Deep renovation of multi-storey multi-owner existing residential buildings: A pilot case study in Italy

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The present paper illustrates the Italian pilot action of the EASEE project (Envelope Approach to improve Sustainability and Energy Efficiency in existing multi-storey multi owner residential buildings), focusing on the analysis of energy refurbishment trends of the Lombardy region residential building stock.

More than 60% of the existing building stock in Lombardy region has been built before the 70 s and it is among the main responsible causes of final energy absorption and corresponding CO_2 emissions with a mean primary energy index for heating of about 202.0 kWh/m^{2}y. The promotion of renovation mea-sures for such buildings, also through innovative solutions, is becoming increasingly important for both containing the greenhouse gas emissions and supporting the growth of the construction sector. To this topic, the work presents the energy renovation of a residential building in the Province of Milan through the application of innovative prefabricated composite panels that integrate both thermal insulation and exterior finishing with textile reinforced mortar. In detail, the paper describes, on one hand, the main design strategies following the preliminary analysis and, on the other hand, the whole installation pro-cess; besides, the performance of the retrofitted envelope is documented by the results of the monitoring campaign.

Keywords: Building envelope renovation, Residential buildings, Prefabricate panels, Energy efficiency

1. Introduction

1.1. EU building stock and energy renovation market

At the current state, the European Union is facing a double challenge: increasing building renovation rates while aiming at achieving "deep renovations". Increasing the current EU renovation rate from 1.2% per annum to 2–3% is essential to meet both the EU 2020 targets and the commitment undertaken in Paris in December 2015. About 75% of the EU's 210 million buildings are not energy efficient, and 75%–85% of them will still be in use in 2050. Ensuring a highly-efficient and fully decarbonised building stock by 2050 is a major challenge. The quality of the energy renovation of our building stock is, therefore, of paramount importance [1].

The ongoing review of the building-related EU legislation must prioritise action to decarbonize the existing building stock by speeding up the rate and depth of renovations.

The Energy Performance of Buildings Directive (EPBD) [2], with the requirement for all new buildings to be nearly Zero-Energy Buildings (nZEB) from 2021 (and from 2019 for public buildings) has raised the bar and the awareness about highly energy performant buildings in the EU. The nZEB definition ([3–9]) should be updated to reflect the new possibilities that a transforming energy market could bring as well as to include the existing building stock. This transition to an nZEB level for all buildings will help mitigate the stress put on the energy system and bring positive environmental effects through the reduction of GHGs, social benefits due to reduced energy bills as well as better living conditions and economic effects through a smarter and more dynamic energy use. Buildings account for around 40% of the total energy consumption and 36% of the CO_2 emissions in Europe and possess the biggest untapped mitigation potential. With the appropriate support, buildings could play a leading role in transforming the EU energy system increasing the speed with which the three biggest CO_2 polluters – the buildings, transport and power sectors – are reducing their climate impact. Energy will be saved, generated,

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Abbreviations: EU, European Union; nZEB, nearly zero energy building; GHG, green house gas; SEN, national energy strategy; PAEE, action Plan for energy efficiency; EASEE, envelope approach to improve sustainability and energy efficiency in existing multy-storey residential buildings; BIM, building information model; PA, Public Authorities; TLS, terrestrial laser scanning; GSD, Ground Sampling Distance; ETAG, European technical approval guidelines; TRM, textile reinforced mortar; HPFRC, high performance fiber reinforced concrete; LCA, life cycle assessment.

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stored and used where people spend most of their time – in buildings. A deep energy renovation of the existing building stock could reduce energy demand by 80% before 2050 compared to 2005 levels. A highly energy efficient building stock, realized by deep renovation and efficient new buildings, brings multiple benefits to demand reduction, but will also enable demand response and the integration of volatile renewable energy increase on the supply side [10].

There is no common definition for "deep renovation": "there are, however, common features among all initiatives, like the will to raise the level of ambition for achieved energy performance, to ensure consistency between short and long term measures and to align the target for the performance of individual buildings with the long-term target for the entire building stock" [11].

An energy renovation market is emerging in Europe and playing a strong role as a stabilizer of the building sector and consequently of the European economy in the period since the financial crisis. Estimates of the energy renovation market were of the order of 109 billion Euros in 2015 and it created 882,900 jobs. The Italian, German and French energy renovation markets alone accounted for almost half of the EU energy renovation market. The Italian National Energy Strategy (SEN) [12] places the energy efficiency among the priorities in the action. At this regard, the Italian "Action Plan for the Energy Efficiency" (PAEE, 2014) [13] identifies the building sector as a key element for achieving the objectives set by the country in 2020. The PAEE, among other things, establishes:(1) the strengthening of minimum energy performance requirements for new buildings and for the refurbishment of existing buildings, leading progressively to the increase of nZEBs, in line with the Directive 2010/31/EU [2] (EPBD recast); (2) the consolidation of the tax deduction system for the energy refurbishment of the existing buildings. An effective way to reduce the CO_2 emissions by means of the decrease of the energy consumption is the energy refurbishment of the existing building stocks, which present a high potential for energy savings in the European countries.

Several research works deal with this topic, presenting the impact of different energy conservation measures carried out on building stocks on the reduction of greenhouse gas emissions. Some studies introduce specific methodologies to evaluate the effects of different energy efficiency strategies and the environmental impact on residential case studies [14–17]. Ma et al. [18], with their study provided an overview of the research and development as well as application of the retrofit technologies in existing building and they defined a systematic approach to proper select and identify the most promising retrofit options for different type of existing buildings. Ruparathna et al. [19], similarly conducted a comprehensive review of contemporary approaches for improving the energy performance but focusing only on operating commercial and institutional buildings.

Corrado et al. [20] highlighted in particular that there is a considerable need for studies, which must focused on behavioral specific improvements. The user involvement is in fact a big challenge in the refurbishment process [21], Sesana et al. [22] involved engineering students with a participatory design process during their academic Integrated Design Refurbishment Laboratory. They defined a Methodology for Energy Efficiency Building Refurbishment (MEEBR) structured into four major phases, and they applied it on two campus buildings and they finally performed validation with Building Energy Performance Simulation tools (BEPS). This study remarks the importance and efficacy of computer simulation in assessing and identifying the most effective upgrades. However, adequate information regarding the building, its services and its operation are vital in achieving a robust and useful model. The same remarks was stated by Di Turi et al. [23], which highlighted the problem of lack of data in energy assessment models.

