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THE INDUSTRIALIZATION OF CONSTRUCTION IN THE SECOND HALF OF THE XX CENTURY

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PREFABRICATED LIGHT STEEL CONSTRUCTION. RESEARCH AND PROTOTYPES FOR HOUSING IN ITALY

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Abstract

The use of steel technologies in the residential sector was deeply influenced by Italian historical events and its distinct cultural background, resulting in limited and occasional outcomes throughout the peninsula. Pursuing a common thread that links the design and technical development of the steel house may provide an opportunity to understand the genuine involvement of Italian technological culture in technical innovation and to critically evaluate individual contributions.

Between the 1960s and 1970s, public and private bodies launched experimental and theoretical design research with a series of production initiatives. Numerous research institutes were established, fostering cooperative relationships between academic institutions and the private sector. Collaboration was encouraged between design teams, bodies, and firms involved in the production and promotion of steel, while some architects attempted to integrate the codes of prefabrication into an all-Italian code of planning geared towards aesthetics. Within the broader context of these activities, research and experiments concerning building prefabrication for residential purposes are examined in the paper, including both "programs" and "coordinated components" for which steel was used.

Keywords

Steel structures, Light prefabrication, Housing, Italy, Prototypes.

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1. INTRODUCTION TO THE LIGHT PREFABRICATION BETWEEN PROJECT AND META-PROJECT

In the 1960s, building industrialization was a prominent topic of discussion [1]. Due to the critical issues raised by the implementation of closed systems and the substantial demand for housing, the residential building sector was designated a privileged area for research and experimentation in the so-called "open manufacturing" [2, 3]. This operational strategy involved a variety of approaches, with the aim of providing answers to the primary "open questions" [4, 5]: the necessary and no longer deferrable adaptation of design techniques to the needs and critical issues posed by new production processes [6]; the development of an operational method that allowed the use of prefabrication system as a tool for enhancing production in the construction sector, with the clarification of the connections between typological models and construction; the use of traditional and innovative materials, in relation to the evolution of production and assembly techniques; the development of a correct relationship between architecture and industrialization to make coherent a new design practice, indeed «the only possibility of industrializing architecture without removing it from its range of artistic activity is not the application to architecture of industrial techniques already established and experiment, but the invention of a construction technique which, although considered to be fully autonomous, falls within the methodological scope of industrial technology» [7].

In this context, various research initiatives related to the industrialization of construction systems for residential purposes and the experimentation of steel, to validate its technical and appearance potential, pursued different directions [8]. The first one comprised a methodological and operational experimentation, wherein the "meta-project" was used not only as an ideological tool to oversee the entire design process across all phases, including conception, programming, production, and construction [9]. Alternatively, more strict design experimentation could be undertaken on the building component or components, with frequently divergent objectives and purposes [10]. The methodology proposed for the *Progetto di elementi edilizi industrializzati per la libera realizzazione di tipologie abitative* (Project of industrialized building elements for the free creation of housing typologies) entailed the incorporation of the definition of "meta-design": it was conceptually associated with "open manufacturing". It was conceived as a logical progression of prefabrication. The term "open" was considered as «the possibility of adapting to the mutability of circumstances, of absorbing external inputs and stress; consequently, an open system should be characterized by constraints of a nature that does not jeopardize its continuous change and adaptation. Therefore, the limitations that must be sought define the objectives as precisely as possible and not the means to comply with the technological adjustments while preserving the figurative nature of the various production categories» [11].

The methodology identified several theoretical tools based on this perspective. The first one was the theory of the "three freedoms", which encompassed the freedom to tailor the building to the user's requirements (flexibility), to incorporate it by the industry in the construction process, and to shape it (particularly its edges and overall appearance). This concept was used in the Clasp, the English system for the construction of schools with a steel framework employed in the postwar period. The second one was related to the "large module", conceived as the principal common factor from which the building's size derived. The third theory was based on the concept of "concentrated anomalies", which entailed the possibility of concentrating heterogeneous disturbance elements (such as ducts, vertical connections, and others) in a few vacant areas of the building. The fourth one was based on the notion of "adaptations", which referred to the possibility of incorporating non-system components, such as accessory components, into the building to be designed. The fifth theory comprised "categorical spaces", defined by ten productive categories [12].

The experimental research titled *Studio di un programma edilizio con impostazione integrale della progettazione, per edilizia residenziale dipendenti Italsider* (Study of a building program with an integral design approach, for residential buildings of Italsider employees) was grounded on a whole design approach, which, from a methodological standpoint, was able to regulate the entire program with the three phases of setting-up, preparation, implementation and also of starting a technical-operational collaboration among all the participants in the construction process [13]. The methodology involved a meta-design approach that guaranteed typological and functional diversity, unification and standardization of industrialized components, selection of construction systems, and adoption of modular coordination. They were based on building type through standard components (built of steel and reinforced concrete), following a specialization relationship linked to the role of the construction elements' set and the typological layout of the entire building. The design experimentation of the system based on steel components for residential and school buildings named Fly had a more ideological objective: to bring architecture back to its primary purpose of the technical culture of building. It sought to reunify architecture and construction «with a different method of analysis of the construction logic that can establish a different history, in which the emphasis on the individual element is replaced by the consideration of the building culture to study the process and not only the result» [14]. Therefore, research became the most suitable dimension for the project, a dimension of discovery, not invention. The design of prefabricated building systems was pursued with the intention of reaching technical-formal rules of the construction system: a network of resilient components of different types, each one corresponding to distinct structural functions, in which the solutions and technical methods of assembly imparted a "decorative" aspect, aimed at comprehending the logical conception of the construction. The structure was not only considered as a static tool but also an ordering criterion from which the objective and tectonic laws were identified [15].

Quite the opposite, the design research on the "steel brick" was based on a more strictly technical-economic vision for immediate usability. The open-cycle prefabrication process was elevated to its most extreme outcomes by developing a singular steel building component that was both modular and versatile, similar to brick in traditional construction [16]. From a production standpoint, this ensured significant degrees of freedom even during the construction/assembly phase of a building, despite the technical-mechanical repetition of industrialized components produced in series. The initiative to experiment with a single component and reduce the assembly phases aimed to evaluate the potential for triggering industrialization processes of building products that can be adapted to self-construction processes [17]. The study titled CREIG-ITALEDIL, namely *Studio per l'inserimento delle strutture e degli elementi costruttivi in acciaio nel procedimento costruttivo a ciclo aperto* (Study for the integration of steel structures and components in the open industrialized building system), aimed to verify, both at the design and construction-production levels, the potential advantages of "manufacturing by components" in steel, specifically the establishment of a unitary and integrated industrialized construction process that afforded a wide range of design choices [18]. The building organism was not the result of a predetermined mechanical procedure for assembling catalog components, according to technical-economic reasons, but rather a conceptual process in strictly architectural terms, which defined it as a collection of interconnected and related components functional to establish an "open system" [19].

2. PROGETTO DI ELEMENTI EDILIZI INDUSTRIALIZZATI PER LA LIBERA REALIZZAZIONE DI TIPOLOGIE ABITATIVE, 1966-67 (DESIGN OF INDUSTRIALIZED BUILDING ELEMENTS FOR THE FLEXIBLE CONSTRUCTION OF HOUSING TYPOLOGIES)

The design research, which was developed for the CECA-Finsider competition, focused on the design of housing units built at an industrial scale and was an opportunity for the application of the theory of "building meta-project" developed by the architect G.M. Oliveri, who headed the design group of the Nizzoli Architectural Office.

A dwelling of 110 m^2 was identified according to the group of users defined in the call, and it was set on a modular square grid with a side of 15 m. The design work included a "system engineering phase" for the development of subsystems that could be produced by different industries that shared the meta-project as a reproductive structure based on the regulations and an "industrial design phase" for the verification of technological, formal, and economic-productive needs [11].

