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Prefabrication as large-scale efficient strategy for the energy retrofit of the housing stock: An Italian case study

Francesco Pittau[a,]*, Laura E. Malighetti[a], Giuliana Iannaccone[a], Gabriele Masera[a]

[a]*Politecnico di Milano – Department of Architecture, Built environment and Construction engineering, Via Ponzio 31, Milan 20133, Italy*

Abstract

In this work a multi-story residential building located in Cinisello Balsamo, near Milan, was considered as case study for the application of two new prefabricated building systems for the energy retrofit. The first one, developed within EASEE, a European project funded by 7th Framework Program, consists in a preassembled insulated panel for the retrofit of facades, based on two TRC thin precast layers rigidly connected to an EPS core. The panels can be easily applied on the external side of existing facades without the use of scaffoldings, providing an additional efficient insulation as well a new external cladding. The second one consists in a preassembled timber panel for existing pitched roofs. The process includes the substitution of the existing roof with modular integrated panels with a high content of recycled materials that can be easily fixed on the existing structures (timber frames, concrete, masonry, etc.). The combination of the two prefabricated construction systems, applied on the case study, allowed the reduction of the building energy demand by 82%.

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Keywords: Refurbishment; energy retrofit; prefabrication; recladding; roof

1. Introduction

In Europe, the building sector is responsible for roughly 40% of the total primary energy consumption. The residential sector is a top priority in terms of maximizing the energy efficiency, since it accounts for almost 63% of the total primary energy consumption of the construction sector [1]. An 80% reduction in global GHGs emissions by

* Corresponding author. Tel.: +39-0341-48-8879; fax: +39-0341-48-8701.
E-mail address: francesco.pittau@polimi.it

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2050 is the fundamental goal suggested by IEA in order to decrease significantly the impact of the building sector on the environment. Similarly, the IPCC defined imminent actions to be actuated in order to decrease the impacts on people and ecosystems and mitigate the related risks on climate change [2]. In 2010, the EU Parliament approved the final version of the Energy Performance of Buildings Directive, which requires each Member State to propose measures to increase the number of highly energy-efficient buildings and to encourage best practices for cost-effective transformations of existing buildings into NZEBs [3]. The greatest potential in reducing the operational energy need is represented by non-refurbished buildings built between 1950 and 1980. Most of the building stock in EU is represented by buildings realized during this period with a high heating demand [4,5]. Such buildings were also indicated to be the most vulnerable to climate change [6]. Therefore, in the next decades, a strategic refurbishment policy of the housing stock is required in order to meet the EU sustainability targets.

In the wide European suburban areas, an important share of the housing stock is represented by multistory residential buildings realized in the post-war period. Usually, such buildings were realized without any concern about energy efficiency and often no maintenance activity were planned during their service lives. Nowadays, this improper building management results in the advanced state of decay of the finishing materials and building services, as well as in the deterioration of the building components mainly due to mold growth. Moreover, this advanced degradation of the building stock also results in a social decay of the suburban districts, which affects the lowest social level of the population with an increasing security risk. The retrofit of the roof, and especially the external walls through increasing the thermal insulation, is the most effective action in order to decrease the energy need for heating and cooling. Regarding multistory buildings, the recladding through the replacement of the existing envelope, or the overcladding of the existing walls with new prefabricated modular elements, provide an efficient strategy for energy savings [7,8].

Nomenclature

EASEE	Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-story and multi-owner residential buildings
ECBCS	Energy Conservation for Building and Community System Program
EPS	Expanded Polystyrene Sintered
ETICS	External Thermal Insulation Composite Systems
TRC	Textile Reinforced Concrete
GHG	Greenhouse gas
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MDF	Medium-Density Fiberboard
NZEB	Nearly Zero-Energy Building
OSB	Oriented Strand Board