According to these published literatures, there are a large number of approaches available for improving the energy performance of existing buildings, but there are very complex and correlated issues involved in the building energy refurbishment, ranging from technic, economic, aesthetic, historical and cultural aspects.

> "Whole-of-building retrofit with comprehensive energy simulation, economic analysis and risk assessment is an effective approach to identifying the best refurbishment solution" [22].

In this scenario, the project EASEE [24] (Envelope Approach to improve Sustainability and Energy efficiency in Existing multistorey residential buildings multy-owner), funded by the European Union under the Seventh Framework Programme for Research and Development, among its main objectives had the development of innovative systems for the reduction of energy use in residential multifamily buildings. In particular, this paper describes the results of the demonstration activities developed within the project with the application of the EASEE methodology and the envelope retrofitting solution to a residential building case study. The description covers all the process, from the modular prefabricated façade system design, through the development in lab to the integration on a demonstrative building with a monitoring campaign.

1.2. The EASEE project: concept and objectives

Buildings dated between 1925 and 1975 were built in an era where there was little or no consciousness of the need to design for energy efficient performance and therefore have the largest energy demand. A common feature of these buildings is that they are usually not forced by specific regulatory constraints for their refurbishment, differently from historical buildings, although the original appearance of the façade needs in general to be kept.

More than half of the European building stock belongs to this category, for a total of more than 80 Millions buildings. Residential buildings represent about one third of these, 10 millions of them being multi-storey buildings, with distributed ownership [25]. This type of buildings are widely diffused in the European cities centres and present common interesting features from the architectural and structural point of view. Considering the Italian existing stock and zooming in particular at regional level [26] (Lombardy region which the pilot case study belongs to), in 2013 the residential buildings were about 11.7 million, and about 49% of the total is located in the climate zones E and F (as defined by D.P.R. 412 [27]) that are mainly characterized by cold winter climates with larger demands for space heating.

Over 60% of the existing building stock has more than 45 years; most of it has been built before 1976 [28] when the first national law regarding energy saving in buildings has been introduced – and more than 25% has an annual consumption between 160 and 200 kWh/m^{2}y [29]. The main energy source is represented by natural gas with 46% of the total, followed by biomass (wood) with 22%, and 19.2% from electricity. In addition, data collected within the Energy Registry of the Lombardy Region [30] confirm an average primary energy demand for the heating season equal to 201 kWh/m^{2}y, with emissions of 43.75 kgCO_2eq/m^{2}y. Other regional data confirm that the mean thermal transmittance of the building envelope is equal to 1.09 W/m^{2}K, about four times the threshold set by the standard at 2021.

Considering the renovation construction processes and the impact of the retrofitting process on the life of the occupants, traditional approaches need scaffolding on the outer façade for very long times (on average between 12 and 24 months for a seven storey building due to the heavy removal of materials and the wet processes involved), requiring occupants to seal the windows and introducing safety issues. Furthermore, scaffolding creates burden

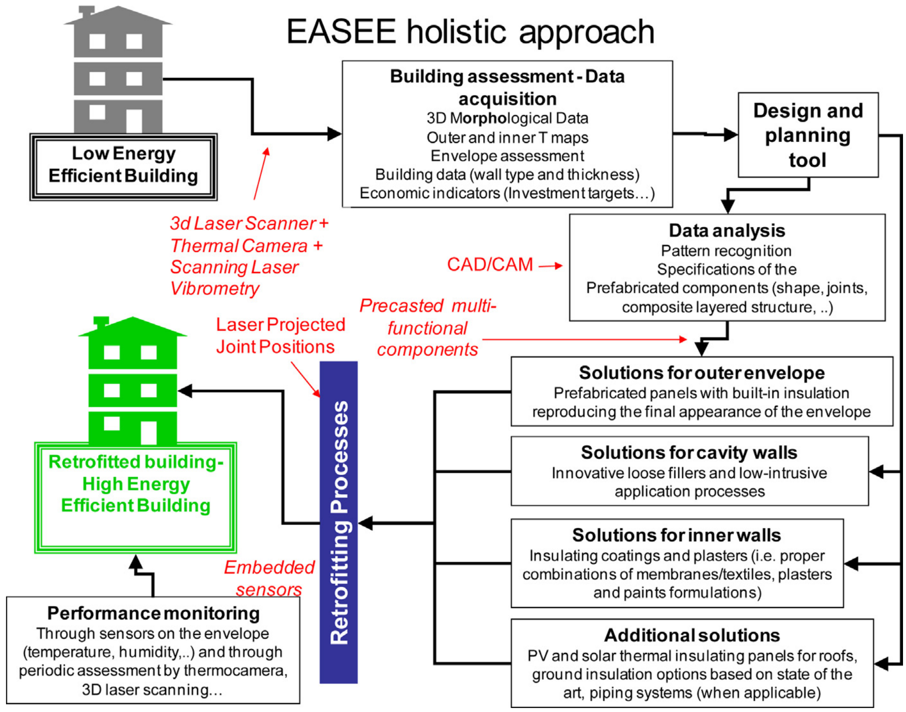


Fig. 1. EASEE holistic methodology.

to the traffic and to the people walking by, apart being an additional cost as normally local taxes to occupy the ground are to be paid.

In this framework, EASEE project aims at developing a toolkit for energy efficient envelope retrofitting for multi-storey and multi-owner buildings, which combines novel design, and assessment strategies, modular prefabricated elements, advanced insulating materials and scaffolding-free installation approaches, to reduce energy demand, minimizing the impact on occupants while preserving the façade original appearance.

EASEE project focused on the 3 main components of the envelope that influence the energy performance of multi-storey building, namely the outer façade, the cavity walls and the interior envelope, by developing innovative and easy to implement solutions ([31,32]).

This paper presents specifically the solution developed within the project for the outer façade combined according to the characteristics of the building to be retrofitted as well as to other non technical parameters as for example cost and location of the building.

The paper is structured according to 6 main sections: Section 1 describe the state of the art on refurbishment trends and regulations for existing buildings with the introduction of the EASEE project are provided; section 2 describes in details the EASEE methodology applied to a demonstration case study presented in Section 3; Section 4 describes the outer envelope retrofitting solution developed within the project; Section 5 presents the results and finally the conclusions are provided in Section 6.

The main lesson learned of the project is that it is possible to reach the final goal of reducing the energy required by the building occupants and the overall retrofitting duration of a deep renovation of existing buildings following an integrated design process – EASEE approach – that combines advanced analysis of the building stock with the development of innovative strategies.