In the subsystem titled the *spazio-struttura* (space-structure), the frame was composed of slabs with integrated beams and pillars [20]. The orthotropic reinforced slabs were sustained by vertical supports placed in the center lines of the modular texture. The structural grid was designed to accommodate building modular units, with a size of 1,575 m^3 (15 m x 30 m x 3.5), that could be joined to form a maximum of six units. The steel columns were available in two standard types, each with a different height and profile to support varying loads. The end plates, large or medium, varied according to their position, external or intermediate, in the spatial reference grid. The slab comprised 7 mm thick flat beams placed along the perimeter and two shells made of pressed steel sheet with a thickness of 15/10 mm, which were connected by welding and filled with an expandable concrete casting. This component could be built with various building options depending on the different architectural typologies and its location: the standard type, prepared in the fabrication shop with

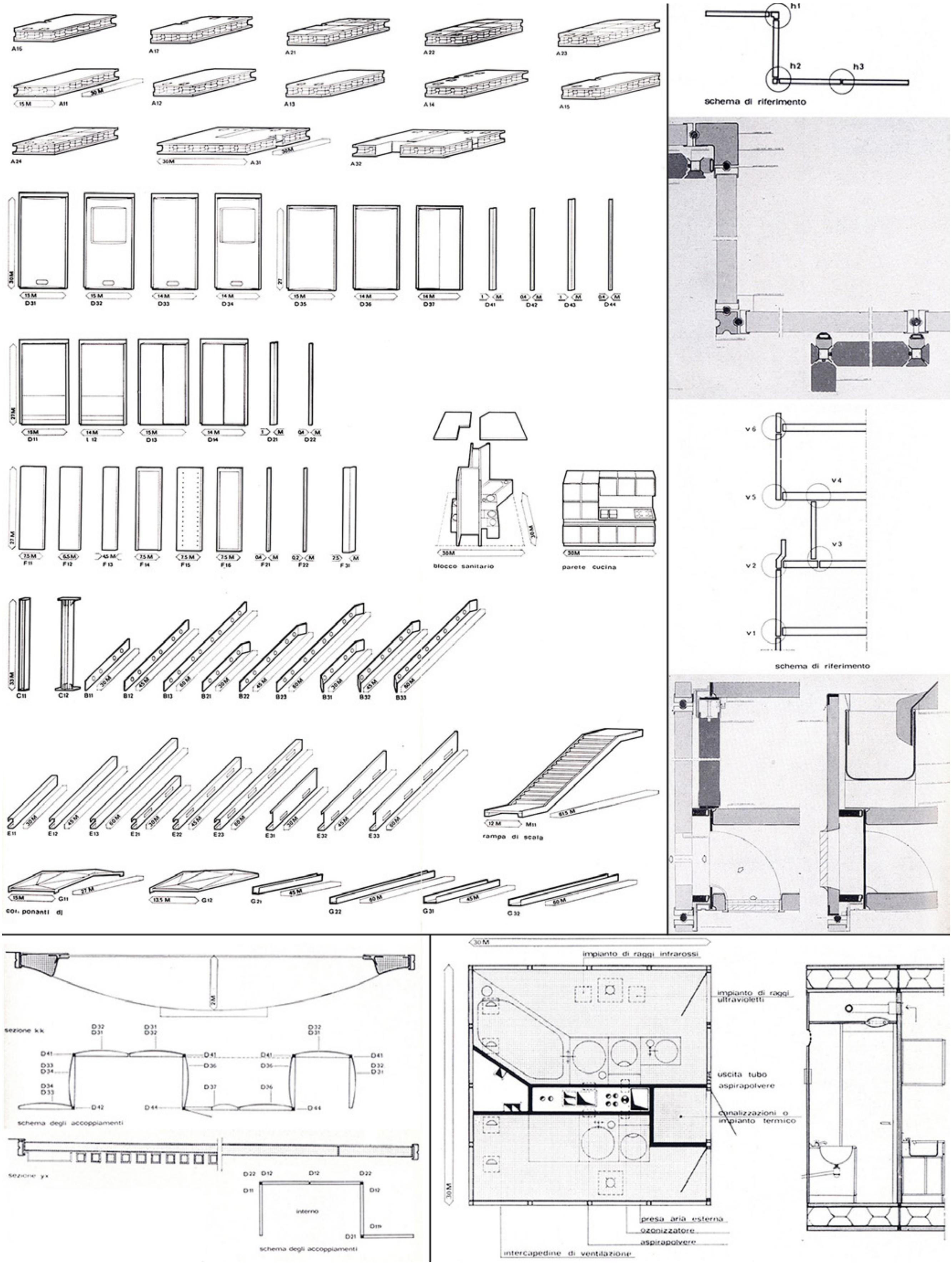

Fig. 1. *The building program developed by Nizzoli and Oliveri. Top left: the components' list. Top right: the vertical and horizontal joints for the façade panels. Bottom left: the diagrams of the possible panels' arrangement. Bottom right: technological features of the kitchen and bathroom units. Source: [12].*

