been tested in Latin America: reinforced ceramic shells, reinforced brick prefabricated vaults, and precast reinforced concrete vaults (see Tab. 1). Several variations exist for each designer who designed them, and in each country where they were built, not only in accordance with the various dimensions of the space to cover but also to specific circumstances. As a result, shell thicknesses vary, ranging from approximately 4 cm for vacuum concrete shells to 12 cm for Dieste's *cerámica armada* shells [16]. Another distinguishing feature includes the different types of ribs, formworks, or molds used to build or precast the various shells designed. The primary material used is wood due to its economy. Moreover, molds made of ceramic material have been used to shape the elements of on-site prefabricated vaults and shells and to shape the elements in reinforced brick or reinforced concrete.

2.1. THE REINFORCED CERAMIC SHELLS

In the thin shell construction process, the improvements made by Uruguayan Eladio Dieste (1917-2000) deserve special attention. He is considered the initiator of the large-scale use of a new construction technique involving the use of local materials (brick for construction and timber for ribs), limiting the consumption of other imported materials, effective because of the simplicity of assembling the elements. It is referring to the so-called *cerámica armada*, consisting of «[…] shells formed by a single layer of tiles laid flat and with continuous joints in both directions so that both in the catenary directrix of the vault and along its rectilinear generatrix can be placed a small metal reinforcement that allows the complex to act as an elastic membrane. Once the ceramic part of the vaults is finished, a top layer of sand and Portland cement is added, in which a thin steel reinforced mesh is embedded to control shrinkage actions […]» [17].

Types of shells	Designer	Country	Typology	Thickness	Type of application	Ribs/formworks/ moulds
Reinforced ceramic shells	*Eladio Dieste*	*Uruguay*	*Gaussian vaults and self-carrying shells*	*<12 cm*	*Community buildings – Industrial buildings*	*Wooden movable ribs*
Reinforced brick prefabricated vaults	*Eduardo Sacriste*	*Argentina*	*Vaults made of bricks set with cement mortar*	*5-7 cm*	*Middle class housing*	*Wooden formworks*
			Vaults made with prefabricated modules			*Light wooden formworks*
	Carlos González Lobo	*Mexico*	*Vaults made with modular prefabricated vaulted elements*	*<10 cm*	*Poor class buildings*	*Vault-mould built on site made of ceramic material*
	Mario Kalemkerian	*Argentina*	*Self-supporting, prefabricated, brick vaults*	*5 cm*	*Strategic buildings*	*Vault-mould built on site made of ceramic material*
			Dome made of brick elements	*12 cm*		*Cover of a water tank used as a formwork*
Precast reinforced concrete vaults	*Álvaro Ortega*	*Colombia*	*Vacuum concrete shells*	*3.8 cm*	*Social housing*	*Wooden formwork built on site*
	Teodoro González De León	*Mexico*	*Structurally independent prefabricated modular vaults*	*N/A*	*Social housing*	*N/A*

Tab. 1. *Overview of the different types of shells/vaults designed and built in Latin America in the second half of the 20th century.*

The layer of brick placed on the intrados, which in most cases remained exposed even after the work was completed, served as a formwork for the reinforced concrete cast in the following phase. The choice of this material – a high-quality product in countries such as Uruguay, Argentina, and Brazil – is related to its high mechanical compressive strength, which can reach up to 1,500 kg/cm^2. Moreover, as Dieste himself states, «[…] for the same strength, brick has a lower modulus of elasticity than concrete, which is an advantage and not a drawback, because it gives the structure greater adaptability to deformation […]» [18]. Other benefits of using brick include better resistance to thermal shock and aging, as well as better acoustic and environmental qualities [19]. This construction system, which makes it possible to obtain structures whose maximum thickness – in realized cases – is 12 cm [20], has been applied for the construction of different shells and vaults belonging to two different categories based on the catenary principle: *bóvedas gausas* and *cascaras autoportantes*.

Among the former – literally "Gaussian vaults" (from the mathematician Karl Gauss, who described the geometry of curved surfaces) – belong those structures in which the double curvature of the geometries used allows structural resistance to loads otherwise not possible with single planar surfaces [21]. These vaults were made by varying the width of the shell's rise from a maximum value at the key to zero at the side walls. The geometric shape was achieved by moving a catenary with a fixed span and variable rise contained in a movable vertical plane that moved while remaining parallel to another fixed vertical plane [20]. In *bóvedas gausas*, the typical span-to-rise ratio is 10. From a structural point of view, the undulating geometry is

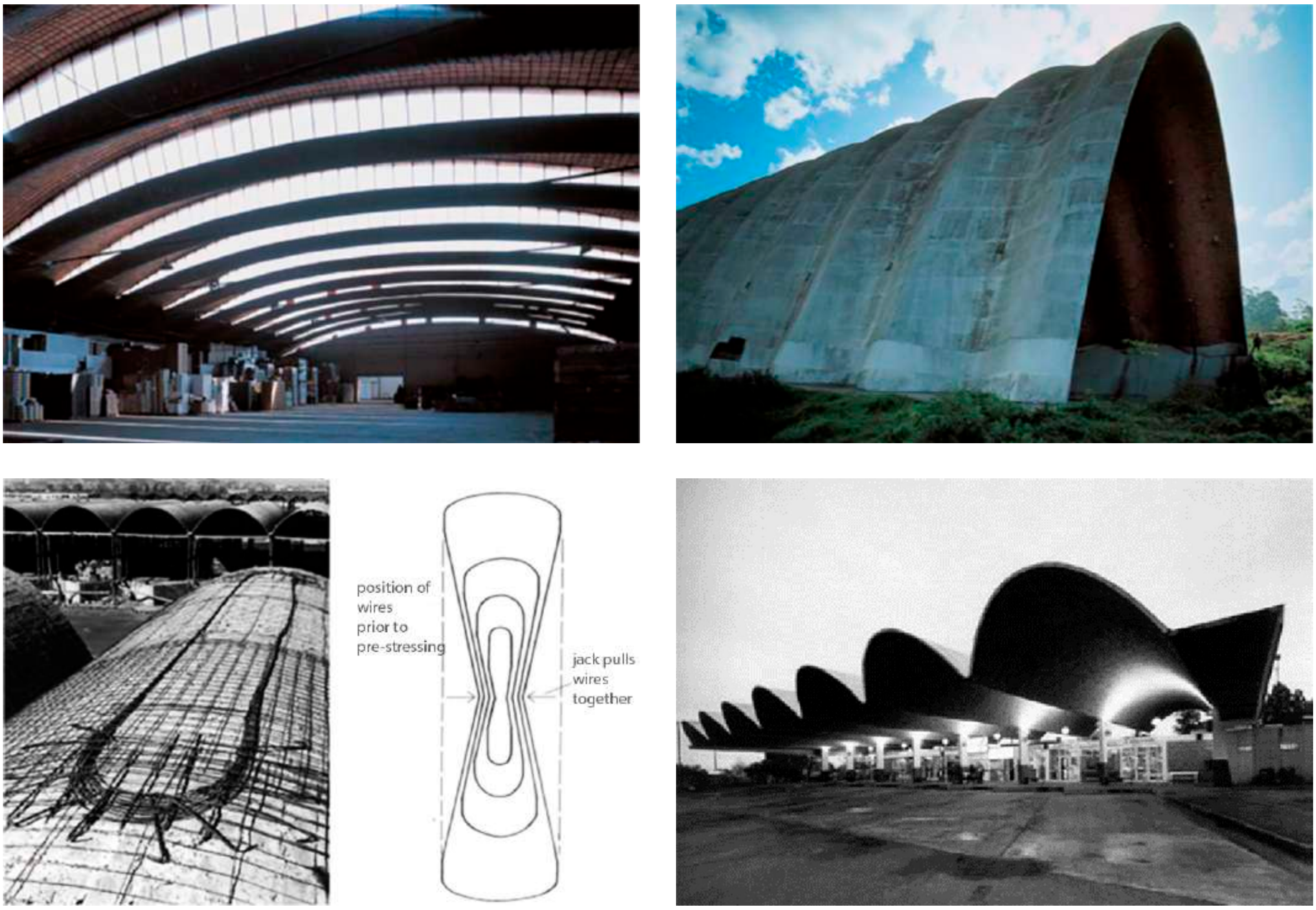

Fig. 2. *Bóvedas gausas. Top left: Cítricos Caputto Fruit Packing Plant. Top right: Cadyl Horizontal Sylo. Cascaras autoportantes. Source: [19]. Bottom left: looped pre-stressing steel. Source: [23]. Bottom right: municipal bus terminal in Salto. Source: [19].*

designed to withstand deformation, providing, at the same time, maximum efficiency in the use of materials. Furthermore, the axial compression of the brickwork by its own weight is ensured by the catenary geometry of the vaults [22]. Examples of such shells are found in the Church of Christ the Worker in Atlántida (1958-1960), the TEM Factory in Montevideo (1960-1962), the Cítricos Caputto Fruit Packing Plant in Salto (1971-1987) (Fig. 2, top left), and the Cadyl Horizontal Sylo in Young (1976-1978) (Fig. 2, top right).

The second category – constituting self-supporting shells – includes cylindrical barrel shells that, given their shape, resist bending as well as compression. Dieste developed an effective pre-stressing method to resist tensile stresses due to bending. This method consisted of placing steel cables in a ring shape on the top of the shells, anchoring them at each end of the shells. Pre-stressing was produced by pinching the cables together at the center point of the rings and conforming them into an "eight" shape (Fig. 2, bottom left). Once the required extension was reached, the wires were held in place by metal clamps. Finally, a concrete screed was cast to cover the wires [23]. The Lanas Trinidad Wool Industrial Complex in Trinidad (1965-1989) and the Municipal Bus Terminal in Salto (1973-1974) (Fig. 2, bottom right) were built using this method, which allowed cantilevers of up to 15 m.

In setting up these systems, particularly the bóvedas gausas, Dieste used the so-called *encofrados* (formwork/scaffolding), which provided a double advantage. In fact, on the one hand, since they could be used repeatedly, it was possible to make considerable savings in terms of materials. On the other hand, equally important was the time savings in both the construction of the ribs themselves and the shells (in fact, it was possible to strike the formwork 24 hours after completing the vault [22]). Each *encofrado* consisted of a rigid steel tube frame supporting a steel truss. Above this, a wooden truss had the task of defining the shape of the vault. The vertical sliding of the two trusses on the frame allowed them to be quickly moved after the construction of each vault and positioned for the installation of the adjacent vault [21].

In the entire production of Eladio Dieste, the load-bearing capacity of shells and vaulted structures depends essentially on their shape and is determined not empirically but through the use of calculation methods usually adopted for reinforced concrete shells [19].

2.2. THE REINFORCED BRICK PREFABRICATED VAULTS

Following the innovative capacity of Eladio Dieste's constructions in Uruguay, in Argentina, an innovative impetus for industrialization and, especially, prefabrication of thin-shell vaulted systems was Eduardo Sacriste (1905-1999) [24].

Sacriste's ability to combine aspects related to local building traditions (*tabicade* vaults were typical in the province of Córdoba) with the innovations he found in some examples of modern architecture (Casas del Garraf by Sert and Torres Clavé, Casa Berlingieri by Bonet and Dieste, Jaoul and Sarabhai houses by Le Corbusier) was useful in arriving at the definition of new techniques for setting up shells and thin vaults in Argentina.

His production focused on the design and construction of small-scale buildings: these were often single-story isolated houses, organized according to several adjacent spans, with heavy masonry walls on top of which the beams to support the vaults were built (Fig. 3, top left). The bricks for the vaults, produced in factories, were set in place with cement mortar to form two or more overlapping layers or a single layer to which a functional layer of concrete was superimposed, varying in thickness from 5 to 7 cm. In the case of House B of the Clérico Hermanos (Fig. 3, top right), built in 1948 in Salta province, the vaulted ceilings are made with a first layer of thin tiles measuring 20 cm x 20 cm (*tijuelas*), while the successive two staggered layers are of ordinary bricks. The mortar used is cement mortar. The spandrels of the vaults are filled with concrete (strong concrete up to 30 degrees from the springing line and, above this, concrete lightened with rice husk ash), on top of which there is a waterproofing layer (Fig. 3, bottom left). A layer of soil was finally placed at the extrados. The sides of each series of vaults terminate with a one-meter-wide flat slab, which acts as a buttress, thus countering the thrusts of the extreme vaults [2]. Another example of a vaulted roofing solution is one in which a single layer of ordinary bricks was laid on top of a lightweight metal formwork with the overlay of a 3-cm functional layer of concrete. In adhesion to this, a layer of about 10 cm of lightened concrete was placed. The extrados was completed using bituminous sheets and tiles for rainwater drainage. Sacriste's acumen is expressed in his ability to design buildings that are easy to build and low-cost (Casa Experimental Clérico Hermanos, Casa Experimental de San Miguel de Tucumán), in which the use of steel, as well as concrete, is kept to a minimum. Another remarkable example is the creation of vaulted buildings for the upper classes (Casa Clérico, Casa Wright), in which the principles of *cerámica armada* learned from the lesson of Eladio Dieste were applied.

Following the growing interest in prefabrication between the 1960s and 1970s, Sacriste and his group also tested various prefabricated thin vault solutions. The main objective was to overcome the scarcity of materials throughout the country and, above all, the lack of skilled labor. An example of an application in this sense is the Casa Carrieri (1961): here, spaces are subdivided according to the prefabricated modules of the vaults (called *costillas*), having dimensions of 3 m by 50 cm and a weight of about 200 kg. These modular elements, when placed together and joined according to their largest side, form the vaults of the different rooms of the dwelling.

On-site prefabrication was done with wooden formworks (as for the vaults of Casa Robert, Fig. 5, bottom right) or in brickwork (as for the vaults of Casa Carrieri) completed with mortar on top of which bricks were placed and joined. The use of a light scaffolding – useful also to allow transport – was provided for connection to the other *costillas* or to the perimeter walls, without the need, therefore, for supporting ribs at the time of installation.

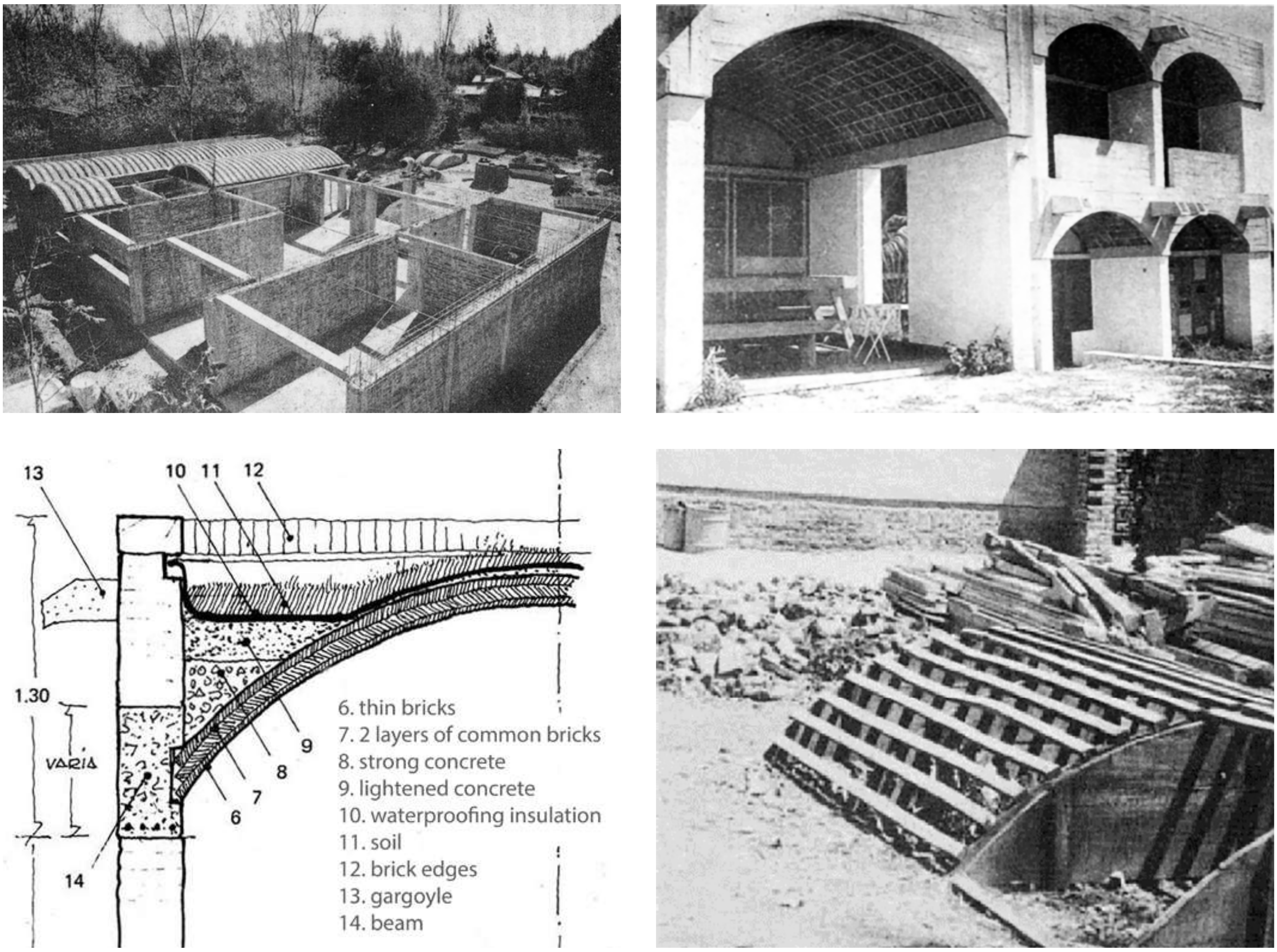

Fig. 3. *Top left: reinforcement of the support beams of the vaults of Casa Carrieri. Top right: gallery of Casa B of the Clérico Hermanos. Bottom left: structural section of the vaults of Casa B of the Clérico Hermanos. Bottom right: wooden formwork used for the vaults of Casa Robert. Source: [2].*

In Mexico, the architect Carlos González Lobo (1939-2021), similarly to what Sacriste developed in Argentina, spent his time, until his recent death, experimenting with and building housing systems intended especially for the poorer classes [25].

Gonzalez Lobo's starting concept was the *gran galpón* (large shed), a large transformable open space covered by a thin vaulted roof that allows for greater volumetry.

González Lobo experienced the so-called "CGL-2 system", taking Dieste's *cerámica armada* as a reference, which he modified according to changing needs and renamed *ladrillo armado*. An evolution of the earlier "CGL-1 system", CGL-2 consisted of modular vaulted elements made of clay bricks held together by steel and concrete reinforcement. The modular elements to be built, also called *costillas*, were conformed as smaller portions of barrel vaults, making them easier to transport and put in place. Each *costilla* was realized on top of a curved mold previously built on site (Fig. 4, left), filled with stones and spoil, and covered with a layer of lean concrete. Each unit involved the combination of a series of bricks placed in the plane, in a double row and single layer. In the joints between the bricks, of about 10 cm, ϕ6 steel bars, and iron wires were placed to form the reinforcement for the subsequent concrete filling (cement and sand in a ratio of 1:4). For the vaulting, the various *costillas* were assembled. The reinforced concrete edge beams were placed on the perimeter walls, while in the key, the reinforcement for a triangular section beam (*cadena triangular*) was installed. Once the concrete was placed, this beam was supposed to reinforce and join the various modules (Fig. 4, right). The vault was completed by a function-


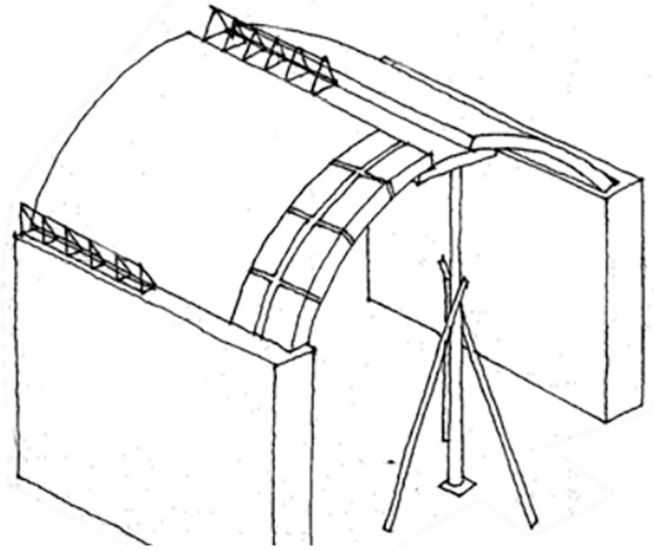

Fig. 4. *Left: Carlos González Lobo raises a costilla from the mold. Right: connections of the costillas with the main structure. Source: [26].*

al concrete layer where the steel-reinforced mesh was placed [26].

An example of the use of precast thin reinforced brick shells made for roofing large buildings is due to Uruguayan architect Mario Kalemkerian. In this case, the system was used to rearrange the arsenal of the Argentine National Army. Kalemkerian's input included design for both the modernization of existing structures and the construction of new structures for use by civil staff [27].

The planned works included installing a series of prefabricated elements, from new roofs for existing buildings to floors and vaults. The latter are self-supporting, prefabricated brick vaults with a span of 13 m, rise of 1 m, and weight of about 6 t, while their thickness is 5 cm, corresponding to the thickness of the bricks with which they were made [15].

The vaults were executed on-site in the close surroundings of the building site (Fig. 5, top left). To simplify the prefabrication work of these building elements, a vault mold (*boveda-molde*) was made of ceramic material, thus obtaining a shape conformed with sand and Portland cement, avoiding edged points to ease detachment during the removal of the formwork. This same vault mold was also helpful in forming the front gables of the vaults. The inner faces of the gables were separated by 5 cm from the formwork, covering them so that, during the lifting procedure, the inner formwork would detach without difficulty.

Once all the vaults were placed in their final position, the anchor bars of the piers and the bars of the edge beams were bent to give continuity to the adjacent panels. Similarly, a steel-reinforced mesh was placed later covered with a mortar layer of cement, sand, and gravel, looking after its subsequent curing (Fig. 5, top right). Finally, the vaulted elements were finished with a white cement layer.

In addition to the main buildings, another planned space within the arsenal was a building to house the Oficina de Relaciones Laborales. The roof of this building is a dome – equipped with a skylight – made of brick elements with a diameter of 8 m and a 40 cm rise, weighing about 200 kg/m on the structure below. The formwork with which this was made is the cover of a water tank near the building (Fig. 5, bottom left).

Bricks used for the construction of the dome were placed following the direction of its construction. For every two rows, a ϕ6 rod was inserted as a bracket. To overcome the dome thrust problem, a reinforced concrete beam with a height of 5.5 cm, coinciding with the thickness of the bricks, was placed along the entire circumference. Another beam, 5 cm thick and 25 cm high, was placed to delimit the skylight. Once the beams were completed, a 2-cm layer of reinforced concrete and an isolating layer of expanded polystyrene sheets were placed on the extrados of the dome. Finally, everything was covered with 3 cm-thick tiles (*tejuelas de campo*) (Fig. 5, bottom right).

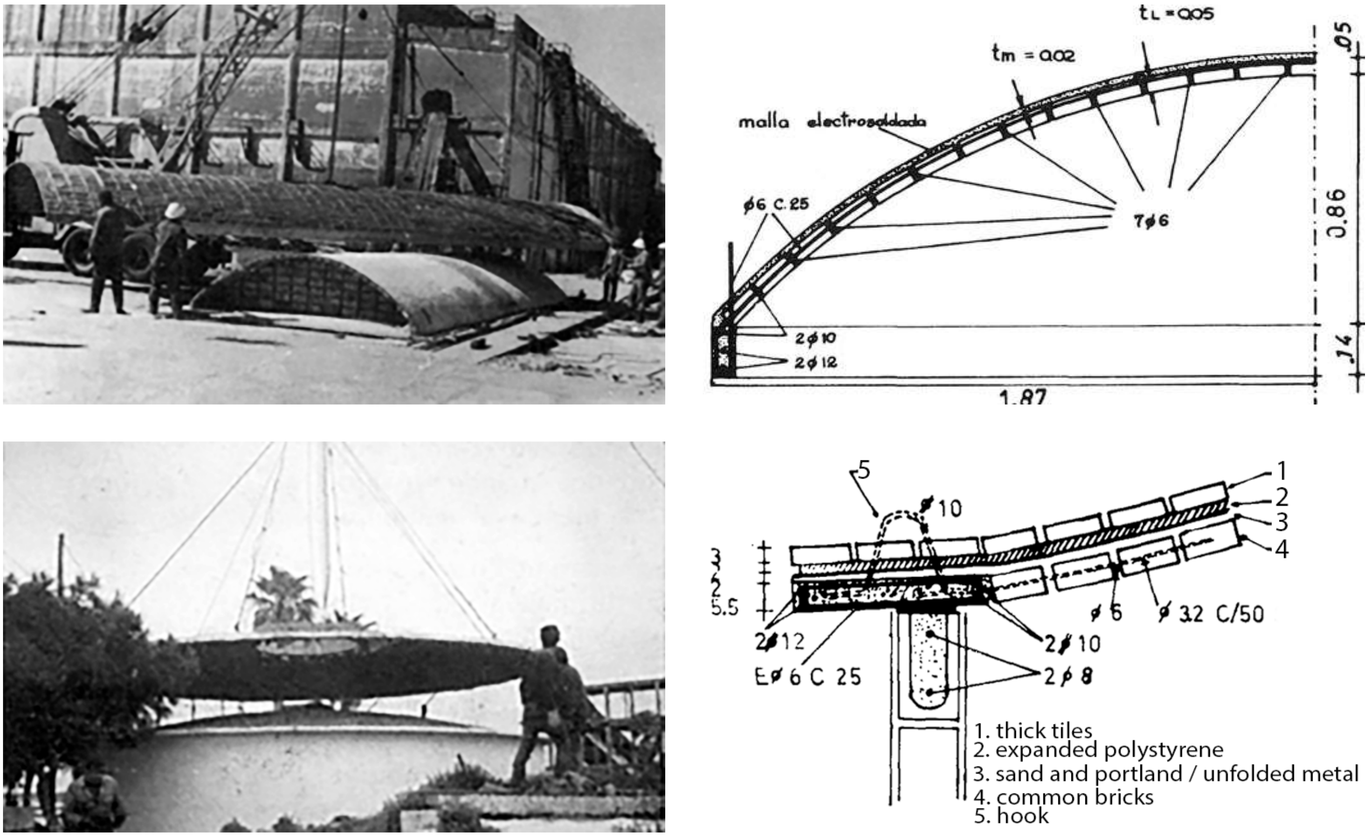

Fig. 5. *Top left: transportation of two of the arsenal vaults. Top right: structural section showing vault reinforcing bars and steel reinforced mesh. Bottom left: lifting the dome from the tank used as formwork. Bottom right: structural section of the dome. Source: [27].*

2.3. THE PRECAST REINFORCED CONCRETE VAULTS

In Colombia, the construction technique of Spanish *bóvedas tabicadas* was imported in the late eighteenth century. This remained almost unchanged until the 1950s. The spread of more modern materials and techniques, in fact, allowed the use of thin shells not only for social housing settlements but also for the roofing of large industrial sheds or factories. Among the most significant innovations in this regard is the use, by Álvaro Ortega, of the patented vacuum concrete system (*hormigón al vacío*) [28].

The patent titled *Method of and apparatus for treating concrete*, registered by Karl Pauli Billner in 1936 and followed by other patents, requires the use of a vacuum pump to remove exceeding water from the wet concrete mix, improving its strength and reducing setting time. The advantages of this system are «[…] increased resistance, economy, elimination of forms and nails, wire, quick construction, all concrete processed with vacuum can be used 24 hours after casting, an increase of resistance against time, maximum compactness and impermeability […]» [29]. Furthermore, there is no need for skilled labor.

Starting in the 1950s, after obtaining the franchise for the Vacuum Concrete de Columbia company, Ortega used the system for residential and industrial buildings. The construction of 102 residential units in the *barrio* (neighborhood) Quiroga in Bogotá from 1951 to 1953 allowed for the large-scale application of the system, which was used to make the external walls and roofing shells. The dimensions of the shells were 5.08 m x 5.18 m, for a thickness of about 4 cm. Each shell was internally reinforced with wire mesh. Construction began with the shaping of the first shell on a wooden formwork, thus making sure that the thickness was kept constant. After that, above this, the other shells were shaped, using layers of paper to divide them from each other. Thereby, each shell formed the mold for the next shell, and this allowed up to eight shells to be made per day (Fig. 6, left). The shells, as well as the panels constituting the walls, were moved by the so-called "Vacuum Lifter method", consisting of suction cups attached to girders hooked to a crane (Fig. 6, right).


Fig. 6. *Left: construction of the shells above a wooden formwork with vacuum concrete. Right: setting a shell as a roofing for a residential unit through the Vacuum Lifter method. Source: [29].*

During and after construction, several critical issues emerged due to inaccuracy in the formation of the different components on site: the non-perfect adherence of the joints between walls and shells, the presence of humidity in the canals formed between the shells, as well as the cracks that appeared due to stresses on the edges of the prefabricated elements.

The solution adopted by Ortega was improved in subsequent commissions concerning the construction of some industrial buildings in Bogotá (Clark's Chewing Gum factory and a warehouse owned by Banco de Bogotá). However, a growing general disinterest in precasting and, at the same time, the availability of more affordable steel quickly led Vacuum Concrete de Columbia to cease operations.

The use of precast systems, industrialized construction processes, and adherence to the principles of modular coordination can be found in other Latin American buildings constructed after World War II. Such is the case of González de Léon's José Clemente Orozco residential complex in Guadalajara, Mexico.

In Guadalajara, central Mexico, another case of the application of thin prefabricated vaults based on a design by Teodoro González de León can be found: the José Clemente Orozco residential complex, built in the late 1950s (1957-1959) [28]. This is a unique example of prefabrication of structurally independent modular vaults to roof 488 single-story housing units.

The module-type consisted of a precast concrete pavilion-type vault to which a perimeter drainage gutter was attached for rainwater collection and disposal. The shells and the panels to form the outer walls were prefabricated on-site and later moved with the aid of cranes (Fig. 7, left).

Given its conformation and small size, such a system allowed a great deal of freedom in the spatial arrange-

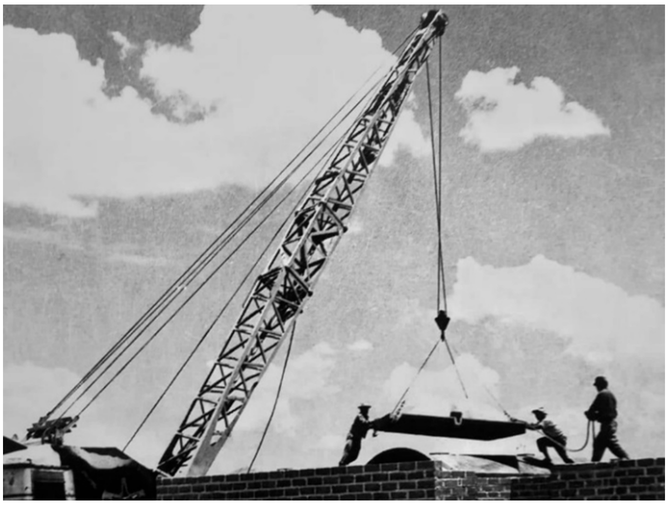


Fig. 7. *Left: setting, by crane, of one of the concrete shells. Right: general view of the residential complex. Source: https://momogdl.com/listing/unidad-habitacional-jose-clemente-orozco/. Accessed on July 15, 2024.*

ment within the urban fabric of the prefabricated modular units while also allowing free aggregation. Modules were distributed and combined to create free spaces of varied sizes and achieve different housing configurations (Fig. 7, right).

3. CONCLUSIONS

In the 20th century, Latin America became a center for developing and testing shell construction techniques and thin vault architecture.

Observation of the illustrated cases, particularly the various building approaches used to build them, allows for a description of some considerations. First, using vault molds for prefabrication on-site reduced the need for formwork and the need to move the parts to the construction site, leading to substantial savings in both time and money. Better scheduling and planning, together with increased oversight during the execution phase, usually allowed for the achievement of incredibly precise concrete proportions, thus resulting in material savings.

Another distinguishing factor in the prefabrication of these vaulted structures was the rapid training and education of the workers who materially constructed the various pieces to be assembled since it was possible to reduce the various stages to repeated and elementary movements.

The use of traditionally derived materials – such as clay bricks – and the availability of plants for their production in the proximity of construction sites has contributed to the overall economy of the system. Also remarkable is the ability to combine these materials with others unrelated to local culture (concrete and steel) so as to overcome their scarcity.

Finally, it is emphasized that the cases investigated refer mainly to the prefabrication of modular vaulted structures functional for use in the building, or reconfiguration, of houses or entire working-class neighborhoods. In addition, the design and configuration of such elements have been useful for the conformation of buildings and industrial warehouses of smaller sizes.

The importance of prefabrication in plants or on-site, the lack or reduced use of ribs, the skillful use and juxtaposition of different materials according to specific needs, the modularity of the built elements, and the possibility of using even unskilled labor are some of the lessons that can be drawn from the case studies and from which it is possible to start designing and installing vaults and thin shells that can be used and reproduced both on a small (for civil buildings) and large scale (for industrial buildings or public infrastructure).

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SCAN-TO-MESHBIM: IMPLEMENTING KNOWLEDGE ABOUT HISTORICAL VAULTED CEILINGS WITH OPEN TOOLS

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Abstract

Accurate three-dimensional (3D) models for Heritage Building Information Modeling (HBIM) remain a significant challenge. This paper proposes a methodology that combines the Poisson Surface Reconstruction (PSR) technique with open-source management software to address this issue. The methodology uses automatically generated mesh models to produce reality-based 3D models of historical buildings. These models are enriched with geometric and semantic parameters according to BIM standards. The resulting methodology, Scan to MesHBIM, is an open 3D interface allowing experts to analyze and create a detailed set of properties adhering to construction rules.

To test the workflow, we selected two case studies of different vaulting types: the Renaissance barrel vault with cloister heads and lunettes from the Ducal Palace in Urbino (Italy) and the Gothic ribbed vault from St. André Cathedral in Bourdeaux (France). The use of implicit surfaces proved to be an efficient means for obtaining accurate 3D objects; then, the enrichment of the 3D models ensures a better understanding and more in-depth management in the field of Cultural Heritage (CH).

Keywords

Automatic surface reconstruction, HBIM, Historical vaulted system, Poisson, 3D mesh.

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1. CHALLENGES OF HBIM METHODOLOGY

The use of Building Information Modeling (BIM) methodology within the frame of cultural heritage (HBIM) offers several advantages for enhancing the knowledge, conservation, and management of cultural assets [1]. There is a significant challenge related to the modeling process regarding historical buildings. Despite advancements in data acquisition techniques, such as digital photogrammetry or terrestrial laser scanning, which have improved the digitalization of historical buildings, complex architectural elements still pose a significant challenge in three-dimensional (3D) representation. It is well known that point clouds obtained with the above-mentioned techniques offer a geometric support that facilitates both the 3D modeling and the generation of two-dimensional (2D) architectural drawings. However, the creation of accurate 3D reality-based models is significantly complicated by two characteristics: firstly, the use of non-standardized construction elements, and secondly, the existence of distortions in the structural elements. When a high accuracy level is required for the parametric 3D model, considerable time is needed to build up each element with all its singularities and shape deviations. Thus, a balance between the demanding modeling process and the reduction of the accuracy level is necessary to achieve an optimal 3D model representation. The pursuit of novel modeling strategies that maintain a proper accuracy level while minimizing the efforts required to obtain 3D models remains essential for the implementation of HBIM methodology.

Although successful workflows regarding HBIM are available in the literature [2], most of them are based on proprietary authoring software, and a lack of shared standards for analysis and management is still noticeable. In developing HBIM objects, semantic segmentation of point clouds plays a pivotal role. Scan-to-BIM workflows, which are prevalent, generate parametric models grounded in reality and enriched with semantic knowledge. These models are crafted through multiple interpretation phases, employing solid or geometric surfaces based on the initial point cloud data.