2. The EASEE methodology for envelope retrofitting

The EASEE methodology is based on a high level of prefabrication with components, which have the final appearance without additional finishing on site, accurate measuring information of the building envelope, are required. The approach to envelope retrofitting is schematically depicted in Fig. 1.

The first step of the retrofitting process consist therefore in a careful assessment of the envelope both from structural and energetic point of view, as well as in terms of other non-technical parameters and indicators that will be useful for the planning of the retrofitting intervention. These analyses can be carried out starting from technical drawings of the buildings that might serve as a guide for a deeper assessment of the envelope characteristics and conditions. Within the project duration the EASEE methodology were applied to 7 demonstration buildings: all the case studies were a brilliant occasion to test the methodology and above all to apply the three different retrofitting solutions even in different climate conditions (Italy, Poland, Spain and Greece). This paper investigate in particular the application of the external envelope retrofitting solution in a residential building in Italy as presented in detailed in the following section.

3. The Italian demonstration building

3.1. The case study description

The Italian demo building was located in Cinisello Balsamo, in the metropolitan urban area of Milan. It was the third largest municipality of the metropolitan city after Milan by population with its 75,203 inhabitants. The urban settlement has a large population size and a high population density and the concentric pattern is predominant in the public housing estates (Fig. 2).

The building (Fig. 3) is a multy-storey and multi-family residential building owned by the Social Housing Agency of Lombardy (Azienda Lombarda Edilizia Residenziale – ALER) Milan division. It was built in 1971 and it is located in Via del Carroccio n.18 in the city of Cinisello Balsamo. It is constituted by three floors above ground and a basement where there are garages for cars (Fig. 4).

The Italian demo building was targeted to validate the retrofitting approach on a large scale, from assessment of the starting conditions to the manufacturing and installation of the modular

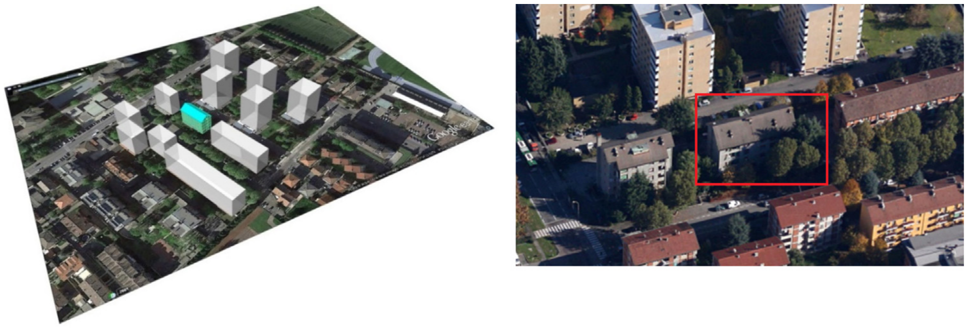
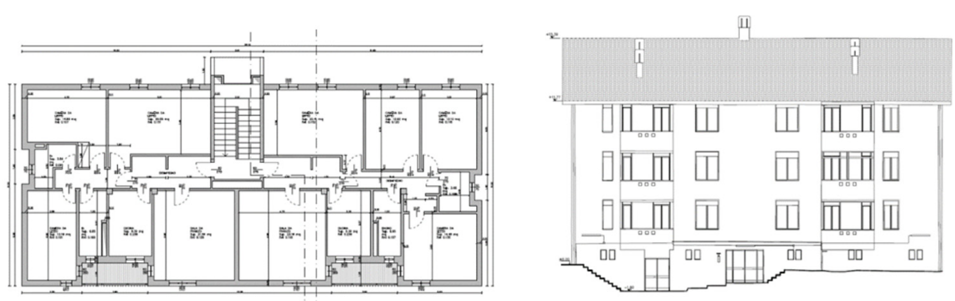


Fig. 2. Italian demo building localization.
(Source. POLIMI Elaboration).

Fig. 3. Italian demo building, North-West façade and South façade.
(Source. POLIMI).



a) b)

Fig. 4. a) Italian demo building typical plan (Source. POLIMI) and b) Italian demo building South façade before the retrofitting.
(Source. POLIMI).

elements to the monitoring of performance after retrofitting. The chosen building was selected among others because it perfectly fulfilled the desired specifications towards the demonstration activities (multi-storey multi-owners residential buildings built between 1925 and 1975). Moreover the information collected from the survey with a thermal imaging camera revealed and confirmed the needs to apply an energy retrofitting in order to solve the high energy losses from the envelope. Among the other reasons, the Italian demo building retrofitting, as a social housing, would improve the importance of replicability and impact of the EASEE approach for future improvement and applications. In particular, by retrofitting the overall building (more than 580 m^2) the following aspects have been assessed:

- panels' colours and textures;
- methodology for building (geometrical and energetic) assessment;
- BIM approach applied to EASEE retrofitting approach;
- yard preparation and installation process;
- impact on the construction process practice and on the occupants as well as on energy efficiency of the building;
- joints installation and technical details around balconies, corners, doors, windows, etc.;
- finishing activities;
- energy performance of the overall intervention.

Monitoring campaigns have been performed before, during and after the retrofitting of the building in order to know the improvements that the retrofitting solutions provided to the building.

3.2. The EASEE methodology application

According to the first step of the EASEE methodology, the building geometrical, structural and energetic assessment has been performed towards a complete evaluation of building boundary conditions. Regarding the existing structure, the building was made with pillars and reinforced concrete beams. The floors were made of reinforced cement, while the vertical closures were made of reinforced concrete. The closures had vertical against a wall with a 8 cm air gap of 5.5 cm. Internally finished with plaster lime. Externally there was no plaster but the closures were in exposed concrete.

The geometrical assessment of the demo building was devoted to: derive plans, elevations and sections (2D) and a BIM model (3D). Both 2D and 3D design are thought as a support for the design of the retrofitting intervention. In particular, the demo building surveys and data modelling carried out consisted in:

- Geometrical survey with geodetic network and laser scanning;
- Building Modelling. Modelling of the building as a support for the design of the external retrofitting and anchoring definition;
- Generation of a Building Information Model (BIM) of the building.

Each of these phases were then detailed in the following subsections.

3.3. *The case study building geometrical survey*

The building geometrical survey topographic has been carried out with two main goals:

- guarantee the desired accuracy for the alignment of scans acquired by Terrestrial Laser Scanning (TLS); and
- give a stable reference system as a support for the anchoring placement.