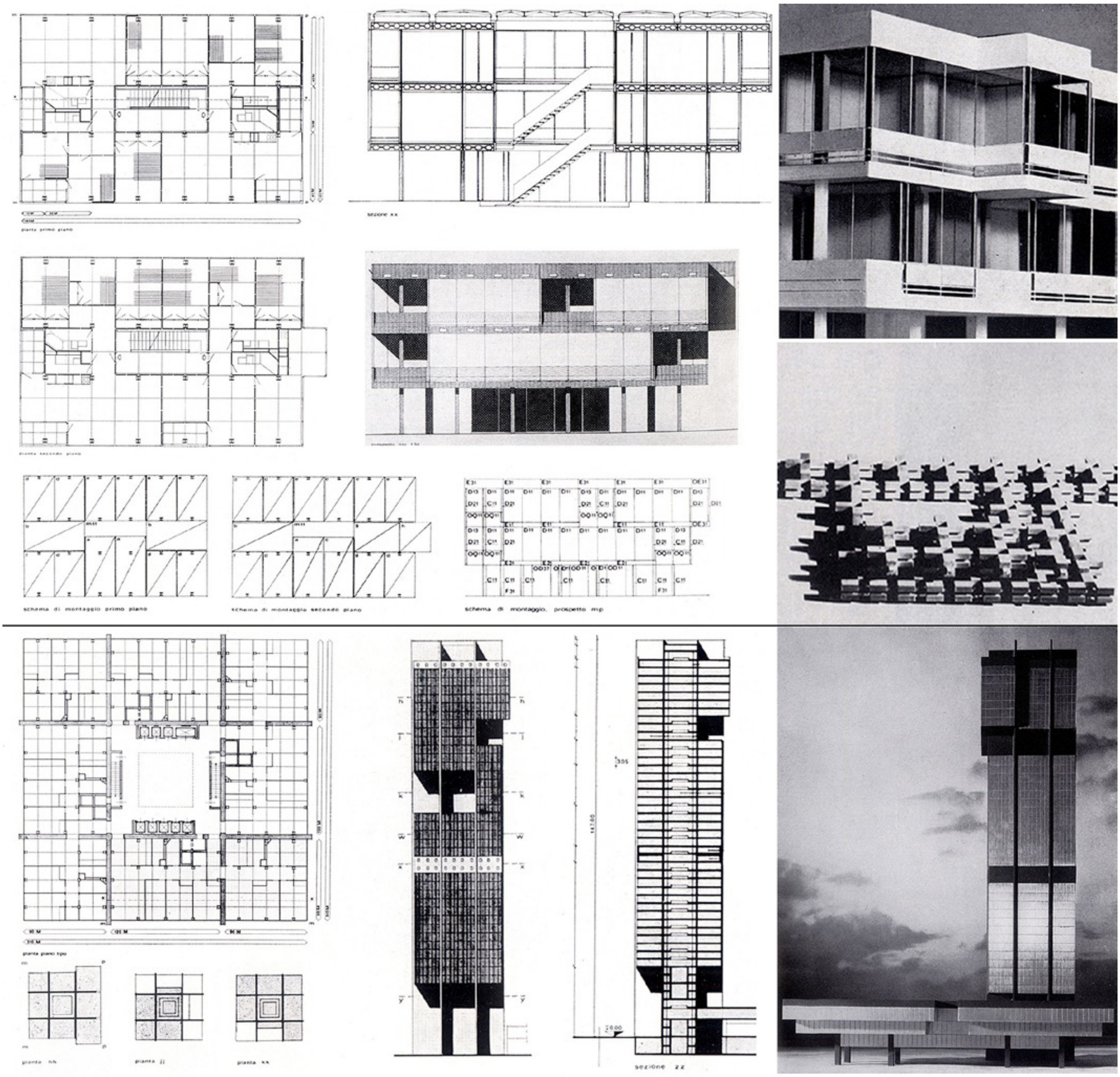

Fig. 2. *The building program developed by Nizzoli and Oliveri. Top: the modular layout of the housing block and its possible repetition in the urban arrangement. Bottom: the use of the same coordination grid for the tower typology and its architectural appearance. Source: [12].*

floor and ceiling, and the loggia-type variant, furnished of raised floor; the technological block-type, equipped with systems; the roof-type with the overlapping of molded plastic elements. The envelope subsystem included two versions of façade panels, built of pressed metal or plastic, with the same connection constraint along the perimeter. The façade panel made of plastic material was designed with a pass-through light to reduce the restriction of openings and enhance internal distribution flexibility (Fig. 1).

This construction system, which was also proposed for the expansion of a neighborhood in Bratislava, was used for multiple building typologies and displayed distinct design implications for each of them [21]. In the single-family dwelling, the criterion of distribution neutrality of the habitable spaces was experimented with, which was defined by the two horizontal components and the uniformity of the transparent envelope. The housing block typology involved using standard components of the building system and adapting additional components, such as the porch. The arrangement of the dwellings and the entire structure could undergo elevational changes in accordance with the kitchen's location and the interior spaces' arrangement, resulting in a distinct external perimeter.

In the tower typology, the central core was based on the concept of the "concentration of the anomalies", and it was built of reinforced concrete, allowing the suspension or the direct support of the eight dwellings characterized by the components of the building system (Fig. 2).

3. *STUDIO DI UN PROGRAMMA EDILIZIO CON IMPOSTAZIONE INTEGRALE DELLA PROGETTAZIONE*, 1960 (BUILDING PROGRAM WITH AN INTEGRATED DESIGN APPROACH)

Following the company's requirements concerning the construction of approximately 12,000 housing units for its employees, Italsider entrusted the CPA group, composed of the engineers S. Colombini and E. Mandolesi and the architect A. Libera, with the task of developing a residential building program. This study was validated in the pilot project of the Salivoli neighborhood in Piombino and executed in various phases. The first phase in 1960 was characterized by the use of two main housing typologies: towers and blocks. The dwellings' arrangement was based on a square module with a side of 3.20 m, which was suitable to guarantee combinatorial flexibility in the planovolumetric schemes, functional adaptability in the various shapes of the housing units, and the unification of the structure [22]. The selection of the module and the implementation of the three-dimensional reference grid also ensured the standardization of all technological components, including the functional blocks of the bathroom and kitchen.

The use of steel was the subject of both technical experimentations, encompassing the design of the building frame and other building components. Furthermore, the research was also carried out from the formal point of view on specific typologies, especially single houses and towers in the phase related to developing prototypes. In the verified prototype, the steel load-bearing frame provided for the unification of the columns and beams, as well as diagonal bracing and connection elements, and the unification of the slabs built off-site with reinforced concrete joists and hollow bricks.

The structure was characterized by athwart frames connected by the exposed beams on the façades, the bracing slabs, and the stairs. The athwart frame was divided into four spans, and HE 120 profiles were used for all its columns that had the height of the building at the far ends and the height of the building levels within, interrupted by the continuous beams. IPE 180 profiles were used for the main beams inside the building, and C-shaped 160 profiles were exposed along the perimeter, bearing the walls of the envelope and ensuring the connection between the athwart frames [13]. According to the structural layout consisting of a hinged frame, the bracing was composed of diagonal elements connected to columns and beams through hinged joints, ensuring the capability of the building to support the horizontal stresses (Fig. 3).

The building program involved the specialized use of steel for the construction of stairs, including a single type of ramp that could be customized to suit various building types. There were two alternative solutions: ramps with steel stringers featuring a free rise and tread made of prefabricated elements in marble grit and concrete or self-supporting ramps made of a single piece of folded steel sheet, with rubber covering for the tread. Both solutions were designed to be produced in the factory and assembled on-site after construction. The same choice of steel characterized the technical features of the windows, which could be shaped with a double or a single frame. The program provided alternative solutions for the walls of the envelope: the traditional type, with the use of separating space between the main layers of the wall that were innovative for the use of heavy or light prefabricated construction elements, respectively made of reinforced concrete panels or steel sheets, but also mixed solution (Fig. 4).