A part of the debate, thus, contributes to automatizing some steps, speeding up procedures, and preserving data accuracy. In this line, the Poisson Surface Reconstruction (PSR) algorithm provides a fast and accurate workflow for the automatic generation of meshes from segmented points cloud and the reconstruction of complex geometries. Our research is focused on the automated generation of triangular meshes that preserve the geometric features of each element in historical buildings, enabling their use in an HBIM open environment. This novel approach is named Scan-to-MesHBIM.

According to the paradigm of object-based parametric modeling, the traditional Scan-To-BIM approaches are based on families generated in authoring software. Our approach enriches the detailed meshes with parameters and data related to the constructive and typological rules, making architectural objects semantically aware. The main contribution of the paper can be synthesized in a quite new method for carrying out reality-based models, automatically exploiting the meshes obtained from laser scanner data, semantically organized, and enriched via International Foundation Classes (IFC) management. Additionally, our Scan-to-MesHBIM approach involves open-source tools. The method is assessed in HBIM analysis of vaulted systems, including components such as lunettes, ribs, and decorative elements, which are considered fundamental parts of architectural complexes but have not yet been addressed with a sufficient level of detail.

Our research aims to improve the 3D modeling process for historical buildings, enabling their effective use within native IFC environments such as Bonsai, the former BlenderBIM add-on [3]. The paper is organized as follows. A literature review is shown in Section 2 with a specific focus on the 3D meshing step, comparing the definition of implicit and explicit surfaces. Section 3 briefly describes the two case studies, followed by the presentation of the available points of cloud data. At the same time, the main paragraphs related to the methodology are the automatic surface reconstruction phase (Section 3.2) and the proper Scan-to-MesHBIM procedure (Section 3.3). Results with different kinds of explanation and discussion about IFC classes and obtained LOD and analysis carried out are presented in Section 4, followed by the future works in Section 5.

2. LITERATURE REVIEW

The 3D digitization of built heritage is considered a pivotal phase in management and analysis but also for planning interventions: dense points cloud and high-resolution digital images can currently provide information for assessment of the state of conservation and risk of historical buildings [4, 5]. Photogrammetry can support the assessment of damages through 3D surface analysis and quantitative evaluation, as well as data about cracks, lack, and erosion on envelope surfaces through digital image processing [6].

The relatively new paradigm of HBIM shows extraordinary potential for the restoration process, especially if connected to cognitive automation. Some authors introduced different perspectives on HBIM modeling, with diagnosis and performance assessment as key aspects [7]. Others developed a “reverse engineering” approach for creating HBIM models of existing buildings, a watershed moment in its management. This method simplifies and organizes the information needed to preserve the existing architectural heritage while utilizing available resources [8]. Some works explored the accuracy of three-dimensional objects, such as vault systems, in terms of geometrical data, decay, and historical or stratigraphical analysis to inform future interventions [9]. The emphasis on Grade of Generation (GOG) and Grade of Information (GOI) during the interpolation of point clouds and model wireframes 3D objects [10] underscores the importance of possessing in-depth knowledge of the cultural asset before undertaking any action, as exemplified by the introduction of the Level of Knowledge (LOK) concept [11].

Following the critical issue of geometry data, Dynamo has emerged as a valuable algorithmic tool for comparing ideal geometry with reality-based models, facilitating the creation of 3D libraries [12, 13]. Although some works have tried to solve this problem related to the BIM format, IFC, and its schema, these proposals incorporate new IFC entities using Non-Uniform Rational basis splines (NURBS). Still, their applicability is limited to specific software [14, 15]. However, the manual development of these parametric 3D objects for comprehensive data analysis data can be time-consuming [16, 17]. NURBS and other Explicit Surfaces techniques [18] are more widely used in the field of HBIM than implicit techniques. Still, the benefits of preserving geometrical features are considered the most suitable choice for testing surface-based reconstruction in a 3D documentation and analysis HBIM project.

An example of an implicit surface can be obtained by the Poisson Surface Reconstruction (PSR) algorithm, a robust and efficient method for reconstructing 3D surfaces from unorganized point clouds. PSR solves the differential Poisson equation, effectively fitting a smooth surface to the input point cloud data and obtaining sharp models [19]. An extension of Poisson that improves the over-smoothing problem is Screened Poisson Surface Reconstruction [20], but its integration in open-source software is still not so widespread. Utilizing deep neural networks as a geometric prior for surface reconstruction [21] addressed challenges such as overfitting artifacts and the approximation of sharp features, demonstrating better performance than existing reconstruction methods. The extraction of essential vertices is a significant step in working with complex geometries. An ordered statistic ranking criteria algorithm using Neuronal Networks (NNs) for the recognition of robust shape points was used in [22]. According to the current situation detailed before, our approach uses implicit methods, specifically the PSR algorithm, to capture the geometrical feature of Architectural Heritage in HBIM environments.

3. MATERIAL AND METHODS

The following paragraphs provide a detailed exploration of the materials and methodologies employed in our study. Two remarkable case studies were selected, each representing a specific period and type of vaulting system: Ducal Palace in Urbino (Italy) and St. André Cathedral in Bordeaux (France). Figure 1 synthesizes the tested workflow based on open tools: it starts with standard data processing followed by point cloud segmentation, automatic surface reconstruction, and the development of an HBIM procedure.

3.1. PRELIMINARY ANALYSIS BASED ON POINT CLOUD SEMANTIC SEGMENTATION

Table 1 represents the input data used in the present workflow, which came from different Terrestrial Laser Scanner acquisitions carried out using state-of-the-art procedures. Then, the data were processed according to a standard workflow in which alignment, decimation, and noise cleaning steps were included. Automatic surface reconstruction relies on density analysis because point density typically decreases according to the scan distance. Concerning this aspect, semantic segmentation was performed in Cloud Compare software to conduct a geometrical and typological analysis of the shape grammar: in our case, to classify the vaulted ceilings. According to widespread workflows in Scan-to-Bim, point clouds are usually semantically segmented to set up the 3D model hierarchy. To accomplish this segmentation, we followed ontologies already developed in compliance with the Getty Art & Architecture Thesaurus [23] and commonly used in other works [24, 25]. As a result, the point cloud files are segmented according to architectural elements with a density of point of 1 cm, a value that increases in some high and hidden areas as was described before. In our case studies, this situation affects the point cloud topography in different ways since the height and geometry presented in them are genuinely diverse. The data input for further steps consists of two different point

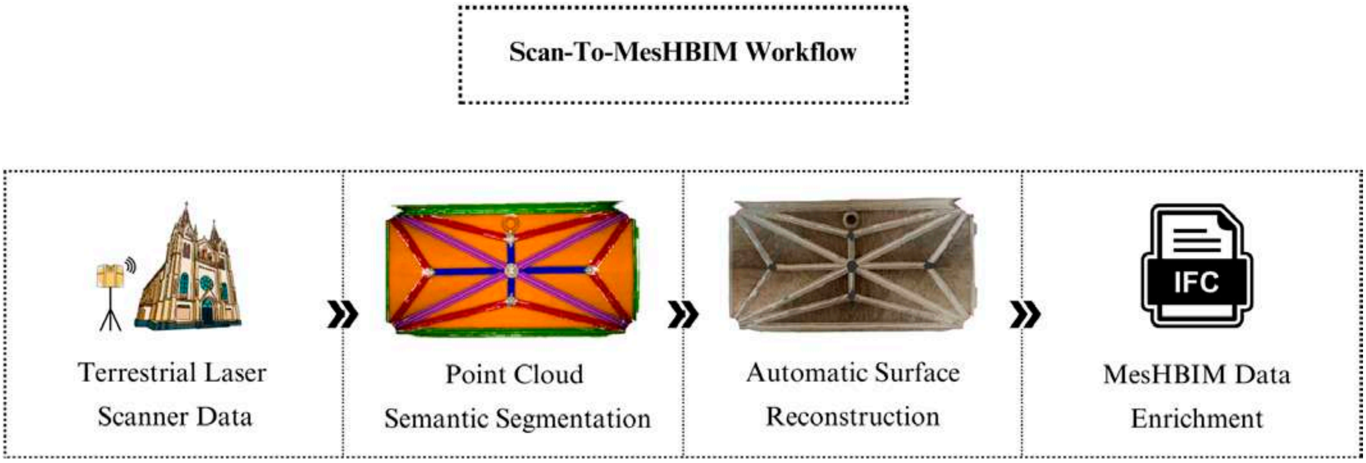

Fig. 1. *Overview of the proposed workflow.*

Location	Tool	N° of scans	Total point cloud	Vault system points	Resolution
Urbino Ducal Palace *Guess Room* 06	Leica Geosystem P40	3	13.523.592	4.901.112	6 mm@ 10m
Cathedral of St. André Fourth Bay	FARO Focus S	3	8.548.996	5.559.218	6 mm@ 10m

Tab. 1. *Dataset of the point clouds used in both case studies.*

clouds where ribs, lunettes, arches, and webs are distinguished to proceed with the 3D meshing step.

3.1.1. CASE STUDIES

The Ducal Palace in Urbino, currently housing the National Gallery of Marche, is a quintessential embodiment of Italian Renaissance architecture and art (Fig. 2a). Baldassare da Castiglione (1478-1529), an author and diplomat, characterized it as a «Palace in the guise of a city» [26]. This remarkable structure reached its zenith in the 15th century under the realm of Federico da Montefeltro, the Duke of Urbino. He engaged some of the most eminent artists of the era, including Luciano Laurana, Francesco di Giorgio Martini, and Donato Bramante, to craft exquisite architectural features, paintings, sculptures, and furnishings. These contributions transformed the Ducal Palace into a unique masterpiece of the Renaissance age, also presenting peculiar construction and typological solutions.

The *Piano Nobile* floor incorporates interesting geometry and constructional archetypal features of that historical period. This floor also houses the *Appartamento degli ospiti* (or *delle Melarance*) which dates back to the first phase of the floor. This intervention was carried out by Maso di Bartolomeo (1454-1464), who came from Florence as a scholar of Filippo Brunelleschi [27]. Our modeling procedure was implemented on a barrel vault with cloister heads and lunettes, a recurrent solution for classical palaces, not only during the Renaissance age. In this room, the directrix of the vault is a segmental arch, while lunettes are spheroidal: although a considerable curvature, it is a structural masonry vault.

Secondly, the St. André cathedral in Bordeaux is undoubtedly one of the city's most representative buildings of the Middle Ages and Early Renaissance (Fig. 2b). As usual, the currently existing construction is the product of several transformations that have taken place throughout the whole life of the building [28]. The origin of the cathedral dates back to the 11th century when the west end was built. During the 12th and early 13th centuries, the cathedral's nave was erected in Romanesque style. The building was enlarged from the end of the 13th to the mid-14th century by adding the transept and the polygonal apse using the Gothic construction system. In the 15th century, several restorations were made in the Ro-

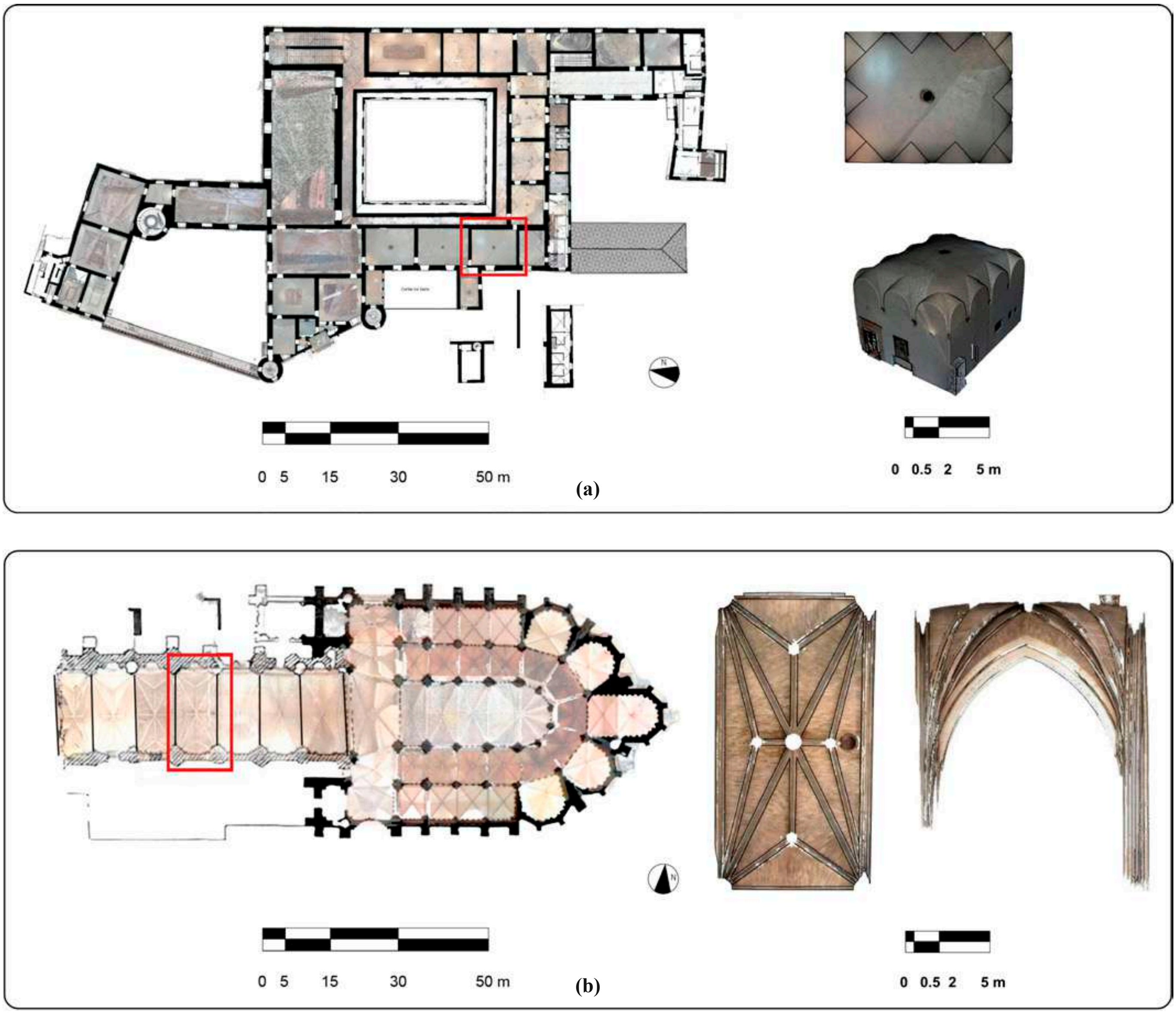

Fig. 2. *(a) Urbino Ducal Palace. Floor plan-Nobile (left). Ceiling and 3D axonometric view of Guest Apartment 06 (right). (b) Cathedral of St. André: floor plan of the entire building (left). Ceiling and south elevation view of 4th bay (right).*

manesque nave, some of which affected the vaulting system. However, such works continued at the beginning of the 16th century, and new ribbed vaults were built covering the old nave. Some vaults added during the 15th and 16th centuries were quadripartite (with only two diagonal ribs inside them), while others included *tiercerons* and *liernes*, establishing a star vault.

Regarding our research, the ribbed vault of St. André cathedral, located in the 3rd bay from the east end, exemplifies late-gothic period constructions. Supposed to have been designed by Mathelin Gallopin during the first quarter of the 16th century, it is geometrically defined by semicircular diagonal arches, two slightly curved *liernes*, and pointed perimetral ribs, as well as the *tiercerons*, all arranged within a five-keystones schema.

3.2. AUTOMATIC SURFACE RECONSTRUCTION

In response to the challenges outlined in Section 2, we have introduced the development of implicit surfaces to assess their performance in comparison to explicit surface techniques, which are used more often in architectural heritage. The data input for automatic 3D mesh generation is a semantically segmented point cloud described in Section 3.1. Open-source software offers many robust tools for 3D meshing, as described before. We opted to use the Cloud Compare software because it incorporates the Poisson Surface Reconstruction (PSR) algorithm, which typically employs a radial basis function (RBF) to represent the surface. The RBF can approximate a wide range of shapes with the Gaussian function, aiding in implicit modeling for PSR [19].

PSR was selected due to its advanced surface reconstruction capabilities, which consider point density distribution values, transformed as a Scalar Factor (SF) that provides surface accuracy and supports the export of refined and confident geometry. This SF analysis is achieved by determining the proximity of the vertices of the reconstructed mesh to the input point cloud. Higher SF values indicate a higher density of points near the vertex. In comparison, lower values indicate a reduced density of points that can be removed or not considered (outliers removal process). In this case, density does not have a specific unit of measure, as it is a relative measure of the proximity of the points in the point cloud to each mesh vertex. Our approach uses points to define a volumetric scalar factor, whose level set between 0 and 0.2 corresponds to the desired surface. The features of it depend on some parameters chosen before the 3D meshing. For instance, the octree value determines how the software algorithm divides the space into eight parts, which is crucial. An octree depth value of 10 was used for irregular or complex objects, indicating the number of subdivision levels. Another parameter is the number of sample points taken to create or define a node during the reconstruction process. After several tests, a point cloud density value between 10.00-15.00 was suitable. It's important to consider that according to the type of acquisition, there is a variable density on almost all the point clouds. Lower sample point values create larger faces, which must be divided into more polygons, resulting in a 3D mesh with more faces. The point weight value chosen was 2.00, considering adequate the predefined value. As an additional step, quadric edge collapse decimation and random vertex displacement algorithms can serve as valuable tools for managing decimated 3D meshes, effectively addressing the limitations encountered in HBIM environments. In contrast, some authors have insight into suitable performance in terms of memory usage and processing time of PSR compared to other 3D meshing techniques in both large and small models. Concerning our case studies, the presence of elements of different sizes is another reason Poisson was chosen.

3.3. THE SCAN-TO-MESHBIM PROCEDURE

In the final stage of this study, an HBIM approach was selected as an experimental method of analysis and management with a high Level of Development (LOD). A high level of geometry (LoG) was also achieved thanks to accurate 3D surfaces obtained in the previous step. As a result, a new procedure, Scan-to-MesHBIM, was implemented and tested on complex vaults.

The first step consisted of identifying a specific HBIM environment lacking in optimizing the process. To address the handling of multiple OBJ files according to the semantic segmentation that requires our workflow, we integrated a Python script into the HBIM project. This functionality reduces time-consuming processes and simplifies their management. Secondly, data enrichment requires a preliminary and exhaustive architectural and historical analysis. A standardized reference has been incorporated to streamline this early HBIM phase. Since all the elements are defined according to the Getty, Art & Architecture Thesaurus, the custom script has been developed to incorporate a button link for facilitating relevant queries on ontologies or normative.

A crucial aspect of this process involves the annotation of geometrical and typological parameters, introduced in Section 3.1. *IfcPropertySets* was used to define these two specific sets of parameters to implement these requirements. IFC file templates are considered essential for data enrichment, implying efficient organization and interoperability with various software applications. Although the IFC 4 schema is chosen, it does not have classes explicitly tailored to vault systems. Therefore, existing IFC Classes have been used to verify their effectiveness in this scenario. For the accurate representation of each element, the *ifcSpace* class has been properly used as a spatial container for all the architectural elements. This entity does not contain a geometrical representation but rather defines the boundaries that delineate the room or area where the vault system is located. The *IfcElementAssembly* class has been selected to describe the lunettes. The entire set of ribs – including ridge, diagonal, and tierceron ribs – is classified as a specific type of *IfcBeam*. Additionally, perimetral arches, which define the plan of the vault based on construction rules, are best represented using *IfcElementAssembly* with "arch" as a predefined type.

The vault's net, depicted as the intrados in our case studies, is introduced in the schema using the *IfcSlab* class, which supports ceiling-specific uses. To ensure the correct use of the IFC schema for historical buildings, custom *IfcSlabType* definitions have been created in our IFC-native data library. These types fully comply with international standards and specifications, ensuring accuracy and interoperability. Figure 3 illustrates some of these implementations.

Link tools were tested to integrate the 3D model with existing 2D documentation and analysis. In this way, the IFC Document can customize metadata for each element, allowing the association with specific floor plans, images, or tables. The geometrical analysis on the floor plan view was stored in *ifcSpace*, which is a suitable solution for integrating everything in the same workspace. Figure 4 shows the potential of the Urbino Ducal Palace HBIM project to achieve this objective.

Lastly, new investigations and drawings in Saint André Cathedral were incorporated into the annotation 3D view, enriching the overall knowledge by providing contextual information about geometrical analysis. This approach tackles verifying design hypotheses about the construction and applied geometrical rules (Fig. 5). Including capabilities, in the present work, different workspaces were used to test the current state of 3D analysis. For instance, the floor plan in Figure 6 shows the geometrical analysis related to the distribution of *tiercerons* and keystones. The same figure also demonstrates the elevation plan of the tierceron rib where the radius and another analysis were performed.

4. RESULTS AND DISCUSSION

The methodology presented in this paper has successfully addressed achieving accurate 3D objects within the realm of HBIM. A balance between complex geometries, acquired data, and representation of 3D analysis has been established. Generating detailed 3D meshes via automatic surface reconstruction significantly streamlined the modeling process for intricate geometries and reduced point density areas commonly encountered in large-scale TLS-scanned buildings. The results show that all 3D objects obtained through PSR in the Ducal Palace case study can be used directly for analysis and management purposes, and successive postprocessing steps are not required. In the case of Saint André Cathedral, only keystone elements present some geometrical issues like holes and non-manifold faces due to the kind of acquisition carried out and the higher location of these elements regarding the scanner laser. In this case, some additional operations of filling and topology reparation are needed. Leveraging the PSR technique, we automated the generation of 3D surfaces via implicit surface models, a pivotal step in the Scan-to-MesHBIM proposed methodology. This approach seamlessly integrates with open-source management software environments facilitating the creation of reality-based 3D models for historical vaults and avoiding the presence of duplicated geometry, and finally entails less error and a higher LOG. The models are visually rich and imbued with geometric and semantic parameters adhering to BIM standards. The Scan-to-MesHBIM methodology, presented herein, culminates in an adaptable open tridimensional interface by utilizing free-form modeling software and enabling experts to create a comprehensive set of properties while allowing and facilitating geometrical analysis and potentially inferring construction rules. Its adaptability is demonstrated by some considerations: the open access code gives the possibility to improve the interface and the kind of managed data with simple coding skills. This customization empowers users to optimize the workflow based on different purposes of the modeling process as well as the specific features of the considered built heritage. The main advantage is, moreover, the data-enrichment adaptability, allowing to obtain models aware of relevant data tailored to specific project requirements, thereby enhancing the usefulness and relevance of the modeling outcomes (Fig. 3). Furthermore, a high Level of Information (LOI) has been obtained, demonstrating the effectiveness of collecting data in case studies already investigated in many analyses and documentation processes, commonly

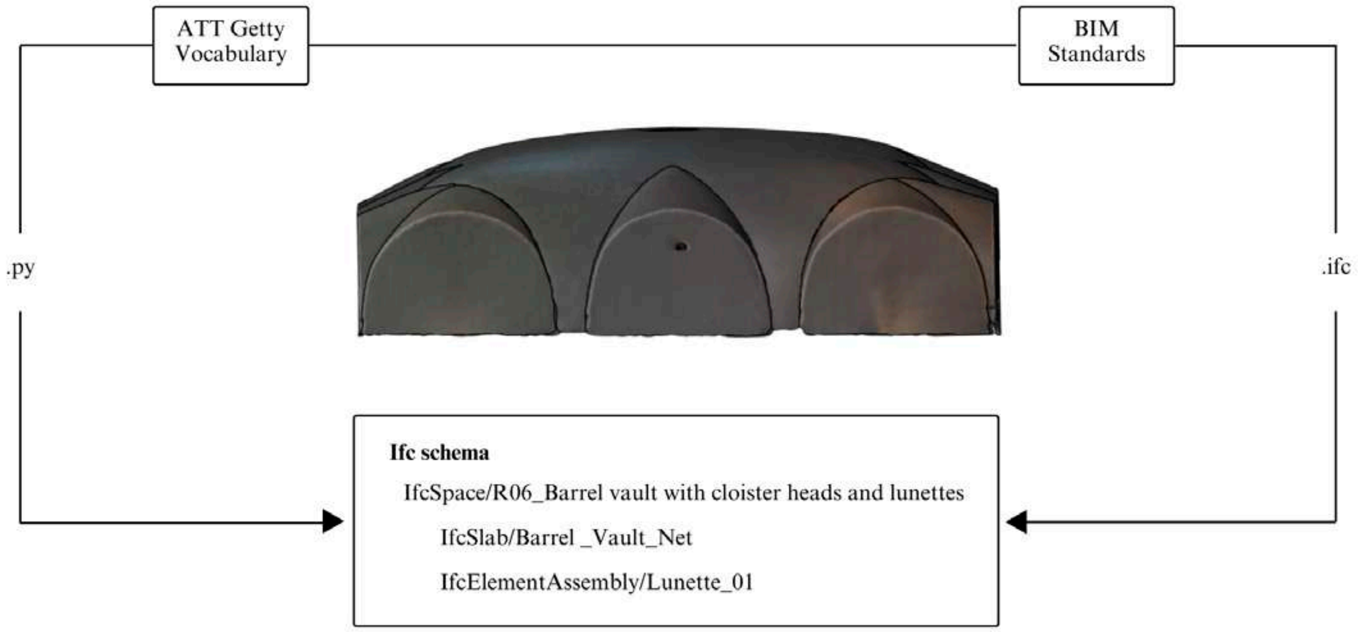

Fig. 3. *HBIM proposal methodology. Ontology and IFC schema used for the Urbino Ducal Palace case study are integrated within the documentation improvements.*

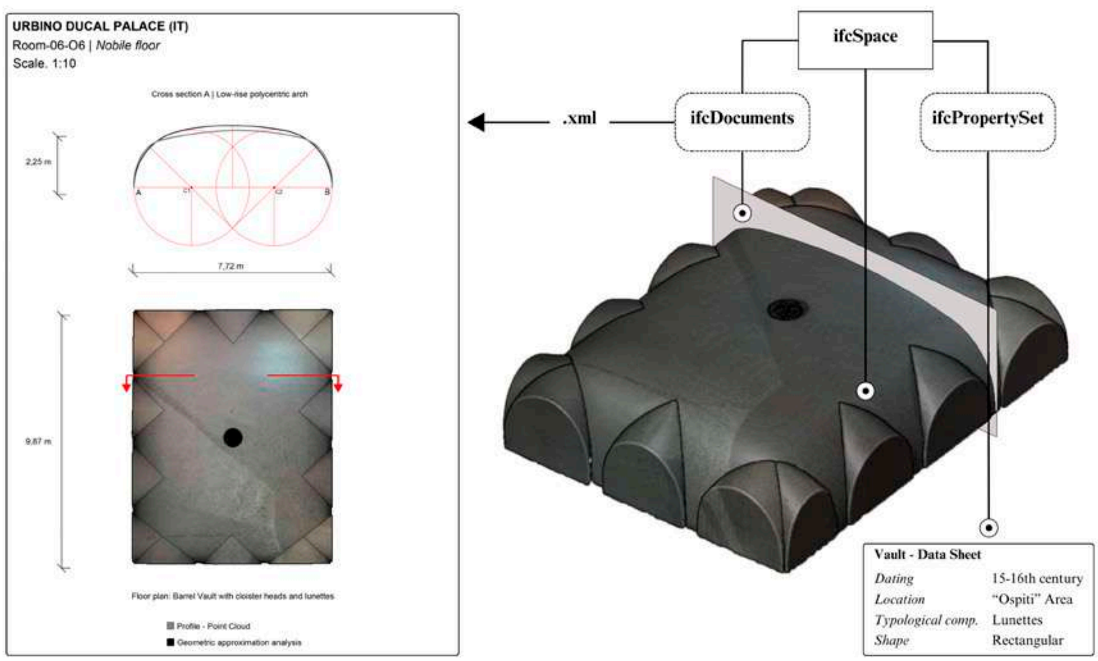

Fig. 4. *2D traditional analysis integration into an HBIM environment: the 3D model with a detailed IFC ontology application is associated with general* ifcPropertySets.

in 2D. As a result, the Ducal Palace vault model is represented by its current irregular shape since they don't follow ideal circumferences or ovals (Fig. 4).

On the other hand, the Saint André case study has been carried out with specific attention to experiencing the benefits that 3D analysis can offer to CH experts. Specifically, the distorted geometry of the vaults was preserved when creating the HBIM model, and the simplification that is almost always needed in the Scan-to-BIM traditional process was avoided. Even so, the design of the ribs has been analyzed using the current geometry of the net in its horizontal projection (Fig. 5) and the elevations of the ribs (Fig. 6). Such data is included in the model itself thanks to its high accuracy, and they can be detected and represented in the 2D projections (both in the horizontal one and in the elevations). As mentioned

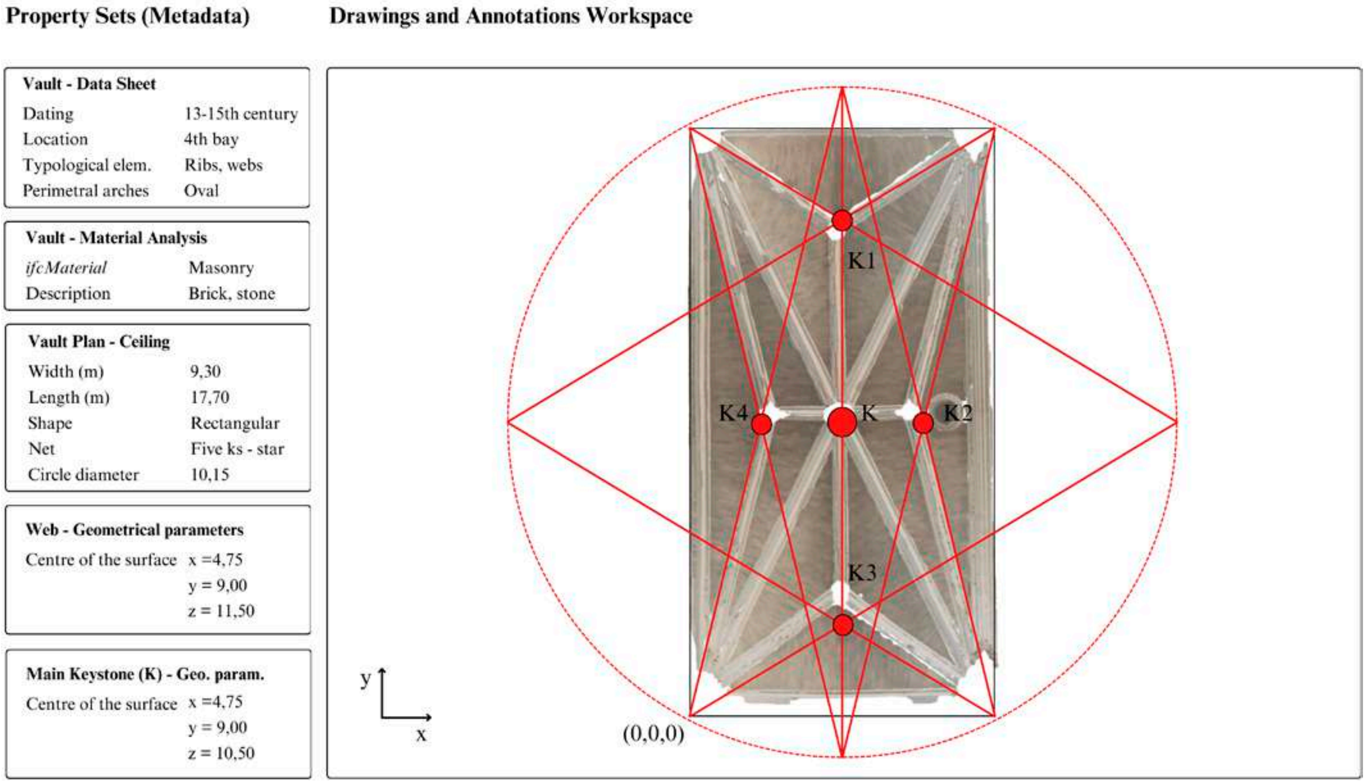

Fig. 5. *St. André Cathedral HBIM project. Left:* ifcPropertySets *related to general and specific analysis. Right: the ceiling plan view (intrados) with a geometrical analysis of the tracing and location of the ribs and keystones.*

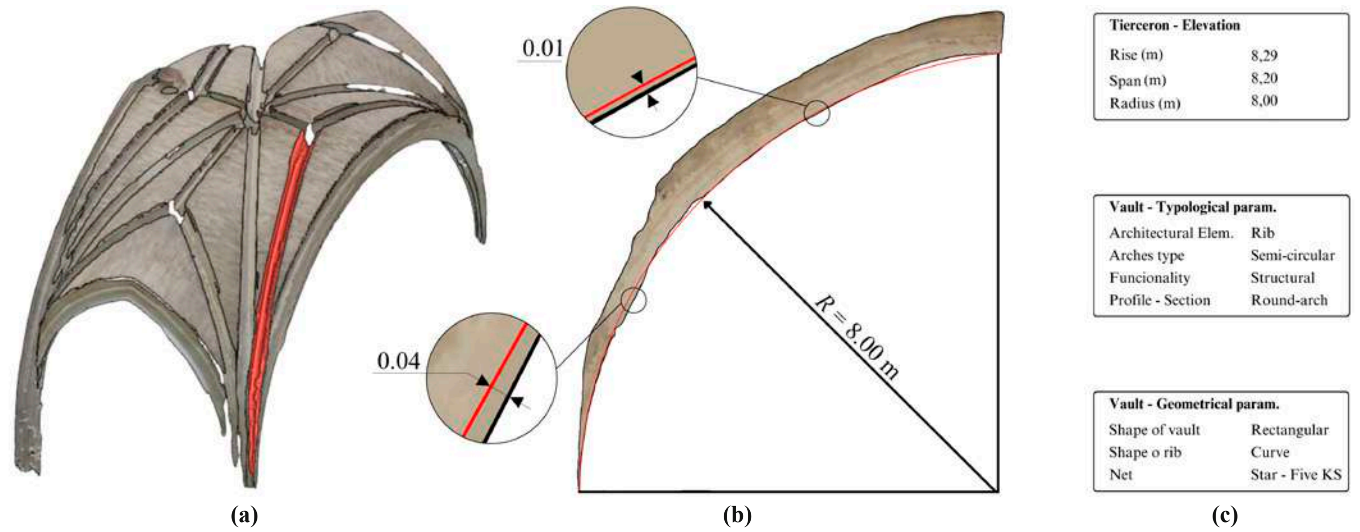

Fig. 6. *3D analysis of Saint André Cathedral: (a) 3D general view with the analyzed tierceron highlighted, (b) elevation view with the curvature analysis of such rib, and (c) tailored property sets of the same architectural element.*

before, it is quite relevant when analyzing the geometric configuration of the ribs and the structural behavior of the entire vault. For this purpose, it is mandatory not to simplify the current geometry of the vault when creating the HBIM model.

The training datasets selected in both cases, Ducal Palace of Urbino and St. André, are satisfactorily enriched for the 3D documentation and analysis in a BIM environment. The effort to preserve geometrical features in both buildings deals with the assumption that LOI and LOG obtained are proportional to LOD and each other. Following these achievements, Table 2 summarizes the entire process and results. In conclusion, this procedure is not focused on saving work time but on preserving the geometric information of the model. This point is critical within the restoration and conservation projects of historic buildings, where accurate data on the 3D objects (including their non-simplified dimensions and the possible distortions and structural movements) are essential.