1.1. Current critical issues of social housing

In Italy, the "housing issue" has returned highly topical in recent years [9]. After a period in which it was not addressed by national policies anymore due to an increased high percentage of owner families, it has been rising today with different characteristics from the past. Until thirty years ago, the housing demand consisted of a highly homogeneous social class. Over the last twenty years this has been altered to several new features. For this reason, a single policy cannot be addressed since it would not be able to respond to the fragmentation of the demand. Thus, new diversified and targeted policies, developed according to the needs of different actors, who represent the demand, is strongly required. Often, the dissatisfaction of the inhabitants of suburban districts is related to a wrong social concept, where no attention was paid on the integration of the inhabitants. Based on this critical situation, in many Italian suburban district the marginalization and social discrimination has risen significantly in the last decades. In many cases, the outdoor spaces were designed without taking into account the needs of the users, and the positive aggregation functions and the social relationship among the tenants were inhibited. Moreover, the quality of the houses is critically inadequate because of the advanced state of degradation due to the lack of maintenance [10]. The current low energy performance of the buildings is mainly related to construction solutions no longer suitable and to the obsolescence of the mechanical systems.

For these reasons, contrary to the past, a new vision for the refurbishment of the social housing should be necessarily redefined, trying to encourage the social integration, both internally among tenants and between the building and the built environment. Particularly, in order to encourage the social integration, new common areas should be provided, as well as a wider range of housing able to meet the different needs of the users. Thus, the refurbishment of the housing stock becomes a complex topic where a multidisciplinary approach is required in order to positively address an energy retrofit.

1.2. Statistics of the housing stock

Many European Countries, in order to meet the EU objectives, are assuming in their building retrofit plans advanced scenarios based on more than one renovated dwelling per minute by 2050. These ambitious programs aim to revive the construction sector through the promotion of the energy efficiency of the obsolete buildings [11].

Buildings dating between 1925 and 1975 were realized in a period where the consciousness about the energy efficiency of the buildings was minimal and most of them account for a very high-energy demand. They are furthermore those that, according to a recent report published by the Architect Council of Europe [12], will require in the next future the greatest investment for the envelope refurbishment to guarantee a future exploitation as residential or office buildings. A common feature of these buildings is that usually they are not regulated by specific constraints, so – differently from historical buildings – it is possible to address them through an intensive refurbishment approach, although the original appearance of the façade in general needs to be preserved.

In Italy, as shown in the following Fig. 1.a, the share of buildings realized in the periods between 1945 and 1990 accounts for roughly 70% of the total, while the annual rate of new constructions realized after 1990 is quite low, less than 1% [11].

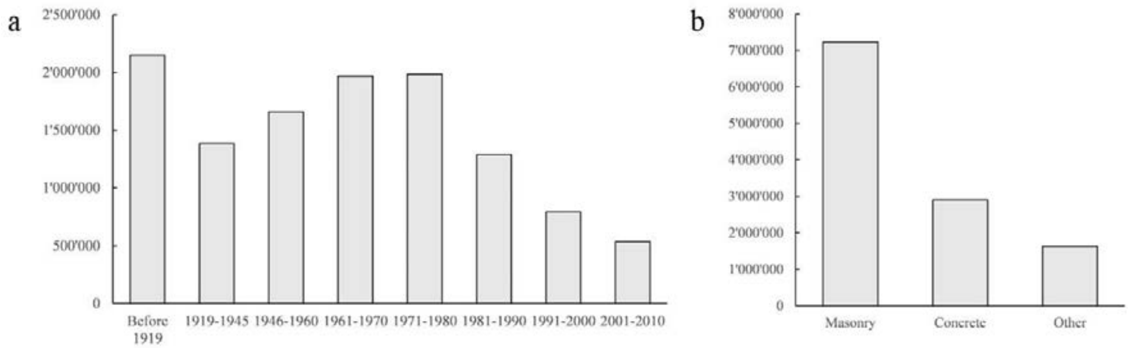


Fig. 1. Number of buildings in Italy: a) for each construction period – 2011; b) for different construction technologies - 2011.

According to the the World Business Council for Sustainable Development [12], more than half of the European building stock (roughly 80 million buildings) is not regulated by any constraint. Residential buildings represent about one third of these, with 10 millions of them multistory buildings. This typology of buildings is widely diffused among the European cities and present common interesting features from the architectural and structural point of view. They often present a linear façade (with or without a render covering), with some three-dimensional architectural elements/patterns and appendices, as well as hydraulic/gas piping or electrical cabling.