In particular, each vertex of the geodetic network was measured by means of a first order total station Leica TS30 performing both angular and range measurements. Benchmarks were measured using Leica circular prisms (centering accuracy 1.0 mm, range 3500 m) while reflective targets were materialized by means of retro reflective tapes (5 cm × 5 cm). For georeferencing TLS scans in the same reference system materialized by the geodetic network a set of 24 checkerboard targets was used. These targets were measured in conjunction with the geodetic network and their coordinates are used as Ground Control Points (GCPs) in the adjustment of TLS scans. The network was adjusted by using a rigorous least squares adjustment. In particular, a free network was performed in order to maximize precisions. Finally, the reference system ambiguity was fixed by assigning arbitrary coordinates (100,100,100) to vertex 200 and fixing the orientation. After network adjustment the estimated accuracy of network vertex was 0.5 mm while checkerboard accuracy was about 3.0 mm.

The TLS survey of the building was aimed at deriving as-built products (floor plans, sections, elevations and 3D models) as a support for the external retrofitting design. In particular, for the demo building the survey consisted in 12 scans, aimed at surveying the building envelope, performed by using FARO – CAM2 FOCUS 3D laser scanner. Each scan consisted roughly of 44 million points determining a mean Ground Sampling Distance (GSD) of about 2 mm. The GSD ranges from 1.5 mm in the lower part of the façade up to 3.5–4 mm in the upper part. Referencing of scans was performed by using as ground control points the checkerboard targets surveyed by theodolite and by means of 15 sphere targets used to strengthen the relative referencing of the scans. The mean referencing precision, evaluated observing residuals on the target measurements, is about 3 mm which was in a good agreement with the accuracy of measured checkerboard targets. These accuracies and the GSD were comparable with the ones traditionally used for standard practice architectural drawings and requirements associated to tolerances in panels production and anchoring positioning.

3.4. *The Building Information Model (BIM) generation*

The TLS data were used as the basis for the building modelling. The different steps of the data implementation from CAD data to building model were outlined as follows: (i) production of 2D products (plan and section of the building); (ii) from Point Clouds and CAD drawing to the 3D Model Object Modelling.

The first step of the modelling phase consisted in the production of 2D products (elevations and sections) of the building starting from the point clouds. These products outlined in a clear way geometrical criticalities and were used for the design phase. In particular, in the case of the demo building an out of plumb of approximately 7 cm was identified in the south-east façade. This element influenced both the modelling of the façade and the choice of the anchoring system in order to guarantee both the bearing capacity and a sufficient on-site regulation of the anchors. Plans and elevations were also used to perform the design of the panel size.

The second step allowed from 2D drawings and point clouds to generate a 3D model of the building (Fig. 5). The main aims of this model were:

- to integrate information coming from 2D plans, elevations and sections;
- to integrate complex geometry information (e.g. out of plumb);
- to identify criticalities and feedback to the design;
- to identify anchoring position.

The possibility to have a 3D model of the building gave the chance to trace berths. This has been possible through the geometric analysis of point clouds. Starting from multiple point clouds, the commercial software Rhino© allowed to represent complex shapes, to extract tracings of anchors and to determine the minimum and maximum distance from the external walls of the whole building guiding in this way the choice of the anchors. In addition, knowing the position of the anchors in the 3D model it was possible to derive

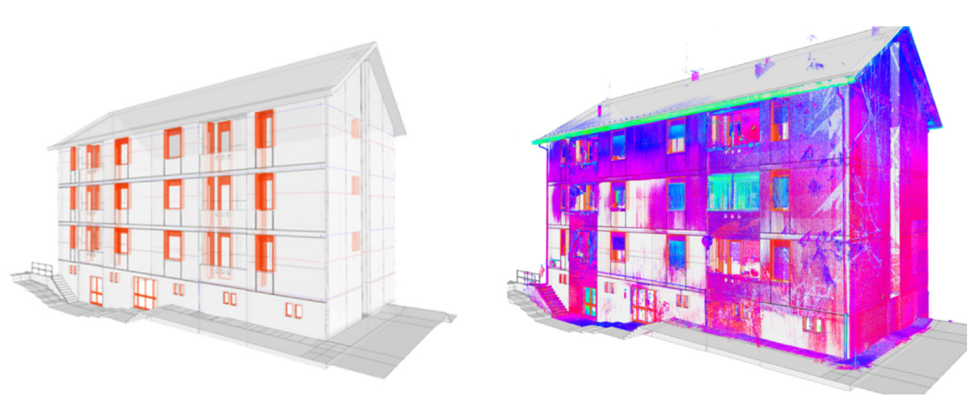
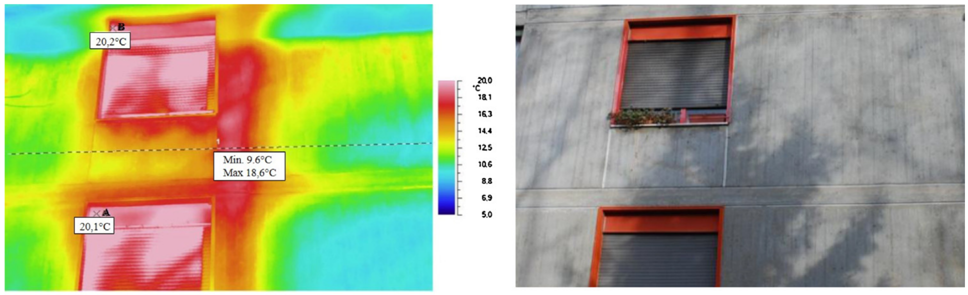


Fig. 5. Demo building 3D modelling: left Rhino© drawing. Right: over position of 3d Cloud on Rhino© model.
(Source: Politecnico di Milano)



a) b)

Fig. 6. Italian demo building thermal imaging survey on South facade.

(Source. POLIMI Elaboration).

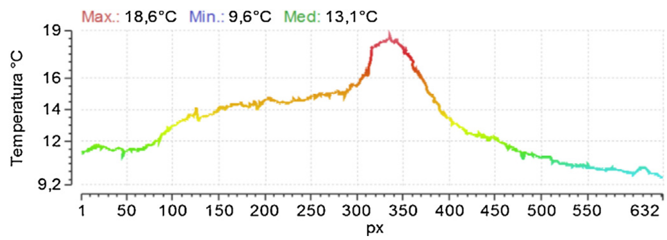


Fig. 7. Temperature profile line of the thermal survey on South façade – Ref.