Parameters	Values		Description of parameters
Processing	a	b	
TMS (hours)	2	4	Time required for manual segmentation
Relative SF	6.25	8.80	Range of relative density as SF
TPSR+t (hours)	0.45	1.5	Time required for Automatic surface reconstruction and texturing
Output	a-b		
LOD	350		Defines the Level of Development of the BIM model components
LOI	400		Describes the Level of Information attached to a component in a BIM model
LOG	350		Establishes the Level of Geometric detail of the BIM model

Tab. 2. *Processing and output parameters established for the HBIM project of a Historical Vaulted System. Urbino Ducal Palace (a) and Saint André Cathedral (b).*

Our approach implies a significant change compared to emerged workflows in which the point cloud is used as a reference for parametric models [29]. The work presented in [30] established a preliminary HBIM phase for restoration planning, and in [31] the potential of decay representation has been leveraged, demonstrating different levels of documentation and management. In our case, the taxonomy was managed for a significant part of the architectural hierarchical structure, and the final goal of the 3D documentation analysis was attained. Up to date, no workflows have been tested to study the typological features, analyze geometry, and infer the structural knowledge of architectural heritage with the same Level of Development. The main advantages of our methodology are the following: a) the use of open access tool in an HBIM environment, b) an efficient management of optimized surface confidence (related to LOG) for complex geometries, c) the possibility to perform 3D analysis for different purposes and d) the readability of colorimetric features thanks to the preserved textures in IFC format. Within this, Figure 7 proposes a comparison with the Scan-to-BIM available workflows.

5. FUTURE WORKS

This research has demonstrated the potential of using implicit surfaces in HBIM environments for data enrichment, especially with high accuracy and without extra working time. Within geometrical and typological analysis already integrated, these HBIM projects tackle the improvement of specific analysis, such as identifying their historical and construction stages or studying their structural behavior, to establish a higher LOI. In this way, further works are being developed to implement the stratigraphic information obtained thanks to the methodology of the Archaeology of Architecture, that is, the

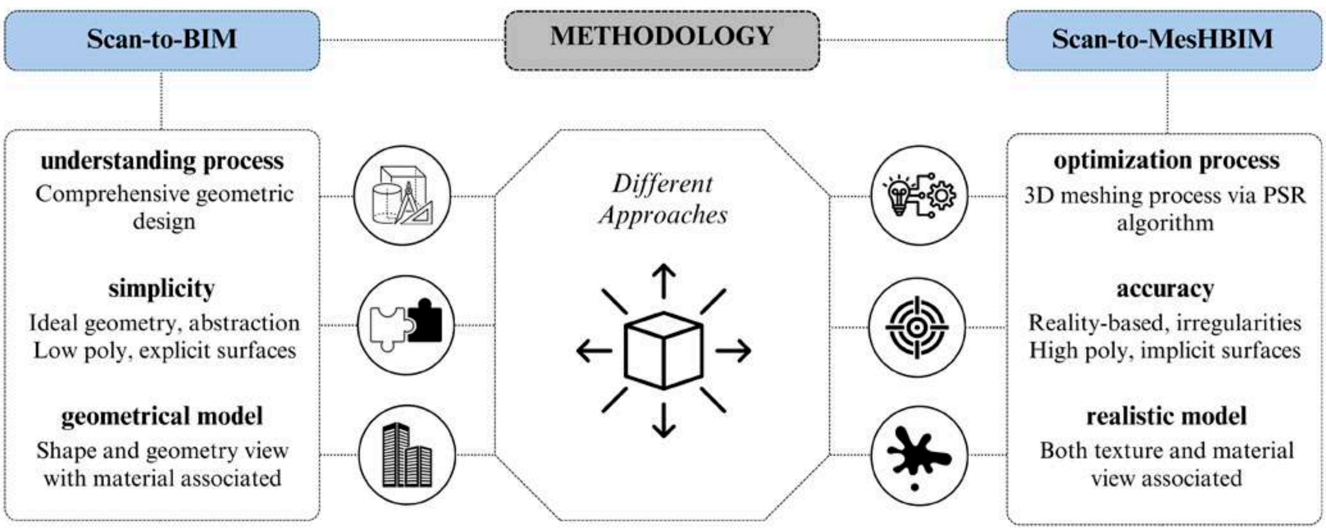

Fig. 7. *Comparison of the current widespread Scan-To-BIM workflows and our procedure.*

data regarding the construction sequence of the several parts of the building. This approach is being implemented in the case study of the Basilica of San Isidoro (León, Spain), which has a rich and long sequence of buildings and transformations that dates back to the Middle Ages until the 20th century. Thus, we expect to create a model using the proposed Scan-to-MesHBIM methodology that automatizes the analysis and data enrichment of the whole data set related to its historical sequence.

Besides, these works allow us to make HBIM models consistent with their rules and complexity, thus implementing workflows that support the conservation and management of built heritage. In the case of other specifications, such as Level of Accuracy (LoA), future efforts should be focused on formulating a specific definition for Cultural Heritage, as the current specification is mainly centered on new construction parameters that require utterly different accuracy commitments. While IFC 4 enables the representation of vaulted systems through different *IfcElements*, several limitations are overlooked. For this reason, developing a new IFC specific to vault systems appears helpful in the context of HBIM methodology for better knowledge, conservation, and management of historical buildings. This necessity entails editing the IFC schema to develop new standards and classifications, thus implying a more extensive comparison with existing taxonomies and vocabularies.

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AUTOMATIC RECOGNITION OF BIO-COLONIZATION PROCESSES ON HISTORIC FAÇADES: APPLICATION ON CASE STUDIES

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Abstract

Many factors (physical, chemical, natural, and human activities) contribute to the degradation of historic buildings. Preventive conservation is a cost-effective approach international preservation bodies recommend to mitigate risks to built cultural heritage. A substantial challenge is bio-colonization, especially by microalgae, which affects brick-facing masonry surfaces due to environmental factors (i.e., temperature and moisture), leading to progressively increasing deterioration. Early detection systems could be useful to reduce damage from these organisms. Advances in computer vision and machine learning, such as convolutional neural networks, offer promising solutions for automating the identification of building pathologies using image collection. This research focuses on developing predictive models using convolutional neural networks to monitor bio-deterioration on historic façades, specifically targeting early-stage microalgae colonization. After a training phase using laboratory-induced bio-colonization on brick samples, the method was applied to real case studies of architecturally significant buildings affected by bio-colonization. In fact, a substantial number of digital images of these buildings, even if taken for other purposes, are available. The work shows that analyzing these images with the trained network facilitates the early detection of bio-colonization, providing a contribution to the field of built cultural heritage conservation.

Keywords

Microalgae, Bio-colonization, Historical buildings, Convolutional neural network, Monitoring.

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1. INTRODUCTION

The deterioration of historic building heritage is driven by a combination of physical, chemical, natural, and human-induced factors [1]. It is recognized that preventive conservation is one of the most cost-effective approaches, also recommended by international institutions involved in preservation [2], and consists of «a set of actions useful for reducing risk situations concerning cultural assets in their context» [3]. Bio-colonization (growth of living microorganisms) is one of the several pathologies affecting historical heritage that should be paid attention to. Historical buildings could be affected by primary (microalgae), secondary (molds and lichens), or tertiary (plants) colonizers, and the restoration of the affected surfaces can be costly. The colonization process by microalgae (primary colonizers) starts from an interaction between environmental factors and the physical and chemical properties of clay brick [4]. In the case of buildings of cultural value, the growth of these organisms could cause severe losses in original materials [5]. Adequate temperature and availability of water can indulge the growth of microalgae and, therefore, the degradation of the material, contributing to the creation of a suitable environment for the growth of other colonizers [4, 6, 7].

Furthermore, porosity and roughness of the substrate can promote algae growth [8, 9]. In this context, the availability of early detection systems based on data collection and images can help limit the aesthetic, chemical, and physical degradation of building surfaces due to bio-colonizers. The topic of computer vision-based automated building pathologies identification (using image processing and machine learning techniques) has attracted research attention in recent years, particularly about crack detection [10] on concrete [11] and masonry structures [12]. A convolutional neural network is a specialized type of deep learning model designed to process and analyze structured grid-like data, such as images. It is particularly effective in tasks involving image recognition and classification because it can automatically learn spatial hierarchies of features through convolutional layers. In the field of architectural heritage, convolutional neural network classification techniques have been used to identify and locate several types of damage (i.e., stain, efflorescence, cracks, and spalling) in masonry buildings [13, 14]. The issue of bio-colonizers on existing buildings has been addressed in [15] about tertiary colonizers (plants).

Regarding the specific problem of microalgae, in literature, there are available works focused on digital images acquired during the growth of microalgae strains in water solution but not on building façades [16]. In this work, to fill the lack of existing literature, the development of predictive models using a convolutional neural network useful to automatically monitor the bio-deterioration status of historic building heritage with facing-masonry façades is proposed. Given that digital images of historical building façades are constantly being captured and collected for various purposes (e.g., photographic documentation and tourist information), as well as automatically provided by surveillance cameras, there is a substantial amount of material available to assess the condition of these surfaces using the proposed method. The findings of this work serve as a preliminary step toward developing tools for the early detection of damage to building façades, particularly biodeterioration.

2. METHODOLOGY

2.1. RESEARCH FRAMEWORK

To reach the proposed goal, the research process was set up as follows: first, an experimental activity has been developed to follow, in controlled conditions, the microalgae growth, considering diverse types of clay bricks and various exposure conditions (temperature, RH%, rain). Then, digital images collected during the experimental campaign were resized and cropped to generate a dataset of about 12.000 sub-images representing the various stages of the bio-deterioration process. A convolutional neural network was trained using the digital images dataset that was obtained. Finally, the method was tested on case studies with brick-facing masonry to verify its applicability as an early detection system.

2.2. EXPERIMENTAL CAMPAIGN

The digital images to be used to train the convolutional neural network were obtained from an experimental campaign in which five types of clay bricks (designated as AH, AL, B, CH, and CL) were selected and tested in five different environmental conditions, reproduced using climatic chambers to accelerate the growth process. Clay bricks differ by color, porosity, and roughness. Considering that bio-colonization causes a shift of the original color towards green-blue nuances, and the initial color spectrum is influenced due to the transition between wetted and unwetted conditions, were chosen three different brick colors: light-red (AH and AL types), dark-red (B type), yellow (CH and CL types). Because the “shape” of the bio-colonization (e.g., spots, lines, areas) is influenced by the surface features and the water retention characteristic of the clay bricks, different microstructures were considered. Different environmental conditions were considered and characterized by different temperatures, RH%, and wetting processes to include a wide range of expected environmental conditions. Surface properties like porosity (according to ASTM D4404-10 [17]) and roughness (according to UNI EN ISO 4287:2009 [18]) of the tested clay bricks were measured. A green alga (Chlorella mirabilis strain ALCP 221B) and a cyanobacterium (Chroococcidiopsis fissurarum strain IPPAS B445) were used to reproduce the bio-colonization process [7]. Microbial strains were cultivated in a Bold's Basal Medium (BBM), formulated following ASTM D5589-09 prescriptions [19]. To reduce testing times, the tests were conducted under accelerated conditions (a visible biological degradation mostly begins after at least one year of natural environmental exposure). Five distinct environmental conditions were chosen to take into account a wide variety of potential real exposures. To find out how changing relative humidity (RH) levels affected algae growth on clay brick surfaces, three distinct RH conditions were replicated in three different climatic chambers.

Saturated solutions were used to condition the indoor environment, as recommended by EN ISO 12571:2013 [20]. The first RH condition (RH1, around 75%) was obtained using a saturated solution of NaCl; the second RH condition (RH2, around 87%) was obtained using a saturated solution of Na_2CO_3; the third RH condition (RH3, about 98%) was obtained using only deionized water. Tests were conducted at constant temperature (27.5 ± 2.5°C) in order to examine the impact of RH only. Each sample had nine distinct locations on its surface that were inoculated with 5µl of the mixed culture at the start of the test. After that, samples were placed, with an inclination of 45°, on aluminum-glass racks inside the climatic chambers, front-to-front along the chamber's long length. In order to protect the test equipment from outside influences such as light, temperature, and relative humidity, it was housed in a closed room. Two neon lights (Sylvania TopLife 39W) able to faithfully reproduce natural light conditions were installed in each growth chamber with the aim of recreating day/night cycles 14/10 h (Fig. 1a). The impact of temperature on algae growth was investigated in the wake of previous studies available in the literature [8, 9]. Until the stagnation phase was reached, accelerated tests were conducted using periodic water sprays on the material's surface (Fig. 1b). Growth chambers (100 × 40 × 53 cm^3) containing 35 liters of BBM inoculated with the mixed cultures represent the test apparatus for this phase of the work. Algal suspension was applied (sprayed) to sample surfaces (8 × 8 cm^2) situated on two 45°-inclined racks made of aluminum and glass. Run/off cycles were programmed to occur every 15 minutes for a total of 6 hours a day (3 hours of run time and 3 hours of rest time). Two 39W neon lights (Sylvania TopLife) have been used to reproduce a day/night lighting cycle of 14/10 hours. Following existing literature [21, 22], two distinct temperatures were chosen for the accelerated tests: 27.5 ± 2.5°C, which falls within the range of ideal growth values (which span from 20°C to 30°C), and a lower value of 10 ± 2.5°C, which falls within the range of suitable growth. A properly modi-

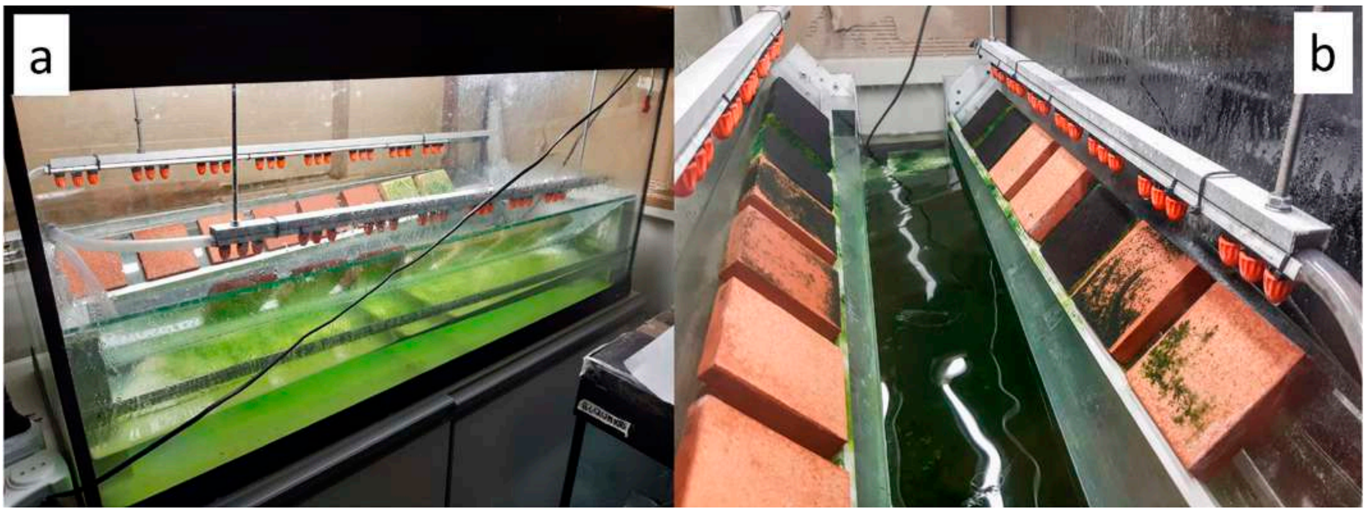

Fig. 1. *The test setup used to evaluate the effects of relative humidity on microalgae growth development (a) and the one used to investigate the impact of temperature (b).*

fied refrigerator (Electrolux RC 5200 AOW2) was utilized to set the lower test temperature. The presence of the wetting cycles makes it reasonable to assume that the relative humidity was always 100%. Temperature and relative humidity sensors (Sensirion SHT31-D) were used to monitor all test settings, with data taken every 10 minutes. During each accelerated growth test, specific analyses were performed to evaluate the algal extent and the biofouling process on the samples' surface [8]. First, colorimetric analysis was done to check how the color changed over time. A spectrophotometer (Konika Minolta CM-2600dD) was used to quantify the chromatic variation (ΔE*) [17]. According to UNI EN 15886:2010 [23] and UNI 11721:2018 [24], the CIELAB color space was used to represent the results. Equation (1) was used to determine color variation in terms of total color difference (ΔE*)

$$\Delta E^* = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \qquad (1)$$

where L^*_0, a_0^*, b_0^* are the color coordinates of samples before the test (time zero), and L^*, a^*, b^* are those evaluated during the accelerated growth phase. The value has been measured on nine different spots on each sample surface every week.

2.3. DIGITAL IMAGE ACQUISITION AND DIVISION

A high-resolution scanner (HP Scanjet G3010) was used weekly to collect digital images to train the convolutional neural network. Previous works [8] have proven the effectiveness of this technique. As mentioned in the following part, the obtained images were elaborated using ImageMagick software. The ImageMagick software (rel.7.1.1-20) allowed the scaling of the images to 1780 x 1780 pixels; these were then cropped to create 256 x 256 sub-images: 49 sub-images were produced from each image. The name and order of every sub-image were changed randomly, and after that, a manual annotation procedure was carried out. Matlab software (rel. 2023a) was used to filter the image's R, G, and B channels in order to make the annotation process easier and take into account the fact that microalgae growth results in a color shift towards green values. Images with microalgal presence traces were labeled as *algae*, while the others were labeled as *no_algae*. Finally, the 13.120 sub-images that composed the annotated picture dataset were split equally into two sections: *train* and *test*. There are 1780 *no_algae* and 4780 *algae* photos in each dataset segment. No filtering was applied to the output images to evaluate the trained and tested convolutional neural network's capacity to operate directly with real pictures [25].

2.4. CONVOLUTIONAL NEURAL NETWORK DESIGN AND TRAINING

A convolutional neural network is called a feed-forward neural network with many convolutional layers layered on top of one another, each one able to recognize increasingly complex forms. Pooling layers (subsampling layers) are included. By calculating a summary statistic from the outputs in the vicinity, the pooling layer substitutes the network's output at specific points. This reduces the spatial dimensions of the representation, which in turn decreases the amount of computation required and leads to more efficient and faster model performance. Following a hyper-tuning procedure, a two-convolution layer was selected to maximize the convolutional neural network's layer count. The first convolutional layer has dimension [32, (3,3)]. The second convolutional layer has the dimension [64, (3,3)]. In order to turn the final matrix into a single array, two pooling layers, two dense layers (256,1), and a flatten layer were added. The first dense layer and the second convolutional layers use the *Relu* activation function. The second "dense" layer has been designated for the *Sigmoid* activation function. RMSprop optimizer (learning rate = 0.001) has been considered. The accuracy measure was displayed because our challenge is binary classification. The ratio of accurate forecasts to total predictions made by the model is known as accuracy. For the training procedure, batch sizes of 20 and 50 epochs were considered. The convolutional neural network has been trained and tested using a Python script (rel 3.9). The convolutional neural network was trained and tested using the *Tensorflow* and *Keras* libraries; then, it was hyper-tuned (parameter optimized) using the *Keras-tuner* library.

2.5. APPLICATION TO CASE STUDIES

Two specific case studies have been selected to demonstrate the practical applicability of the proposed model: the Mole Vanvitelliana and the Rocca Roveresca, two historical buildings of high architectural value that exhibit evident bio-colonization problems.

The Mole Vanvitelliana (Fig. 2) is a large, pentagonal architectural complex from the 18th century, located by the sea in the port area of Ancona (Marche region, Italy). This structure, also known as the Lazzaretto, originally served as a quarantine station for those arriving by sea in Ancona (a precautionary measure to monitor and control the spread of contagious diseases). Over the years, the building has been repurposed for various uses, including military and commercial functions, and today, it operates as a multifunctional cultural center. Designed in the 18th century by the architect Luigi Vanvitelli, the Mole Vanvitelliana is a unique example of architecture and a notable symbol of the city of Ancona. The main building of the complex is enclosed within a perimeter wall. Both the primary structure and the surrounding wall are constructed with brick-facing masonry. Notably, the sloped, rain-exposed perimeter walls show significant signs of bio-colonization, whereas the vertical walls of the main building, which are sheltered from the rain, do not exhibit such issues.

The Rocca di Senigallia, also known as Rocca Roveresca after the Della Rovere family who commissioned its construction (Fig. 3), is located in Senigallia (Marche region, Italy), and it stands as one of the most significant

Fig. 2. *The Mole Vanvitelliana, Ancona, Marche Region, Italy.*

Fig. 3. *The Rocca Roveresca, Senigallia, Marche Region, Italy.*

monuments of both the city and the region. As it appears today, the fortress is the result of centuries of transformation. Originally built during the Roman era as a defensive tower, it evolved into a medieval fortress in the 14th century and eventually took its current form as a typical Renaissance fortified residence in the 15th century. The monument consists of two interconnected structures: the central body, intended as a noble residence, is surrounded by a military defensive structure. The noble residence is encircled by a highly regular structure: a quadrilateral enclosure with four low circular towers at the corners, all connected to each other and the central building by an integrated system of vertical and horizontal communication routes. As in the previous case, the perimeter walls are made of brick-facing masonry. As shown in the figure, some portions of the structure, particularly those with a sloped configuration that makes them more exposed to weather conditions, exhibit signs of bio-colonization (specifically, the lower parts of the perimeter walls). In contrast, other areas are more protected and do not suffer from this issue.

Two different datasets of images were collected from the two case studies. Firstly, digital images extracted from video surveillance HD cameras were collected to evaluate the model's applicability to this type of data source. The second dataset consisted of images of brick-facing masonry façades captured manually using an HQ resolution camera. All the images were resized to the same dimension (1780 x 1780) using the ImageMagick tool, rel.7.1.1-20, and cropped to obtain ca. 1,550 256 x 256 pixels sub-images coming from video surveillance cameras and ca. 500 sub-images of 256 x 256 pixels from the HQ resolution camera images.

3. RESULTS

3.1. CONVOLUTIONAL NEURAL NETWORK TRAINING AND TEST

A trained, tested, and validated convolutional neural network has been used to determine the beginnings of the microalgae development process. The plot of the historical training and test procedure is displayed in Figure 4. The accuracy using the "training" and "test" datasets has been displayed after each epoch (iteration on the whole dataset). When the final accuracy or the ratio of accurate predictions to all predictions produced by the model is 0.83, meaning that 83% of the photos, whether they included microalgae or not, were identified correctly.

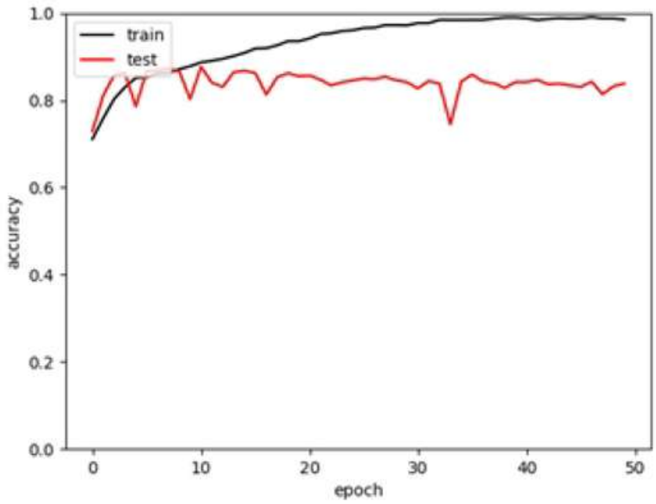

Fig. 4. *Plot of the "training and test" history process. The black line represents the accuracy obtained at the end of each epoch during the training process. The red line represents the accuracy obtained at the end of each epoch during the test process.*

3.2. AUTOMATIC DETECTION OF BIO-COLONIZATION ON CASE STUDIES

The trained model was applied iteratively to verify its recognition ability in real cases. The trained network was first used to detect bio-colonization presence in images collected by security HD cameras. The application of the method to this group of images highlighted that the ability to recognize bio-colonization on the brick-facing masonry façades is affected by several factors. Dividing images from surveillance cameras results in low-resolution sub-images, reducing recognition effectiveness. Moreover, images acquired from security cameras include other elements (ground, grass, roads, roofs, stone, metallic elements, etc.) that were not included in the original dataset. If the cropped image contains objects different from the bricks, convolutional neural networks frequently fail, reducing total accuracy to unacceptable values. This clearly highlights two things. First, there is a need for higher resolution images, and second, there is a necessity to expand the dataset used to train the convolutional neural networks by including images of the brick

Fig. 5. *Some examples of images extracted from HD security cameras installed at the Mole Vanvitelliana and the Rocca Roveresca.*

Fig. 6. *Some examples of images collected with HQ resolution cameras at the Mole Vanvitelliana and the Rocca Roveresca.*

surface and images featuring all elements present on and around building façades (Fig. 5).

Then, the trained network was used to detect bio-colonization presence in the second group of images, those directly collected near the building façades, which include only bricks with and without bio-colonization (Fig. 6). In this scenario, accuracy improves to 0.68 but remains below the one achieved after the training and testing phases (0.83). Thus, enhancing resolution and excluding non-brick elements improved the recognition performance of the trained convolutional neural networks.

However, the not-perfect matching among the colors of the bricks used to train the convolutional neural networks and the color of the historical clay bricks of the case studies, along with the potential presence of other types of bio-colonizers and/or stains, reduced the accuracy achieved with real images.

It is important to note that no image filtering was conducted to evaluate the performance of the trained and tested convolutional neural networks to work directly with real images.

4. CONCLUSIONS

Architectural heritage is subjected to many deterioration problems; one of these is the phenomenon of bio-deterioration and, in particular, microalgae growth. Following the preventive conservation approach, this work aims to provide a tool for "early" damage detection in order to reduce major invasive interventions, moving from restoration (intended as those activities needed to repair serious deteriorations) to a more inclusive approach based on continuous care and supported by data collection, regular monitoring, inspections, control of environmental factors and maintenance activities. In this context, predictive models based on convolutional neural networks that can detect microalgae growth on facing-masonry surfaces were studied and developed. The convolutional neural network has been trained with images collected during an experimental campaign. The model obtained after the training phase is able to recognize the beginnings of the bio-colonization process on several types of clay bricks and can rely on an accuracy of 83%. The initial results from applying the described procedure to a case study were promising but nonetheless highlighted some issues. While automatically obtained images from surveillance systems proved less effective (due to their low quality and the inclusion of contextual elements that interfere with the recognition system), using high-quality images, even those taken for other purposes, yielded significantly better outcomes. However, the application to case studies has not yet achieved results comparable to those obtained in laboratory samples, indicating that further refinement is still needed. To address the primary limitation identified, it will be necessary to extend this study by expanding the dataset through additional experimental activities and incorporating real-world images that capture all elements found on building façades and their surroundings, as well as images of various types of bio-colonizers, into the training process.

Authors contribution

The paper was elaborated as a team, but M.D. designed and directed the project and developed the neural network; A.G. and E.Q. designed and performed the experimental phases, and F.M. contributed to data collection and case-study-related activities. Writing, original draft and writing, review and editing are realized by the authors unless otherwise specified.

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INDOOR ENVIRONMENTAL QUALITY IN AN APULIAN KINDERGARTEN

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Abstract

Indoor environmental quality (IEQ) in school buildings is crucial for the health and well-being of students, educators, and staff. Poor air quality and inadequate thermal conditions compromise students' comfort and can lead to potential long-term health issues. Since children's comfort differs from adults', it is important to consider surveys on IEQ in school buildings. For this reason, this paper focuses on air quality and thermal comfort in kindergartens in Italy. An IEQ monitoring campaign was conducted within a kindergarten, with data used for thermal comfort and IAQ analyses, including CO_2 levels generated by occupants and thermal discomforting hours. The simulations of carbon dioxide levels showed that the amount of CO_2 accumulated in the classrooms exceeds the threshold recommended by ASHRAE guidelines. During the winter seasons, CO_2 levels are significantly higher than those accumulated in summer due to the limited ventilation practiced during the colder months. Moreover, thermal comfort analyses indicate that the summer season can be problematic due to overheating: 42% of the occupied hours during the monitoring period exceeded the temperature threshold, causing thermal discomfort for the occupants. The winter thermal comfort analyses demonstrated that heating systems are essential to maintain temperatures within comfort thresholds.

Keywords

School buildings, Indoor environmental quality, Ventilation strategies, Carbon dioxide levels, Sustainable design.

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1. INTRODUCTION

School buildings serve a social and educational purpose as centres for learning and development, carrying the liability of ensuring a safe and comfortable environment for students, educators, and staff. However, the COVID-19 pandemic has posed significant challenges to these principles [1]. The implementation of restrictive measures, the necessity for social distancing, and an increased understanding of the risks posed by viruses have underscored the issues in the design of indoor spaces [2].

In recent years, growing concerns about the health impacts of poor indoor air quality (IAQ) have highlighted the need for better ventilation and regular air quality monitoring, as high CO_2 levels can impair cognitive function and increase student absenteeism [3]. Alongside IAQ, research underscores the equal importance of thermal comfort for occupant well-being and performance. Ensuring optimal IEQ in educational settings is often challenging due to outdated building designs, poor insulation, and inefficient HVAC systems [4]. These challenges are even more pronounced in Mediterranean climates, where school buildings are typically ventilated naturally without cooling systems [5]. During the summer months, indoor climate control depends only on natural ventilation; however, when outdoor temperatures are excessively high, this approach can cause thermal discomfort within classrooms. Although natural ventilation in the warm months effectively maintains CO_2 levels below threshold limits, it frequently results in thermal discomfort. Conversely, natural ventilation is minimized during winter to retain the heat generated by heating systems [5]. Consequently, while thermal comfort is preserved, CO_2 levels tend to be significantly higher than in summer [5]. These issues are particularly relevant in Italy, where many school buildings are outdated, overcrowded, and inadequately ventilated, further complicating efforts to create environments conducive to learning and occupants' comfort [6]. In a specific way, kindergartens are emblematic buildings for managing IEQ because they host preschool-aged children who are particularly sensitive to environmental factors [3]. Children have a different thermoregulation capacity than adults: their body surface area is larger in proportion to their weight, causing them to lose heat more quickly and making them more susceptible to temperature fluctuations. Their respiratory systems are still developing, so prolonged exposure to poor air quality can negatively affect their growth and development [7]. Moreover, the nature of preschool activities, such as group play, increases their exposure to pathogens, including viruses [8]. Therefore, kindergartens represent a significant challenge in terms of ensuring high IEQ. Acknowledging the issues underscored by the pandemic, it becomes imperative to introduce new design strategies for buildings that ensure healthful, safe environments, offering both optimal air quality and proper thermal comfort [1]. To develop effective new design guidelines, the first action should be a detailed examination of the current conditions of school facilities to identify critical areas for enhancement. In this context, the research presented in this article focuses on evaluating the indoor environmental quality of a naturally – ventilated kindergarten in Bari, Southern Italy. By aligning with the current state of the art, this research aims to assess air quality and thermal comfort in a preschool building, analyse the effectiveness of natural ventilation strategies, and provide recommendations for improving IEQ in similar settings. The paper is divided into several sections: the initial section explains the methodology applied in the study, along with a description of the school used as the monitoring sample; the following section presents the analysis results; the last section discusses the outcomes and their implications.

2. METHODS AND MATERIALS

The methodology of this study is structured into four key phases. First, data was gathered through a real-time monitoring campaign conducted in two classrooms of the selected kindergarten. Following this, the collected data were analysed. The third phase involved developing an energy knowledge-based model of the kindergarten, which was subsequently calibrated in accordance with the ASHRAE 14:2014 standard. Finally, simulations of accumulated CO_2 levels were performed during the occupied hours in the monitored classrooms, and the thermal comfort was evaluated using the Daily Discomfort Hours (DDH) metric.

The following sections provide a more detailed explanation of each phase of the methodology.

2.1. THE MONITORING CAMPAIGN

The school building selected for the monitoring campaign is the John Fitzgerald Kennedy kindergarten (Viale Kennedy 46, Bari BA - 40°45'36", 73°59'2.4"). The facility operates from 8:00 am to 1:30 pm and is open from September to June.

The school, constructed in 1982, is a single-story building with a compact design and includes a basement level used as a technical room. It has a surface-to-volume ratio (S/V) of 0.33. The building envelope consists of brick with an air gap but lacks thermal insulation, as confirmed by the Apulian Regional Portal for School Buildings (ARES) [9]. The interior and exterior are both finished with plaster, while the floors are made of concrete slabs with a ceramic tile finish. According to the ARES portal, the envelope includes metal frames for windows and French doors, which are reported as requiring replacement. The monitoring campaign involved measuring indoor and outdoor temperatures and relative humidity (RH) using three EL USB Data Loggers (designated in this study as sensors A, B, and C). Data collection occurred over 15 days during the spring-summer season in two occupied classrooms: classroom A was monitored from June 13, 2023, to June 27, 2023, and classroom B from May 23, 2023, to June 6, 2023. The classrooms have metal fixtures (doors and glass doors) with single glazing and roller shutters, and the ARES portal has indicated that a complete replacement is necessary. Classroom A has a 40 m^2 surface area, 118 m^3 of volume, hosts 20 children, and is oriented to the South-East, while Classroom B has a 44 m^2 surface area, 133 m^3, hosts 22 children, and is oriented to the South-West. All the IEQ analyses presented in this paper refer to Classroom A, as it is representative of the building. Additionally, among the two monitored classrooms, Classroom A has the most challenging orientation for overheating, being south-east facing, and is the one most exposed to solar radiation during occupancy hours.

The sensors were installed at key locations within the classrooms (Fig. 1), each placed at a consistent height of 2 meters above the floor. Sensors A and C were placed respectively outside and inside the windows most frequently opened by educators during occupancy hours for ventilation. Sensor B was located on the opposite side to sensors A and C. The sensors were programmed to record IAQ parameters at 2-minute intervals, and during the analysis phase, the data was averaged into 20-minute segments.

The comparison of temperature readings from sensors B and C allowed the determination of the temperature fluctuations that the classrooms experienced during the monitoring period. Sensor A and sensor C data were analysed to assess the ventilation strategies employed in the classrooms during school hours. Occupied days were consolidated into a single standard occupancy model, referred to as *OC Day*, which represents the actual classroom usage conditions for that season. Likewise, temperature readings from unoccupied days were merged into a standard model known as *N-OC Day*, representing an unoccupied classroom.

2.2. THE SCHOOL BUILDING ENERGY MODEL AND INDOOR TEMPERATURE TRENDS

The school's geometric model was created using Autodesk Revit software. Once the 3D model was created in Revit, it was transformed into an analytical and energy model, then exported to the energy simulation software Design Builder. The energy model in Design Builder was supplemented with Ventilation, Occupation, and Lighting Schedules, with the heating and cooling system turned off. Cooling systems were excluded from the analysis as they were not present in the building. Heating systems were also omitted to better assess the building's passive thermal behaviour without the aid of mechanical systems. To proceed with the calibration of the energy model, a current climatic file was generated using the actual weather data measured from the monitoring stations, specifically from station 467 (Bari Osservatorio) [10], to be used as boundary conditions for the simulations [11]. The calibration process was conducted manually,

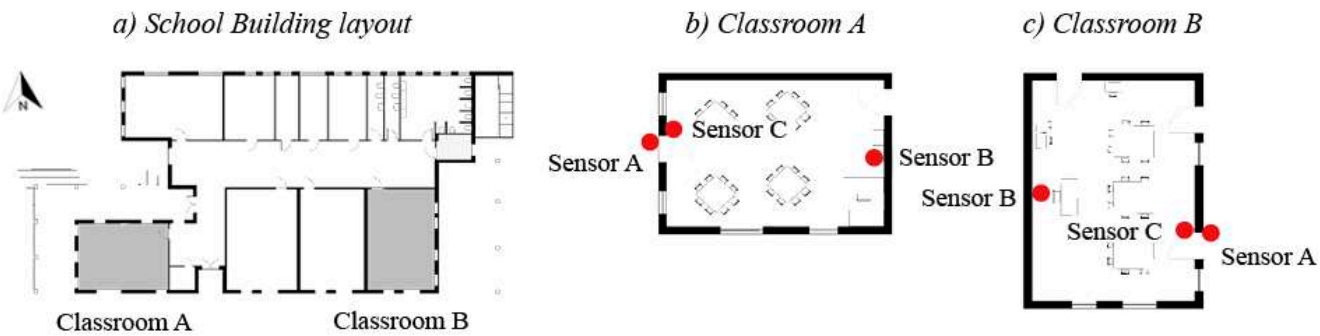

Fig. 1. *Positioning of the sensors in the monitored classrooms.*

following the guidelines of ASHRAE 14:2014, ensuring the NMBE and CV(RMSE) indices were within the acceptable ranges for hourly calibration, with the NMBE within ±10% and the CV(RMSE) below 30%.