In Italy, as shown in the above Fig. 1.b, almost 7 million buildings were realized in masonry, while roughly 2.8 using reinforced concrete. Other construction technologies (e.g. timber, aluminum framed systems, etc.) are not largely diffused yet for the realization of multistory buildings. According to a report published in 2008 [13], a large part of this European existing building stock, mainly with cavity external walls, still needs to be insulated and there is a lack of practical technical solutions in this area.

2. Modular off-site prefabricated construction systems for the energy retrofit of multistory buildings

The prefabrication-based systems are able to provide an immediate response to the housing needs – both new and renovated houses – and to the related social services. Nowadays, most of the modular prefabricated systems are also able to reproduce the original façade minimizing the construction site related discomfort for the occupants. Moreover, a new approach for the promotion of the multi-functionality in the façade system (e.g. integration of piping systems for solar thermal panels, natural ventilation, HVAC and energy management, etc.) would be definitely required to increase the overall cost-effectiveness. Among prefabricated building systems, the wood pre-assembled components are those that are accounting for the largest growth in the Italian market. The benefits in using preassembled timber components for building constructions are manifold: the manufacturing costs can be significantly decreased by the seriality and modularity of the production, while their fast assembly ensures a short duration of the onsite construction, without decreasing the structural stiffness and the thermo-acoustic performances.

Lahmann [14] shows that the development of models and construction technologies based on the optimization of the raw materials is becoming a fundamental topic in the next years. Generally, prefabricated construction technologies allow the optimization of the manufacturing process, as well as decreasing the carbon emissions during material processing and assembly. Modular timber constructions, especially if based on massive wooden elements (plywood, LVL panels, CLT, etc.), allow to store a great amount of carbon into the structure (almost 50% of the mass). Moreover, considering their high seismic resistance, the large use of wood systems for the realization of multi-story residential buildings may lead to increase significantly the seismic safety in the next future.

Similarly, Spiehs [15] shows the benefits in the large use of preassembled wood-based construction systems in building. Differently from traditional construction systems, which are mainly based on labor-intensive, handcrafted components assembled onsite, preassembled timber construction systems are able to respond positively to the contemporary needs of living, ensuring high performances and reliability, as well as saving construction time and installation costs. Both in new buildings and in refurbishment and retrofit of existing buildings, several positive benefits in using these construction technologies can be achieved. Often, in the refurbishment of existing buildings the need of reducing the costs of the on-site construction without decreasing the level of precision of the assembly may be a crucial priority.

Recently in the EU, several researches were carried out in order to share the results of the different experiences on the application of prefabricated modular systems for the recladding of existing façades. An interesting research project carried out by Höfler et al. [16] is substantially based on the study of the application of large prefabricated modules on existing façades. Through the use of prefabricated façade modules, a significant reduction of the U-value was achieved through the elimination of existing thermal bridges. Nevertheless, the values obtained are not comparable in any case to those that can be measured in new buildings. The replacement of windows is the only operation to be performed from inside. Thus, the inconvenience to the users are reduced and the construction site can progress without creating particular discomfort to the tenants.

Similarly, Silva et al. [17] developed and tested a small dimension modular element for the retrofit of a building façade in Portugal. The module was developed to be easily applied and removed. The structure of the panels is based on two steel U-profiles which are connected by small cylindrical connectors to a T steel shaped substructure, installed on the existing wall. The standard dimension of the panel is 1 m x 1 m, with a thickness of about 18.8 cm and a weight of about 32 kg/m^2. Thus, the handling and transportation operations are facilitated in every construction stage, due to the small size and light weight of the elements. Moreover, the maintenance is facilitated due to the possibility of an easy disassembly of the modules from the metal substructure.