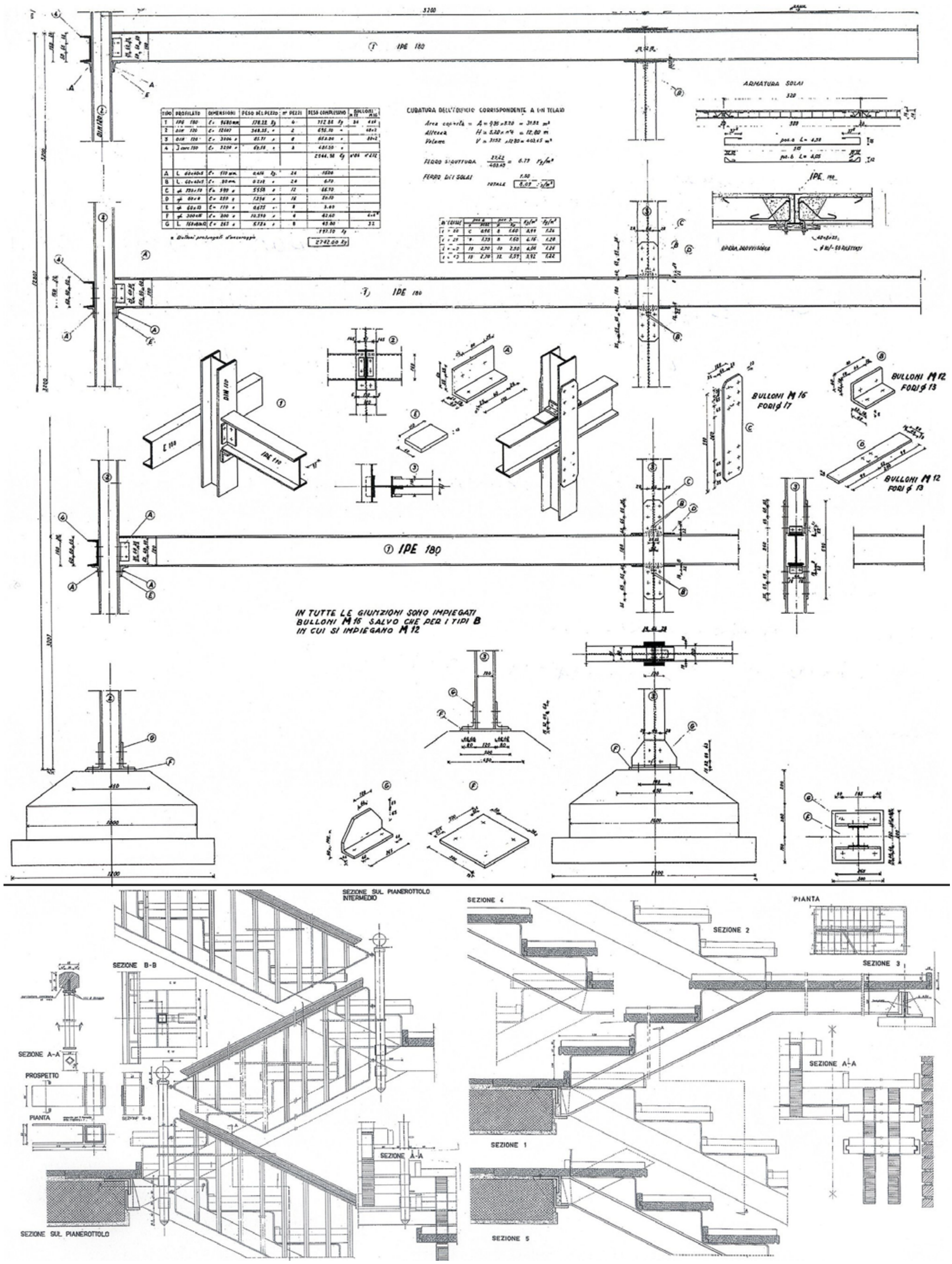

Fig. 3. *The building program developed by Colombini, Mandolesi, and Libera. Top: the typical hinged steel frame for the housing block. Bottom: the details of the staircase. Source: [23]*

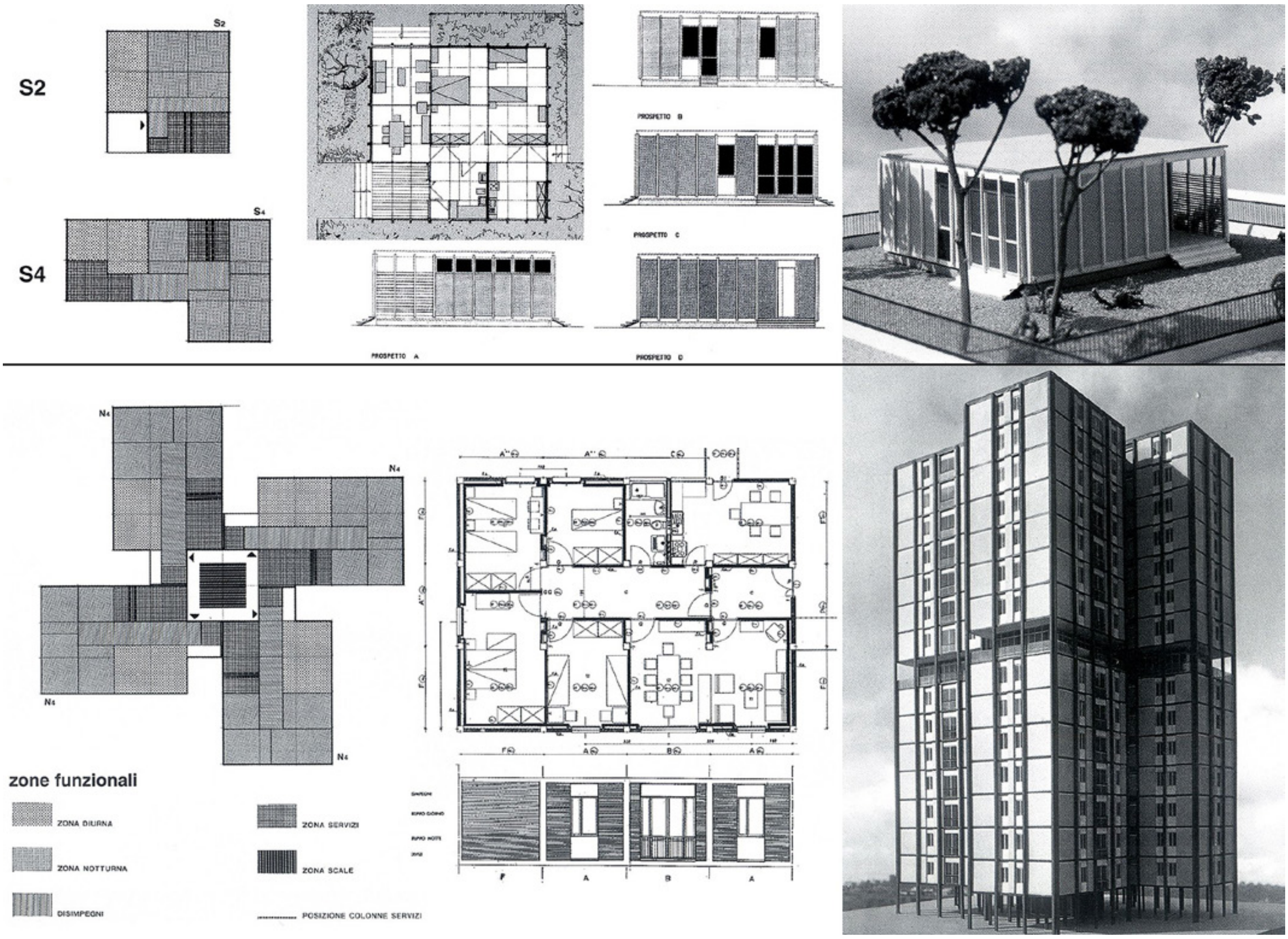

Fig. 4. *The building program developed by Colombini, Mandolesi, and Libera. Top: the single-family house with its modular coordination also displayed on the elevations. Bottom: the features of the tower typology composed of the arrangement of four dwellings. Source: [23]*

4. FLY CONSTRUCTION SYSTEM FOR RESIDENTIAL AND SCHOOL BUILDINGS, 1965

Designed by Angelo Mangiarotti, the Fly construction system aimed to introduce an entirely prefabricated lightweight construction system. The experimentation of the system was supported by a company that produced metal components for furniture; consequently, the modular spatial grid chosen by the architect to organize the internal spaces was set dimensionally identical to that of the furniture with module M equal to 96 cm x 96 cm. To guarantee a high demand for the construction system and consequently achieve adequate profits, the company decided to offer many prototypes to customers who could customize both the layout and the envelope, which was proposed in two versions, one with façade panels in concrete, the other in steel [24].

The Fly system allowed the creation of one- or two-story buildings that were also suitable for terraced house layouts. The steel structure, composed of tubes, had 4 to 6 M spans, depending on the layout. The position of the pillars was based on the modular grid, which also determined their alignment: the perimeter pillars were external to the modular grid, while the internal ones were aligned to longitudinal axes and juxtaposed to the main transverse trusses; consequently, the grid had a tartan pattern, to allow the insertion of spaces corresponding to the transversal dimension of the pillars. The foundations could be built on prefabricated reinforced concrete plinths or slabs with pre-finished flooring [25]. The upper floors were made of reinforced concrete and placed above a double frame of beams: the main ones were placed longitudinally and made up of U-shaped profiles and plates to compose rectangular tubes; the