After constructing the energy model, further analyses were carried out on the calibrated energy model. Ventilation Schedules were established and applied to the energy model according to the ventilation hypotheses *Hp.1*, *Hp.2*, and *Hp.3* as defined in paragraph 2.4. Simulations were performed for each ventilation hypothesis to assess the indoor temperature trend of classroom A under the different ventilation strategies. The *Hp.1* and *Hp.2* ventilation simulations were performed during classroom A's monitoring period (from 13/06/2023 to 27/06/2023); the *Hp.3* simulation was carried out over a sample period of winter conditions (from 23/02/2023 to 6/03/2023). Data generated from the simulations were aggregated into a single standard model for each ventilation hypothesis, averaged hourly across all days, and then compared with the external dry bulb temperature data using the same energy model.

2.3. THERMAL COMFORT ANALYSIS

Daily Discomfort Hours (DDH) [12] were adopted to assess thermal comfort during summer and winter. The simulations were conducted from 13/06/23 to 27/06/23 for the summer period and from 23/02/23 to 9/03/23 for the winter period, adopting the *International Weather for Energy Calculations 2* (IWEC2) weather file for Bari as boundary condition [13]. The DDH index was used to quantify the number of hours in a day when the Indoor Operative Temperature ($T_{o,in}$) surpassed a defined thermal comfort limit (T_c): with this logic, it quantified the intensity and duration of thermal discomfort. DDH was calculated according to the below equation (1):

$$DDH = \sum_{i=1}^{24} (T_{o,in} - T_c) \tag{1}$$

where, $T_{o,in}$ [°C], was obtained from energy simulations, while T_c [°C], the daily temperature limit, was calculated according to the EN 16798-1 standard for comfort Class I. During summer, *discomfort hours* occur when $T_{o,in}$ exceeds the upper threshold limits; during winter, *discomfort hours* occur when $T_{o,in}$ is below the lower limit [14].

2.4. ESTIMATION OF THE CARBON DIOXIDE LEVELS

Assessing indoor air quality requires careful consideration of the carbon dioxide levels within the confined area. Carbon dioxide acts as a proxy for air quality, and in the absence of precise monitoring tools, its levels can be estimated using the following equation (2) [15]:

$$C(t) = C_{ext} + \frac{\frac{G\times10^6}{ACH\times V}}{3600} - \left(C_{ext} - C_0 - \frac{\frac{G\times10^6}{ACH\times V}}{3600}\right) e^{\frac{-ACH\times t}{3600}} \tag{2}$$

where, C_{ext} ([ppm]) is the external carbon dioxide level, C_0 ([ppm]) is the threshold CO_2 concentration for classrooms in this study, G ([m^3/s]) represents the estimated CO_2 production rate (which varies by age, sex, and physical activity) [16], V ([m^3]) is the volume of the classroom, ACH ([h^{-1}]) indicates the air changes per hour, and t ([s]) denotes time. C(t) indicates the level of carbon dioxide present in the confined environment at a specific time t. These parameters were applied in simulating carbon dioxide levels: ACH of 2.5 h^{-1}, C_{ext} = 450 ppm [17], C_0 = 1000 ppm [16], V = 118 m^3, G = 0.0029 l/s. This value was derived by averaging the CO_2 production of a male child aged 3 to 6 years, which is 0.0030 l/s, with that of a female child of the same age, which is 0.0028 l/s [16].

Different ventilation hypotheses, *Hp.1*, *Hp.2*, and *Hp.3*, were considered for estimating CO_2 levels (Fig. 2). *Hp.1* and *Hp.2* ventilation strategies mirror typical summer ventilation practices, where the environment is continuously ventilated during classroom occupancy. Under *Hp.1*, windows are opened once the children have arrived, while in *Hp.2*, they enter classrooms that have already been ventilated. *Hp.3* represents a winter-specific ventilation strategy characterized by short, intermittent air exchanges throughout the classroom occupancy period. In this scenario, windows are partially opened for 10-minute intervals (from 09:16 am to 09:26 am, from 10:16 am to 10:26 am, from 11:16 am to 11.26 am, from 1:16 pm to 1:30 pm) [18]. CO_2 level simulations were repeated using a hypothetical classroom volume, *Vol.2*, which is larger

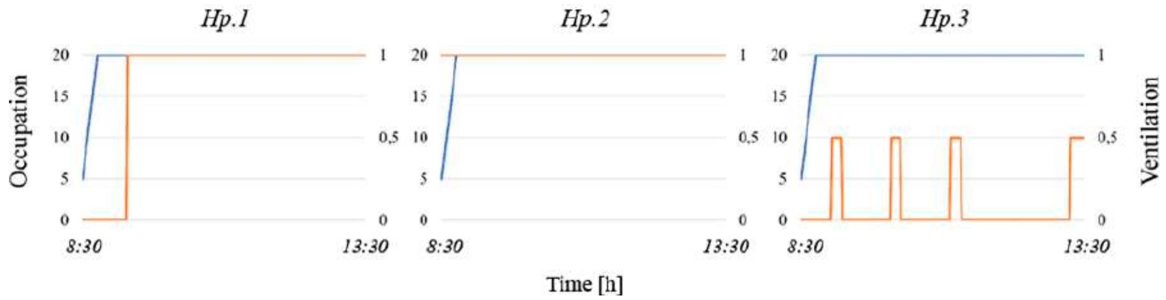

Fig. 2. *Ventilation strategies implemented in this case study,* Hp.1, Hp.2 *and* Hp.3.

than the actual volume of classroom A, to assess the impact of room size on CO_2 levels. *Vol.2* is set at 170 m^3, representing a 44% increase in the volume of Classroom A.

3. RESULTS

The results of this study are outlined in this section, and they refer to the monitoring and analyses related to Classroom A, as it was previously indicated to be representative of the case study. The first part provides a summary of the kindergarten monitoring campaign results. The second part shows the findings from the calibration of the energy model. The third section presents the results from the thermal comfort analyses, while the final part focuses on the outcomes of the indoor air quality evaluation, with the results of the carbon dioxide levels simulations.

3.1. RESULTS FROM THE MONITORING CAMPAIGN: ΔT, RELATIVE HUMIDITY, AND USERS' BEHAVIOUR

As previously noted in the Methodology section, the data gathered from the monitoring campaign were analysed to assess the current condition of the kindergarten. This paragraph presents the results related to the temperature deltas measured in Classroom A by the data loggers and the humidity levels the room was subjected to during the monitoring period. The data loggers' temperature data analysis is also discussed, providing insights into the users' behaviour regarding ventilation, specifically when and how ventilation was practiced during the classroom's occupancy hours.

Figure 3a shows the temperature differences, or deltas, recorded by sensors C and B in the two monitored classrooms during the experimental period. It is assumed that the negative ΔT values are caused by air leaks through the fixtures, especially noted during the night. The presence of outdated fixtures, which require complete replacement as noted by the authority on the ARES portal, supports this hypothesis. The analysis results of the relative humidity data are shown in Figure 3b. The graph displays a discontinuous curve, indicating a peak RH of 74% and a minimum value of 44.5%. The average relative humidity was approximately 61%, slightly above the health and safety regulations' recommended limit for maintaining healthy school environments. The recommended range for RH is 40-60%, as indicated by the green area in the graph (Fig. 3b) [19].

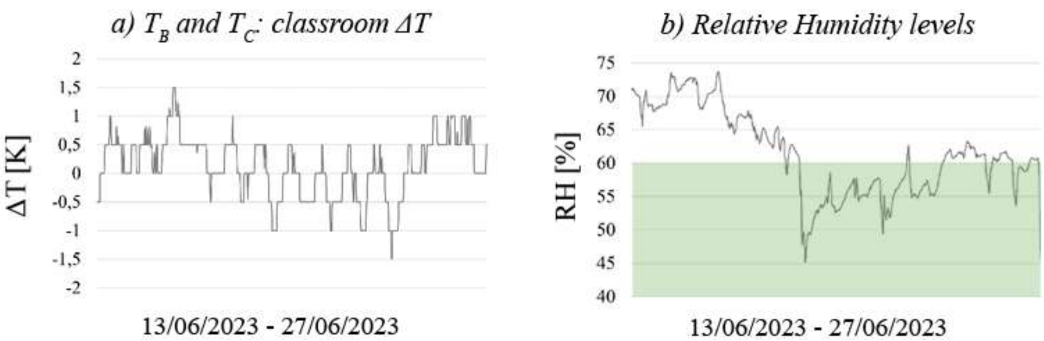

Fig. 3. *(a) Temperature differences recorded between sensors A and C, indicative of the temperature deltas to which Classroom A was subjected during the monitoring period, and (b) Relative Humidity (RH) levels measured inside Classroom A.*

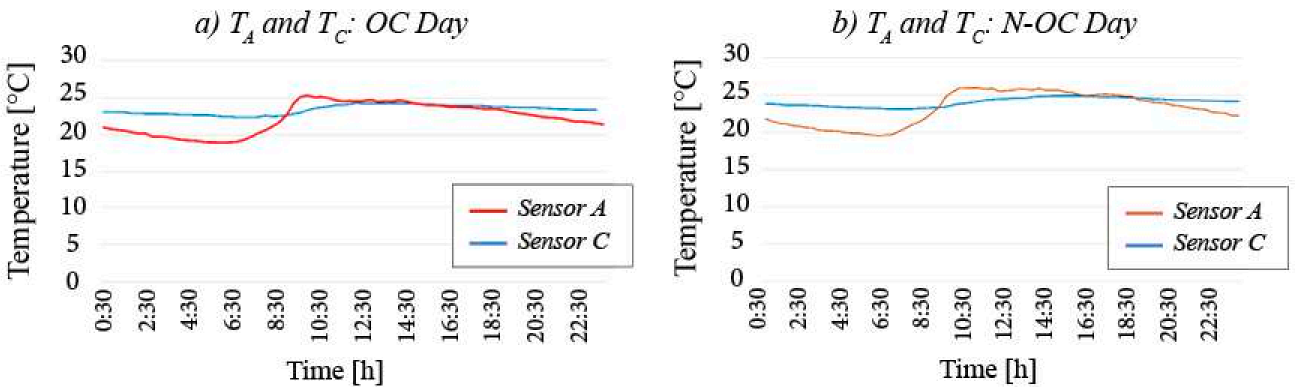

Fig. 4. *Trends of indoor temperature (Sensor C) and outdoor temperatures (Sensor A) of Classroom A on (a) days with occupancy* (OC Day) *and (b) days without occupancy (*N-OC Day*).*

Based on the temperature analysis from sensors A and C, standard ventilation models were developed for both the day with occupancy (*OC Day*) and the day without occupancy (*N-OC Day*). These models allowed us to understand that during the monitoring period, the users maintained constant ventilation during the classroom's occupancy hours. The temperature variations for both daily models are depicted in Figure 4. In the early part of the occupied day, the indoor temperature trend in the classroom is lower than that of the outdoor temperature. During occupancy hours, this pattern reverses: as the windows are opened, the classroom temperature increases due to the external thermal load heating the space. The *N-OC Day* ventilation model shows a similar trend between external and indoor temperatures, but indoor temperatures do not increase as they do in the occupied scenario because the classroom remains unoccupied, and ventilation is not carried out.

3.2. CALIBRATION OF THE SCHOOL BUILDING'S ENERGY MODEL AND INDOOR TEMPERATURE TRENDS

The calibration results of the energy model, as shown in Figure 5, compare simulated temperature data with measured ones on days when the building is occupied (Fig. 5a) and unoccupied (Fig. 5b). The indices defined by the ASHRAE Guideline 14:2014 [11] comply with the standards, as they fall within the established ranges for both occupied and unoccupied days (Tab. 1).

Standard Day Model	*NMBE*	*CV (RMSE)*	*Maximum percentage error*	*Maximum ΔT*
OC Day	0.23%	0.27%	2.18%	0.5 °C
N-OC Day	0.46%	0.53%	2.33%	0.55 °C

Tab. 1. *Calibration index results defined by the ASHRAE 14:2014 Guidelines for energy models that use hourly data.*

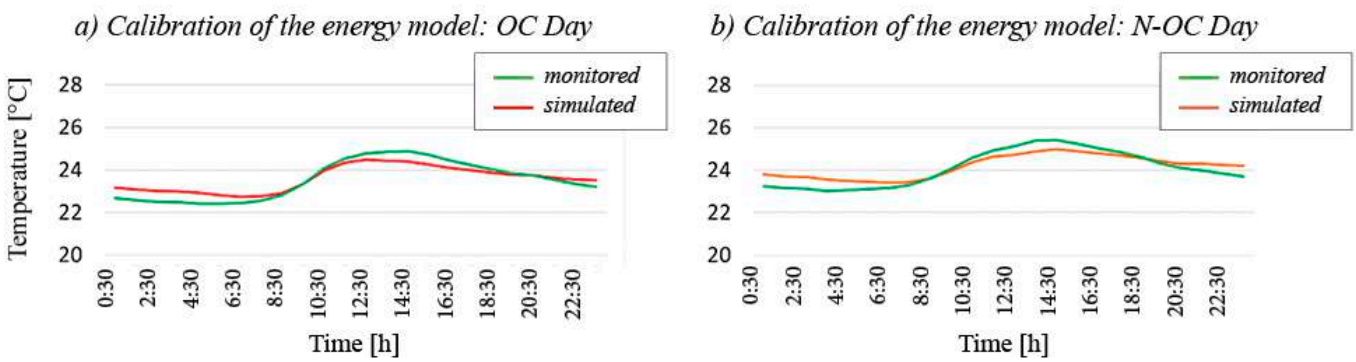

Fig. 5. *Comparison between the monitored and simulated temperatures using the energy model for both occupied and unoccupied days.*

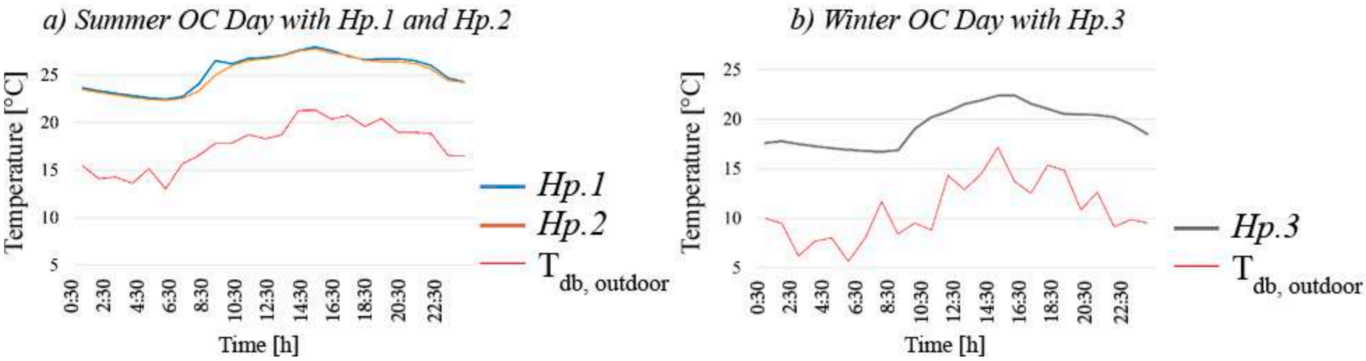

Fig. 6. *(a) Simulation of the occupied days using the* Hp.1 *and* Hp.2 *ventilation strategies and (b) Simulation of the occupied days using the* Hp.3 *ventilation strategy.*

The simulations of indoor temperature trends in classroom A resulted in different curves for each summer ventilation hypothesis, as described earlier in Section 2.4. The results for the summer ventilation strategies *Hp.1* and *Hp.2* are depicted in Figure 6a. The comparison of the two curves (Fig. 6a) reveals that both ventilation hypotheses produce similar trends. The temperature increases steadily in the morning, then levels off during the day and remains stable thereafter. At 7:00 am, both curves start with temperatures near 20°C. In the *Hp.1* curve, the temperature steadily rises until it peaks shortly after the classroom becomes occupied since the windows are closed when students arrive under this ventilation scenario. When the windows are opened, the temperature decreases. The curve under *Hp.2* remains stable throughout the day. The curves differ at the start of the school day: the *Hp.1* hypothesis shows an increase in the initial phase, whereas the *Hp.2* hypothesis maintains a more consistent trend throughout the day.

The temperature curve in Figure 6b corresponds to the trend produced by the winter ventilation hypothesis *Hp.3*. During the morning hours, the temperature steadily increases. The peak temperature occurs around midday, reaching slightly above 20°C. Following the peak, the temperature gradually declines for the rest of the day.

3.3. THERMAL COMFORT EVALUATION: DAILY DISCOMFORT HOURS ANALYSES RESULTS

The thermal comfort analyses of the classroom reveal significant seasonal differences. During the winter (Fig. 7), the $T_{o,in}$ fluctuates, often exceeding the limits of the thermal comfort zone indicated in grey. This suggests that the children may have experienced suboptimal cold conditions, indicating a potential need for improved insulation or better heating management. Out of 360 simulated hours, 45% fall within the thermal comfort zone, while the remaining 55% represent hours of discomfort. However, when narrowing the analysis to the 90 hours of actual classroom occupancy, it is observed that 65% of these hours provide comfortable conditions, while 35% fall into the discomfort zone.

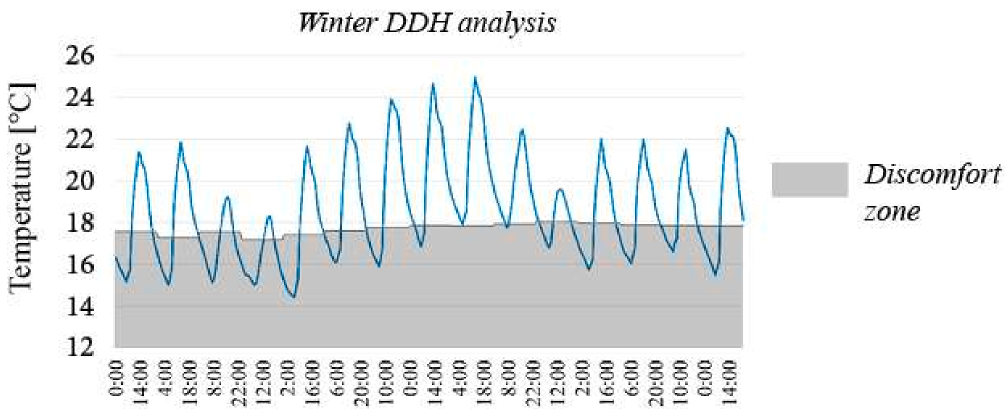

Fig. 7. *$T_{o,in}$ trend during the sample winter period. The grey area represents the thermal discomfort zone for cold months (EN-16798).*

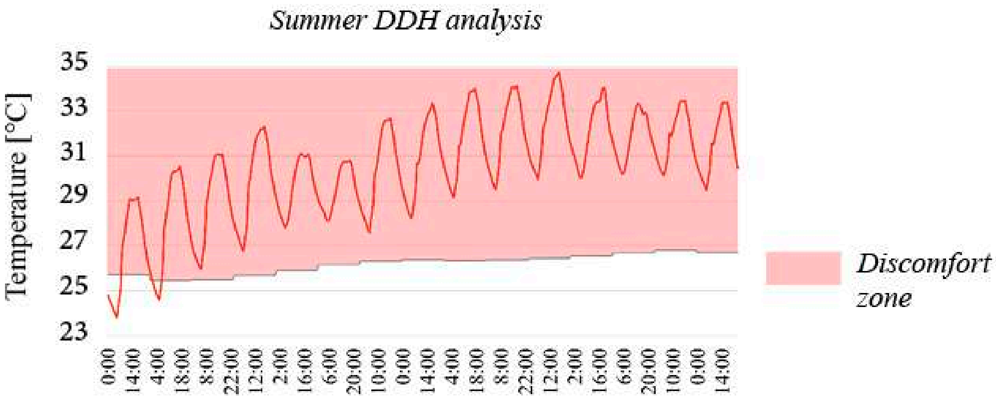

Fig. 8. *$T_{o,in}$ trend during the Classroom A monitoring campaign period. The red area represents the thermal discomfort zone for warm months (EN-16798).*

In the summer period (Fig. 8), the situation appears even more critical, with the $T_{o,in}$ frequently surpassing the thermal comfort zone indicated in red. Discomfort conditions characterized 96% of the total hours. When considering only the hours of actual classroom occupancy, all of them fall within the discomfort zone.

3.4. INDOOR AIR QUALITY EVALUATION: RESULTS FROM THE CO2 LEVELS SIMULATIONS

The carbon dioxide simulations in classroom A resulted in varying scenarios. Under the summer ventilation scenarios, *Hp.1* and *Hp.2*, the carbon dioxide levels generated by the occupants stay constant since they are continuously produced and ventilated out. The distinction between the two ventilation strategies becomes particularly clear during the initial occupancy hours: in the *Hp.1* scenario, children arrive gradually in a room with closed windows, which are only opened later, maintaining constant ventilation after that. As a result, the CO_2 concentration curve under the *Hp.1* scenario shows a spike in the early phase. Under the *Hp.2* ventilation strategy, the initial CO_2 spike does not occur because the children arrive in a room that has already been ventilated, allowing the CO_2 produced to be directly expelled without accumulation. In each case, the carbon dioxide concentrations exceed the set threshold of 1000 ppm (Fig. 9).

Using the *Hp.3* ventilation strategy, the carbon dioxide level simulation produced an irregular CO_2 trend. Specifically, the simulated CO_2 levels are considerably higher than those observed under typical spring and summer environmental conditions (Fig. 10).

The simulations of CO_2 levels conducted with the increased volume of Classroom A, *Vol.2*, demonstrate how indoor pollutants accumulate more slowly. As a result, the curves representing these levels in the graphs are lower than those obtained with the original volume. However, despite the slower accumulation, CO_2 concentrations still exceed the established limit of 1000 ppm.

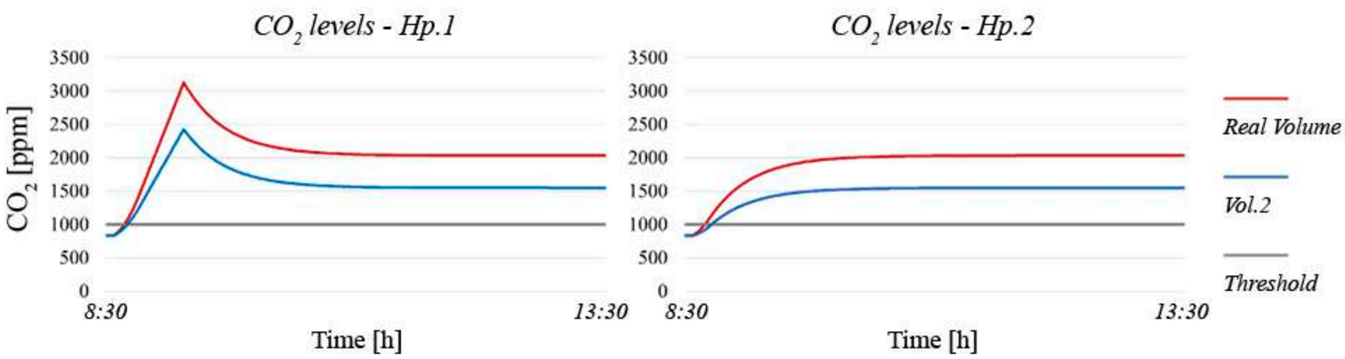

Fig. 9. *Carbon dioxide levels simulations with summer ventilation strategies,* Hp.1 *and* Hp.2. *The red curves represent the simulations conducted with the actual volume of Classroom A, while the blue curves represent the simulations performed with the increased volume,* Vol.2.

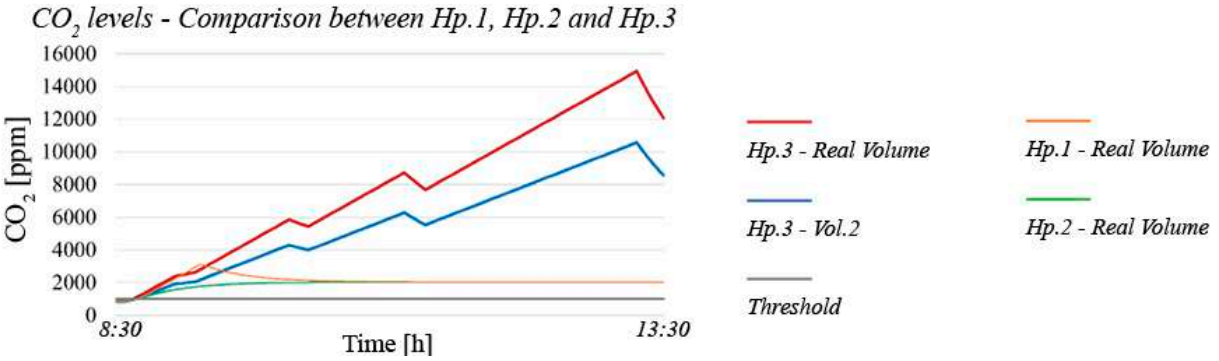

Fig. 10. *Comparison between the carbon dioxide levels simulated with all the ventilation hypotheses.*

4. DISCUSSION

This paper provides a comprehensive overview of the indoor environmental quality at the John Fitzgerald Kennedy kindergarten in Bari. The monitoring campaign in the kindergarten, along with the data analysis and the simulation of thermal comfort and indoor air quality, provided interesting insights into the current state of this school building. Analysis of the collected data (Fig. 3a) indicates that classroom temperature variations hinder the maintenance of a stable indoor temperature. It was hypothesized in this study that the observed negative temperature variations result from air infiltration through windows, particularly at night. The presence of outdated windows, as noted in the ARES portal, supports this hypothesis.

The collected data on relative humidity reveal that, throughout much of the monitoring period, the levels fell short of the standards set by both Italian and international regulations to ensure safe and healthy indoor environments (Fig. 3b) [19]. Maintaining proper control over indoor relative humidity levels is crucial, particularly in buildings occupied by fragile users, as is this case.

The analysis of the trends in internal and external temperatures suggests that the occupants maintain constant ventilation during the warm season (Fig. 4a). This is a common strategy in buildings without cooling systems and under favourable wind conditions (in terms of direction and speed), it can have positive effects on thermal comfort within the classroom [5]. However, a more in-depth comparison between outdoor and indoor temperatures reveals a more complex situation: during periods of occupancy, the indoor temperature of the classroom tends to increase not only due to the activities inside but also because outdoor heat infiltrates the environment. As a result, by opening the windows, the classroom quickly reaches thermal equilibrium with the outside, reducing the effectiveness of natural ventilation as a cooling strategy. Instead of lowering the internal temperature, this practice can facilitate the entry of external heat, thereby compromising the potential benefits of natural ventilation in maintaining a comfortable indoor climate. However, among the ventilation strategies analysed, some stand out as particularly effective in ensuring a more uniform level of comfort within the classroom. Simulations of indoor temperature trends under different ventilation strategies have yielded valuable insights into indoor thermal comfort. The *Hp.2* summer ventilation strategy is particularly effective in maintaining consistent indoor temperatures throughout the day (Fig. 6a), indicating that a well-managed ventilation approach can prevent potential classroom overheating during summer and enhance internal thermal comfort. In this scenario, the windows are opened before the occupants arrive, allowing for a pre-cooling effect that contributes to the overall stability of indoor temperatures. The *Hp.1* ventilation strategy results in more significant temperature fluctuations early in the school day; without ventilation upon the arrival of users, temperatures increase due to passive overheating caused by the influx of occupants and rising external temperatures. Except for this early difference, the two curves reflect similar thermal behaviour in space, as both assume a constant ventilation regime.

The curve for the winter temperature trend under *Hp.3* shows a distinct pattern compared to the summer models

(Fig. 6b). The simulated rise in temperature during classroom occupancy hours is attributed to passive heating from solar gain and occupants' activity, leading to heat buildup in the absence of natural ventilation. This pattern is adjusted by brief ventilation periods that result in minor heat loss; nevertheless, in the *Hp.3* regime, these intervals are insufficient to properly dilute indoor pollutants or remove the carbon dioxide generated by occupants, as illustrated in the CO_2 simulation analysis. This finding highlights the need for scheduled natural ventilation that balances air quality and heat retention, particularly during the colder months, to provide comfortable indoor conditions [20].

The analysis of thermal comfort during the summer period reveals that relying solely on natural ventilation is insufficient to prevent thermal discomfort (Fig. 7). Although classrooms with natural ventilation have lower CO_2 levels than those with mechanical ventilation, they tend to experience higher temperatures [21]. The south-east exposure exacerbates this issue, leading to all occupied hours falling within the thermal discomfort zone. This critical situation necessitates targeted interventions to improve summer conditions, such as implementing cooling strategies and solar shading [23]. While the south-east exposure is less problematic in winter and generally allows for greater thermal comfort compared to summer (Fig. 8), maintaining optimal conditions for the children still requires a reliable heating system.The CO_2 level simulations highlight the necessity of effective ventilation strategies to maintain CO_2 concentrations below the threshold. Between the two summer ventilation strategies, *Hp.1* and *Hp.2*, the latter was more effective in lowering carbon dioxide levels, owing to the pre-ventilation of the space before occupants enter (Fig. 9). By avoiding CO_2 concentration spikes, this strategy ensures a well-ventilated and clean environment. On the other hand, the *Hp.3* winter ventilation strategy is typically used during the colder months when the heating system is operational. During the winter, ventilation is minimized to avoid heat loss and energy waste from open windows, leading to a notable decline in indoor air quality [5]. The simulations using the third ventilation strategy demonstrate how winter CO_2 accumulation can surpass the acceptable threshold (Fig. 10). Therefore, it is essential to implement an effective natural ventilation strategy to limit indoor pollutants produced by occupants [20]. In crowded spaces, the COVID-19 Report No. 33 from the Italian National Institute of Health advises that ventilation systems be activated before occupants enter. This approach can be integrated into naturally ventilated buildings, allowing occupants to arrive in a pre-ventilated space, thereby improving pollutant removal, as shown by the CO_2 simulations [24]. The volume of the enclosed space is another critical factor in indoor air quality analysis. Environments with smaller volumes are observed to reach saturation faster compared to larger ones [25]. While the carbon dioxide simulations with the increased classroom volume (*Vol.2*) show that even with a larger space, CO_2 levels still exceed 1000 ppm, this approach can nonetheless contribute to improving air quality.

5. CONCLUSION

This study identified critical issues in Italian school buildings that negatively affect occupant comfort, emphasizing the need for energy retrofitting and fixture replacement to improve indoor environmental quality. The research highlighted that seasonally adapted ventilation strategies are crucial to enhancing both thermal comfort and air quality. Finally, the study demonstrated the importance of comprehensive monitoring and data analysis in developing efficient management programs and ventilation systems that optimize building performance and occupant well-being.

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Authors contribution

E.C. contributed to the writing of the manuscript, the creation of the figures, and data analysis. L.M.C. and F.C. were responsible for reviewing the manuscript. F.M. and F.F. coordinated work.

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CRITICAL ANALYSIS OF RESTORATION PRACTICES AGAINST RISING DAMP

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Abstract

The restoration of architectural heritage from rising damp is a complex technical and scientific challenge. The paper illustrates a comprehensive approach to address this issue. It highlights critical information gaps and specific topics that need further investigation in the state of the art and current practices. The research methodology adopts a multidisciplinary and holistic approach to the restoration process with the integration of historical investigation, knowledge of building elements and materials, non-invasive diagnostics for identifying degradation phenomena, methods and materials for restoration, and long-term monitoring.

The research activity is part of a broader project aimed at establishing operational protocols with advanced technologies for the planned and preventive maintenance of architectural heritage. The outcome will be a digital platform, an open-access tool to support integrated building design and conservation, ensuring sustainable conservation practices to managing rising damp and related issues.

The paper focuses on the restoration processes of two significant case studies: the Church of San Gennaro in Capannori (Lucca) and the Church of San Giuseppe in Rosate (Milano). The research results provide valuable insights into the effectiveness and durability of different intervention methods. Moreover, the critical analysis facilitates the choice of best practices for sustainable building heritage conservation.

Keywords

Restoration process, Rising damp, Infrared thermography, Church of San Gennaro in Capannori (Lucca), Church of San Giuseppe in Rosate (Milano).

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1. INTRODUCTION

Rising damp is a significant and increasingly recognized problem in the restoration and conservation of architectural heritage. In fact, humid conditions can seriously compromise masonry's structural and aesthetic integrity with irreversible damage. Despite the growing interest in this topic, some critical gaps still exist in the scientific and technical literature. The lack of standardized protocols for evaluating the effectiveness of intervention methods is one of the fundamental issues. Most of the works focus on individual case studies, which hinder the comparison between the different available techniques [1, 2]. The fragmentation of the current state of the art makes it difficult to establish a hierarchy of effectiveness between the different methods and to state generalizable conclusions. Moreover, a significant research gap exists in the long-term monitoring and durability of interventions.

Different methods and techniques against rising damp are available nowadays. There is a significant variability in their working, invasiveness, applicability, and effectiveness. Standard techniques include chemical barriers, physical barriers, active and passive electro-osmotic techniques, and inversion or neutralization of electromagnetic polarity [1, 3]. Table 1 summarizes the main methods and techniques currently used against rising damp, highlighting both advantages and disadvantages. Once rising damp is stopped, removing salt efflorescence, and using breathable plasters and finishes are essential treatments to allow for the proper evaporation of residual moisture and to prevent the formation of new salt deposits. A comprehensive intervention that integrates the practices mentioned above is required to ensure the long-term effectiveness and sustainable conservation of building heritage.

Despite extensive research on rising damp, documentation on the effectiveness of intervention methods remains incomplete and fragmented. The literature highlights the need for additional comparative and long-term studies to provide recommendations and best practices.

A multidisciplinary approach that considers all aspects of the building, from its history and typology to di-

Technology	Description	Advantages	Disadvantages
Physical barriers / Chemical barriers	Horizontal or vertical waterproof membranes installation / water reppellent resins and silicones injection	▪ Good initial effectiveness	▪ High invasiveness ▪ High costs ▪ Damage of structural integrity
Electrosmosis (active and passive)	Active: Use of electrical pulses to reverse the flow of water in capillaries through electrodes Passive: Exploit differences in natural potential	▪ Minimally invasive ▪ Adjustable electric field intensity	▪ Variable effectiveness ▪ Periodic maintenance
Reverse polarity	An alternating electric field tries to cancel the capillary force by reversing the movement of water	▪ Non-invasive ▪ Easy to install ▪ Low energy consumption	▪ Variable effectiveness ▪ Power supply
Electromagnetic fields	Uses electromagnetic fields generated by devices placed near or inside the walls to alter the surface tension of the water, reducing the ability of the water to rise through the capillaries	▪ Non-invasive ▪ Low operating costs	▪ Few scientific studies ▪ Complementary techniques
Pulsed frequency system	Devices that emit specific current pulses or frequencies to interfere with the natural capillary rising process of water	▪ Non-invasive ▪ Easy to install	▪ Variable effectiveness ▪ Power supply ▪ Continuous maintenance ▪ Few scientific studies
Drainage systems	Installation of drains to remove water from foundations	▪ Low hydrostatic foundation pressure ▪ Versatility of application	▪ High installation costs ▪ Invasive ▪ Not always applicable ▪ Not always effective
Dehumidifier plasters	Use of porous plasters to allow the moisture evaporation. These products don't resolve the cause of rising damp	▪ Ease of application	▪ Periodic replacement
Environmental dehumidification	Use of dehumidifiers to reduce indoor humidity	▪ Non-invasive ▪ Simple to implement	▪ Power supply ▪ Continuous maintenance

Tab. 1. *Main methods and techniques against rising damp.*

agnostic interventions, is required to tackle rising damp and develop an effective restoration protocol. In particular, diagnostics has a crucial role in identifying degradation phenomena and short and long-term monitoring of interventions.