Finally, Kobler et al. [18] carried out a study based on the design of small panels with highly standardized dimensions. In this proposal, a partial prefabrication system was investigated where an integration with other strategies and technical solutions was evaluated. The result was the design of a small panel that includes the windows, the solar shading, the system elements and other technical details. The module is designed to be applied to vertical strips (if the openings are arranged in line) and, ideally, to all the parts of the vertical envelope where a window is needed. The envelope areas uncovered can be completed either by conventional techniques or by other various types of prefabricated panels.

3. Case study description

An existing residential building located in Cinisello Balsamo, near Milan, was considered as a case study. The building, shown in Fig. 2, a three-story residential building built in 1971, is included in a large public housing district in a highly degraded urban area.

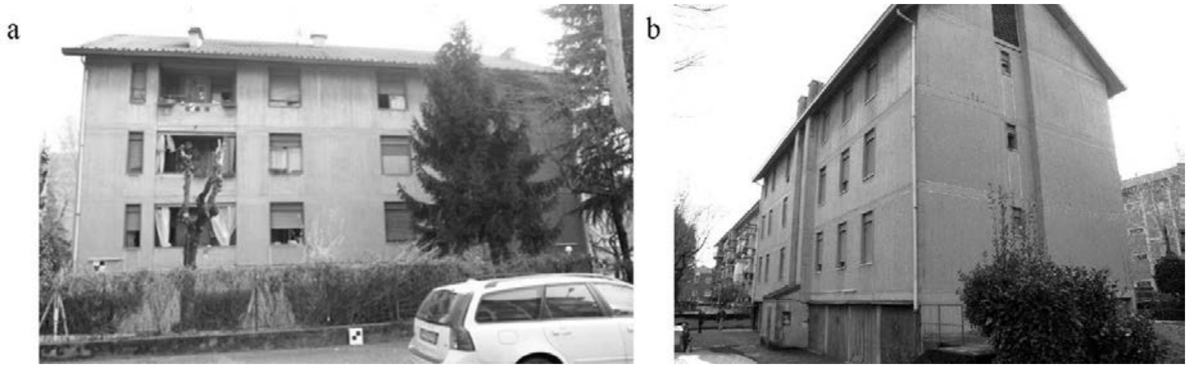


Fig. 2. a) south façade of the multistory building; b) north-west corner.

The plans were designed based on a standard floor, evenly repeated in elevation as shown in Fig. 3. Globally, the building contains six flats, two on each floor with two different sizes.

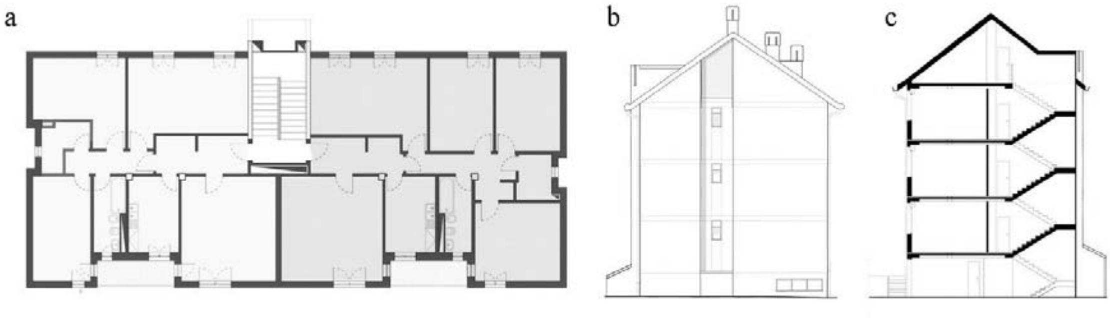


Fig. 3. a) Typical floor; b) west elevation; c) cross section.

The load-bearing structure was realized using reinforced concrete with central columns and external reinforced concrete walls. The slabs, as well the pitched roof, are made of hollow block floors, while the external walls are based on 35 cm thick, non-insulated cavity walls made of exposed reinforced concrete (20 cm), an air gap (5 cm) and an internal brick layer (10 cm). The yearly energy consumption of the building, due to a very low thermal resistance of the envelope (both opaque and transparent), is significantly high. The volume is compact, with a rectangular area of 11 m x 25 m. The facades are regular in elevation and the pitched roof, accessible only for maintenance, is ventilated and symmetric, with the east- and west-oriented faces approximately 6 m long. For this reason, an energy retrofit was considered for this case study, based on the application of a modular construction system that can be easily applied as a replacement of the existing roof.