(Source. POLIMI Elaboration).

their position and give this as an input for the on-site tracking by means of the total station.

By combining both geometrical and stratigraphic information a BIM Building Information Model of Cinisello Balsamo Demo was generated, also taking into consideration the different structural elements following the constructive logic of the building: elements of the cover, walls, insulation, panels, roof, pillars and beams (object oriented approach to the design).

The potential of the parametric software permitted to manage the modularity of the panel. Changes can be made directly without having to restart the project. Indeed, the parametric logical allows to change the height (z), the width (x) and maintain the thickness (y) constant. Taking into consideration the modular nature of the EASEE external retrofitting solution the parametric concepts fitted very well with the adopted solution. Indeed, once the panel element has been created, it could be "reshaped" by simply changing its parameters. Stratigraphic information was included as main information through the single type of panel. The transmittance and the change of material has been imported in the energy analysis software for further analysis. Concerning the energetic assessment, the building is supplied by a district heating, and the heating terminals in each apartments are radiators. The thermal survey has been conducted with therma imaging camera with a sensor of 307.200 pixel (640 × 480) and a frame rate of 30 Hz.

Fig. 6 represents one example of the outputs that derives from the survey and the respective critical analyses of the data collected. Specifically, Fig. 6a represents the thermal image of a portion of the South façade with A and B points analyses of the surface temperature, while Fig. 6b is the visible spectrum.

Fig. 7 represents the temperature profile of the – line 1 individuated on the South façade in Fig. 6a.

From the thermal imaging, it is clear the need to improve both opaque and transparent performances improvements in order to reduce energy losses and thermal bridges from the envelope. The main critical points are closed to the windows and the connection between floors and roof due to non-homogeneities of materials.

4. The EASEE outer façade solution

As described in the introduction, the EASEE project leads to the creation of three envelope retrofit solutions. This section provide an overview of the outer solution developed within the Task 2.1 of the project.

The conceptual design of prefabricated insulation panels started focusing on the main typological, morphological and technological features of a typical residential buildings and aiming at preserving the building envelope exterior features or, wherever possible, at improving architectural features with a reduced extra-load on existing structure. Moreover, lightness and fast and easy assembly techniques were the major concern together with the goal to install the solution without fixed scaffolds to reduce impact on inhabitants' life.

In this scenario, two different concepts (single layer and multilayer) of prefabricated shapeable retrofitting panels were preliminary compared and assessed in order to select the best option to be brought forward and tested into the demonstration building.

The single layer solution studied were made of a single extruded polystyrene (XPS) panel molded to impart the wanted 3-D shapes and superficially finished to allow for a broad range aesthetic options while providing the performance (e.g. fire, impact, etc) requirements according to the current regulations for panels (ETAG 004) [33].

The definition of the multilayer solution, started from a range of four possibility: A) Textile Reinforce Mortar (TRM) (int.) + insulation layer + TRM (ext.); B) TRM (int) + insulation layer + High Performance Fiber Reinforced Concrete HPFRC (ext); C) insulation layer + HPFRC eventually reinforced with AR-glass fabrics (ext); D) shaped insulation layer + ribbed HPFRC or TRM structure (ext).

The initial choice of the expanded polystyrene as insulation material is mainly due to its low cost and to its hygrothermal and mechanical properties, together with the possibility to be cut in the desired size. In particular, considering the mechanical properties, it is suitable because of the not excessive stiffness, the good compressive and the tensile strengths and the shear modulus.

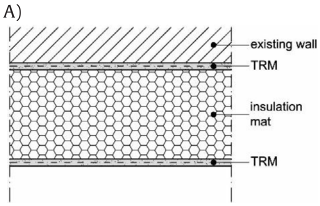
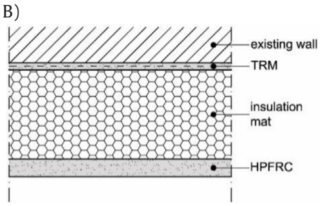
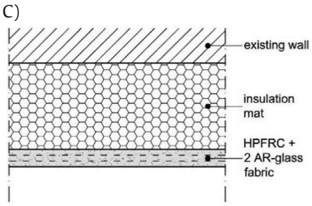
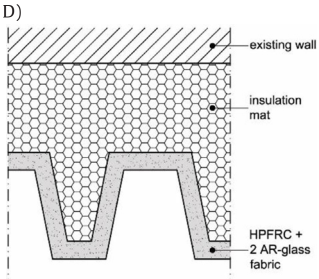
Based on the advantages and disadvantages reported in Table 1 the “A” multilayer panel combination was selected to be compared with the single layer panel solution: in particular, stability, durability and lightweight oriented the choice.

In order to compare the two solutions (single and multilayer) and to choose the final version of the EASEE outer envelope panel, different tests and various parameters were investigated regarding: structural aspect (four point bending test, bending test after freezing and thawing cycles, dimensional stability); hygrothermal behavior, LCA, anchoring and installation system and aesthetic aspect. Referring to the results of the analyses on the above listed topics, the multilayer panel resulted the best option to fulfil the project objectives. Indeed the multilayer panel presented a better bending behavior in respect to the single layer panel. Moreover the hygrothermal simulation definitely showed that the multilayer panel was expected to have a low condensation, both with non-urban and urban weather data simulations, in respect to the single layer (even if a resin based finishing coat is provided). Furthermore the multilayer panel presented a higher flexibility concerning to the aesthetic features, size, anchoring systems as well as installation procedure, with respect to the single layer panel. Moreover, the single layer panel installation seemed to be more time and cost consuming, due to the size reduction necessary to resist the wind pressure. However both the panels have a comparable behavior regarding the dimensional stability and the bending test after freezing and thawing cycles, which in the single layer panel case, even increased.

In conclusion, the EASEE precast multilayer panel outer solution was obtained by coupling a layer of Expanded Polystyrene (EPS) 100 mm thickness with two layers of TRM 125 mm thickness. TRM is a cementitious composite in which the matrix is reinforced with one or more layers of glass, carbon or aramid fabrics. The average tensile load achieved by the fabric is equal to 157.4 kN/m (the test was displacement-controlled by imposing a constant stroke rate of 100 mm/min). The production of the panel is occurred, unlike the normal practice of prefabrication, through the casting of the concrete in the vertical in a modular formwork with variable position shores, specially designed within the project. Using mixed pigments in the TRM casting, it has been possible to obtain different coloration. Furthermore, by applying during the casting a special silicone matrices, it has been possible to imprint on the exposed faces of the different panel shapes and reliefs.