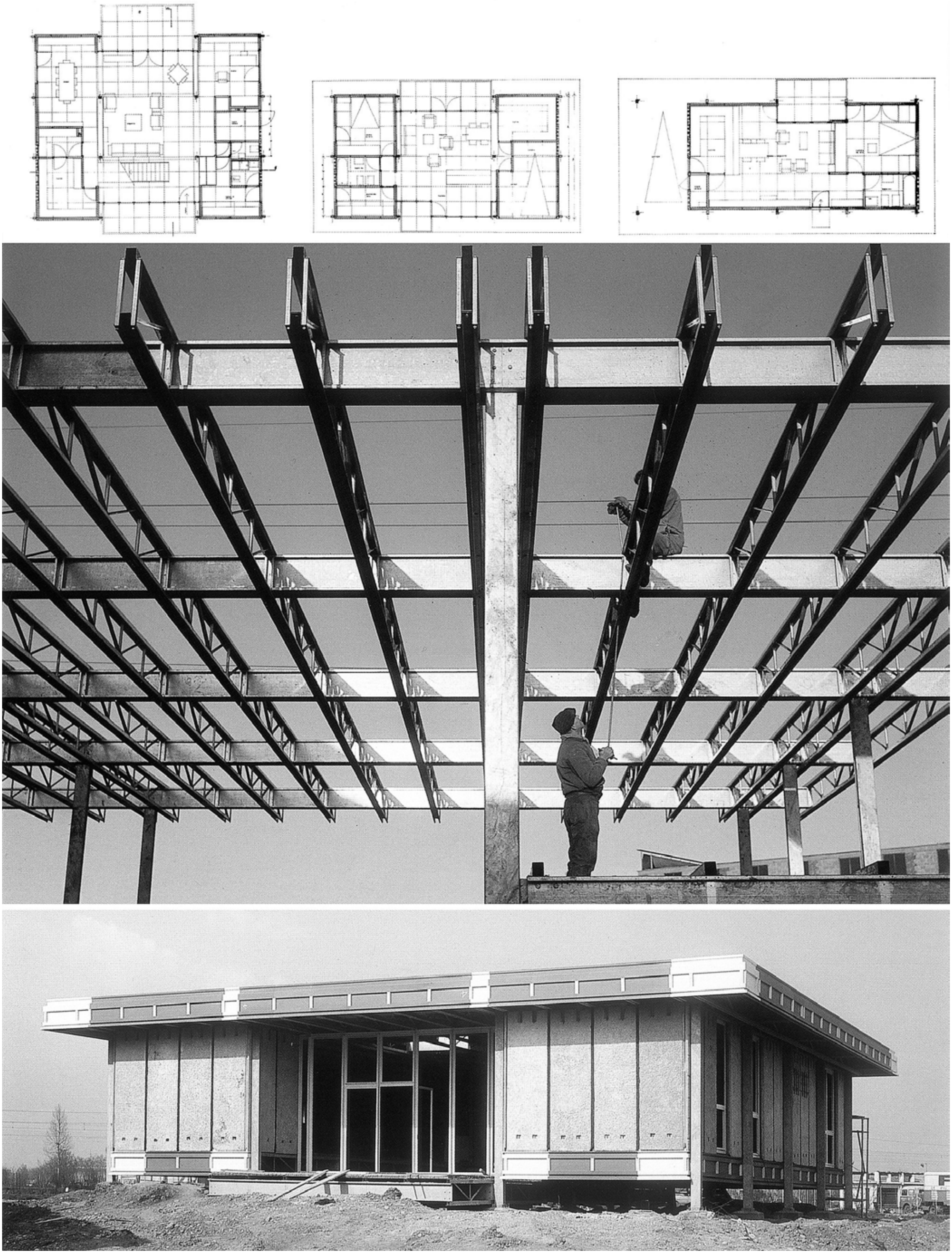

Fig. 5. *The Fly construction system designed by Mangiarotti. Top: the modular coordination of building system components for the arrangement of different types of dwellings. Middle: the assembling of the structure. Bottom: the prototype of the single-family house. Sources: drawings [24]; photos [15].*

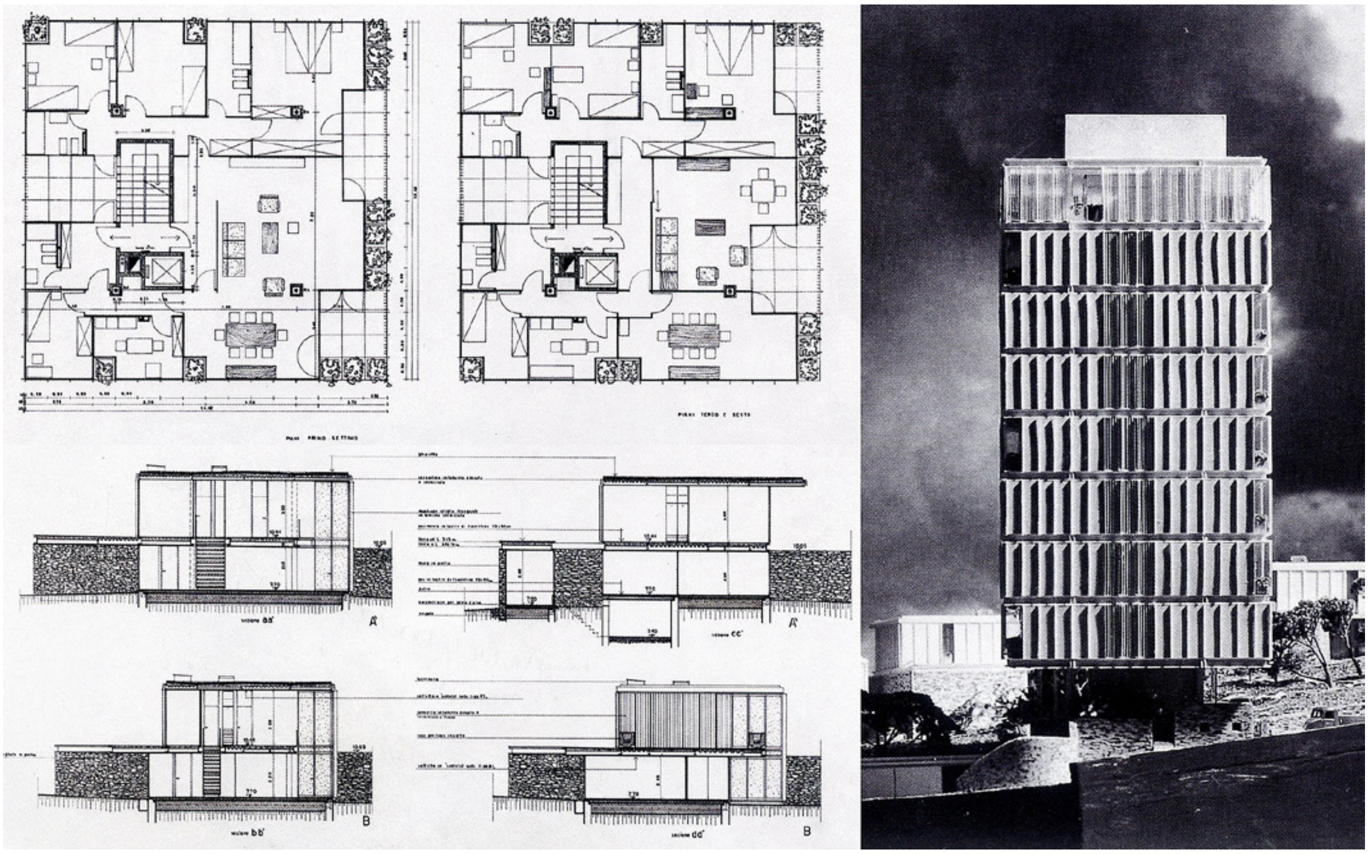

Fig. 6. *The Fly construction system designed by Mangiarotti. Top left: the plans of the tower with different arrangements of the living spaces. Bottom left: the two-story houses surrounding the tower. Right: the maquette of the tower. Source: [15].*

secondary ones were placed transversally and made up of flat trusses. Each of them had top and bottom chords juxtaposed to the primary frame to reduce the number of connections between the beams (Fig. 5). The decks, both on the roof and at the base, were entirely covered with metal sheets, which reiterated, as in a modern entablature, the length of each module of the tartan. Some prototypes were built for construction validation, but production of the Fly system was suddenly stopped due to economic problems (Fig. 6).