4. Strategies for the energy retrofit of the case study

The actions on the existing building stock, especially when dealing with social housing multistory buildings, are complex tasks that require a careful and intensive preliminary analysis. The first study was aimed to the definition of the residual thermal performance of the building envelope. The analysis were carried out both through numerical models, based on the assumed physical properties of the materials, and through in situ investigations with the measurement of the thermal losses through the envelope, as shown in Fig. 4.

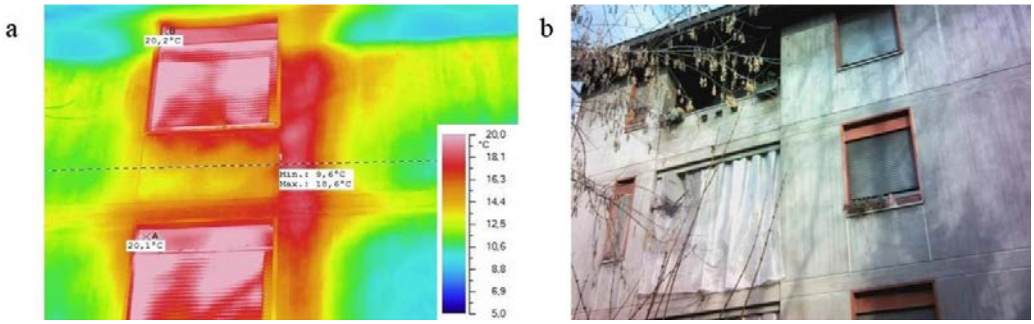


Fig. 4. a) superficial temperature of the external finishing; b) the investigated north façade.

Finally, the interior spaces were verified in terms of usability and flexibility. Through this approach, the unverified requirements were detected and the optimal retrofit strategies defined. A preliminary analysis phase, if properly performed, can provide solid basis for an appropriate intervention plan, commensurate with the needs of the customer. Moreover, if related to a predictive modeling process, the compliance of the proposed solutions can be quantified and setup on the bases of the final goals. After this stage, as shown in Fig. 5, the main actions taken into account for the building retrofit were two. The first involved the internal layout, in order to optimize the living spaces, create new common areas and differentiate the size of the flats. The second, instead, was focused on the technological aspects by the use of prefabricated building components for the reconstruction of the pitched roof (Habitat panels) and the thermal improvement the external walls (EASEE panels).

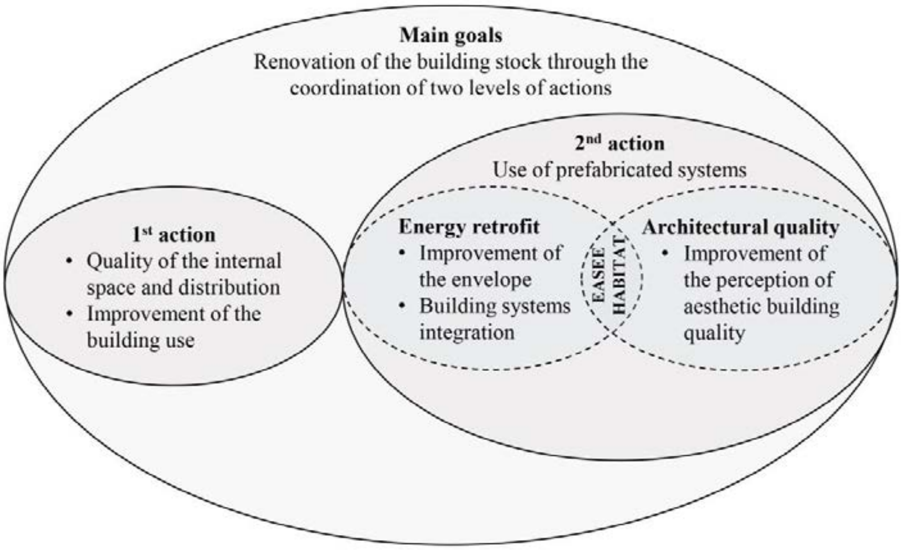
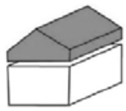
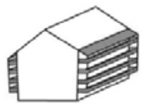
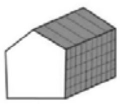


Fig. 5. Action strategies for the refurbishment and the energy retrofit of the building.