This work aims to provide a holistic view of the current state of the art on rising damp management and identify issues requiring further investigation and implementation. The research investigation is focused on the critical analysis of two case studies belonging to listed building heritage: the Ancient Church of San Gennaro in Capannori (Lucca) and the Church of San Giuseppe in Rosate (Milan). Site inspections during previous restorations revealed, in both buildings, widespread efflorescence, sub-efflorescence, and biological patinas, as well as slight detachment of plaster, peeling of paint films, alveolation, decohesion and crumbling of building surfaces. A comprehensive research methodology was adopted, combining historical and technical approaches, including the study of historical documents, literature review, and analysis of construction and material characteristics. This approach provided a deeper understanding of the structural and conservation challenges and the effectiveness of conservation solutions.

The investigation included detailed condition assessments and identification of structural problems using non-invasive diagnostic techniques, focusing on infrared thermography (IRT) to detect hidden defects such as moisture and material degradation that could affect structural stability. Passive infrared thermography (IRT) is applied in various fields, with various methodologies tailored to specific contexts. Active IRT is particularly useful in material characterization and stratigraphy of localized areas of historic buildings [4–6]. Its usefulness in building historical and evolutionary analysis is well documented, particularly for monitoring phenomena such as moisture in structures, although its application is often limited to specific areas [5, 7–10]. However, there is a need for a standardized procedure for thermographic analysis because the measurements are conducted using different and not comparable methodologies [6, 7, 11].

The literature highlights key factors for reliable thermographic analysis: analysis timing, understanding IRT principles, accurate calibration of thermal cameras, and use of digital and mathematical thermal models [4, 9, 11, 12]. The integration of IRT with 3D models, often supported by drones, to locate specific features during analysis is a promising emerging trend.

Research into the use of IRT for assessing material performance and quantifying moisture content is still evolving. However, simultaneous measurements and continuous surveys are suggested for best practice protocols and quantitative results.

Infrared thermography combined with other non-destructive techniques provides a comprehensive view of building conditions, promoting preventive conservation and continuous monitoring and the potential evolution towards 4D models [12–15].

Despite skepticism about the reliability of IR thermography, proper technical training of operators in both execution and data interpretation can provide qualitative information in real time. Moreover, the minimum requirements of the thermal camera must be a sensor of 320x240 pixels, a thermal resolution of 0.05°C, and an IFOV of 1.5mrad [4, 16].

This study is part of a more comprehensive research program to define operational protocols based on the best technologies currently available for the conservation, preventive, and planned maintenance of architectural heritage. The outcome of the research activities is the development of a digital platform, configured as an open knowledge tool, to support integrated design and the conservation of historic buildings.

The proposed operational protocols consider the entire restoration process, particularly for architectural heritage affected by rising damp, and include the use of CNT®-Domodry® technology to resolve the phenomenon. This innovative dehumidification system, patented by Domodry®, generates weak, impulsive electromagnetic waves suitably modulated within a defined frequency range and completely harmless [17–19]. Applying this technique against rising damp and verifying its effectiveness through case studies are parts of specific conservation recommendations for the architectural heritage according to the principles of restoration (compatibility, minimal intervention, reversibility, recognizability) and sustainability of the interventions.

2. CASE STUDIES

This study examines the Ancient Church of San Gennaro in Capannori (Lucca) and the Church of San Giuseppe in Rosate (Milan), both of which have had CNT devices installed to control rising damp. Specifically, two devices were installed in San Gennaro in 2021 and one in San Giuseppe in 2016.

The Ancient Church of San Gennaro is of great historical and artistic importance. It is one of the most important examples of Romanesque religious architecture in the Lucca area for its rich decoration and the presence of a recently restored sculpture of an angel attributed to Leonardo Da Vinci. The church stands in the old center of the small town of Capannori, located on the border of the Lucca plain and the Valdinievole. The structure was built in the 12th century above the former construction dating back to the 9th century. The sandstone sack masonries are made with a local porous sandstone known as Matraia stone, named after the locality of the quarry about 12 km away from Capannori [20]. The church preserves the medieval three-nave plan and original decorations. The apse was modified in the 18th century, and a square bell tower was added in 1840 next to the north facade. The building has undergone numerous restorations over the years due to the widespread presence of rising damp and related degradation phenomena such as detachment and decohesion of surfaces.

The Church of San Giuseppe was built in the 18th century along the central urban axis of the town of Rosate. It is one of the remarkable examples of Mannerist Baroque architecture in the Province of Milan. The church has a central octagonal plan with a rectangular presbytery. It is built in brick masonry with decorative details made in gilded stucco and artfully crafted painted wooden doors. A dome with a central painted medallion and stucco relief covers the church. The presbytery, surrounded by polychrome marble balustrades, has a barrel-vaulted ceiling. The facades are entirely plastered. The main facade is characterized by a double order of pilasters and a stone entrance portal.

The first documented restoration occurred in 1940 and focused on consolidating the roof and internal masonry, which were severely damaged by rising damp. However, this restoration proved ineffective, and in 1963, further interventions were required on the masonry, including replastering. In June 1969, additional restoration work was conducted, and the plastic and painted decoration of the interiors was renewed by the painter Taragni [21].

The late restoration of the building was carried out between 2016 and 2017 following the collapse of the roof. This project involved stabilizing and repairing the roof and dome. In addition, due to the ongoing problem of rising damp, a more rigorous technical and scientific approach was adopted. The aim was to thoroughly assess the condition of the building and implement definitive solutions to the existing problems, optimizing the use of resources and minimizing future expenditure in terms of time and cost.

3. MATERIALS AND METHODS

The analytical process was carried out in several phases, starting with a thorough assessment of the condition of the buildings and the identification of pathologies using non-invasive diagnostic techniques. This included a preliminary microclimate assessment using a thermo-hygrometer for environmental parameters and a contact thermo-hygrometer for surface parameters.

Thermographic surveys were conducted using a "NecH2640" thermal camera to verify the presence of rising damp in the masonry of both case studies. This thermal camera fully complies with the recommended standards and ensures the results' reliability thanks to its characteristics: geometric resolution of 640x480 pixels, thermal resolution of 0.03°C, and an IFOV of 0.6mrad. The monitoring has also been carried out for three years at San Gennaro Church and seven years at San Giuseppe Church, providing crucial data to evaluate the effectiveness and durability of the solutions implemented.

Hourly readings of relative humidity and indoor air temperature (24 data points per day) were recorded for one year in the Church of San Gennaro using Domodry® RH-T sensors (temperature range: -20°C to 60°C, accuracy: 0.3°C; RH range: 0-100%, accuracy: 2%; over 3 years of storage capacity). Two IDROSCAN® sensors (measuring range: 1500 to 2500 u.i., accuracy: 2 u.i.; over 3 years of storage capacity) were used over the same period to measure masonry moisture in "idroscan units" (u.i.) daily.

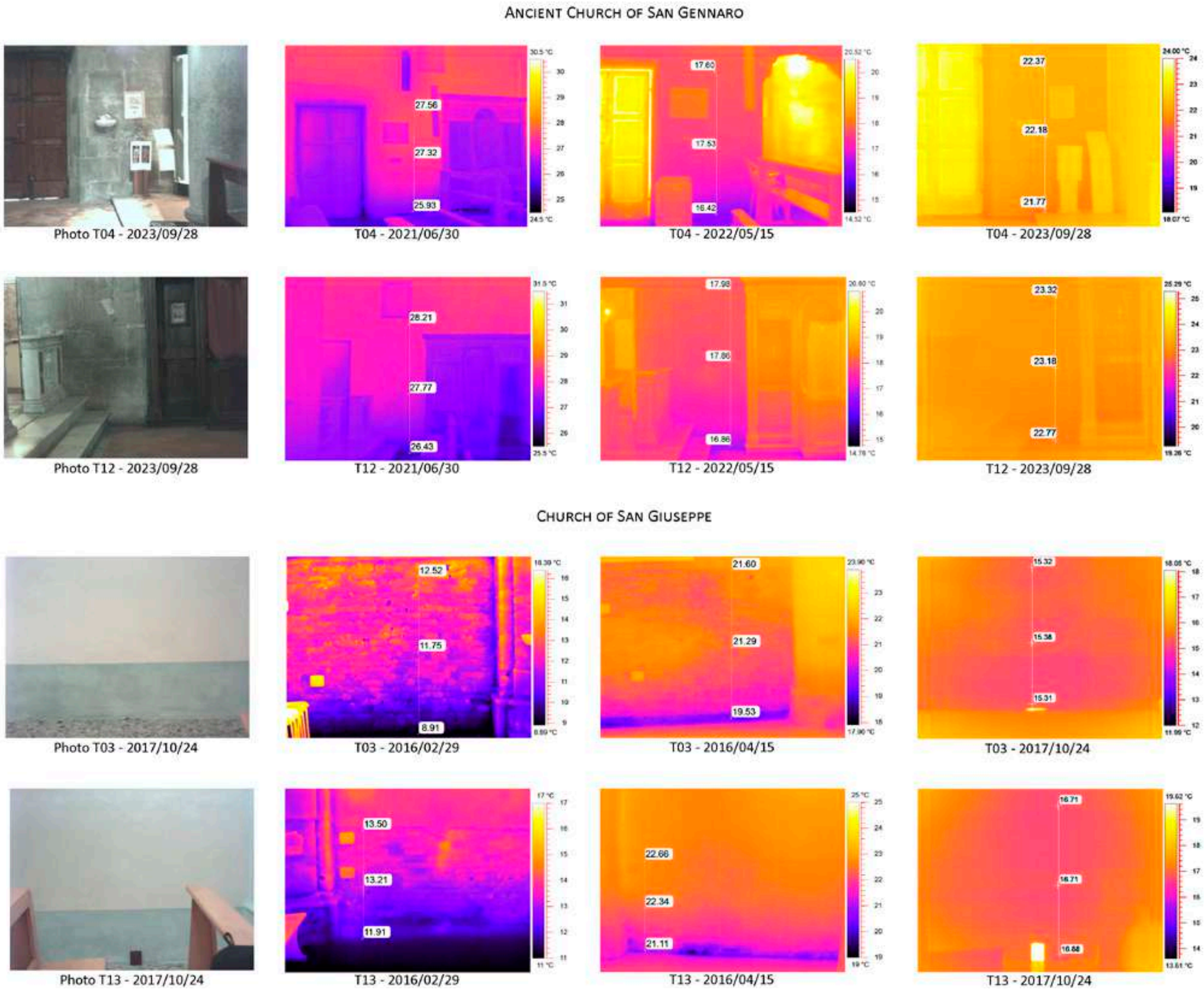

Fig. 1. *IR thermography with the indication of temperatures along the wall carried out during the diagnostic campaign.*

Data was stored on the CNT device or sensor and later downloaded by a technician or automatically via the Domodry Control Center when internet access was available.

The thermographic survey was conducted in the Church of San Giuseppe to control the effectiveness of the CNT system against rising damp. It also allowed the localization of thermal critical areas where sampling was performed for gravimetric analysis. Samples were taken at six critical points for a total of 16 samples. At each point, samples were taken at depths between 5cm (S) and 10 cm (P) from the outer surface and at heights of 50 cm (B), 100 cm (A) and 150 cm (AA) above the ground. Samples were taken with a low-speed drill to avoid overheating, per UNI 11085 "Natural and artificial stone materials - Determination of water content: weight method". The samples were placed in an airtight glass tube and weighed in the laboratory using a balance with an accuracy of 0.001g. The samples were dried up to obtain a constant mass at 105°C in an electrically heated laboratory oven with an accuracy of ±2°C.

Ancient Church of San Gennaro		
	Indoor	Outdoor
UR	49,70%	41,00%
T_{air}	25,8 °C	26,0 °C
T_{dew}	14,5 °C	11,7 °C
U_{sp}	10,21 g/kg	8,51 g/kg

Church of San Giuseppe		
	Indoor	Outdoor
UR	63,40%	79,10%
T_{air}	17,2 °C	11,6 °C
T_{dew}	10,3 °C	8,3 °C
U_{sp}	7,65 g/kg	6,79 g/kg

Tab. 2. *Environmental parameters during the preliminary IR surveys.*

4. RESULTS

Preliminary thermographic surveys (Fig. 1) and environmental analyses revealed the presence of rising damp in both case studies, which critically affects both pathological conditions and the indoor microclimate (Tab. 2).

Due to the widespread occurrence of the above-mentioned pathologies, the installation of CNT® devices was chosen to stop rising damp (Fig. 2). Thermographic tests were conducted at one-year intervals and then again two or more years after installation.

The Domodry® sensors installed in the Ancient Church of San Gennaro alongside the CNT system for continuous monitoring of wall moisture and environmental conditions provided essential data for real-time evaluation of the system's performance and optimization of intervention strategies to ensure complete and timely drying. The results showed a reduction in masonry moisture after the activation of the CNT devices, with an estimated timeline for complete evaporation of residual moisture by September 2023 (Fig. 3). Throughout the monitoring period, the indoor relative humidity generally remained below the recommended threshold of 50%, with occasional spikes above this level. The indoor temperature averaged between 18°C and 22°C, maintaining comfortable conditions. The dehumidification rate was slightly slower than expected, probably due to the significant wall thickness and high initial water content.

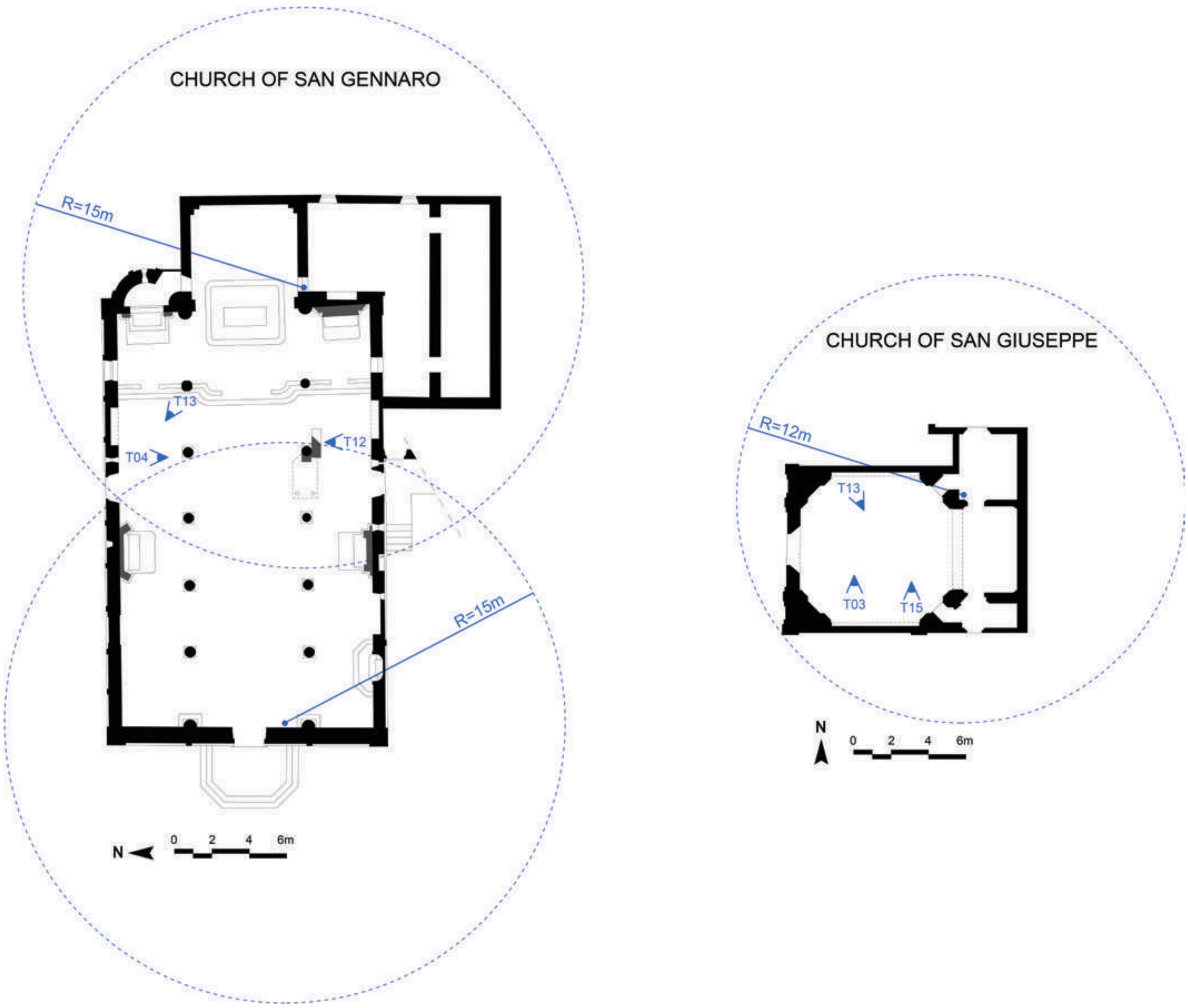

Fig. 2. *Localization in the two case studies of CNT devices with indication of their radius influence and viewpoints of thermographic analysis.*

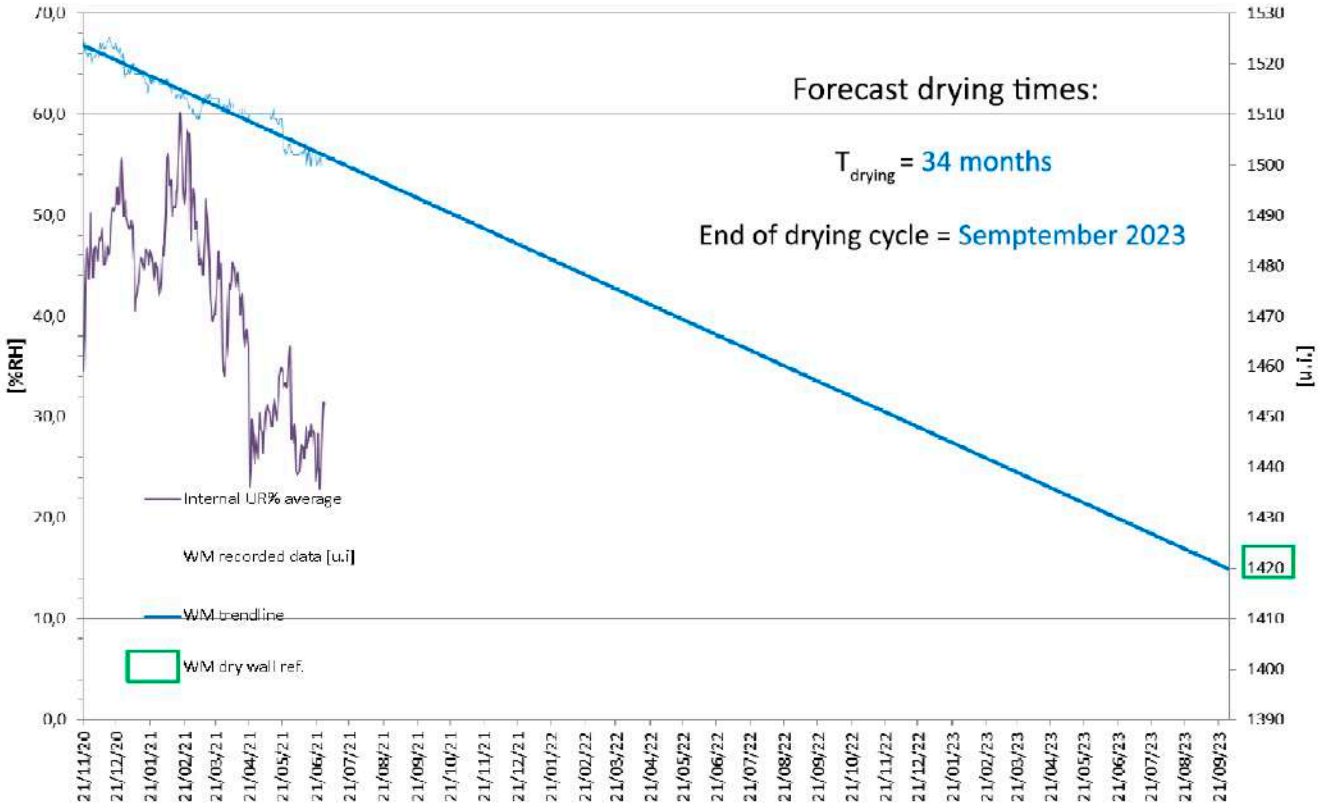

Fig. 3. *Wall humidity: Forecast drying times from 2020/11/21.*

The effectiveness of the CNT system was also validated by thermographic surveys (Fig. 1). At the time of installation of the system on 2020/11/20, it was impossible to carry out thermographic mapping due to unfavorable thermo-hygrometric conditions. The combination of high relative humidity and low temperatures would have reduced the rate of water evaporation, leading to an underestimation of wall moisture by thermography. Therefore, thermographic surveys were conducted seven months after installation and revealed anomalous thermal patterns in the walls, with a significant gradient in surface temperature distribution. The upper sections, approximately 1.2-1.5m above ground, showed average temperatures 2°C higher than those close to the ground, with peaks of up to 2.6°C. This thermal gradient indicated the presence of rising damp. During the inspection on 2022/05/10, the thermographic survey showed a reduction in the thermal anomalies along the vertical extent of the walls. This confirmed both the stopping and regression of the capillary rise phenomenon and the progress towards natural drying of the walls. Finally, during the final inspection on 2023/09/28, the thermographic analysis showed a substantial disappearance of thermal anomalies, and the walls showed no residual moisture and contained only physiological moisture levels.

In the Church of San Giuseppe, the effectiveness of water content evaporation was confirmed by the gravimetric tests conducted in three diagnostic campaigns: before the installation of CNT devices in 2015, in 2016, and in 2024. The tests (Figs. 4 and 5) showed that wall moisture levels were close to normal physiological levels for dry masonry, except for a slight hygroscopic moisture detected in the P1-AP area. It was also noted that surface samples from the plaster had a slightly higher water content than those from deeper within the masonry. Additionally, the S3-LP sample showed a moisture content of 7.84%, more than twice the value of 3.5% of the physiological humidity content. This anomalous data, confirmed by the results of the thermographic surveys, depends on localized infiltration.

The plaster applied during the last restoration of the Church of San Giuseppe showed whitish deposits and detachments due to efflorescence. The presence of hygroscopic salts was confirmed by thermographic surveys that highlighted colder areas in the form of “leopard spots” (Fig. 6). This drawback underlines the importance

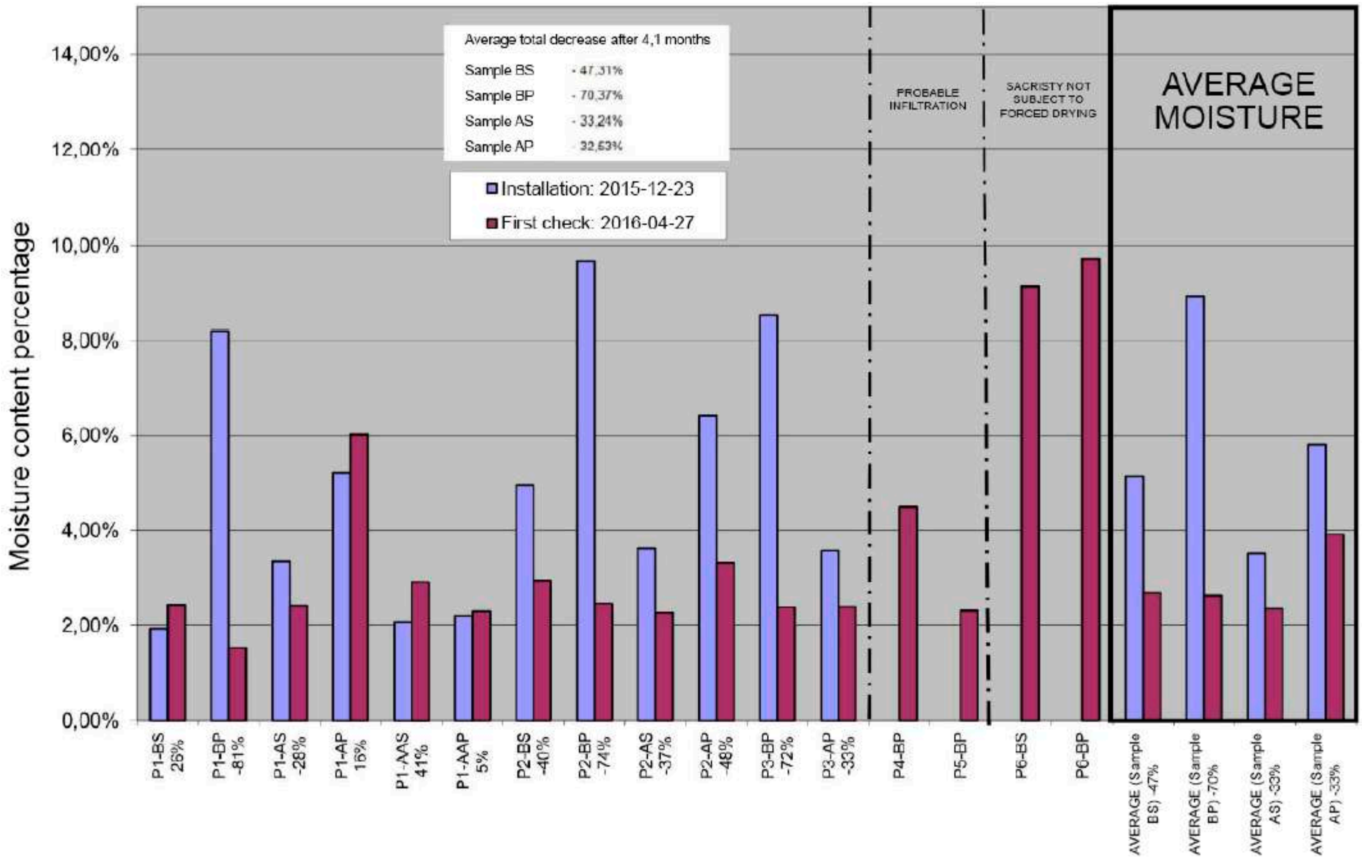

Fig. 4. *Graph of the measured humidity, samples of 2015 and 2016.*

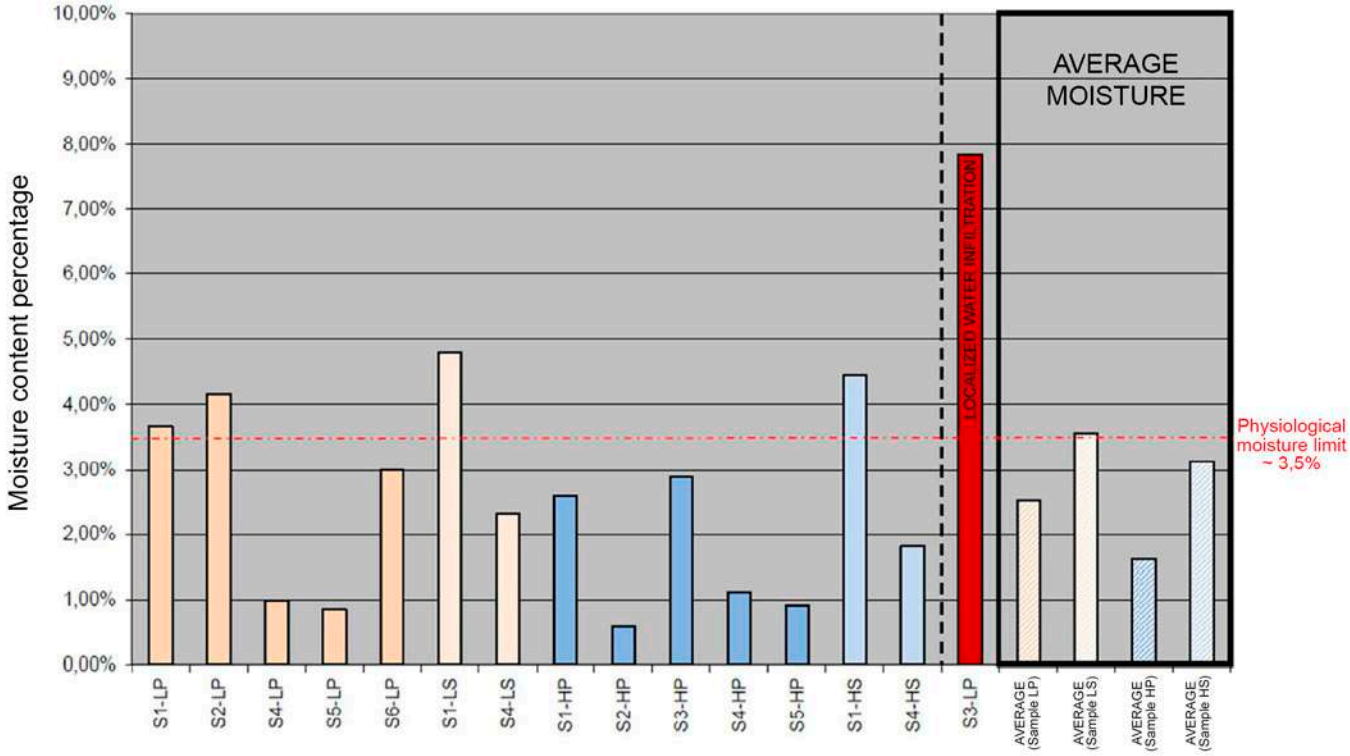

Fig. 5. *Graph of the measured humidity, samples of 2024.*

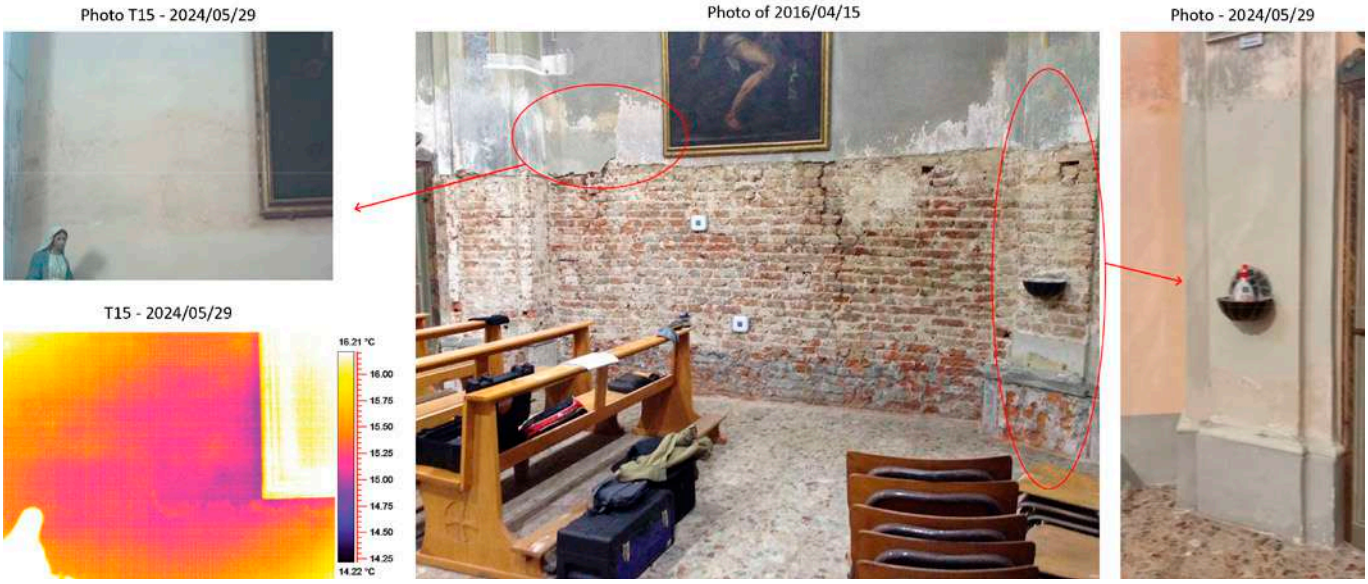

Fig. 6. *Monitoring of restoration in the Church of San Giuseppe, Rosate (Milano).*

of cleaning surfaces from hygroscopic salts before any other intervention in the restoration process.

The Church of San Gennaro case study presented a different scenario, characterized by an integrated and detailed approach to managing rising damp [22]. This case highlights the importance of targeted, sequential interventions for effective restoration of historic buildings.

A preliminary survey, using drones and 3D laser scanning, mapped areas of degradation and critical conditions to ensure safe and informed interventions. Prior to consolidation, chippings and damaged mortar were mechanically removed. Petrographic analysis using a polarizing optical microscope of original plaster and masonry stones allowed the choice of lime plaster. After the last restoration of the Church of San Gennaro, the only issue was the persistence of dark stains on the columns whose surfaces were not cleaned from hygroscopic salts (Fig. 7). Thermographic analysis confirmed that the stains were not caused by moisture. After an initial drying process by natural evaporation, the next step was the removal of hygroscopic salts using compresses using Japanese paper and sepiolite and subsequent washing

Fig. 7. *Monitoring of restoration in the Ancient Church of San Gennaro, Capannori (Lucca).*

with deionized water. This method of salt removal was chosen for its effectiveness and minimal impact, reducing the risk of damage to historic surfaces while ensuring thorough cleaning that preserves the original structure. The compresses were left in place long enough to absorb and remove the salts. This experience provides a model for the management of moisture and salts in other historic buildings and demonstrates the effectiveness of combining natural drying techniques with salt removal. Moreover, the salt removal showed that the stain may be due to a reaction between previous paint and moisture/salts, resulting in discoloration and flaking. Further analysis is underway to determine the type of paint used.

Preventive measures were also taken to prevent future external water infiltration, including the reconstruction of cornice edges and facade moldings. These architectural elements are essential for the properly drainage of rainwater, protecting the walls from erosion and preserving the exterior decoration of the monument.

5. DISCUSSION OF RESULTS

The investigations carried out in the two case studies contribute to the development of a protocol for best conservation practices, including each stage of the restoration process from the preliminary phase of building components and materials knowledge, the identification of pathological conditions up to the on-site verification of the effectiveness and durability of interventions.

A comprehensive diagnostic plan is a fundamental requirement of sustainable restoration. It allows us to assess and monitor the building's condition over time, optimizing the time and resources required by restoration. The diagnostic plan of building heritage must primarily include non-destructive qualitative and quantitative analyses (e.g., macroscopic observations, thermo-hygrometric parameters, IR thermography, colorimetric test, scotch tape test, water absorption test) [23]. Before any subsequent invasive testing, these diagnostic methods should be used (e.g., weight tests, optical microscopy, X-ray diffraction on powders, spectroscopy, and X-ray microtomography).

The research activities have also shown that, in most cases, invasive diagnostic techniques require small quantities of materials. Moreover, the sampling can be conducted on degraded or already detached parts of the building without compromising the building's state of preservation.

The design of restoration interventions requires a holistic view with a synergistic dialogue between different interdisciplinary competencies to overcome the current single-issue approach. Previous interventions on architectural heritage masonry surfaces have shown that rising damp is often an issue to the durability of interventions [24].

Therefore, the priority action in the restoration process must be stopping the rising damp using non-invasive and sustainable technologies, such as the CNT-Domodry. However, the use of devices against rising damp is a necessary but not sufficient measure to ensure the effectiveness of restoration [19]. Mechanical ventilation systems should also be installed to improve ventilation and air circulation, ensure the proper removal of residual masonry moisture, and avoid the formation of condensation and crystallization of hygroscopic salts.

Cleaning building surfaces is another compulsory requirement. It allows the removal of physical, chemical, and biological pathologies due to the presence of water in the masonry. Removing efflorescence and sub-efflorescence is essential for preventing the degradation of the finishing applied during the restoration. Figure 8 illustrates the detachment of the plaster applied during the last restoration of the Castle of San Basilio in Pisticci (Matera) caused by the presence of efflorescence, although rising damp was stopped [19].

In treating biodeterioration on stone surfaces, once the pathogens have been identified, attention must be paid to the possible presence of photoautotrophic and heterotrophic microorganisms, which must be eliminated simultaneously to prevent further degradation. To ensure sustainable and compatible interventions, natural-based products can be applied by packs, brushing, or spraying until saturation. These natural-based products can provide long-term efficacy without causing collateral damage to the substrate [24, 25].