5. THE BUILDING SYSTEM BASED ON THE "STEEL BRICK", 1971-1974

At the beginning of the 1970s, the *Consiglio Nazionale delle Ricerche* (CNR) financed an industrialized building program to produce housing at a proportional cost to the average per capita income. The study involved testing a building component patented by the engineer Michele Pagano, the "steel brick". This experimentation took place within the *Centro Studi per l'Edilizia dell'Università di Napoli* (CESUN), directed by Pagano, without directly involving companies in the construction sector. This proposal for a modern industrialized brick was aimed at effectively guaranteeing the maintenance, at a conceptual level, of the relationship between the design, production, and assembly phases. It was conceived to allow a balance between freedom of design, adequate sizing of production cycles, and automation and technological unification for the assembly stage [26]. The element was a "brick" with a steel structure, measuring 60 cm x 60 cm x 30 cm, that could provide high thermal and acoustic insulation (Fig. 7).

During the prototype testing phase, another component of different dimensions was added to the first one: it measured 60 x 30 x 30 cm and was shaped to allow for corner connections between adjacent walls and the positioning of vertical elements inserted into a wall. The construction system was characterized by specific requirements: modularity of the spatial structure, adaptability and flexibility to different grids, high statically overdetermined, and reduction of the weight-ri-

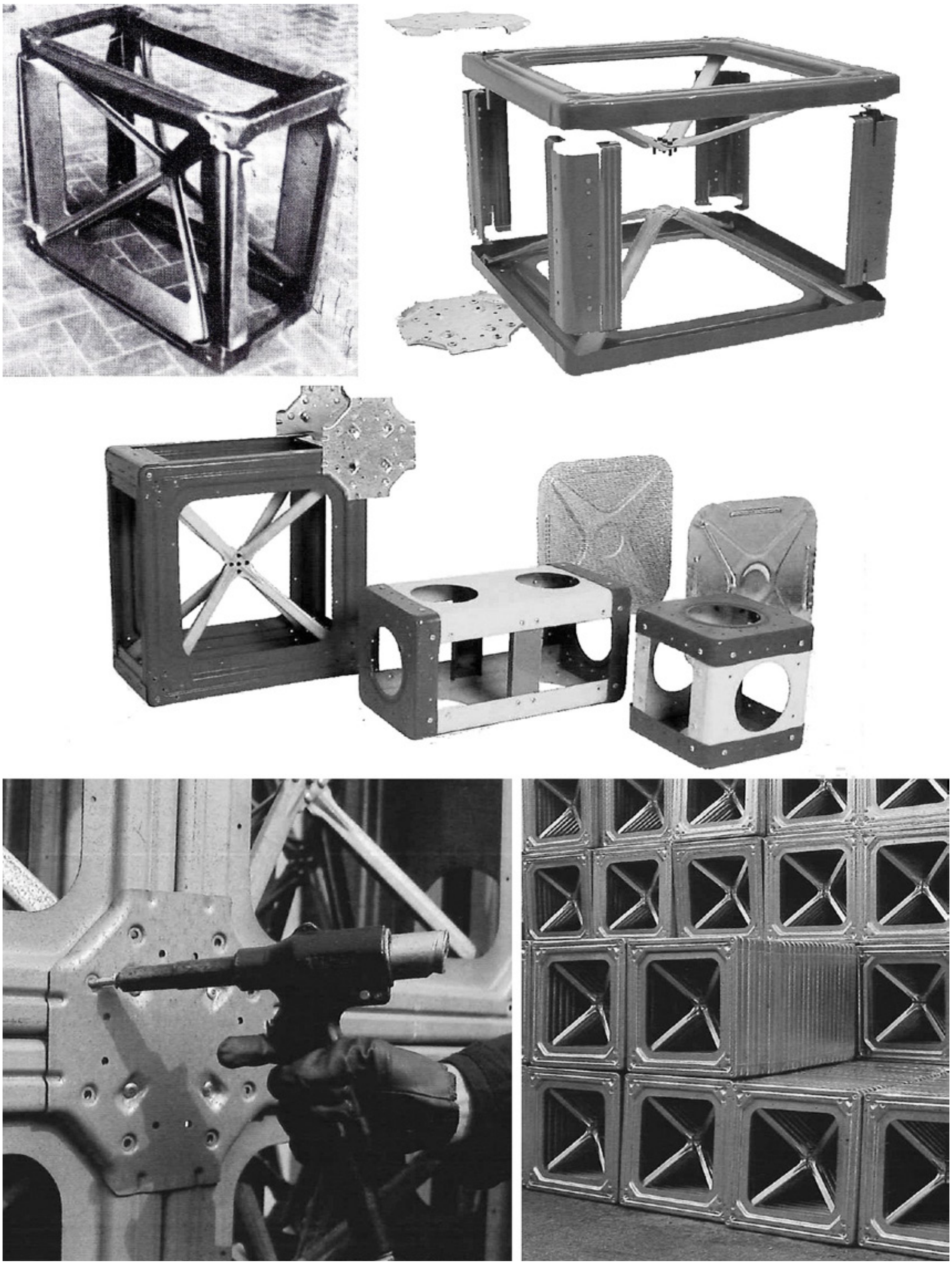

Fig. 7. *The steel brick developed by Pagano. Top: the first prototype and a focus on its metal components. Middle: the various sizes of steel bricks in the last version of the building system. Bottom: the use of joining plates and the ease of storing the metal components. Source: Archivio Michele Pagano.*

gidity ratio and the overall weight of the building. The brick was prefabricated in the factory by cutting "Spedo" type sheet metal (13/10 mm thickness) and molding frames, corners, as well as frames equipped with guides and fins. The assembly stage involved molding the half-brick on the chain of the cutting machine with cross bending, having the next half-brick rotated by 90°, bringing the two parts together, with a polystyrene panel in between, and nailing the diagonals in the middle. The two sandwich panels (sheet metal and hardboard) with an internal layer of polyester and resin were formed in multiple presses. The octagonal assem-