The EASEE panel was tested on the case study for the façade recladding by installing a second skin, while the Habitat roofing panel, which allowed the realization of an attic space, was adopted to replace the existing roof. The use of prefabricated systems, typically more lightweight than traditional construction solutions, allowed a reduction of permanent dead loads, with less stress on the existing structure.

The main action categories considered in the project are shown in the following Tab. 1.

Table 1. The three action categories considered for the building refurbishment.

Scheme	Action category	Description
	Story addition with shape continuity	Extension of the living volume through the construction of a new upper floor. The geometry of the original building is preserved.
	Façade addition	Extension of the external space through the addition of new volumes and technical elements (solar shading systems and balconies).
	Envelope recladding	Addition of a second opaque skin applied on the existing walls and substitution of the existing roof. The new prefabricated elements, directly connected to the structure, also play the role of new cladding system.

4.1. Use of prefabricated systems: the EASEE panel

The EASEE prefabricated panels consist of two thin TRC layers with an interposed EPS insulation. The TRC is a composite material consisting of a fine grain concrete matrix with high resistance, reinforced by a textile grid able to increase the bending capacity of the panel [19]. EPS is one of the most used materials for the thermal insulation because it combines low thermal conductivity with economy and simplicity of application. The maximum dimensions that can be achieved by the panel depend on the application. In general, the limit is 330 cm in height and 150 cm in width. The total thickness, as shown in Fig. 6, is 12.4 cm: 1.2 cm for each TRC layer and 10 cm for the EPS insulation. The panel has a specific mass of 50 kg/m^2.

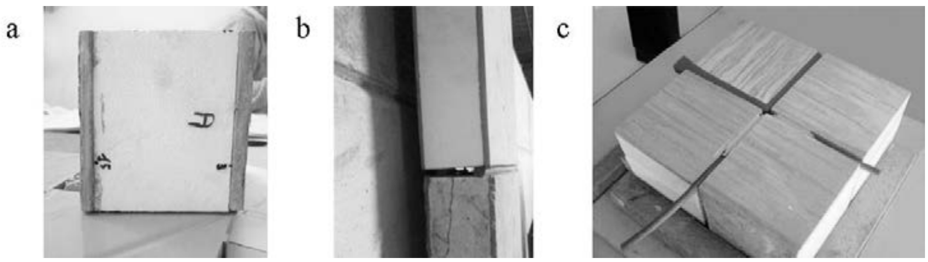


Fig. 6. a) composition of the panel; b) mechanical fixing on the existing wall; c) air and water sealing of the structural joints.

The joints between the panels were closed using a low elastic sealant with high ageing resistance. Silicon was laid on a polyurethane backfill material in order to reduce the risk of cracking. Around the whole perimeter of the test facade, the cavity between the panels and the existing wall was closed using a polyurethane foam sealant. Thus, the air permeability was drastically reduced and a non-ventilated air cavity created.

The finishing of the vertical walls with EASEE solution can also reproduce the original finishing of the building in exposed concrete. The possible customization of the finishing is a special feature of the TRC material, and it can be achieved either with the use of special textured molds in the formwork, and/or with the integration of pigments or colored aggregates in the cement mix. As shown in Fig. 7, for the realization of the new finishing of the facades, various shades of grey were obtained through pigments added to the concrete mix.