The cleaning of masonry made in weak materials, such as calcarenite and Matraia stone, can be done with sorghum brushes or by cycles of spray washing with de-

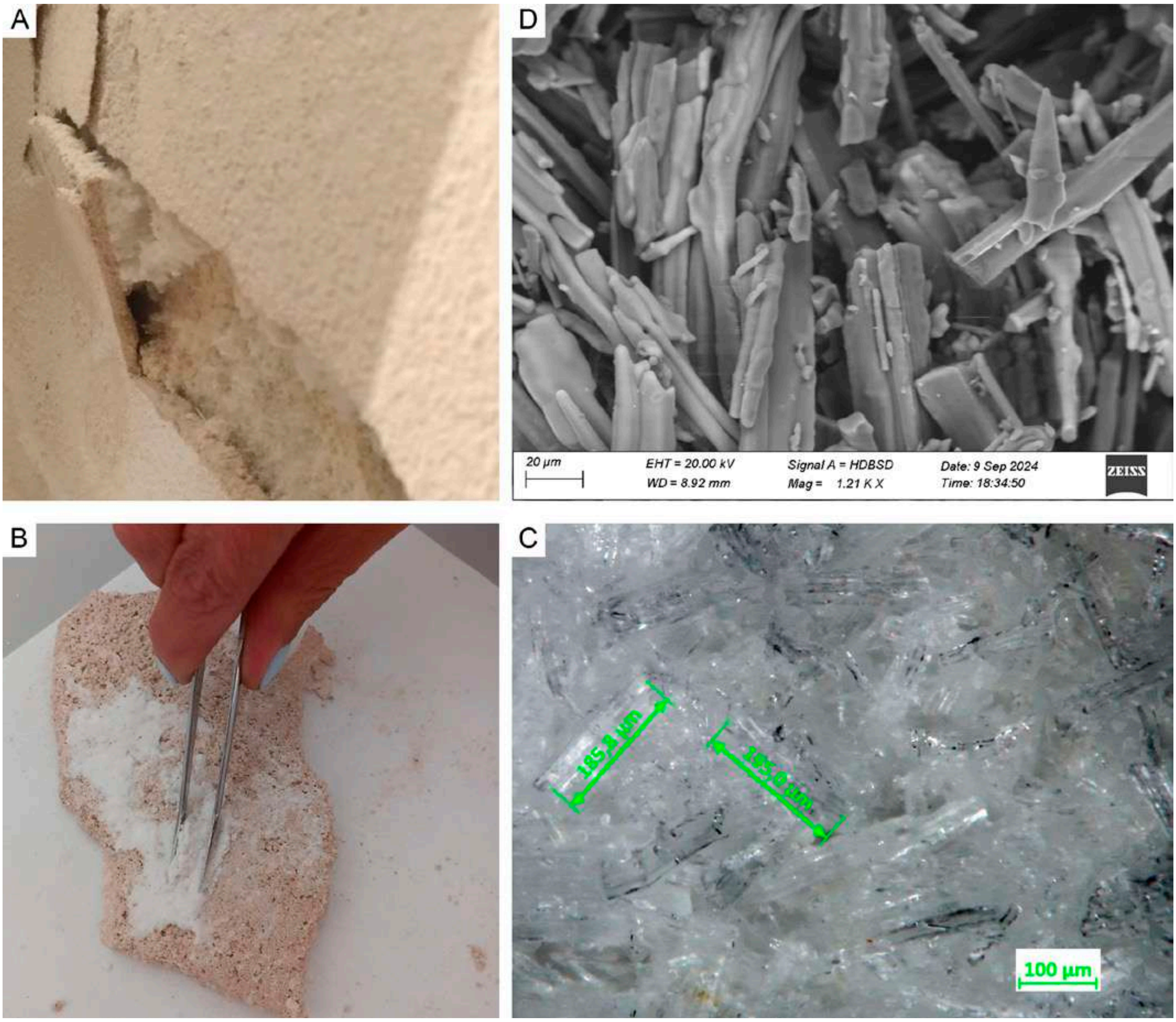

Fig. 8. *(A) Plaster detachment; (B) sampling of salts; (C) optical microscopy of saltpeter crystal; (D) Scanning Electron Microscopy (SEM) of saltpeter crystal.*

mineralized water, using a test brush for more stubborn incrustations. In any case, testing small, inconspicuous areas before proceeding with surface cleaning is advisable to avoid any abrasive effects.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

The research activities are part of a broader project to develop a digital protocol of best practices for architectural heritage conservation, focusing on preventive and predictive maintenance against rising damp. The findings of investigations highlight the critical role of IR thermal analysis in diagnostic and short- and long-term restoration monitoring.

The critical analysis of restorations has shown a widespread lack of preventive, planned maintenance. Current conservation practices often prioritize emergency actions for single-issue problems without adopting a multidisciplinary approach. The research results contribute to the development of guidelines for a conservation protocol that addresses all stages of the design process, from the preliminary study of materials and building components to the monitoring of the short and long-term effectiveness of interventions using non-invasive diagnostics.

The variability of methods and equipment for IR surveys can affect the comparability and reliability of results. Therefore, developing standardized protocols for thermography and other diagnostic techniques is essential to improve data comparability and diagnostic accuracy.

It is necessary to extend the case studies to a broader range of buildings, historical periods, and climatic conditions to validate and generalize the findings. Moreover, long-term monitoring allows the effectiveness and durability of the technologies and methods used, providing a more comprehensive insight into the suitability of these conservation techniques.

Future research could explore the integration of innovative technologies, such as predictive models based on AI and drones for continuous monitoring. These innovations could provide new tools for more accurate assessment and management of architectural heritage.

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Authors contribution

Conceptualization, G.B. and A.G.; methodology, G.B.; resources, G.B. and A.G.; data curation, G.B.; writing and editing, C.R.; review, G.B. and C.R.; supervision, A.G. All authors have read and agreed to the published version of the manuscript.

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ASSESSING THE MITIGATION POTENTIAL OF ENVIRONMENTAL IMPACTS FROM SUSTAINABILITY STRATEGIES ON STEEL CONSTRUCTION VALUE CHAIN: A CASE STUDY ON TWO STEEL PRODUCTS IN ITALY

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Abstract

Life Cycle Assessment (LCA) plays a crucial role in sustainability evaluations and impact assessments, especially in the field of environmentally and eco-friendly materials or system production and building design for the construction sector. However, stakeholders and professionals tend to use LCA mainly to develop an Environmental Product Declaration (EPD) or assess building sustainability certification. This research investigates the possibility of using the LCA results to assess the potential for further mitigation of the environmental impacts on the construction industry. Starting from a previous study on the steel construction value chain performed by authors to develop two steel product datasets for the Italian LCA database, this work aims to identify how sensitivity analysis can guide industries in choosing sustainability strategies to mitigate their impacts further. The study focuses the sensitivity analyses only on one specific sustainability strategy for each of the two previously analyzed steel products (A. beams and angles and B. hollow sections), thus potentially limiting the generalizability of findings to a broader range of sustainability strategies but demonstrating the feasibility of the proposed method and its replicability to other products and production scenarios.

Keywords

Life cycle assessment (LCA), Construction sector, Steel building materials, Environmental impact, Sensitivity analysis.

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1. INTRODUCTION

The construction sector is a major contributor to global greenhouse gas (GHG) emissions and energy consumption, responsible for nearly 40% of global energy use and approximately 38% of all energy-related carbon dioxide emissions. In particular, the Breakthrough Agenda Report of the International Energy Agency (IEA) [1] reported that the buildings sector emissions in 2022 represented around a third of total energy system emissions, including buildings operations (26%) and embodied emissions (7%) associated with the production of materials used for their construction. To get on track with the Net Zero Emissions Target set by the European Green Deal [2], the operational emissions need to fall by about 50% from their 2022 level by 2030, and embodied emissions need to fall by 25%.

Across the world in 2020, around 1900 million tons of crude steel were produced, with just over 50% of that used for buildings and infrastructure [3]. The steel used in buildings accounts for around 8% of the world's carbon emissions, and on average, every ton of steel produced leads to the emission of 1.85 tons of CO_2 into the atmosphere [4]. This makes the steel industry the single most significant contributor to industrial emissions, and at the same time, it has the vital challenge of reducing its CO_2 emissions, an action that involves important technological changes [5].

Various latest studies [9–11] deal with the sustainability assessment of the steel industry to highlight the potential route to decarbonizing steel production and to individuate the factors that contribute towards carbon emission through the whole life cycle of steel products used for buildings. Moreover, the literature underlined the increased global awareness of environmental issues and the consequent increase of pressure on the construction industry to mitigate its environmental impact through assessment methodologies that cover the whole building life. In this context, Life Cycle Assessment (LCA) has emerged as a vital tool in this effort, offering a comprehensive approach to evaluating the environmental impacts associated with all stages of a building's life cycle – from raw material extraction, manufacturing, and construction, to use, maintenance, and disposal. LCA allows for a detailed assessment of energy use, emissions, and other environmental effects, providing crucial insights that can help reduce the carbon footprint of construction activities and support more sustainable practices [11, 12].

The use of LCA in the construction sector has been supported by the development of dedicated databases that provide specific environmental data for various construction materials and practices. For instance, in Italy, the Banca Dati Italiana LCA (BDI-LCA) [13], a database developed by the Arcadia project, offers comprehensive data on local construction practices, including those based on steel, which can be used to perform more accurate LCAs [14, 15]. These databases represent a source of reliable reference data to be used by professionals or stakeholders to identify strategies to reduce environmental impacts both at the material choice phase of building design and at the material production phase by industries.

However, many companies in the steel construction sector face significant challenges in applying LCA data effectively. There is often a lack of understanding about how to integrate or use those data into the operational strategies to improve the overall sustainability performance and boost the decarbonization path. The sector's dependence on long-lasting, high-emission materials and technologies limits the transition to lower-emission alternatives since those materials can be used for decades, thereby "locking in" higher emissions levels [16].

Furthermore, while various international and national initiatives encourage the reduction of GHG emissions in the construction sector, the practical application of these guidelines remains challenging. Companies often struggle to interpret LCA results. For the steel industry, understanding the impacts' variation of the various scenarios, starting from the LCA results, is crucial for making informed choices regarding materials and processes that could cause minor impacts. The LCA use can identify critical areas where changes in material use or production methods could substantially reduce carbon emissions, such as the shift from blast furnaces to electric arc furnaces [17].

Despite the growing availability of LCA tools and environmental data, there is still a gap between the full potential of LCA to improve sustainability and its practical implementation within the steel construction sector [18]. This paper seeks to address this gap by examining how LCA results can further support the evaluation of specific sustainability strategies along the entire steel value chain and consequently assess their implementation feasibility to boost further reductions in GHG emissions. On this basis, the research question that guided the overall study has been defined.

RQ: *How can the steel construction industry leverage its product LCA data results to identify, study, and choose the most suitable sustainable strategies to reduce its carbon footprint?*

To reach this goal and to reply to the RQ, the study has been grounded on the definition and conduction of sensitivity analysis of LCA results to explore potential sustainability strategies that steel construction stakeholders can adopt to support the industry's transition towards a more sustainable practice.

Specifically, the study begins as a follow-up research activity of the Arcadia project, which ends with the LCA report of two selected steel products for buildings, chosen among the others as the most used in the Italian context, and the development of their respective datasets implemented in the BDI-LCA. The authors used the LCA results of this prior study [19] as input for their new sensitivity analysis to evaluate the respective impacts' variation on the steel value chain of two selected Sustainable Strategies (SSs): 1) the implementation of renewable energy sources for the steel production; 2) the shift from blast furnace method to electric arc furnace technologies for the steel production.

After the contextualization and motivation of the study definition in this introduction, coupled with RQ and overall contents, Section 2 describes the methodology defined and followed in this study. Section 3 presents the sensitivity analyses in detail, clarifying the boundary conditions and motivating the choices made to set up the work. Section 4 focuses on the summary of the results and their critical discussion, reviewing the most relevant impact categories for all the studied scenarios. Finally, Section 5 concludes the article by summarizing key insights, underlining practical and theoretical contributions of using sensitivity analysis on LCA product results as a supporting tool for the decision-making process of corporate sustainability reporting for construction industries, and outlining potential avenues for future research and sustainable practices.

2. METHODOLOGY

In this section, the methodology followed for the study is described and graphically summarized in Figure 1. As mentioned in the introduction, the main scope of the work is to perform sensitivity analysis to address the presented RQ. Accordingly, the study has been divided into five interrelated phases.

Phase 0, presented in Section 1, illustrates the research framework which focuses on the steel value chain for construction and the inputs of this study, i.e., the LCA datasets assessed for two selected steel building products (beams and angles – product A and square and rectangular hollow sections – product B) implemented in the BDI-LCA, developed by the Arcadia project with the support of stakeholders of the steel value chain. The RQ derived by those industries, which – after having provided Environmental Product Data for the study – and verified their impacts, would like to deeply understand the results of the LCA report with the scope to enhance LCA integration in practice and its potentialities along the entire value chain for the construction sector.

Phase 1 illustrates the definition and structure of the sensitivity analysis performed to explore the environmental impacts of two sustainable strategies, one per each steel building product studied. The choice of the Sustainable Strategy for each steel product is derived from direct interaction with the respective business owner considering their industry investment in sustainability.

For steel product A, the industry, having already implemented new technologies for steel production, requests to investigate the possibility of reducing electricity consumption by integrating renewable energy sources (Sustainable Strategy 1 – SS1).

For steel product B, the Sustainable Strategy 2 (SS2) chosen by the second business owner has been the implementation of a more efficient steel production method. Three scenarios have been studied for each Sustainable Strategy to examine different levels of implementation of the sustainable strategies and their correlated impacts: Scenario 0 (SC0), which corresponds to the baseline scenario, Scenario 1 (SC1), and Scenario 2 (SC2).

Phase 2 focuses on the elaboration and discussion of the results based on 16 selected impact categories (IC), defined within the Environmental Footprint (EF) 3.0 method by the European Commission's Product Environmental Footprint (PEF) initiative [20]. The analysis has been performed by calculating the percentage of impact variations for each scenario compared to SC0 for each sustainable strategy, with the final goal of studying their influence on specific environmental impacts. The graphical representation of the results helps to identify the potentialities and barriers associated with each scenario.

Phase 3 aims to critically review the results of the sensitivity analyses to define implementation path suggestions and practical recommendations useful for the stakeholders' choice concerning the adoption of the investigated SS for mitigating their environmental impacts. This method will facilitate identifying and evaluating critical environmental factors associated with each stage, providing valuable insights for sustainable decision-making.

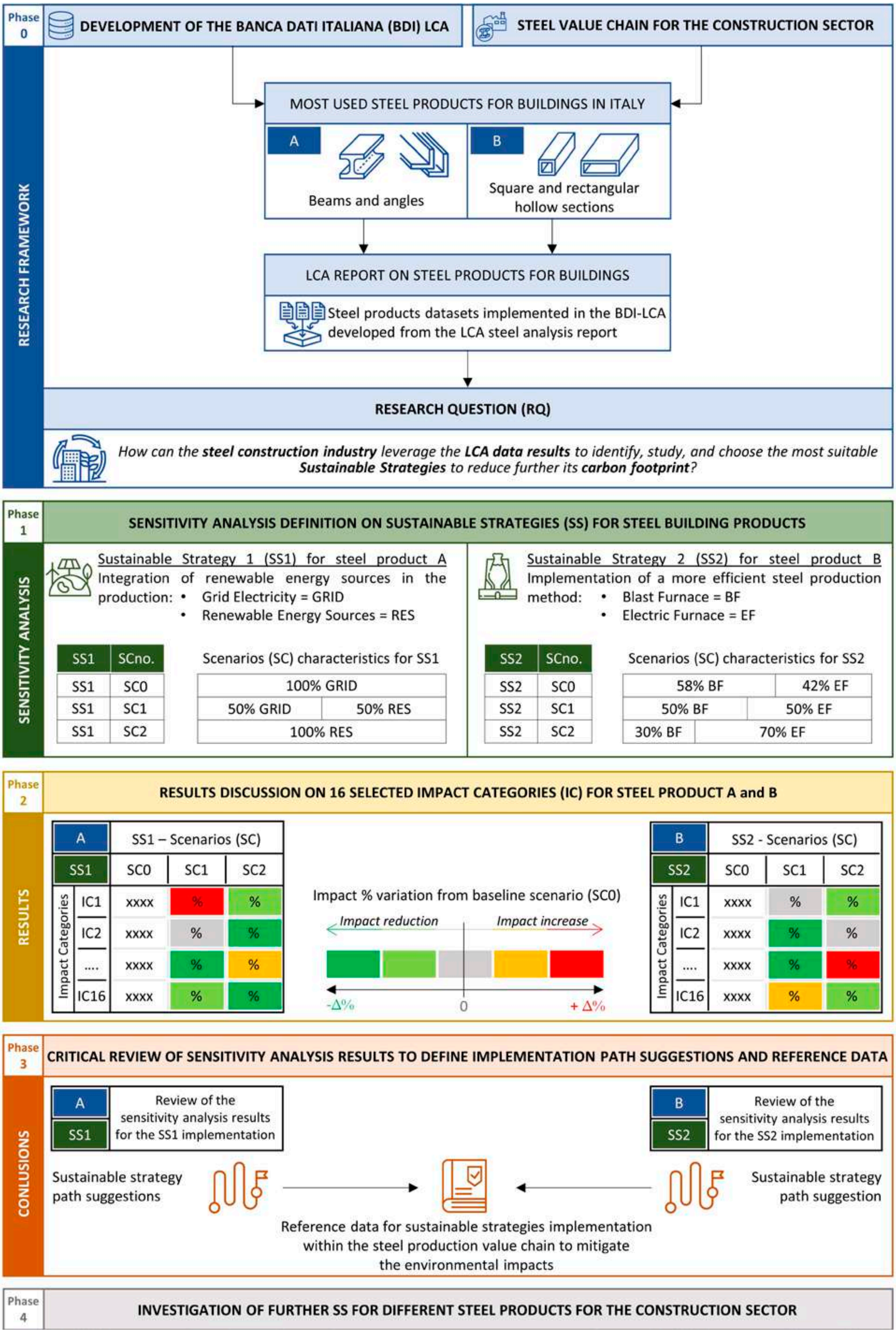

Fig. 1. *Graphical summary of the study methodology.*

Finally, Phase 4 outlines potential future research directions based on the findings and limitations of the current analysis. Further research may explore a broader range of steel products and sustainability strategies to address these limitations and enhance the method's robustness and applicability.

3. SENSITIVITY ANALYSIS

Sensitivity analysis is a well-known method for understanding how variations in input parameters can affect the environmental impacts of products and processes. In the steel construction sector, where production processes are highly energy intensive and contribute significantly to global environmental impacts, the application of sensitivity analysis can help identify factors influencing environmental performance and facilitate the application of more efficient sustainability strategies.

Prior studies [21–23] have highlighted the benefits of the application of different sustainable strategies in the steel industry. For instance, Suer et al. [24] conducted a comprehensive review of LCA methodologies for steel production and highlighted the potential for renewable energy integration to significantly reduce greenhouse gas emissions and environmental impacts.

The authors remarked that the integration of renewable energy sources and the transition to electric arc furnaces could substantially reduce the carbon footprint of the steel industries. Some other recent research works [25, 26] noted the high potentialities of LCA methodologies and, in particular, the relevance of their results analysis to support the corporate sustainability plan definition to invest in a more circular supply chain, with the final aim to enlarge the company sustainability framework and the choice of the applicable strategies that can provide a more significant impulse on carbon footprint reduction.

In this context, this study focuses on the sensitivity analysis definition for two steel products, A and B, considering 16 selected Impact Categories (IC), summarized in Table 1, according to the IC EF 3.0 method, which includes the key environmental indicators such as global warming potential, ozone depletion potential, and particulate matter, to provide a comprehensive understanding of the environmental impacts of different steel production strategies.

The Sustainable Strategies analyzed, as anticipated in the methodology description, are two (SS1 – integration of renewable energy sources; SS2 – implementation of a more efficient steel production method), and they are investigated for steel products A and B, respectively.

Code	Impact Category name	Unit
IC1	Climate change	kg CO_2 eq
IC2	Ozone depletion	kg CFC11 eq
IC3	Ionizing radiation	kBq U^{235} eq
IC4	Photochemical ozone formation	kg NMVOC eq
IC5	Particulate matter	Disease incidence
IC6	Human toxicity, non-cancer	CTUh
IC7	Human toxicity, cancer	CTUh
IC8	Acidification	mol H^+ eq
IC9	Eutrophication, freshwater	kg P eq
IC10	Eutrophication, marine	kg N eq
IC11	Eutrophication, terrestrial	mol N eq
IC12	Ecotoxicity, freshwater	CTUe
IC13	Land use	Dimensionless (Pt)
IC14	Water use	m^3 depriv.
IC15	Resource use, fossils	MJ
IC16	Resource use, minerals, and metals	kg Sb eq

Tab. 1. *List of the Impact Categories (IC) chosen for the sensitivity analysis.*

3.1. SS1: INTEGRATION OF RENEWABLE ELECTRICITY SOURCES IN THE PRODUCTION PROCESS

Sustainable Strategy 1 (SS1), applied to steel product A, integrates renewable energy sources to cover the steel production process per different quantities of percentages. As explained in the methodology, the SS1 choice derives firstly from the request of the business owner to investigate this SS, having already invested in a more efficient method of steel production covered by electricity consumption and needing to cover this energy consumption by more sustainable sources. Therefore, the integration of renewable energy sources, such as photovoltaic, wind, or solar systems, can cover part of all electricity consumption and, consequently, reduce greenhouse gas emissions and other environmental impacts.

Besides the baseline scenario SC0, which represents the current industry situation, two other scenarios have been investigated concerning the percentage of integration of renewable energy sources. In SC0, the production process relies entirely on grid electricity; in SC1, a 50% mix of grid and renewable energy is considered, reflecting an intermediate level of transition towards sustainable practices, and SC2 corresponds to the complete shift to renewable energy sources, to demonstrate the maximum potential reduction of this strategy.

3.2. SS2: IMPLEMENTATION OF MORE EFFICIENT STEEL PRODUCTION METHODS

Sustainable Strategy 2 (SS2), applied to steel product B, focuses on enhancing the efficiency of steel production by optimizing the use of electric furnaces over traditional blast furnaces. The business owner of product B chose this strategy to evaluate the innovation investment in electric furnaces, which offer a more sustainable alternative with lower emissions and improved energy efficiency, particularly those powered by renewable energy sources.

Similarly to the SS1, even for the SS2, three scenarios have been evaluated to explore the impact of different furnace technology mixes. The baseline scenario SC0 presents a mix of 58% blast furnace and 42% electric furnace. SC1 proposes an equal mix of 50% blast and 50% electric furnaces, while SC2 presents a 30% blast furnace and 70% electric furnace mix. This range of scenarios can help evaluate the environmental benefits of progressively increasing the proportion of electric furnace use in steel production.

For both SS, as anticipated in the methodology, the selected strategies highly depend on the starting point and the needs of the industry, as well as the specific steel product considered. Therefore, the study focuses on the comparative assessment of each specific chosen strategy to identify the most efficient setup for the steel product studied. Future research should incorporate a wider range of sustainability strategies to cross-analyze the overall strategies and identify the optimum solutions.

4. RESULTS AND DISCUSSIONS

This section presents the sensitivity analysis results for each sustainability strategy (SS1 and SS2) applied to steel products A and B, respectively. The results are detailed in Table 2, highlighting, for each scenario, the environmental impacts across the 16 selected ICs defined in Table 1.

The results for steel product A on Sustainable Strategy 1 show that the ICs with the highest values in SC0 are the ecotoxicity freshwater (IC12) and the use of fossil fuel resources (IC15), respectively, with values of 8.66 CTUe and 13.1 MJ. Those high values highlight significant environmental impacts associated with using the electricity grid in the production process. In contrast, the categories with the lowest impact values in SC0 are IC6 and IC7, both related to human toxicity, indicating minimal impacts in these areas. SC1 and SC2 have the same ICs with the highest and lowest values as SC0, but while IC12 and IC15 show reduced values in line with the percentage increase of electricity produced from renewable energy sources, the categories related to impacts on human health (IC6 and IC7) show higher values in SC1 and SC2 compared to SC0.

Similar to SS1, the results for steel product B on SS2 also show that the ICs with the highest values in each

IC	Product A - Sustainable Strategy 1 (SS1)			Product B - Sustainable Strategy 2 (SS2)		
	SC0	SC1	SC2	SC0	SC1	SC2
IC1	9.33E-01	8.08E-01	6.63E-01	1.60E+00	1.47E+00	1.13E+00
IC2	1.24E-07	1.02E-07	8.20E-08	7.78E-08	7.30E-08	6.05E-08
IC3	9.30E-02	7.60E-02	5.85E-02	1.26E-01	1.31E-01	1.45E-01
IC4	3.03E-03	2.80E-03	2.51E-03	6.77E-03	6.14E-03	4.50E-03
IC5	1.18E-07	1.17E-07	1.15E-07	1.12E-07	1.04E-07	8.33E-08
IC6	8.42E-09	1.55E-08	1.50E-08	3.50E-08	3.21E-08	2.46E-08
IC7	1.90E-09	3.93E-09	3.92E-09	2.05E-08	2.16E-08	2.46E-08
IC8	3.64E-03	3.09E-03	2.47E-03	7.02E-03	6.51E-03	5.20E-03
IC9	2.28E-04	2.10E-04	1.79E-04	7.78E-04	7.22E-04	5.77E-04
IC10	8.76E-04	8.03E-04	7.10E-04	1.58E-03	1.47E-03	1.17E-03
IC11	9.25E-03	8.48E-03	7.48E-03	1.62E-02	1.49E-02	1.19E-02
IC12	8.66E+00	8.65E+00	8.02E+00	3.36E+01	3.03E+01	2.17E+01
IC13	1.27E+00	1.24E+00	1.13E+00	4.29E+00	3.86E+00	2.75E+00
IC14	2.75E-01	2.08E-01	1.40E-01	3.64E-01	3.56E-01	3.35E-01
IC15	1.31E+01	1.08E+01	8.62E+00	1.72E+01	1.61E+01	1.32E+01
IC16	2.33E-07	2.63E-07	2.62E-07	1.71E-05	1.49E-05	9.21E-06

Tab. 2. *Results of the sustainability analysis conducted on product A for SS1 and product B on SS2, respectively, for three different scenarios (SC0-SC1-SC2).*

scenario are the freshwater ecotoxicity (IC12) and the use of fossil fuel resources (IC15). SC1 shows reductions in most categories like human toxicity, non-cancer (IC6), and Land use (IC13), reflecting the benefits of a higher percentage of steel produced by electric furnaces. However, ionizing radiation (IC3) and human toxicity, cancer (IC7) increase slightly, indicating similar trade-offs as observed in SS1 and suggesting that while comprehensive strategies reduce many impacts, some categories may still experience adverse effects.

Comparing SS1 and SS2, both strategies effectively reduce the environmental impacts in most categories, such as ecotoxicity, freshwater (IC12), resource use, and fossils (IC15). While SS2 achieves a higher reduction in Human toxicity, non-cancer (IC6) from SC0 to SC2 compared to SS1, the latter significantly reduces the impact of Ionizing radiation (IC3).

However, both strategies show increases in specific categories, such as human toxicity cancer (IC7), highlighting situations where applying sustainability measures for specific impacts may require implementing different strategies.

In the following paragraphs, a more in-depth discussion of the results is carried out to identify the potential and barriers associated with each sustainability strategy and scenario analyzed.

4.1. SS1: INTEGRATION OF RENEWABLE ELECTRICITY SOURCES IN THE PRODUCTION PROCESS

The sensitivity analysis for SS1 reveals significant potential reductions in environmental impacts. Figure 2 displays the results across the 16 ICs, comparing the percentage variations (Δ%) between the baseline scenario (SC0) and SC1 or SC2, providing indications of the efficacy of each strategy.

The graph presents a color legend illustrating the percentage impact variations between the scenarios to better understand the results for each IC. The color legend ranges from dark green, representing a Δ% reduction of at least 50% compared to scenario SC0, to dark red, corresponding to a Δ% increase greater than 100%. This color gradient helps quickly identify which impact cate-

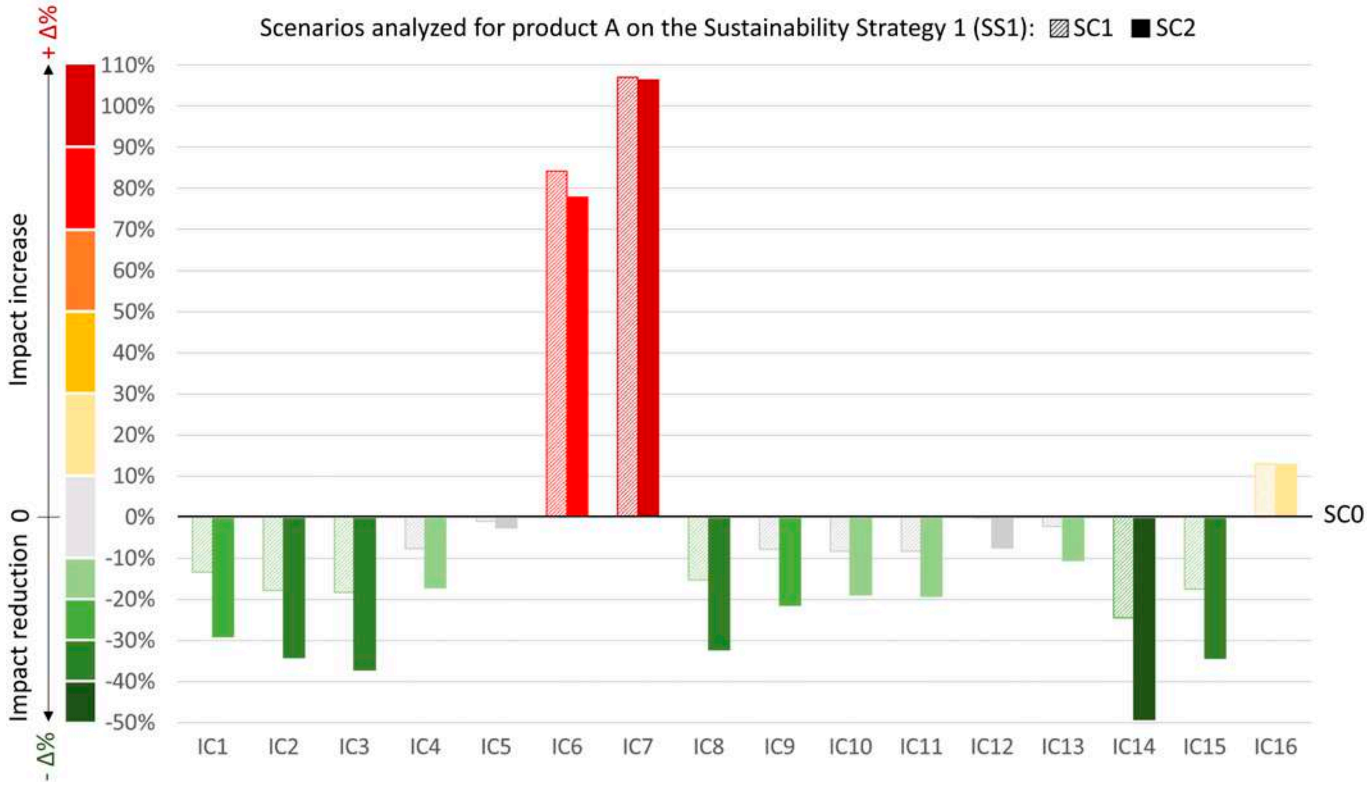

Fig. 2. *Percentage impact variations between baseline scenario (SC0) and the analyzed scenarios (SC1, SC2) for product A (beams and angles) on the Sustainability Strategy 1.*

gories are most affected by integrating renewable energy sources to cover electricity needs.

Data show a substantial reduction in several key impact categories in line with the proportion of integration of renewable energy sources. For example, in scenario SC1, there is a notable decrease in ozone depletion (IC2) by 17.8% and in ionizing radiation (IC3) by 18.3%. The reductions are even higher in SC2, with a decrease of 34.0% and 37.1%, respectively. These results suggest that transitioning to renewable energy sources can significantly mitigate stratospheric ozone degradation and reduce radioactive releases that account for adverse health effects.

Furthermore, the impact category related to water use (IC14) presents the highest percentage of impact reduction in both scenarios, reaching almost a 50% decrease in SC2 compared to SC0. This reduction highlights the potential of renewable electricity sources to contribute to global sustainability goals of lower water consumption and promote a circular economy. On the contrary, a few impact categories, such as human toxicity (IC6 and IC7), show increases in both SC1 and SC2, with a maximum increase of 107.0% for IC7 in SC1 compared to SC0. This trend indicates potential trade-offs, where the shift from fossil to renewable electricity sources increases human toxicity, likely due to the materials and processes involved in the production of renewable energy technologies. In this case, a dedicated investigation should be conducted to identify which strategy, in combination with the analyzed one, could balance the impact variation.

In conclusion, the results of SS1 reveal a general environmental benefit in shifting towards renewable energy sources. However, the increase in a few impact categories highlights the need for a balanced approach that considers all environmental dimensions to avoid unexpected consequences. Moreover, it is essential to remark that the presented results refer to the use of a specific energy mix in a reference year. The results and the environmental benefits of this SS1 could vary in dedicated scenarios considering different geographical contexts and the temporal evolution of the national energy mix.

4.2. IMPLEMENTATION OF MORE EFFICIENT STEEL PRODUCTION METHODS

The sensitivity analysis for SS2 focuses on implementing a more efficient steel production method for steel building product B. Similarly to the analysis conducted for SS1, Figure 3 shows the results across the 16 ICs, using the same color legend to illustrate the percentage variations (Δ%) between scenarios.

The results demonstrate how a higher percentage of electric furnace steel could provide environmental benefits across most impact categories. The mineral and metals resource use category (IC16) shows the highest Δ% reduction in both scenarios, reaching 46.3% less resource use in SC2 compared to SC0. This outcome supports the adoption of electric furnaces, as they reflect less material input and waste generation compared to traditional blast furnace methods. Furthermore, in SC2, three other ICs, photochemical ozone formation (IC4), freshwater ecotoxicity (IC12), and land use (IC13), present Δ% reduction higher than 30%.

In SC1, there are moderate reductions in climate change (IC1) by 8.2% and acidification potential (IC8) by 7.2%. The most significant improvements are observed in SC2, in which IC1 decreases by 29.3%, and acidification potential IC4 reduces by 25.8%, indicating that electric furnaces, which are generally more energy-efficient and produce fewer emissions, can help reduce the environmental footprint of steel production.

However, two impact categories, ionizing radiation (IC3) and human toxicity cancer (IC7), show increases in both SC1 and SC2, reaching 15.0% and 20.1%, respectively. These increases could be attributed to higher electricity consumption and related emissions when the electric furnace is used more intensively. This observation suggests that while electric furnaces are beneficial for reducing specific emissions, their overall environmental performance may be influenced by the source of electricity and the efficiency of the technology.

In summary, the results for SS2 demonstrate that increasing the proportion of electric furnace use can lead to significant environmental improvements, particularly in reducing greenhouse gas emissions and resource use. However, the observed increases in certain impact categories highlight the need for a more in-depth analysis of all potential effects when designing sustainability strategies. The balance between maximizing environmental benefits and minimizing trade-offs is crucial for achieving long-term sustainability goals in the steel industry.