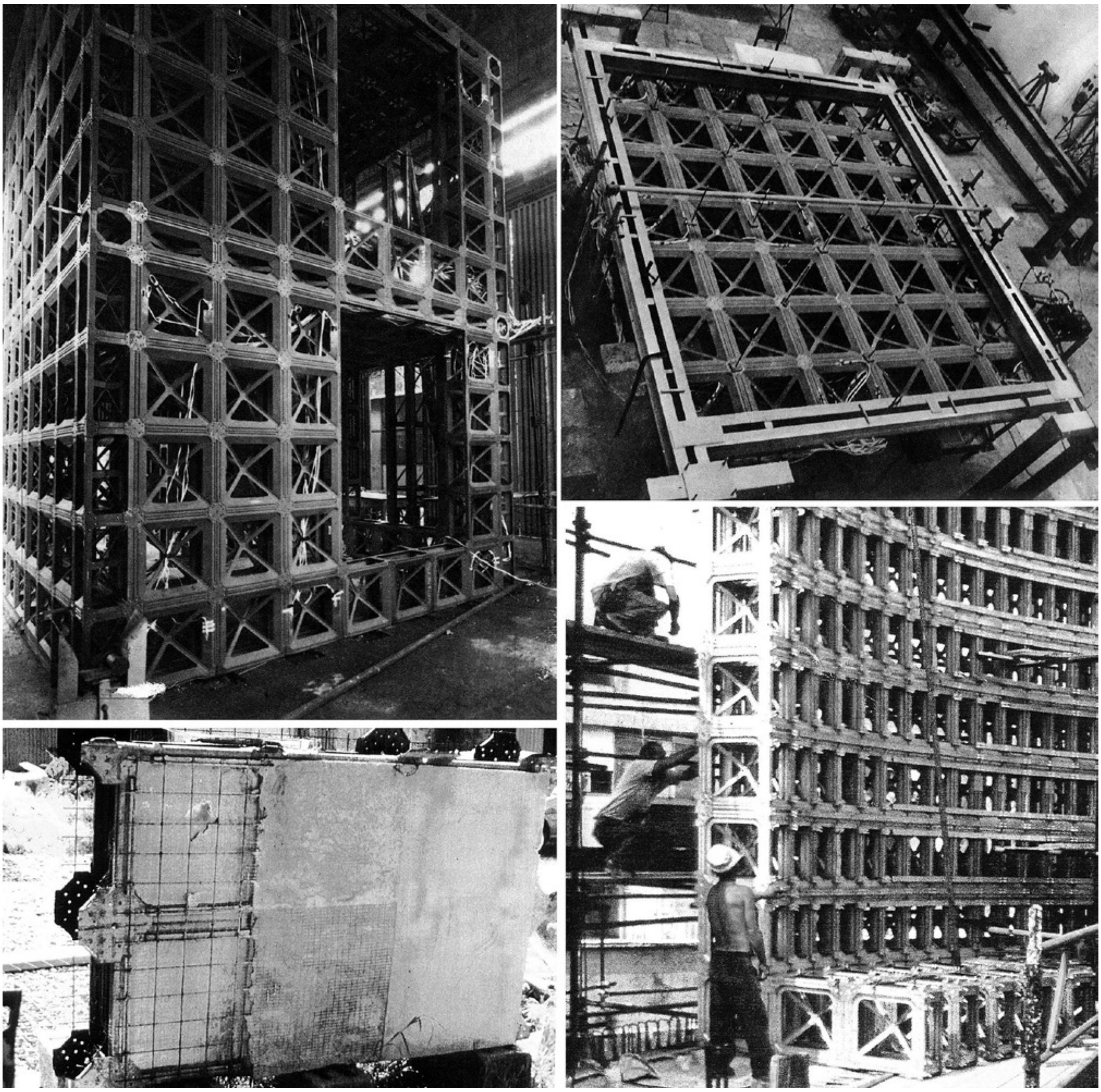

Fig. 8. *The steel brick developed by Pagano. Top left and right: the walls and slabs composed of steel bricks and tested in the laboratory of CESUN center. Bottom: a curved wall made of steel bricks and the mock-up of the wall. Source: Archivio Michele Pagano.*

bly plate was added to this component, with 4 nails, flat or angular, and the system-supporting skirting board in rigid expanded polyester [27]. The steel bricks, each one with a weight of 4 kg, could be placed side by side and mechanically assembled to form floor or wall elements (Fig. 8). Consistent with the objectives set, the research determined the cost based on the number of bricks per room (for a 28 m^2 room, approximately 158 bricks were needed) and the cost of the entire structure was estimated (800,000 *lire*).

6. *STUDIO PER L'INSERIMENTO DELLE STRUTTURE E DEGLI ELEMENTI COSTRUTTIVI IN ACCIAIO NEL PROCEDIMENTO COSTRUTTIVO A CICLO APERTO*, 1970 (STUDY FOR THE INTEGRATION OF STEEL STRUCTURES AND COMPONENTS IN THE OPEN INDUSTRIALIZED BUILDING SYSTEM)

The research was promoted by CREIG-ITALEDIL and entrusted to the group coordinated by F. Donato and E.

Piroddi together with E. Mandolesi, M. Grisotti, and G. Tardella. The first phase of the research highlighted the role that steel could have in prefabricated buildings. This analysis represented the starting point for a quantitative and qualitative evaluation of the components and areas of steel application in an Open Industrialized Building System. The evaluation also had to concern the methods of correlation between all the technical elements of the building in terms of combinability, based on dimensional coordination on a modular basis, and the design of the joints through coordination of connection capabilities. To guarantee the flexibility of the layout, the group coordinated by Donato and Piroddi introduced, among the technological characteristics of each component, the "degree of autonomy" that it could assume compared to the others related to it. For these components, the design is concerned with the product's characteristics and the production process, with a "redesign" approach of other components and other more complex technological elements [19].

The steel frame was designed starting from one of the components, a six or four-way "separated joint" (Fig. 8) based on which different classes of modular dimensions were defined (2x2, 2x3, for HE 100; 3x3 or 3x4 for HE from 120 to 200 and 4x4 for HE from 220 to 300); a subsequent step consisted of determining characteristics of the correlations between the node, the column, the beam, and the braces inclined at 45° degrees (Fig. 9). The objectives of integration and correlation inspired the design

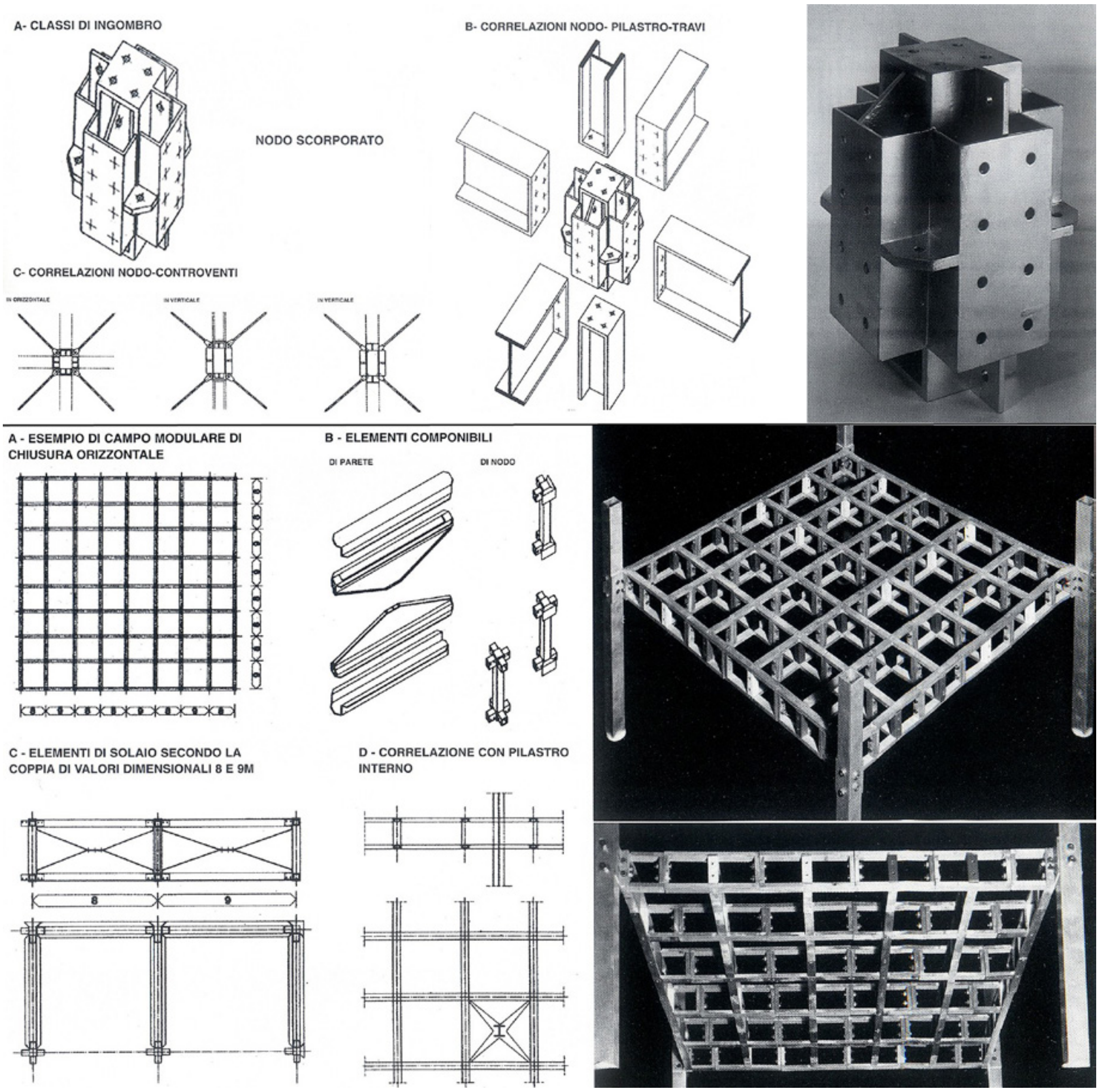

Fig. 9. *The steel components developed by Donato, Piroddi, Mandolesi, Grisotti, and Tardella. Top: the structural features of the joint useful for the connection of columns and beams. Bottom: the interlocking joists and diagonal braces of the grid slab. Source: [23].*