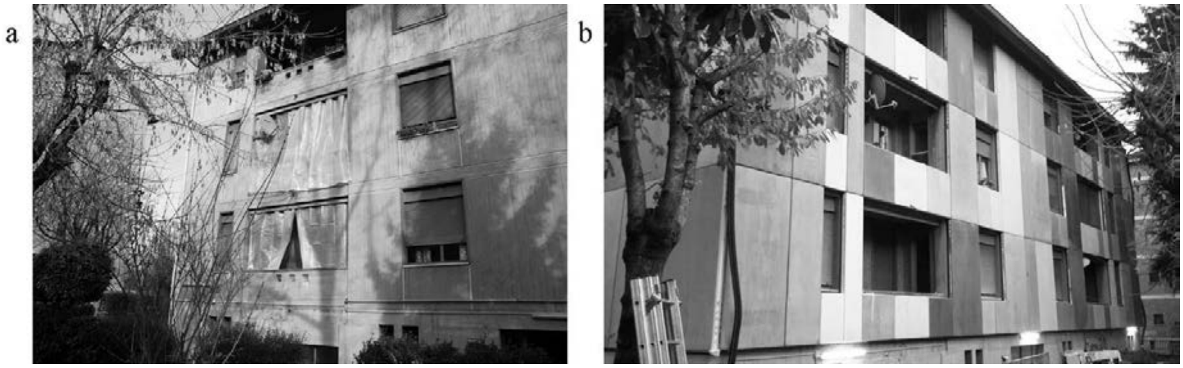


Fig. 7. a) the south façade before the recladding; b) the south façade after the installation of the prefabricated insulated panels.

The connections are a crucial part of the whole process. Their position must be accurate and precise, because the involved tolerances are reduced. A particular "box system" is provided with a special slot that allows the movement with a crane for easier lifting. The manufacturing process is rigidly controlled in the factory and the simplicity of the onsite installation is one of the main benefits of the system. The components arrive on site ready to be installed, making the operations much faster with limited discomfort for the users.

4.2. Use of prefabricated systems: the Habitat roofing panel

The Habitat panel was developed within a research project where several local social cooperatives were involved. The aim of the project was to define a new prefabricated building element which can be totally manufactured by non-skilled workers of a cooperatives. Thus, the concept was developed around a wood-based composite panel with a high content of recycled materials to be installed as a replacement of existing roofs [20].
The base version to be applied on the roof of the case study was developed around the concept of an asymmetric, non-load bearing panel, created through a multi-cell OSB box. As shown in Fig. 8, the panels can be installed on the existing framed structures. In the internal cavity, different types of insulation products with high content of recycled material can be easily used.

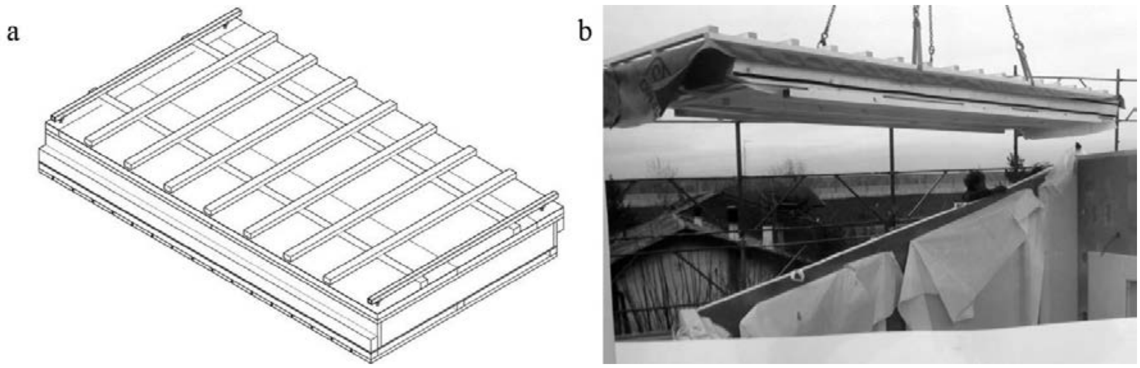


Fig. 8. a) Structure of the Habitat panel; b) on-site installation of a similar preassembled roofing module.