For the demonstration building three different colours were produced: white, natural and anthracite and a test matrix was conducted with reliefs of 50 mm vertical stripes [34]. The overall design of the facades has been optimized by evaluating at the same time the composition quality, the size and number of panels to be produced. The final design configuration consists of 186 pan-

Table 1
Advantages and disadvantages for the different solutions of the precast multilayer panel.

Technological Solution	Advantages	Disadvantages
A) 	- weight minimization (30–50 kg/m^2 neglecting boundary details); - good dimensional stability and mechanical properties; - no problems related to differential shrinkage; - simultaneous casting of the two cementitious layers; - extended linear-elastic behavior; - expected good durability;	- thin external concrete layer; - difficulty in reproducing thick moldings;
B) 	- quite high impact strength; - good dimensional stability and mechanical properties; - extended linear-elastic behavior; - expected good durability;	- difficulty in reproducing thick moldings; - postponed casting of the two cementitious layers; - increased weight with respect to solution “A” (53–88 kg/m^2 neglecting boundary details);
C) 	- high impact strength; - single cementitious layer to be cast; - small weight (38–63 kg/m^2 neglecting boundary details);	- possible problems related to differential shrinkage; - lower stiffness if compared with solutions “A” and “B” - lower bearing capacity if compared with solutions “A” and “B” (higher number of anchoring points requested); - difficulty in reproducing thick moldings;
D) 	- the mechanical behavior takes advantages of the shape stiffness; - possibility of reproducing thick moldings; - just one cementitious layer to be cast.	- high depth and consequent increase of the global thickness of the wall; - good mechanical behavior as the one expected for solutions “A” and “B” involves a high thickness; - the insulation layer has to be shaped; - increased weight if compared with the other solutions (the weight depends on the geometry of the moldings).

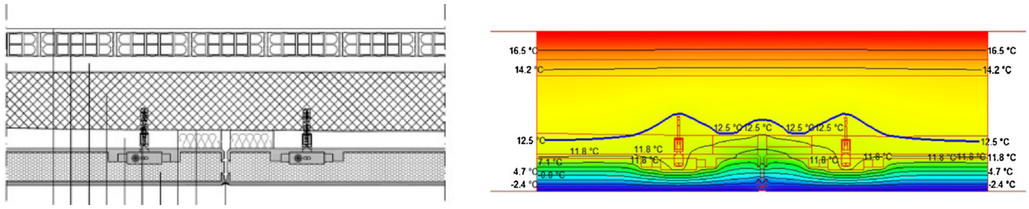


Fig. 8. a) Technological detail b) Isotherms calculation using finite element method.
(Source POLIMI elaboration with [35]).

els divided into 28 different types of size, color and texture finish. During the design of the panel, it was also essential the study of the critical points of the façade: in particular, the definition of the joints between the panels and the windows and/or balconies interfaces. This activity has highlighted the following requirements to be fulfilled: be possible to replace damaged panels or other façade components; ensure the air tightness of the casing in connection with the existing building and ensure the necessary tolerances for the assembly and the related movement of the various elements that constitute the facade. The criticality of the joints has been solved by combining two products: a curtain cord polyethylene coupled with an acrylic silicone sealant with low modulus of elasticity. The infill bead (diameter 20 mm), not absorbing and not degradable, has allowed the filling of the junction before application of the silicone material. The coupling of this material with the acrylic sealant with low modulus has allowed the perfect sealing of the expansion joints and the connection between panels, a solution that also allows the compensation of any movement avoiding cracks and detachments. Specifically has been employed a silicone sealant neutral curing and very low elastic modulus with exceptional resistance to aging and with a service temperature range from −50 to +150° C and with an elongation at break comprised between 220 and 290%. A verification of the solution chosen were performed specific finite element analysis. Fig. 8b shows how the critical heat flux occurs at the point of connection of the panels, however, being almost parallel to the isotherms as you get closer to the outermost layer, it means that the heat transfer is essentially 1D, and this indicates good performance. Therefore, the chosen solution allows avoiding thermal bridges between the panels. From the technological point of view, the panels are designed to be positioned externally to the existing wall through four punctual connections, represented in total from 492 stainless steel anchors of different sizes and types adjustable in the three space directions. The interspace between the panel and the existing masonry, the variable geometry as a function of the outside lead of the existing wall, has been treated to function as a non-ventilated air chamber, and then as an additional resistive layer. For this reason, it was sealed on the perimeter through self-expanding polyurethane foams combined with the sealing strips to the air.

The final solution of the prefabricated system was analyzed before its implementation on the demonstration building through detailed drawings and specific controls (Fig. 8a and b). The models of the analysis were subsequently validated by the results of the monitoring campaign carried out both in summer and winter months.

4.1. Panels installation procedure

The installation process was performed without traditional scaffolding and interference with the normal daily activities of the tenants and under different steps. The anchoring tracing, has permitted to identify, from the executive project prepared on geo-referenced three-dimensional survey, the position of the anchors. For this purpose it was used a GPS total station positioned on the network designed during the geometrical survey. Following the different anchors, divided by type, according to the weight of the panels and to the distance respect to the façade, were positioned. Firstly the positions of the points, corresponding to the lower raw of the panels, has been identified in order to have a correct reference for the upper lines of the panels. Before their handling, a polyethylene self-expanding tape has been placed between the panels on the internal perimeter of each element to ensure the thermal isolation of the joint. The next step allowed through a special hook, installed on a crane, to lift the panels in the right position. An operator, positioned on an aerial platform, moved the panels to the final position. Subsequently, for each panel's line, it was performed the sealing of the interspace to minimize the convective air movements. The final phase, of joints' closing and guttering laying, has been always conducted through mobile platform. All the operations were carried out in conditions of absolute safety and construction site cleaning.

The envelope was entirely retrofitted: in this way it was possible to identify the building's behavior before and after the application of EASEE solution. Pictures below provide the final design of the 4 facades where the yellow part represents traditional retrofitting, and the gray part the EASEE panels with different finishing surfaces (color and matrix). Due to limited spaces and dimensions of the lodges and of critical points (i.e. windows – roof areas), yellow areas (Fig. 9) have been carried out with the External Thermal Composite System (ETICS) with EPS insulation coating glued and doweled to the wall instead of the prefabricated panels.

During the construction phase some details have been improved to make better and faster solutions in the connection between EASEE solution and the traditional solution and to finish the covering solution next to balconies and windows (Fig. 10).