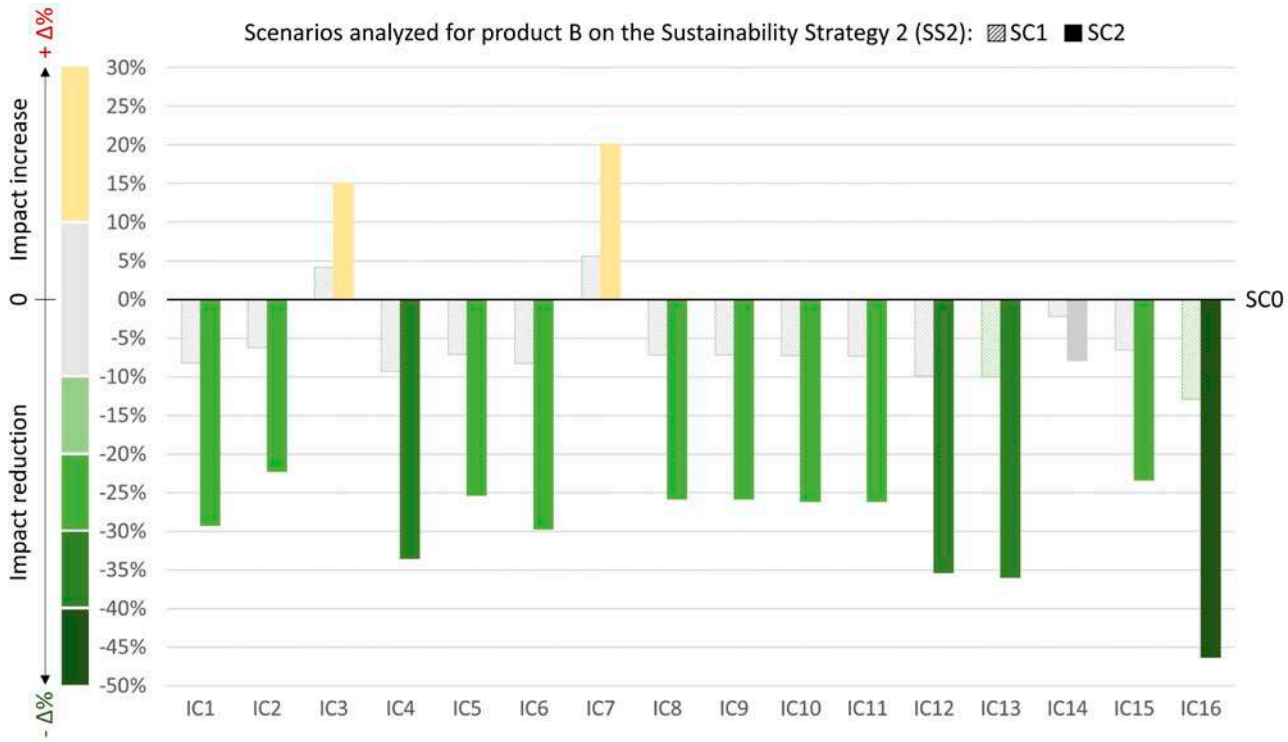

Fig. 3. *Percentage impact variations between baseline scenario (SC0) and the analyzed scenarios (SC1, SC2) for product B (square and rectangular hollow sections) the Sustainability Strategy 2.*

5. CONCLUSIONS

This research has undertaken a sensitivity analysis of LCA data results of two selected steel products to support the steel companies in evaluating their environmental sustainability, proposing sustainable strategies for improvement, and verifying their applicability to further reduce their carbon footprint. Various scenarios were examined to reduce environmental impacts by analyzing two specific sustainable strategies for two steel construction industries, compared with the baseline model corresponding to the current situation.

The significance of this research lies in its ability to contribute valuable insights and guidance for industry stakeholders and policymakers. By quantifying the variation in the environmental impacts compared to the baseline scenario and recommending sustainable options, this study can support decision-makers with the necessary tools to implement sustainable practices in the steel construction sector. However, it is important to underline that the results presented in Section 4 are limited to the specific product and the analyzed industry; therefore, to generalize the effects and to implement the studied sustainability strategies effectively, the stakeholders should adopt a multi-faceted approach that takes into consideration their own production line, products portfolio, geographical context, technological innovations, policy support, and market needs.

In the following, some specific suggestions for implementing each sustainable strategy are given.

For SS1, the integration of renewable energy sources should be pursued alongside investments in cleaner, less resource-intensive technologies for renewable energy production. Industry stakeholders could explore partnerships with renewable energy providers to ensure the shift to renewables does not increase other environmental impacts. Moreover, adopting advanced energy management systems could optimize energy use and minimize emissions. Velimirović et al. [27] suggest that using smart grids and energy-efficient technologies can further enhance the benefits of renewable energy integration in industrial processes.

For SS2, maximizing the use of electric furnaces should be complemented by measures to improve energy efficiency and reduce emissions from associated processes. This could include adopting best practices for scrap selection and handling to minimize impurities and enhance furnace efficiency and investing in advanced filtration and waste management systems to mitigate increases in impact categories such as ionizing radiation. Additionally, policies that incentivize the use of recycled materials and the development of cleaner steel production technologies will be crucial in driving the adoption of these practices. Majumder et al. [28] highlight the role of policy frameworks in supporting technological innovation and promoting sustainable practices in the steel industry.

To facilitate the adoption of these strategies, it is recommended that the steel construction sector develop a comprehensive, regularly updated database of LCA data for different production methods and sustainability strategies. Such a database would allow stakeholders to make informed decisions based on current and accurate information.

However, even if the methodology for LCA sensitivity analyses conducted in this study can offer valuable insights into the field of eco-design and prospective life cycle results valid for the decision-making process of corporate sustainability reporting for steel industries, it is important to acknowledge certain limitations of the study.

Firstly, the geographical coverage and the reliance on specific data sources introduce a level of uncertainty to the results. Not all the data used for the analysis rely on specific and verified data sources, such as BDI-LCA, but some are statistical data that may have limitations in terms of accuracy or comprehensiveness, potentially impacting the overall reliability of the findings. Moreover, these assumptions imply that results are related to a specific location in a reference year. At the same time, it could be interesting to investigate their variation considering different geographical contexts and the temporal evolution of other data (such as the national energy mix).

Secondly, the coverage of products and sustainable strategies is another limitation to consider. This study focused its analysis on two specific products and one particular sustainability strategy for each of them, potentially limiting the generalizability of findings to a broader context. Nevertheless, in terms of computational aspects, this application of the proposed method allowed a first round of verification of its usability, avoiding a more resource-intensive validation on more complex products and scenarios that could lead to longer analysis times and higher costs, making it less feasible.

Despite these limitations, the method presented in this research holds promise as a tool for evaluating sustainable strategies and solutions, and it complements traditional life cycle assessment results by providing a quantitative perspective on future developments. Researchers and practitioners should consider these limitations when applying this method and interpreting the results. Further research may explore strategies to address these limitations and enhance the method's robustness and applicability. Given these limitations, future research should incorporate a broader range of steel products and sustainability strategies coupled with dynamic life-cycle assessment models that reflect real-time data and technological advances, providing a more in-depth understanding of the long-term impacts of companies' carbon footprint and developing a collection of reference data for different products for the construction sector.

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Authors contribution

Conceptualization of the research, M.M.S., F.S., F.C. and C.R.; conceptualization of the paper, M.M.S. and F.S.; methodology, M.M.S. and F.S.; investigation, M.M.S., F.S., F.C. and C.R.; data curation, M.M.S.; writing, review and editing, M.M.S., and F.S.; data visualization M.M.S.; supervision, F.C. and C.R. All authors have read and agreed to the published version of the manuscript.

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METHODOLOGY FOR IMPROVING MANUFACTURING AND ASSEMBLY OF LIGHTWEIGHT PREFAB SYSTEMS

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Abstract

The increasing adoption of prefabrication in the Global North reflects a response to the urgent demand for safe and affordable housing. This demand is compounded by the necessity to meet contemporary standards for aesthetic quality, structural safety, and energy performance, all within the context of the current climate and safety challenges. Prefabrication, underpinned by the principles of Design for Manufacturing and Assembly (DfMA), offers a pathway toward modernizing construction practices. Specifically, lightweight steel profile technologies, particularly suited for low- and mid-rise buildings, offer an efficient solution to meet these evolving demands. However, to achieve widespread adoption, further optimization is necessary. The reduction of material use, fabrication waste, and production time, alongside cost reduction, will be critical in aligning prefabrication technologies with sustainable development goals. This paper presents an eight-step methodology in which manufacturing and assembling strategies are considered since product development and according to which materials and components are selected, prototyped, and tested to optimize both mechanical and environmental performance. The methodology has been validated through an academic and industrial venture that aimed to optimize a lightweight cold-formed steel volumetric system for housing applications. The study demonstrated to achieve a system that fully met the structural requirements while also minimizing the use of material, waste, and production time. In doing so, this work contributes to a broader effort to modernize construction practices and address the dual imperatives of safety and climate resilience.

Keywords

Prefabrication, Automation, Housing, Building engineering, Sustainability.

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1. INTRODUCTION

The recent report *Modernise or Die* by Farmer [1] called for the UK industry to increase the adoption of pre-manufactured solutions in the construction industry to tackle the housing shortage discussed in the country for over a decade. The report provided evidence of a government incapable of delivering at the scale and speed that was required to respond to the request for thousands of new homes. The report recommended boosting collaboration between industry, government, and academia to improve the development and acquisition of prefab systems that could provide sustainable and more affordable systems. In line with that, the UK government supported industrial ventures promoting knowledge transfers between academia and industry to develop innovative systems.

This paper presents an iterative methodology for improving the manufacturing and assembly of prefab systems based on structural and manufacturing optimization. This methodology has been applied and validated within the research project “Optimization of cold-formed steel systems for large scale manufacturing of modular housing”, which aimed to develop a modular housing system for two-story single-family houses to be delivered across the UK and be characterized by having a high mechanical capacity, low embodied carbon and short production time. The system is based on the use of thin profiles, which are made of Cold-Formed Steel (CFS) profiles which are manufactured by bending thin sheets of galvanized steel into various shapes, providing high strength-to-weight ratios while being lightweight. The research project aimed to optimize the system by moving away from an “all-steel” design approach [2] that accounted only for the steel members for carrying the vertical and horizontal loads and, instead, develop a sheathing-braced design approach that can consider the bracing contribution provided by sheathing panels, when properly connected to the steel members. This methodology, which is codified in the USA [3], is still not codified for application in Europe and therefore requires experimental testing to be applied. The work aimed to shift the structural design of these CFS modular homes from the all-steel design to the sheathing-braced design to reduce the amount of material, facilitate manufacturing, and reduce embodied carbon. The iterative methodology for optimizing both the system and the manufacturing process had parametric design, prototyping, and experimental testing at its core. The interrelation between design, testing, and manufacturing process is of paramount importance for the development of affordable and safe construction systems. Indeed, several studies have emphasized the importance of the close integration of design, testing, and manufacturing processes in developing affordable and safe prefabricated housing systems. In the following section, the developed methodology for optimizing Manufacturing and Assembly (DfMA) is discussed in Section 2.1, with the results in terms of the manufacturing process discussed in Section 3.1. The experimental testing methodology and results carried out to evaluate the mechanical behavior of the newly developed optimized system are discussed in Sections 2.2 and 3.2, together with the comparison with the system commercialized before the optimization. Section 4 reports the main conclusions, highlighting the impacts of the research and reflecting on the multidisciplinary methodology.

2. METHODOLOGY FOR THE DEVELOPMENT OF DESIGN FOR MANUFACTURING AND ASSEMBLY

The methodological approach developed and validated in this work encompasses design informed by manufacturing and assembly, having prototyping and testing at its core.

2.1. DESIGN FOR MANUFACTURING AND ASSEMBLY

Design for Manufacturing and Assembly (DfMA) is an engineering approach that simplifies product design to make manufacturing and assembly processes more efficient, cost-effective, and reliable. It integrates design with production by considering the limitations and capabilities of manufacturing and assembly from the very beginning of the design phase. The ultimate goal is to reduce costs, enhance quality, and minimize production time [4, 5]. Prefabricated systems benefit from modularity and standardization, but only when design and manufacturing processes are tightly aligned. This integration ensures that design innovations are compatible with factory processes, allowing for faster assembly and fewer errors onsite [6, 7]. Additionally, testing at multiple stages, both in prototype and production, can verify the safety and performance of materials and joints, further improving the structural integrity of prefabricated housing.

This project focused on optimizing the structural system of a cold-formed steel (CFS) modular housing system, which was being introduced to the UK market, to improve factory production efficiency and reduce material waste. In CFS construction, load-bearing walls are the most critical components as they directly influence the structural integrity of the building [8–12]. Therefore, accelerating wall production was vital. A key challenge was to develop a lateral resisting system that moved away from a jungle of steel elements that were difficult to be integrated with the insulation and finishing system to streamline instead a more optimized system in which steel and finishing could be integrated. Therefore, the DfMA process (Fig. 1) started by identifying standardized components that could be readily found in the market. Then, an assembly strategy of sub-components and complete modules was identified. The interrelation between those two brought to the selection of the most appropriate materials and components. Specifically, in order to improve the time-consuming process of attaching CFS profiles to sheathing panels, which also needed to ensure safe movement along the production line, it was essential to optimize screw and sheathing patterns while still maintaining the necessary mechanical performance. Given that previous studies have shown a direct relationship between a CFS wall's shear capacity and the number of connections between the steel frame and sheathing [3, 9, 11, 13], this research explored, through prototyping and testing, how variations in screw spacing could impact structural performance. The aim was to automate the placing of the connection by enabling the use of a high-speed paneling system in wall assembly. To enable that, a larger flexibility in screw patterns was necessary. Therefore, an experimental investigation was conducted to evaluate the impact of different connection distances and patterns on mechanical performance, with the findings directly informing adjustments to the production process (discussed in Sections 2.2 and 3). The defined system and production process were assessed through environmental impact analysis, and when this was satisfactory, the system became ready for lean production.

Fig. 1. *Design for Manufacturing and Assembly methodology.*

2.2. EXPERIMENTAL CAMPAIGN

Experimental testing was adopted to mechanically characterize the main structural components of the proposed composite system, in which CFS profiles collaborate with both oriented strand board (OSB) panels and cement panels (CP) to withstand both vertical and horizontal loads. Indeed, the mechanical performance of CFS structures sheathed with boards is influenced by the response of the shear walls under horizontal loads. Various factors directly influence the behavior of CFS shear panels, including the type and thickness of the sheathing board [8–13], its placement (on one or both sides), the thickness of the CFS sections, loading conditions, aspect ratio [14], opening size [15], fastener type, and the spacing between the fasteners [2, 11, 13].

To assess the lateral response of CFS shear walls under in-plane loading, an extensive experimental campaign was articulated in three phases [16, 17]. The first phase included 32 tensile strength tests for the steel material, 20 lap-shear tests on screws, and 27 shear tests to determine the shear strength of connections between steel profiles and either oriented strand boards or cement board panels. The second phase was devoted to full-scale wall tests on fully sheathed wall panels, and the third phase looked at the lateral behavior of walls with openings and allowed a comparison between the newly proposed system and the previous one having X-steel bracing. Specifically, in the second phase, four walls with a length of 2400 mm and fully sheathed on one side of the CFS frame were tested under in-plane shear loading. The third phase, instead, aimed to evaluate the effect of openings on the shear response of CFS walls with a wall length of 4800 mm. In particular, three wall typologies with opening configurations were tested; representative of a ground floor rear wall (GF-RW) with a large opening, a ground floor front wall (GF-FW) with a door and a window opening, and a typical first floor (FF) with openings. These wall typologies were selected to represent the worst-case scenarios in terms of opening ratio among those to be manufactured by the housing provider, and they had a sheathing area ratio between 0.53 and 0.77. Moreover, two tests were performed on walls having the same geometrical con-

Fig. 2. *The overall experimental campaign, with Phase I to study the tensile strength of steel members, shear capacity of screws, and shear behavior of connections; Phase II to characterize the shear behavior of walls fully sheathed with OSB and CP; and Phase III to study the shear behavior of walls with openings and compare them with previously commercialized systems having steel bracings.*

figurations of GF-RW and FF but which represented the "Standard" system designed by the industry before the beginning of the research project led by the Author, and they used steel bracing to achieve the required shear capacity. These last two tests were performed to understand the changes in terms of wall shear strength and stiffness due to moving from a steel bracing to a sheathing braced approach. Figures 2 show the experimental campaign tests.

Each wall was constructed using studs, tracks, and blocking profiles made from C profiles (C100-41-1.6) with a steel thickness of 1.6 mm and a nominal grade of 450 MPa. The studs were spaced 600 mm apart. Three rows of blocking were installed: 610 mm from the bottom, at the mid-height of the wall, and 213 mm from the top. The lower blocking was positioned to accommodate cement panels (CP) at the bottom portion of the wall, helping to prevent humidity buildup (Fig. 3). Full-height 15mm oriented strand board (OSB3) panels were installed in the central section of the wall to serve as the primary shear-resisting elements. Additionally, OSB panel strips were placed near the top of the wall, intended for later assembly in the production line. This allows flexibility when moving and lifting the wall during the module assembly process. Self-tapping screws were used to fasten the sheathing panels to the CFS members, with spacing ranging from 75 mm in the central part of the GF-RW to 300 mm for the OSB strips at the top of the walls (Fig. 4). These variations were selected to meet the necessary shear capacity while enabling the use of high-speed paneling systems in the central areas. Fewer screws were used in areas where manual fastening with a hand screwdriver was required. In accordance with the perforated design method requirements, Simpson Strong-Tie HTT22E hold-downs were installed at the bottom corners of the walls during testing. The entire geometry of the tested walls with openings can be found in Kechidi & Iuorio, 2022 [17]. Additionally, ledger beams

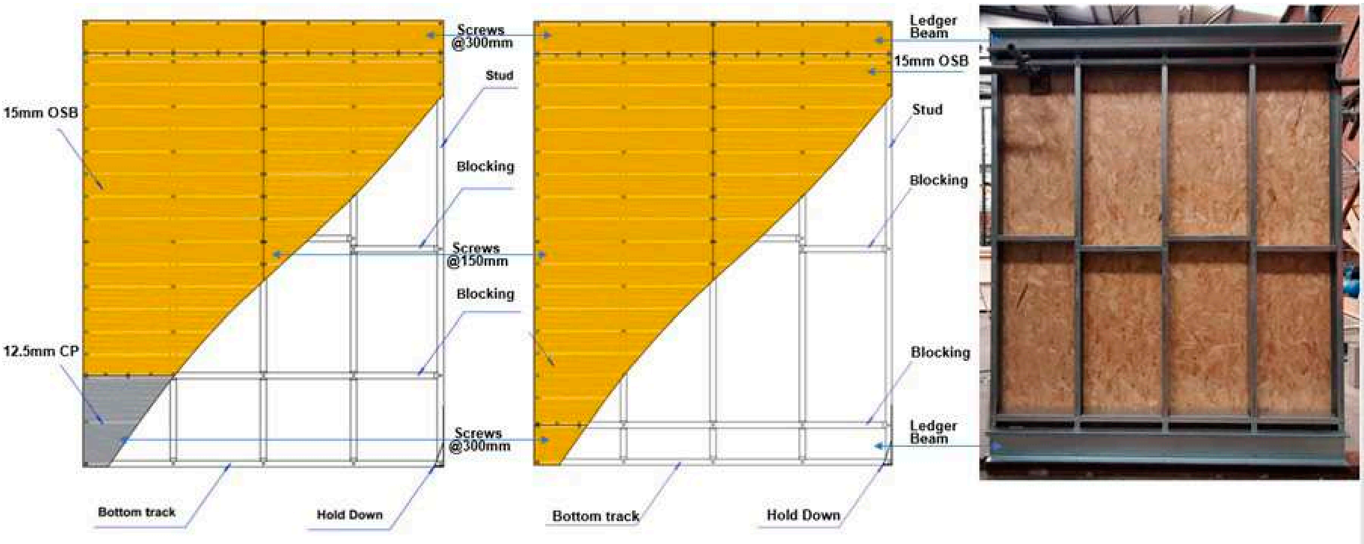

Fig. 3. *Geometry of the fully sheathed tested walls.*

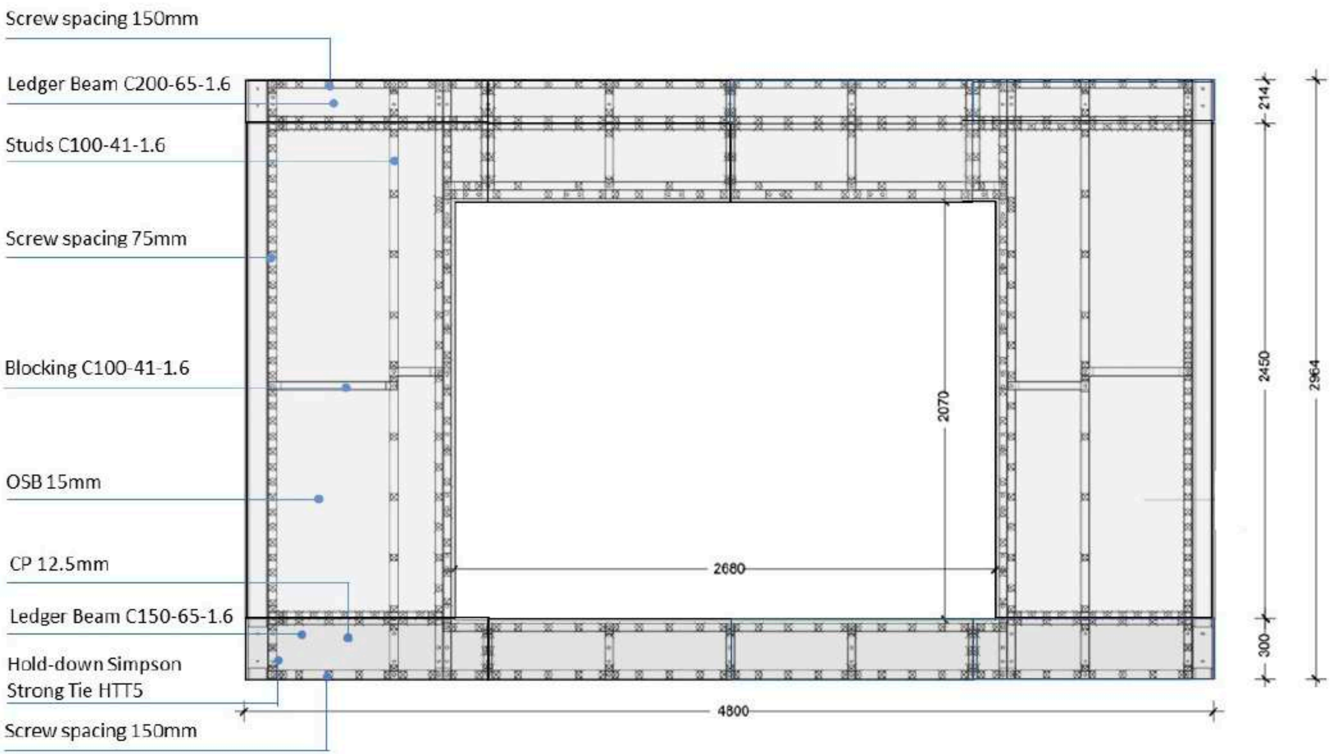

Fig. 4. *Geometry of the wall with opening (typology GF_RW).*

were placed at both the top and bottom of the wall, on the interior side, to simulate the presence of floors (Fig. 3). The tests were conducted using displacement-controlled quasi-static loading, following BS EN 594 (1996) [18], the standard currently used in the UK for testing walls of both wooden and CFS frames. This standard specifies the specimen setup and the loading protocol. The walls were pre-assembled in the factory and transported to the lab, where they were positioned vertically on a composite rectangular hollow base beam made from two welded U-sections and secured to the lab floor. A U-shaped spreader beam was placed on top of the walls to distribute the horizontal load evenly (Fig. 5). Vertical and horizontal displacements were recorded using Linear Voltage Displacement Transducers (LVDTs). The test results are discussed in Section 3.

Fig. 5. *Test rig of the walls with openings: (a) ground floor with 2 openings (GF-FW); (b) ground floor with one large door (GF-RW); (c) first floor (FF-FW) with two openings.*

3. RESULTS

3.1. DESIGN FOR MANUFACTURING AND ASSEMBLING

A high-speed panelizing system (Fig. 6a) was introduced to automate the process of attaching sheathing boards (the outer layer of the wall) to the CFS wall frame. This is typically a highly repetitive process, usually done by hand with a screwdriver, but by automating it, the DfMA-driven production line drastically reduced assembly time while maintaining accuracy and quality. Indeed, a typical CFS wall segment of, for instance, 2400 mm length x 2700 mm height, sheathed on one side, when designed to resist high lateral loads, can require having screws spaced at 100 mm on the edge and 300 mm in the center, having as such as 180 screws. Locating them at a precise distance from the edge of the panel is essential to avoid local failure of the panel. Therefore, their manual placing can take several minutes. Instead, the particular configuration of sheathing boards and the

Fig. 6. *Production line of the developed modular system showing: (a) ground floor assembly; (b) high-speed panelizing system for connecting the sheathing boards to the wall steel frame; (c) line production of the walls; (d) assemblage of the floor and wall system; (e) line production of the volumetric modules; (f) modules ready to be transported on-site for assembly.*

screw pattern, defined based on the results of the experimental campaign on connection systems (phase I) and wall systems (phases II and III), allowed to place 600 screws per minute. This system allows for the wall panels to be produced at a faster rate, improving production efficiency. The walls were then flipped vertically to be completed in a line-based manner, similar to an automotive assembly line. Each station in the line is designed to add a specific component, such as insulation, waterproofing, vapor barrier, and applying exterior finishes (Fig. 6c). Then walls and floor systems were connected, and all the services were integrated, up to realizing complete volumetric units, corresponding to the ground floor and first floor of the house systems to be delivered on-site. The design ensured that the components fit together seamlessly, reducing the need for adjustments or rework during assembly. The DfMA approach ensured that all connections between floors and walls were simplified for fast and secure attachment, allowing the modules to come together in an efficient workflow. The result was a modular volumetric housing system with consistent quality that could be produced quickly, up to six full volumetric units per week.

3.2. EXPERIMENTAL TEST RESULTS

Observations from the wall tests revealed that the CFS frame tended to deform into a parallelogram shape, while the sheathing boards tended to rotate. However, due to the presence of ledger beams at the top and bottom of the walls, along with the specific sheathing configuration – full-height panels in the center and shorter panels at the top and bottom – the central section of the walls experienced greater deformation. This determined pull-through of the screws predominantly around the edge of the central panels. In particular, the central sheathing panels underwent more significant rotation. This was true for both walls without and with openings. This demonstrated that small screw spacing was necessary in the central parts of the walls, as they were the most subjected to deformation, while larger spacing could have been adopted in the top and bottom strips. The following subsections discuss results for the second and third phases in detail.

3.2.1. TEST RESULTS FOR FULLY SHEATHED WALLS

Test results indicated that wall collapse was primarily dictated by the sheathing-to-frame connections in all GF specimens. At the global level, the steel frame deformed into a parallelogram, causing a rigid rotation of the sheathing panels. This led to the tilting and pull-through of the screws, followed by cracking in the CP panels and the breaking of the panel corners at the edges. Table 1 summarizes the results, showing that the GF walls had an average maximum strength of 41.79 kN and an average stiffness of 2.32 kN/mm, while the FF walls demonstrated an average strength of 62.48 kN and stiffness of 2.04 kN/mm. This indicates that walls with only OSB panels have at least 1.5 times the shear strength compared to similar walls with CP panels at the bottom.

3.2.2. TEST RESULTS FOR WALLS WITH OPENINGS

In terms of failure mode, in the case of the walls with two openings (GF-FW and FF-FW), the first cracks appeared in the top right and bottom left corners of the opening farthest from the applied horizontal load (details G and M in Fig. 7), followed by cracks at the other corners. In these walls, the bottom sheathing panels showed no significant deformation. The GF-RW walls

	Wall	Test number	Shear Strength	Stiffness
			[kN]	[kN/mm]
Phase II	GF	2	44.12	2.48
		3	39.46	2.17
		Mean	41.79	2.32
	FF	2	60.92	1.95
		3	64.04	2.13
		Mean	62.48	2.04
GF stands for Ground floor; FF stands for First Floor				

Tab. 1. *Test results for fully sheathed walls in terms of shear strength and stiffness.*

Fig. 7. *GF-FW wall before and after testing, with wall failure details of the: balcony right corner (B), bottom left corner (C), bottom right corner (D), door top corner (E), relative displacement between top and central panel (S).*

exhibited significant diagonal cracks at each corner, with extensive propagation in both the OSB and bottom CP panels (Fig. 8). The results in terms of shear strength at F_{max} and stiffness, as defined by BS EN 594 (2011), are reported in Table 2 for walls with openings (labeled as GF-FW, GF-RW, and FF-FW) and the two walls with opening and steel bracing (labeled as GF-K, and FF-K).

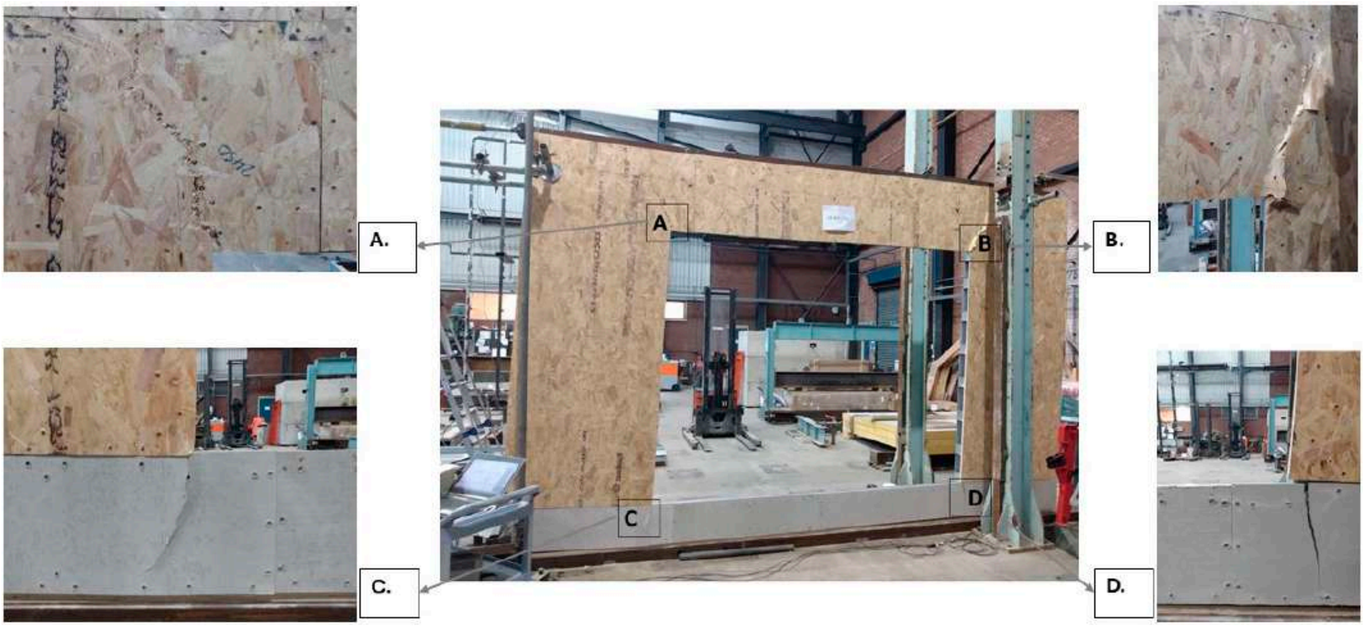

Fig. 8. *GF-RW wall after testing, with wall failure details of each opening corner.*

	Wall	Test	Shear Strength	Stiffness
			[kN]	[kN/mm]
Phase III	GF-FW	1	55.62	2.02
		2	61.4	2.49
		3	61.61	2.54
		Mean	59.4	2.35
	GF-RW	1	64.3	1.79
		2	64.9	1.71
		3	58	1.95
		Mean	62.40	1.82
	FF-FW	1	58.68	1.7
		2	59.7	1.87
		3	60.14	1.94
		Mean	59.51	1.84
	GF-K	1	64.41	1.36
	FF-K	1	66.58	1.91

Tab. 2. *Wall tests results.*

Notably, GF-FW and FF-FW displayed similar shear strengths, around 59.5 kN, though GF-FW was stiffer. GF-RW, despite having a large opening and a 75mm screw spacing in the central area, showed a higher shear strength of 62.4 kN but lower stiffness (1.82 kN/mm) due to the large opening.

When comparing the results obtained in Phase II and III, it appears evident that the opening mostly influences the stiffness of the walls. Indeed, when comparing the FF-FW with opening, with a similar without opening (from phase II), the stiffness decreased by about 6.4%. It is also evident that reducing the screw spacing has a more significant contribution to the shear strength of the walls.

Comparing walls with openings braced only by sheathing panels to those with steel bracing reveals that steel bracing slightly increases shear strength. However, in terms of stiffness, GF-FW exhibits greater stiffness than GF-K. Despite this, these wall systems are rarely used to their total shear capacity in low-rise buildings up to two stories. Walls without steel bracing fully meet the required capacity, even with large openings. Since unbraced walls reduce material waste, lower embodied carbon, and speed up construction, they were the preferred option.

4. CONCLUSIONS

Early-stage collaboration between designers and manufacturers can significantly reduce material waste, improve construction speed, and lower overall costs. Integrating testing throughout the design and production phases can identify and address potential issues such as structural performance, thermal efficiency, and durability early, leading to more reliable outcomes. Automated production systems, guided by digitally integrated designs, can lead to precision in assembly, reduced labor costs, and minimized rework. When combined with rigorous testing protocols, these processes ensure that housing systems meet safety standards and maintain affordability. This paper presented an iterative methodology, which was developed and validated to optimize a prefab system, which leverages the composite action between CFS profiles and sheathing panels while simplifying the manufacturing and assembly process. At its core, the methodology involves prototyping and testing, and it is informed by the challenges to be overcome to speed up the manufacturing process. For this specific case, the main challenge was to automate screwing connections while providing the required lateral capacity to the system. The experimental testing demonstrated the achievement of a system that fully met the structural requirements while also minimizing the use of material, waste, and production time. In particular, in terms of minimizing material, moving from a steel-braced approach to a sheathing-braced approach, allowed to reduce the use of steel by 12%. This had a significant impact not only in terms of manufacturing efficiency but, in particular, in terms of environmental impacts, with the new system achieving an embodied carbon (EC) of 254 kgCO2e/m², compared to 290 kgCO2e/m² obtained for the standard system, representing a 12.5% reduction in CO2e. Since steel components are the main contributors to the carbon footprint of lightweight steel systems, optimizing their use is essential, as highlighted in previous studies.

The proposed methodology in which manufacturing and assembling strategies are considered since product development and according to which materials are selected, prototyped, and tested to evaluate both mechanical and environmental performance can significantly impact Italian research, which is advancing sustainable constructions. Indeed, by addressing embodied carbon in construction materials and processes, the methodology can push the Italian building sector towards more environmentally friendly practices. This is particularly important in Italy, where sustainability and energy efficiency are growing priorities in the context of the EU's Green Deal and climate goals. Moreover, looking specifically at prefabrication techniques, the presented study can demonstrate how prefabrication can lower construction time and carbon footprint, making it more attractive for local industries. In the future, optimizing prefabricated construction through this methodology can create opportunities for Italian manufacturers and suppliers to gain a competitive edge, fostering growth in the green economy and boosting exports of innovative building systems.

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Author contribution

Conceptualization, visualization, writing (original draft, writing, review and editing), methodology, funding, project administration, O.I.

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DIGITALIZATION OF EXISTING BUILDINGS TO SUPPORT RENOVATION PROCESSES: A COMPARISON OF PROCEDURES

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Abstract

The low energy efficiency in our built environment underscores the urgent need to renovate existing buildings and implement cost-effective interventions. Increasing end-user awareness and providing a clear framework for efficient workflows for professionals to widely adopt renovation best practices is critical. Digital technologies are crucial in this context, as they streamline the renovation process by reducing time, costs, and errors and improving interoperability. A major application of these technologies in the Architecture, Engineering, and Construction (AEC) sector involves organising data into digital models that can manage various process stages, from planning to monitoring. The initial data collection on existing buildings is essential, yet current methods are often expensive and time-consuming. Although research has explored the trade-off between accuracy and feasibility in data acquisition and processing, a balanced approach that considers the affordability of survey methods and the effectiveness of the resulting data for further modelling has yet to be finalised. This study compared three data acquisition and processing strategies based on their limitations, potential, and requirements for BIM-based digital modelling. Despite some limitations in detailed roof and façades geometrical modelling, all methods were suitable for energy performance simulations. Results provide insights into optimising digital acquisition methods for large-scale renovations.