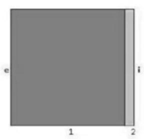
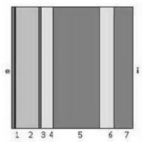
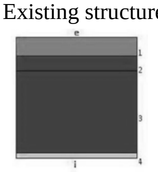
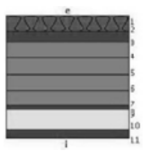
The module was developed to span the whole roof with a single element, from the eaves to the ridge, with a rapid, precise and economic onsite installation. For the realization of the eaves, separate elements were designed in order to decrease the thickness of the cantilevering parts. The eaves were designed through the use of KVH beams with variable section, laterally fixed to the panel box through special slots on the shorter side.

All the membranes, both the inner one with the function of vapor control layer and the outer waterproof one, were designed to be totally integrated off-site into the element. This resulted in a detailed study of the overlaps of the various membranes, in order to ensure the correct airtightness between the different modules, avoiding damages due to concentrated leakages. Similarly, the ventilation battens were studied in order to be assembled directly off-site within the panel. Based on this option, two special transverse elements, one on the eaves and the other on the ridge, were provided for moving and handling the panel during the transportation and the onsite installation. Particularly, two galvanized steel tubular elements were rigidly connected to the OSB box, in order to support the temporary loads generated by lifting and positioning the panel during the onsite installation. On the basis of the technical and geometrical aspects of the case study, the sizes of the various pre-assembled modules were optimized and adapted to the new framed structure. Moreover, all the most common roofing accessories (e.g. roof windows, roof top protection systems, chimneys, collectors, etc.) can be totally integrated in the panels, avoiding additional complex operations during the onsite construction.

5. Conclusions

This work was developed with the aim of showing the steps required for the rehabilitation of multi-story buildings when fully preassembled modular elements are adopted. Based on the results obtained from the case study analysis (a multi-story public housing building located in a municipality near Milan), the phase of rehabilitation of the interior spaces is extremely complex. Several alternative distribution proposals were carefully evaluated to determine the most effective one able to respond to the imposed objectives. The quality of use of the apartments was finally improved by defining repeatable spatial units able to satisfy the demand in compliance with the quality requirements. The feasibility assessment of the proposed solutions for the building envelope retrofit was another key objective. The main advantage achieved by the application of large prefabricated construction systems is definitely in the rapidity of the construction and in the reduction of the fixing points. Moreover, as shown in Tab. 2, the thermal resistance of the envelope was significantly improved, with a reduction of the primary energy consumption for heating by 82% (from 198 kWh/m^{2}y to 35 kWh/m^{2}y).

Table 2. Comparison between the external walls and the pitched roof structures before and after the refurbishment.

EXTERNAL WALL			
Existing structure		Refurbished structure	
	Thickness: 0.21 m Mass: 501 kg/m^2 Therm. resistance: 0.28 m^{2}K/W U: 3.52 W/m^{2}K		Thickness: 0.51 m Mass: 598 kg/m^2 Therm. resistance: 3.41 m^{2}K/W U: 0.29 W/m^{2}K
PITCHED ROOF			
Existing structure		Refurbished structure	
	Thickness: 0.32 m Mass: 337 kg/m^2 Therm. resistance: 0.88 m^{2}K/W U: 1.13 W/m^{2}K		Thickness: 0.30 m Mass: 78 kg/m^2 Therm. resistance: 5.35 m^{2}K/W U: 0.19 W/mK

However, difficulties related to the handling and the poor compatibility with complex and irregular geometries were observed. The main limitation found in the application of EASEE panels for facades consists in the variability of the air cavity generated between the panels and the existing wall. If, on the one hand, the flexibility of the joint allows the adaptability of the panel to the irregularity of the existing surfaces, on the other it constitutes a threat to the energy efficiency of the retrofit operation.

The Habitat roofing solution was designed to be manufactured and marketed by social cooperatives. This aspect represented a fundamental issue which implied the need to design a solution based on the resources and capabilities of the cooperatives. For this reason, the structural function was not included in the panel, since it would require complex operations and the use of equipment that could not be provided by the cooperatives. However, the application of the solution on the case study showed that the structural integration could result in evident advantages. In addition, the reduction of the costs for the structure would necessarily result in an increased cost of the panel, which could still be beneficial due to its standardization.

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