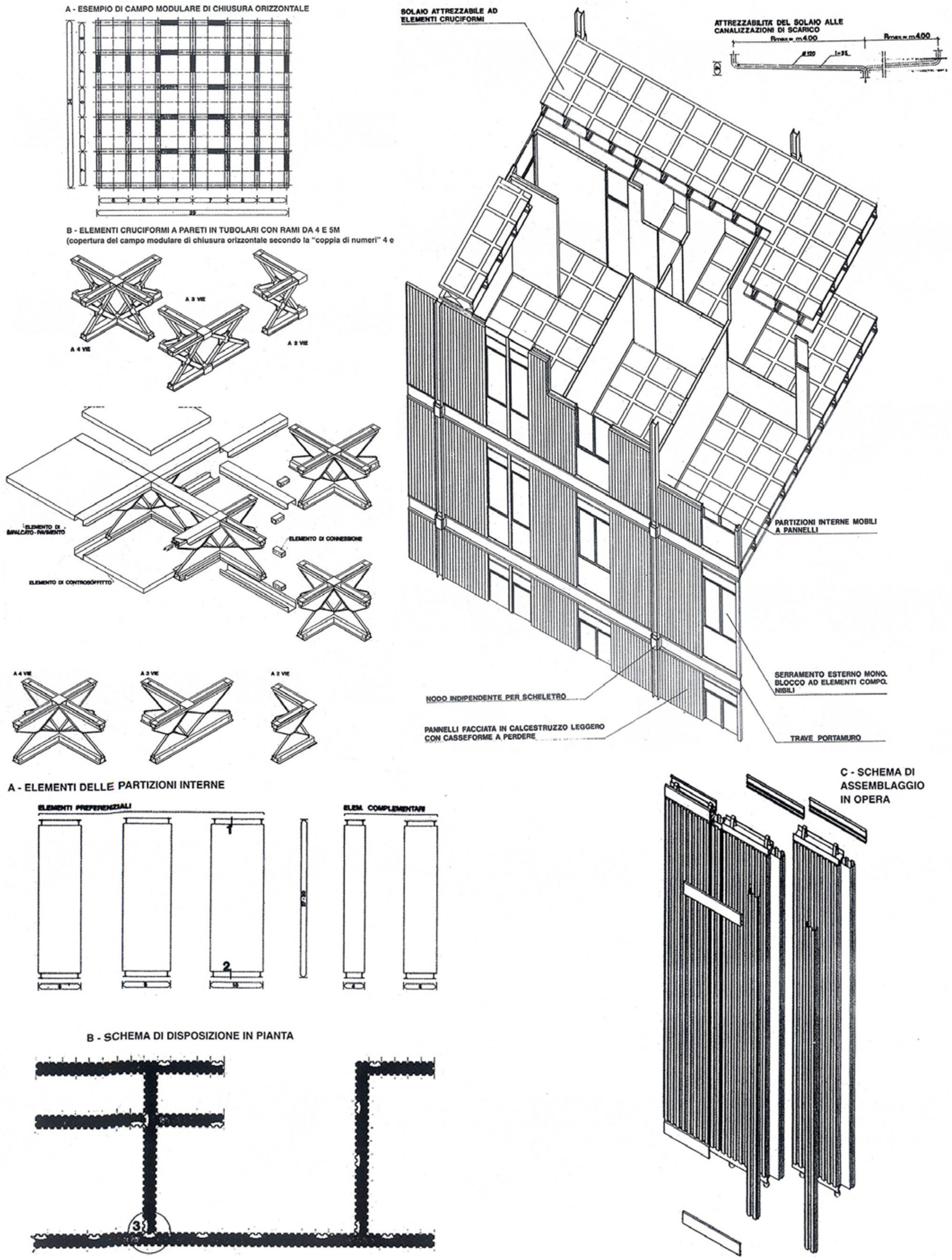

Fig. 10. *The steel components developed by Donato, Piroddi, Mandolesi, Grisotti and Tardella. Top right: the general arrangement of building components for the organization of a housing block. Top left and bottom: some focus on the grid slab and the envelope panels. Source: [23]*

of the floor component. It was supplied in two different technical-constructive solutions. The "slab that can be equipped with modular node and wall elements" consisted of cruciform steel elements consisting of a four-, three- and two-way node element, depending on the position in the structural grid of the slab and open-section columns. These elements were correlated to the technical solutions for the floor and suspended ceiling. The "floor that can be equipped with cruciform elements in galvanized steel" was made of cruciform elements and supplied in two versions: one made of tubes and the second made of sheet metal. These cruciform nodes were assembled using hidden joints, and, as before, the entire system could be correlated with the floor and suspended ceiling using dry assembly methods. Both slab solutions involved the modular coordination of the structural grid with the wall uprights (Fig. 10).

7. CONCLUSIONS

The reconstruction of the events linked to research for the prefabrication of steel construction systems is faced with the difficulty of finding documents and sources. However, this reconstruction shows how, around the theme of industrialization in the residential construction sector, the choice of a non-traditional material such as steel has shifted towards ideologically free, albeit culturally different, attitudes. This shift has favored some experiments that have investigated not only the technical-constructive but also design characteristics regarding some typological and stylistic models. In addition, the centrality of operational tools, imposed by the need to define a different design practice, ensured levels of overall quality of results, both in terms of product and process innovation, as demonstrated by the selected case studies, in the case of prototypes as well as in sporadic pilot project interventions.

Among the case studies, the proposal developed by the group composed of G.M. Oliveri and other professionals from the Nizzoli Architectural Office is an exception compared to the topic of the prototype reaching. Indeed, it only focused on the design of the construction system and its potential applications, which is different from the other examined cases, whose comparison leads to an assessment of the various levels of their diffusion. The prototype of structural components and their connections was achieved in the case of the CREIG-ITALEDIL building system, despite the direct support of a company specialized in the steel construction sector. In the case of the Fly construction system, the prototype development involved all the building components, even if were not related to the structure and the use of steel. Unfortunately, its functional flexibility, particularly envisaged for the construction of houses and schools, was not translated into its wider application. Another fate befalls the Italsider building system, which successfully overcame the prototype phase and was used in constructing the Salivoli district in Piombino, even though it represents its only result. The construction system based on the steel brick, which is an anomaly in comparison to the others as it involved a single component for the conception of an entire structural system, was the only one that was used for multiple applications, thanks to a longer-lasting experimentation, also pushed with the Irpinia earthquake of 1980. The steel brick was indeed employed for the related activities of reinforcement and reconstruction of the historic building heritage, as well as in new construction of buildings that were significantly distinct from the housing typologies for which it was initially designed, such as the church built in San Giorgio a Cremano between 1988 and 1989 [27].

The peculiarity of the construction system based on the steel brick is also reflected in some recent studies aimed at rediscovering its potential and verifying the overcoming of some critical issues that reduced its diffusion and application, mainly linked to the initial construction procedure, which involved the use of costly molds. For instance, the use of CNC machines opens up new production scenarios for this building component, which could allow for greater penetration into the construction market [28]. This continuity of experimentation cannot be found in the other examined cases, which remain unique. However, some experiments demonstrate the potential of steel structures that will be further appreciated, including the advantages of cold-formed steel profiles, as experimented by Mangiarotti and employed today for construction systems that can be adapted to various housing typologies.

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