Keywords

Existing building, Retrofitting, Data acquisition, Data processing, 3D modelling.

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1. INTRODUCTION

Despite global efforts to address climate change, the building sector remains one of the most impactful in terms of emissions and consumption. It is widely recognized that the renovation of existing buildings, often poorly performing, is one of the possible actions to achieve pursued targets [1]. The adoption of digital tools and procedures in the Architecture, Engineering and Construction (AEC) sector not only offers potentially significant advantages but is also progressively becoming imperative [1–5]. In this context, Building Information Modelling (BIM) plays a pivotal role, thanks to the benefits it potentially offers to various stakeholders in the AEC industry [3–6].

While the time is ripe for its adoption at the professional level in designing new buildings, its use in renovation projects is still constrained by several limitations

[3, 6–14]. One of the key reasons for the gap between BIM applied to new and existing assets is the difference in the management of data and information used as input to create virtual models. In the former case, established standards are clearly defined for each project phase, both by formal regulations and community common practice. At the same time, it is more difficult to adopt these standards for representing existing assets [6, 10]. Indeed, available data does not always meet modelling requirements (e.g., density, metric reliability, geometric accuracy, visual fidelity [18]) that depend on models' goals, i.e., documentation and reconstruction, simulation, design, and the monitoring of various interventions (e.g., energy efficiency, structural integrity, valorisation).

Given the wide range of potential input data and the need to avoid information redundancy, it is essential to clearly define the model's purpose from the outset [6, 11, 12]. For the construction of a three-dimensional model, geometrical information is always necessary but required features and accuracy change consistently with modelling goals. So far, the level of development, detail, and accuracy have been the object of interest of many studies and regulations. Semantic and volumetric reconstruction is necessary to carry out performance evaluations [12], while a more detailed representation of complex geometries can be necessary for philological documentation [6, 7, 15], executive design of interventions [1, 10, 16, 17] or for running Life Cycle Assessments [11].

Many researchers have explored innovative technologies and methodologies for acquiring three-dimensional point clouds finalised to build virtual models [7–9, 14–17, 19–23]. These include range-based, i.e., terrestrial or mobile laser scanners [6–9, 14, 15, 19, 22] and image-based systems, i.e., terrestrial and aerial photogrammetry [9, 14–16, 20–23]. At the current state, terrestrial laser scanners are recognized for their accuracy [7, 8, 14, 16], despite their high cost and procedural constraints have spurred interest in mobile lasers [19, 22] and photogrammetric solutions, which offer dynamic and fast data acquisition, but with some trade-offs in precision [12, 20, 21, 23].

Two key insights from the above-mentioned studies are worth focusing on: the potential for integrating different acquisition systems to overcome specific constraints without compromising the usefulness of data for defined purposes [9, 15, 18, 23] and the necessity of having a systematic methodology aimed at balancing accuracy with feasibility under real-world conditions [18]. However, cited studies mostly focus on one of these aspects at a time, typically acquisition [7–9, 14, 16–23] or modelling issues [3–6, 10–13, 24], then taking both into account can bring a valuable contribution to achieving convergence.

This study contributes to examining these issues by comparing the results obtained from an experimental survey campaign and assessing their relevance for the construction of a BIM-based model. This work examines such models with a view to simulating current and predicted energy performance and design interventions. Tests included the investigation of a case study (acquisition and processing of geometric data) following three different strategies and the construction of an as-is model in a BIM environment. The tested strategies were therefore evaluated according to the appropriateness of the results for developing an effective model and their cost-effectiveness and timeliness. The illustrated experimental activities have been conducted within the European project ARV, aimed at defining and validating strategies based on digital procedures to support renovation processes.

The paper is organised as follows. In Section 2, tested strategies for the digitalization of existing buildings and the case study are described. Section 3 illustrates, compares and assesses the results of the strategies applied to the case study. Finally, Section 4 brings together conclusive considerations on tested strategies and outlines future research developments.

2. PHASES, MATERIALS AND METHODS

Three different strategies (S1-S3) were tested on a representative case study to compare their feasibility and the suitability of their results for the investigation of current energy performance. The common trait of the three strategies lies in the potential benefits they offer to the users, as their implementation is expected to be more cost and time-efficient than traditional methods.

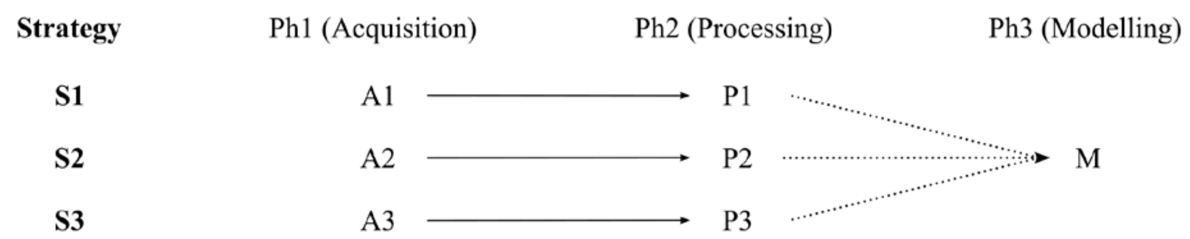

Fig. 1. *A scheme showing the relations among tested Strategies (S1, S2, S3) for Acquisition (A), Processing (P) and Modelling (M). Source: © 2023, the research group.*

This study is subdivided into three main phases, as depicted in Figure 1, where the first two phases belong to and characterise the application of each strategy (Section 2.2), namely:

- a first phase (Acquisition, Ph1), where the data necessary to reconstruct the building geometry are acquired through scans and pictures;
- a second phase (Processing, Ph2), where acquired raw data are processed, separately or combined, to obtain three-dimensional point clouds of the external surfaces of the building. After defining the necessary requirements linked to the model goals, the suitability of acquired and processed data is then assessed;
- in the third phase (Modelling, Ph3), the data collected in the previous two phases that complied with the defined requirements are finally assembled into a BIM environment (Section 2.3). In this phase, several tests are carried out to verify the suitability of the exported three-dimensional model for running energy simulation.

2.1. THE ARV CASE STUDY

A residential building was chosen as a case study to perform its digitalization in a BIM environment. The case study is one of the six demonstration cases developed in the ARV H2020 European project, which aims to create climate-positive circular communities and increase the building renovation rate in Europe. The Italian demonstration project consists of the renovation of a private residential building located in Trento, in northeastern Italy (Fig. 2). It is a T-shaped three-story building occupying an area of 254 m², surrounded by a courtyard. It houses nine independent units and their unheated ancillary spaces (cellars and attics). The elevation of the north wing of the building starts from the ground floor, while the other part includes a lower basement and is staggered in height by half a floor. The outer walls have plaster finishes, while the northern wall presents some stones slightly protruding from the flat surface. Balconies protrude from the south and the west façades, while the north and east façades feature single and double-hung windows of various sizes. The structure is made of concrete and stone, and there is no insulation between the interior and the

Fig. 2. *An aerial view of the case study (left) and a view of the northeast side (right).*

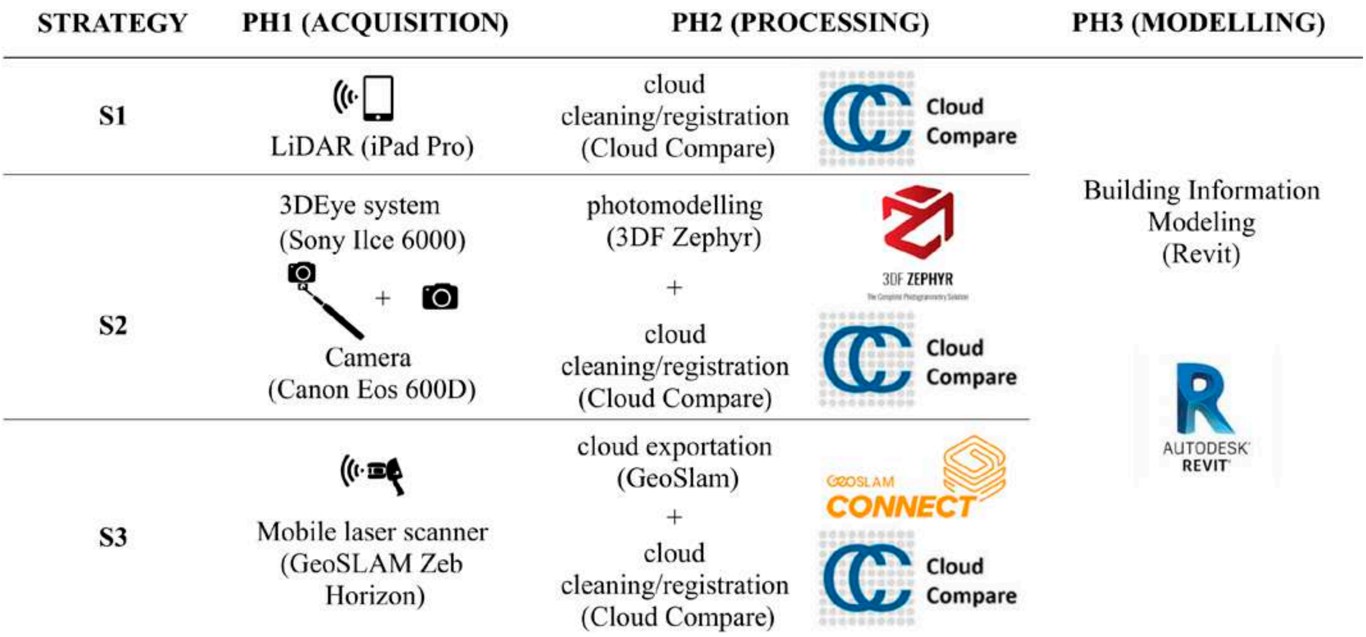

Fig. 3. *The scheme shows adopted tools tested for each strategy (S1, S2, S3). Source: © 2023, the research group.*

unheated rooms or between the interior and exterior of the building. The heating and cooling systems are independent for each apartment, and the windows were recently replaced in two of the nine units.

The retrofit solution involves the use of a prefabricated wood-based modular system, designed as a retrofit kit to enhance the energy efficiency, indoor comfort, and architectural aesthetics of the existing building and applied on the east and north façades for demonstration purposes [24, 25]. The manufacture and installation of the prefabricated panels require very accurate geometrical reconstruction of the building's shape to ensure proper fit [16, 17, 24]. A functionally equivalent ETICS system is applied on the other walls.

2.2. STRATEGIES APPLIED TO THE CASE STUDY

In the following paragraphs, the methods adopted for the first two phases (Acquisition and Processing) of each strategy are described, and an overview of tools (Fig. 3), costs and time is provided. Building characteristics such as size, shape, and context were considered when planning the acquisition activities. To obtain reference points valid for all the strategies necessary for processing and comparing other acquired data, 100-point coordinates on the existing building surfaces were preliminary recorded through a total station (Topcon GPT 1001). In addition, the contractor provided a dense cloud obtained from the combination of a TLS cloud and a cloud from photo-modelling through an unmanned aerial vehicle photo. At the end of the processing phase (second phase), for each strategy, different outputs have been imported into Cloud Compare free software using the coordinates of the topographic points as references.

2.2.1. POINT CLOUD FROM LOW-COST LIDAR SCANS (S1)

The first tested strategy consists of acquiring building external surfaces with LiDAR (Light Detection and Ranging) scanning technology. This one has been recently developed [14, 19] also into everyday devices [23], making it accessible in terms of costs and ease of use.

The LiDAR technology of an iPad Pro was used to acquire scans through a free application, Scaniverse, that allows objects of different sizes to be scanned. The maximum distance for scanning is 5 m for large objects (building portions) and 2 to 5 m for small objects (e.g., windows, details, etc.). The costs associated with instruments only included the purchase of the iPad. Since the building is taller than 5 m, a lifting platform was necessary to reach the second and third floors from an adequate distance. Including tests, 30 scans were acquired for each level, and each scan represents a portion of the

Fig. 4. *The acquisition phase with iPad Pro from the lifting platform (left). An overview of acquired scans (right). Source: © 2023, the research group.*

existing building, overlapping with those of surrounding portions (Fig. 4).

Single scans, exported from the app in .las format, were imported into Cloud Compare, and 9 of them were selected. They were aligned to the topographic points with a semi-automatic procedure that implies the recognition of at least 3 reference points. Aligned clouds were cleaned through segmentation and noise reduction and then joined into a single cloud. Cloud alignment and cleaning are semi-automatic procedures. The processing time depends on the number of scans and, therefore, on the building size. There were no costs related to the use of software in the acquisition and processing phase since tests are carried out with free apps and software (Scaniverse, Cloud Compare).

2.2.2. POINT CLOUD FROM PHOTOGRAMMETRY (S2)

The second strategy involves the acquisition of pictures of the building and their use for three-dimensional photo-modelling. The ease of purchasing acquisition tools (cameras) makes this solution appealing for widespread diffusion. Two sets of tools were used for the acquisition of photos:

- 3DEye system, composed of a 9 m telescopic pole, a mirrorless camera (Sony Ilce 6000), a gimbal device to control camera orientation and stabilisation, and a tablet to control framing and shooting from the ground level. This system allows the acquisition of photos of the external walls of the entire building from a distance of about 2 m and different orientations;
- Reflex camera (Canon Eos 600D), used from the ground level and a lifting platform, which allowed acquiring photos of entire facades from different perspectives.

The costs related to instruments involved the purchase of 2 cameras and the auxiliary devices to use the telescopic system (telescopic stick, gimbal, and tablet). Through the 3DEye system, a set of 960 detailed photos was acquired from the ground level (Fig. 5), and a set of 142 context photos was acquired through the reflex camera from the ground level and the lifting platform.

The 3DF Zephyr software by 3DFlow was used to generate a point cloud through a photogrammetric process. All the context photos and 802 from the detailed ones have been selected, considering that overlapping between photos is necessary for the software to correctly reconstruct the position of the cameras. After importing them into the software workspace, 50 reference points, coinciding with topographic points, were identified on each photo to generate the scattered cloud. Then, the 50-point coordinates from the topographic survey were inserted to correct camera positions and generate the dense cloud. Processing time depends on the number of photos and the building size since individuating reference points is a manual procedure. Processing costs involved the purchase of the software licence.

Fig. 5. *The acquisition phase with the 3DEye system (left). An overview of acquired photos (right). Source: © 2023, the research group.*

2.2.3. POINT CLOUD FROM SLAM (S3)

The third strategy consists of adopting the SLAM (Simultaneous Localization And Mapping) scanning technology to record building geometric features. This technology permits obtaining point clouds comparable to TLS ones for density and accuracy without the constraint of a static, slow acquisition [14, 19]. Theoretically, these devices can acquire points up to 100 m distant, but the loss of precision increases with distance and the cost of these tools is still relatively high.

A portable dynamic and georeferenced device by GeoSLAM, Zeb Horizon (provided by Semprebonlux s.r.l.), was used for the acquisition of a single scan from the ground level and the lifting platform (Fig. 6), but since the building height is about 12 m, it could have been scanned entirely without using the platform.

Once acquired, the scan was exported from GeoSLAM software in .las format and imported into Cloud Compare free software as a point cloud. Then, it was aligned with topographic points and cleaned. Processing costs include purchasing a licence of compatible software to export the acquired cloud.

2.3. POINT CLOUDS REQUIREMENTS FOR ENERGY AND GEOMETRICAL MODELLING

After transferring raw data into a digital environment as point clouds, the third phase (Modelling, Ph3) started. Firstly, it was assessed that collected data matched specific requirements consistently with the model goals. In particular, their functionality for the following goals was tested:

(a) transfer to an energy analysis software (e.g., Design Builder) for as-is and post-intervention simulations;
(b) design of the renovation intervention through prefabricated panels.

Geometrical and informative modelling carried out in Revit followed some well-established steps outlined by several works [4, 8–10]:

i) insertion and localization of topographic and point cloud in Revit;
ii) creation of the levels using the cloud as a reference;
iii) insertion of perimeter walls using the cloud as a reference;

Fig. 6. *The acquisition phase of the north façade with GeoSLAM Zeb Horizon from the ground floor photos. Source: © 2023, the research group.*

iv) insertion of the roof by tracing the cloud;
v) insertion of openings and balconies on the façades using the cloud a as reference;
vi) creation of internal subdivision, slabs and walls separating units;
vii) insertion of room entities that define the volume and use of the different spaces;
viii) insertion of information on installations for each unit, i.e., heating or cooling plants;
ix) insertion of information on stratigraphy for each type of object inserted into the Revit model (e.g., walls, floors, windows, roofs), i.e., layers thickness and related materials thermal properties (density, thermal conductivity, emissivity);
x) building localization and orientation.

Steps i) to v) are needed for both goals (a) and (b), but different levels of detail and accuracy are required for the two purposes. In fact, too many details in the geometric reconstruction typically led to errors in the transmission of surfaces and volumes from the BIM software to the energy analysis software (a) [4, 15]. In this case, an orthogonal grid can be traced from the cloud and used to obtain a simplified volumetric model, making the millimetre accuracy of the cloud scarcely meaningful. Conversely, in order to be useful for the design of the intervention through prefabricated elements (b), the model must have reliable geometry of the external surfaces, including out-of-plumb, bulging, and non-perfectly orthogonal angles. In this case, the positioning of openings, balconies, pipes, and other elements protruding from the façade must have a maximum error of a few millimetres (1σ 4mm-7mm), as explained in [16, 17]. Therefore, external surfaces and openings should be modelled using the cloud as a reference only if it satisfies strict correspondence with the existing building. In this study, the obtained clouds are evaluated, considering the levels of geometric accuracy consistently with both (a) and (b) goals.

Finally, all the steps, including the insertion of non-geometrical information (vi-x) deduced from a technical report, are necessary for the building energy modelling and simulation (a).

3. RESULTS

In this Section, the results obtained through each of the three strategies are illustrated in terms of:

- resulting cloud features, i.e., number of points, medium density, minimum and maximum distance from the topographic survey and the reference cloud, measured through the Cloud-to-cloud function of Cloud Compare (as summarised in Tab. 1);
- cost-effectiveness, using quantitative indicators such as costs of the instruments and software, processing time and ease, and suitability of outputs for modelling with both (a) and (b) purposes (as summarised in Tab. 2).

Strategy	Raw data	Dimension	Medium density	Min. distance	Max. distance	Standard deviation 1σ
	-	[points]	[points/m]	[mm]	[mm]	[mm]
S1, LiDAR cloud (iPad Pro)	30 scans	5.707.700	20.465	d = 3,0	D = 27,4	90
S2, photogrammetry cloud (3DEye system + reflex)	944 photos	1.835.233	15.216	d = 5,8	D = 98,3	65
S3, SLAM cloud (GeoSLAM Zeb Horizon)	1 scan	45.492.604	270.147	d = 2,1	D = 30,0	50

Tab. 1. *Comparison of clouds obtained through the tested strategies.*

Strategy	Cost*	Acquisition time	Processing time	Modelling suitability	
	[€]	[hours]	[hours]	(a)	(b)
S1, LiDAR cloud (iPad Pro)	1.000/ 1.500	1 (ground level) 2,5 (lifting platform)	0,25/cloud (alignment)	Yes (no roof)	No (yes ground attach)
S2, photogrammetry cloud (3DEye system + reflex)	4.000 + softwar e	1 (ground level) 2 (lifting platform)	more than 16 (ref. points individuation)	Yes (no roof)	No
S3, SLAM cloud (GeoSLAM Zeb Horizon)	15.000/ 60.000	0,5 (ground level + lifting platform)	0,25/cloud (alignment)	Yes (no roof)	Yes (no roof)

* Reported costs are relative at the time of writing. The values are indicative and are given to compare tested strategies.

Tab. 2. *Comparison of costs, acquisition and processing time and modelling suitability related to the tested strategies.*

3.1. POINT CLOUD FROM LIDAR SCANS (S1)

In Figure 7a, the main results obtained through S1 are reported in terms of cloud visualisation. As can be seen, the acquisition obtained with the LiDAR incorporated in iPad Pro allowed the generation of a sufficiently homogeneous cloud (Fig. 7b) that fits well into the topographic survey boundaries. Some portions are less accurate, namely, those scanned from farther than 5 m, those strongly exposed to bright light or backlighting during the acquisition procedure, and large homogeneous areas, such as plaster-finished surfaces. The comparison with the TLS cloud (Fig. 7c) shows that lying planes are not always unique and perfectly straight, mainly due to a lack of reference points.

This strategy proved to be successful in the acquisition from the ground level and narrow spaces, thanks to the ease of handling the device. Scanning distance from the object, lack of reference points on the surfaces, and lighting conditions influenced the density and accuracy of the clouds. Reflecting objects, such as metal and glass, were not appropriately acquired. Instead, proper three-dimensional reconstruction is guaranteed for surfaces rich in detail or three-dimensional references, as seen for the grounding or in the presence of objects protruding from flat surfaces, such as stones on the north façade.

Scanning the upper levels from the lifting platform did not lead to high-quality results due to difficulties in manoeuvring and, therefore, control scans and overlapping. However, acquisition times were relatively fast (less than 1 hour to scan the first floor and about 2.5 hours for upper levels) compared to a traditional static survey (TLS or topographic survey). It took about 30 minutes per scan, resulting in about 4.5 hours to obtain the final single-point cloud.

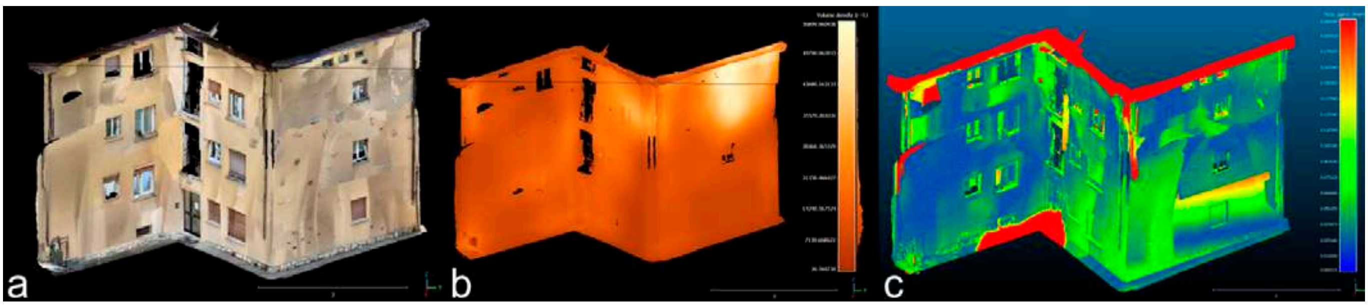

Fig. 7. *(a) The point cloud of the northeast façades obtained through iPad Pro scans; (b) the cloud density distribution; (c) the cloud compared with TLS cloud, with the closest points highlighted in blue. Source: © 2023, the research group.*

3.2. POINT CLOUD FROM PHOTOGRAMMETRY (S2)

In Figure 7a, the main results obtained through S2 are reported in terms of cloud visualisation. The generated dense cloud fits into the topographic survey boundaries; however, it is sparse, and its density is not homogeneously distributed (Fig. 8b). The minimum and maximum distances from topographic reference points have a remarkable gap because the cloud is very sparse in some points and therefore difficult to compare with the topographic cloud.

Some areas are more scattered and correspond to those strongly exposed to bright light and backlighting during the acquisition procedure and to those for which positions were not correctly reconstructed for lack of reference points (Fig. 8a). In general, many pictures acquired from different perspectives provided a correct three-dimensional reconstruction of the object. By combining both sets of photos – context and detail – the density and accuracy of the clouds were optimised. The comparison with the TLS cloud showed that the planes reconstructed through photogrammetry are almost straight (Fig. 8c).

The influence of lighting conditions, reflecting objects, and reference points on density and accuracy are also valid for this strategy. Indirectly, the distance from the object also influenced the resulting clouds since as the distance increases, the resolution of photos and cloud density decreases. However, even if the obtained cloud is relatively sparse, photogrammetry allows for obtaining a cloud with straight planes for façades. Therefore, this technique is reliable for reconstructing the building's geometric features.

In addition, the acquisition of photos through a telescopic system has fewer physical constraints than traditional or mobile scans. Therefore, it is possible to acquire data on slightly taller objects (9-15 m). Acquisition times were relatively fast compared to a traditional static survey (TLS or topographic survey). Including 3DEye telescopic stick handling around the entire building for each floor, the acquisition of both sets took about 1 hour for the ground level and about 2 hours for the upper levels. Processing times required more than one day because it included many tests, and since cloud density and accuracy depend on the number of photos used for the photogrammetric reconstruction, but processing time increases with the number of photos.

3.3. POINT CLOUD FROM SLAM (S3)

In Figure 9a, the main results obtained through S3 are reported in terms of cloud visualisation. The acquisition through a SLAM device allowed obtaining a cloud that fits well into the topographic survey boundaries and ho-

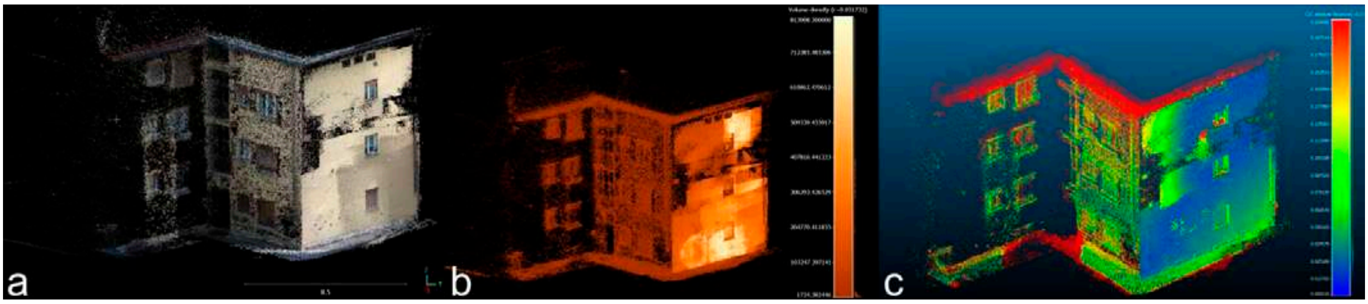

Fig. 8. *(a) The point cloud of the northeast façades obtained through photogrammetric reconstruction; (b) the cloud density distribution; (c) the cloud generated with photogrammetry compared with TLS cloud, with the closest points highlighted in blue. Source: © 2023, the research group.*

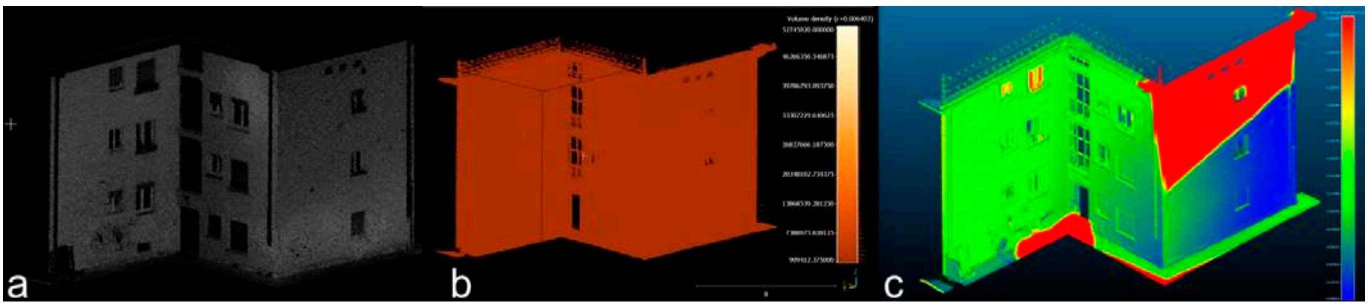

Fig. 9. *(a) The point cloud of the northeast façades obtained through SLAM scanning; (b) the cloud density distribution; (c) the cloud acquired with GeoSLAM Zeb Horizon compared with TLS cloud, with the closest points highlighted in blue, the farthest in red. Source: © 2023, the research group.*

mogeneously dense (Fig. 9b). As shown in Figure 9c, the comparison with the TLS cloud shows that the reliability decreases with increasing scanning distance since more distant points (red points in the image) have not been reached with the lifting platform but have been scanned from the ground.

This third strategy performed well in the acquisition from the ground level and narrow spaces, thanks to the device's ease of handling. It took about half an hour, including manoeuvring the lifting platform. Unlike the first two strategies, which revealed weakness in acquiring surfaces with few reference points, SLAM technology proved suitable for acquiring large and homogeneous surfaces. Processing was fast since it is mostly semi-automatic, and a single scan had to be aligned to the topographic points. In addition, the quality and reliability of the clouds depended on distance but not outdoor conditions. This means that the quality and reliability of clouds obtained are ensured even in uncontrollable conditions, such as natural lighting and intrinsic features of the building. Despite the costs of implementing this strategy, it allows for the acquisition and processing of data on small and medium buildings in a very short time.

3.4. ASSESSMENT OF REQUIREMENTS FOR DIGITAL MODELLING

The last consideration regarding the obtained results deals with the suitability of obtained point clouds for modelling goals. According to the comparison with the topographic survey and TLS point cloud, the accuracy of data acquired through the three strategies was acceptable to build a three-dimensional reconstruction of the external shape of the case study, as defined in point (a) of

Fig. 10. *The point cloud of the case study overlapped with the 3D model in the BIM environment. 3D and 2D visualisation of rooms allow for verifying proper separation between spaces before import in energy analysis software. Source: © 2023, the research group.*

paragraph 2.3. In particular, steps ii) and iii) are used to position openings and other objects lying on the façades (step v).

The BIM model was exported in .hbjson and .idf formats via the Pollination plug-in, allowing it to manage surfaces and volumes directly from Revit. At first, it was not possible to derive a model on which to carry out the analysis due to irregular geometries, non-orthogonal angles and excessively fragmented spaces. To solve this problem and avoid errors in the recognition of closed regions and to allow the correct computation of volumes (Fig. 10), near-orthogonal corners and non-perfectly-straight walls have been rectified, and indoor layouts have been simplified, assuming habitation units as homogeneous thermal zones. Another issue dealt with the rooms, which cannot be managed from the plug-in interface and need to be placed correctly in the Revit model, on the right level, and with proper height settings. A 3D visualisation of rooms (Fig. 10) allowed a quick check of their correct position. After several exportation tests from Pollination and subsequent adjustments, the three-dimensional geometry appeared readable in the energy analysis software (Design Builder).

All the resulting clouds allowed the reconstruction of an as-is volumetric model for running energy simulations, even if none of the obtained clouds could have been used to properly model the roof geometry (step iv).

None of the obtained point clouds could have been used for a detailed design project with prefabricated panels, as defined in point (b), since, as can be seen in the last row of Table 1, their accuracy does not meet the required criteria for off-site construction, 1σ between 4 and 7 mm, according to [16, 17].

4. DISCUSSION

This study aimed to compare different acquisition and processing strategies based on key parameters such as cost, time, and accuracy while assessing their suitability for the construction of a digital informative model. This experiment explored the potential of these strategies for digitising the built environment for different purposes. The methodological approach allowed for a balanced evaluation, considering both the accuracy of the results for rapid retrofit interventions and the practical feasibility in terms of ease, time, and cost.

Using a low-cost LiDAR-equipped device (iPad Pro) to scan the building, the first strategy proved sensitive to factors like distance from the object and lighting conditions, resulting in irregular and inconsistent surface densities. However, the device's affordability, ease of use, ability to avoid occlusions, and speed of acquisition and processing are notable strengths.

The second strategy, which generated a point cloud using photogrammetry (3DEye system and a reflex camera), shared similar strengths and weaknesses but was hindered by a slower processing workflow and lower quality in the resulting clouds.

The third strategy, employing GeoSLAM scans, revealed similar limitations and advantages compared to the first approach. While GeoSLAM produced better results under real-world conditions, its higher cost remains a drawback.

Photographic sets and SLAM scans are less constrained by distance than common LiDAR devices, making them more suitable for surveying entire buildings. However, the density and accuracy of LiDAR-generated clouds are similar to those produced by SLAM technology. As a result, while it may not be feasible to scan an entire medium-sized building using a low-cost LiDAR device, it remains a viable option for smaller, accessible sections such as ground-level areas. From the experimental findings, it is clear that while the first two strategies are easy to apply, they are insufficient for the complete 3D modelling of medium or large buildings. Integration of different techniques can yield better results, though the quality and reliability of the data may still be affected by uncontrollable factors like lighting and the specific features of the building. The advantages and limits revealed by each strategy are summarised in Table 3.

Integrating the resulting clouds into a BIM-based model was tested, and their suitability for two modelling purposes was evaluated. Combining energy evaluation tools within the BIM workflow requires simplified geometry models to overcome interoperability challenges between systems, and the accuracy obtained by clouds can be sufficient for a volumetric model aimed at running pre- and post-intervention energy simulations. In

Strategy	Limits	Advantages
S1, LiDAR (iPad Pro) scans cloud	Distance from the object Homogeneous surfaces Light conditions	Easy to handle Avoid occlusions Fast acquisition and processing Low-cost
S2, Photogrammetry cloud (3DEye sys. + reflex camera)	Distance from the object Homogeneous surfaces Light conditions Slow processing	Easy to handle - avoid occlusions Fast acquisition Low-cost
S3, SLAM cloud (GeoSLAM Zeb Horizon)	Distance from the object High costs	Easy to handle Avoid occlusions Fast acquisition and processing

Tab. 3. *Limits and advantages of tested strategies for acquisition and processing.*

contrast, the geometric uncertainties encountered do not make resulting clouds suitable for the three-dimensional reconstructions aimed at the detailed positioning of prefabricated components, such as modular systems for retrofitting.

Through this experimental process, the study identified potential solutions to fill the gap between accuracy needs and actual feasibility. However, some questions still need to be addressed, such as the integration of different levels of detail within the same BIM model for various purposes, the implementation of models for comparing retrofitting solutions, simulating pre- and post-intervention energy performance, designing high-precision interventions, and the validation of these models' reliability.

5. CONCLUSIONS

This study contributes to the growing body of research exploring methodologies for the digitization of existing buildings, offering a comparative analysis of three strategies – LiDAR (iPad Pro), photogrammetry (3DEye system + camera) and SLAM (GeoSLAM) – oriented towards 3D modelling for the energy renovation of buildings. Each method was evaluated based on its feasibility, cost-effectiveness, and suitability for 3D modelling aimed at energy performance simulations and design of retrofitting intervention.

LiDAR (iPad Pro) offered fast acquisition and processing, especially for ground-level data. However, its accuracy decreased at longer distances, under poor lighting conditions, and when scanning larger or homogeneous surfaces. Photogrammetry provided reliable geometric data for straight surfaces but required more time and manual intervention for aligning reference points. Its results were influenced by lighting conditions and distance, leading to sparse clouds in some areas. SLAM emerged as the fastest and most efficient method for capturing large surfaces and navigating tight spaces, with results that were less affected by lighting. However, accuracy decreased with distance.

Despite these differences, all three methods generated point clouds suitable for developing geometrical models for energy performance simulations. However, none were accurate enough for detailed design tasks such as prefabricated panel construction, mainly due to inaccuracies in the façade details.

The experimentation findings emphasise the trade-offs between speed, cost and accuracy of each method, highlighting the importance of setting specific requirements upstream of a project. The results suggest a careful selection of data acquisition and processing methods tailored to modelling goals, particularly when high-precision data is required. Hybrid approaches integrating multiple technologies may best balance cost and precision.

Future improvements should aim to refine tested methods, enhancing the combination of efficiency and accuracy, potentially through integrated approaches. Furthermore, research must be carried out to implement and validate modelling strategies according to different purposes.

Authors contribution

Conceptualization, E.B. and G.M.; data curation, E.B. and G.A.M.; writing – original draft preparation, E.B.; writing – review & editing, G.M.; visualization, E.B.; supervision, R.A., M.D., G.A.M.; funding acquisition, R.A.

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