Fig. 11 provides an overview of the main steps performed during the external retrofitting of the Italian demonstrative pilot building case.

During building retrofitting the occupants have always expressed interest and very positive attitude towards the works. During the construction phase they really appreciated the absence of scaffolding and the possibility to perform daily activities in full freedom. Moreover, they also experience the quick installation of the panels themselves. The widest façade of the building have been indeed retrofitted in approximately 10 days. The total retrofitting lasted less than 3 months.

4.2. Metering with the monitoring campaign

A monitoring campaign has been conducted on the building before and after the retrofitting process with the acquisition of punctual data and imagery fields rendition in order to calculate the thermal transmittance of outside wall. The methodology followed for the monitoring campaign was the heat-flow meter method. The punctual measurements performed using thermal fluxmeters required a defined period of data acquisitions with the rate of one set every 15 min and a series of operational warnings. Thus, known the surface temperatures (inner/outer); the value of wall thermal transmittance was calculated. The measurements allowed to get

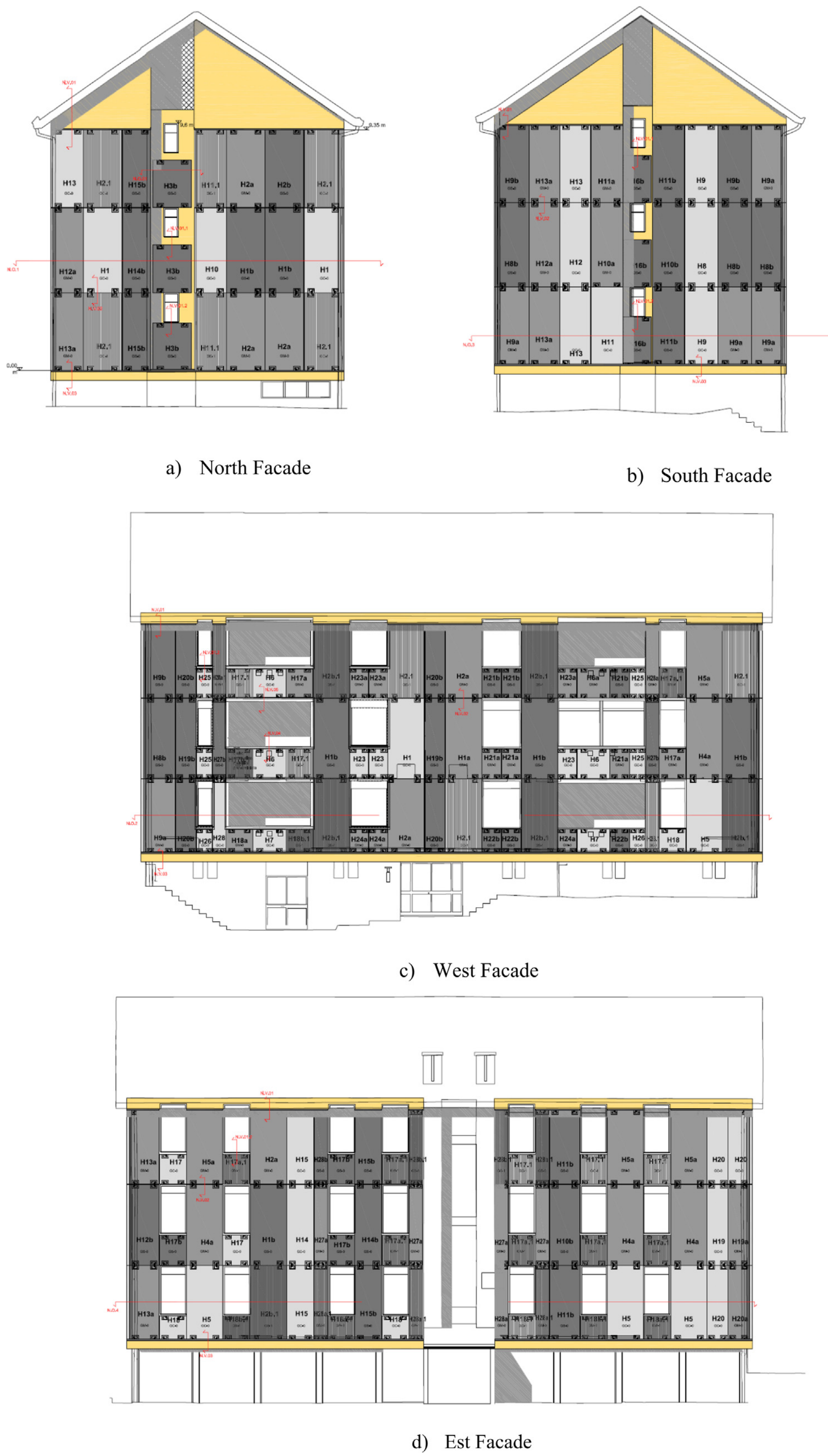


Fig. 9. Italian demo building final design drawings.

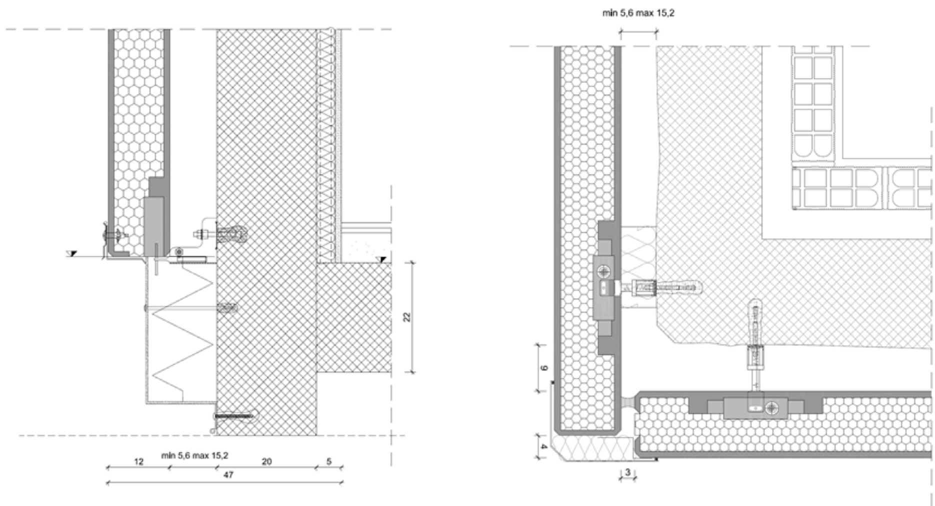


Fig. 10. Technical detailed drawings of the adopted solutions. Left: lower part of the wall. Right: wall-windows section. The thermal bridge will be solve during the windows renovation.

a) Panel's lifting by crane

b) Panel's assembly in parallel to the line of the façade via rocker

c) Panel's positioning through inclusion in the boxes of the panels of the facade on the HALFEN pins

d) Positioning of the covering panels with crane

Fig. 11. steps of installation processes and technical details.

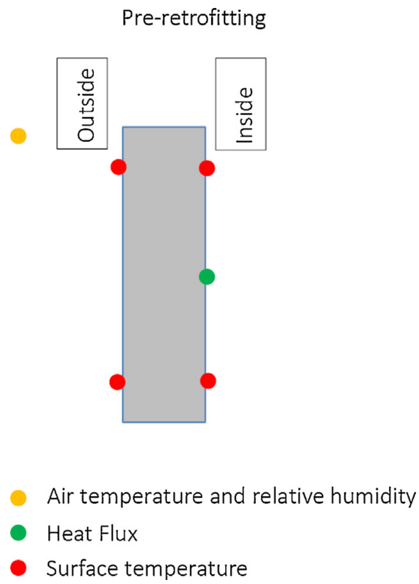


Fig. 12. Scheme identification of the sensors pre-retrofitting: four surface temperature sensors, one air/humidity sensor and one heat flux sensor.
(Source. POLIMI Elaboration).

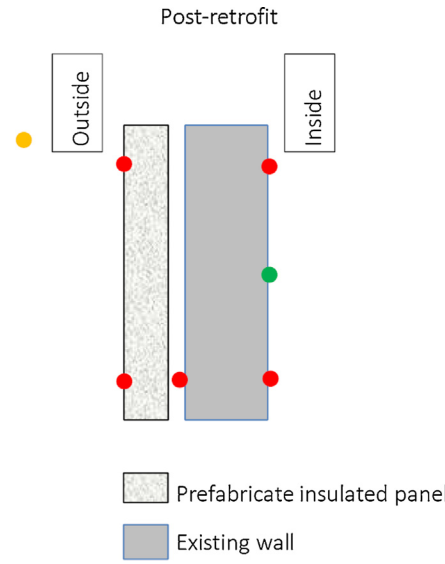


Fig. 13. Scheme identification of the sensors in the Italian demo building post-retrofitting: five surface temperature sensors, one air/humidity sensor and one heat flux sensor.
(Source. POLIMI Elaboration).

the real value of thermal transmittance of the building envelope, which, as known, differs from the theoretical value calculated in the design phase, as reported in the UNI 10351:2015 [36]. Indeed, UNI EN 1934: 2000 [37] and ISO 9869: 1994 [38] are taken into consideration for the method of thermal flux-meter.

The European Standard project EN 15063:2008 [39] specifies and describes in detail the methods to be used on site in order to measure the thermal transmittance of the building envelope: the thermal flow meters method is expressly mentioned following the ISO 9869:1994 [38]. This method, however, is partially invasive and slow and the results strongly depend on the outer environmental conditions and on the users behavior in the building during the survey (whose collaboration in the management of the living rooms is strictly required).

The infrared thermal survey technique combined with the heat flux metering in situ permitted to understand and investigate in a comprehensive and fast way the performance of the wall.

Figs. 12 and 13 represent the scheme of the sensors' application. For what concerns the inner space, a heat flux meter that detected the thermal flow between inside and outside was positioned as well as a temperature sensor, which measured the surface temperature of technical element and a data logger for managing the data detected. On the outer side, indeed, there were two temperature sensors that detect the surface temperature and a thermo-hygrometric sensor that detected the air temperature and the relative humidity.

5. Results and discussion

The in-situ measurements have allowed verifying the real behavior of the installed system both in terms of surface temperatures and thermal transmittance. The measuring instruments were placed on a wall portion of the housing representative, facing north-east in order to avoid the direct solar radiation effect. On the inner side wall a heat flow meter have been positioned for the measurement of heat flow with a measuring range between −2000/+2000 W/m^2 and uncertainty of 5% for 12 h and a contact temperature sensor (Pt100), with a possible range −50/+70 °C and resolution of 0.1 °C for the surface temperature measurement of the technical element. On the outer layer of the existing wall, further temperature probe has been positioned in order to monitor the behavior of an air gap between the insulating panel and masonry. Outward, another probe was applied to detect the external surface temperature of the composite panel. A thermo-hygrometer, through Pt100 and capacitive sensor uncertainty with ± 1.5%, has allowed detecting the level of temperature and outdoor air humidity. All sensors were connected to a data logger set for sending data to a server every 6 min. Before the measurement sensors placement, the thermographic survey has contributed to verify the homogeneity, in terms of surface temperatures, and the absence of system plant components. Measurements were performed during both summer and winter season. Specifically, the graph of Fig. 14 shows the measured values and the calculation of the thermal transmittance by the progressive average method in accordance with regulatory standards[5], for the period between 19 and 23 December 2015. As shown by the graph of Fig. 13, the detected thermal transmittance is equal to 0.270 W/m^{2}K, this value indicates that the interspace set has a positive influence on the overall behavior of the technology package facade. In the design phase, various retrofitting scenarios have been identified and the relative reduction of energy consumption has been measured. In the first scenario, corresponding to the application of the prefabricated insulating panel, a reduction of primary energy demand has been estimated of 30.4%, reducing the energy demand from 184 to 128 kWh/m^{2}y. In the second scenario, which considers only the replacement of existing windows (U_W value of 1.4 W/m^{2}K) the reduction of energy use is assessed to be about 39% with a calculated post-intervention value of 112 kWh/m^{2}y. In the case of a combined action the simultaneous application of the two strategies (new windows and insulating panels) allows an energy reduction of 69%, reaching an energy consumption equal to 57 kWh/m^{2}y (reduction of 127 kWh/m^{2}y and 13 t/CO_2 not emitted par year).

The simulation results has been compared by real data. The energy consumption measured for the last five years has been reported in the figure below. The energy consumption of the winter season 2015–2016 is reduced by 36% respect the previous season with and energy saving of about 52 kWh/m^{2}y (Fig. 16) confirming the building energy simulation results.

The Fig. 15 shows the temperature levels of the different wall layers after retrofitting. As shown by the graph the cavity tem-

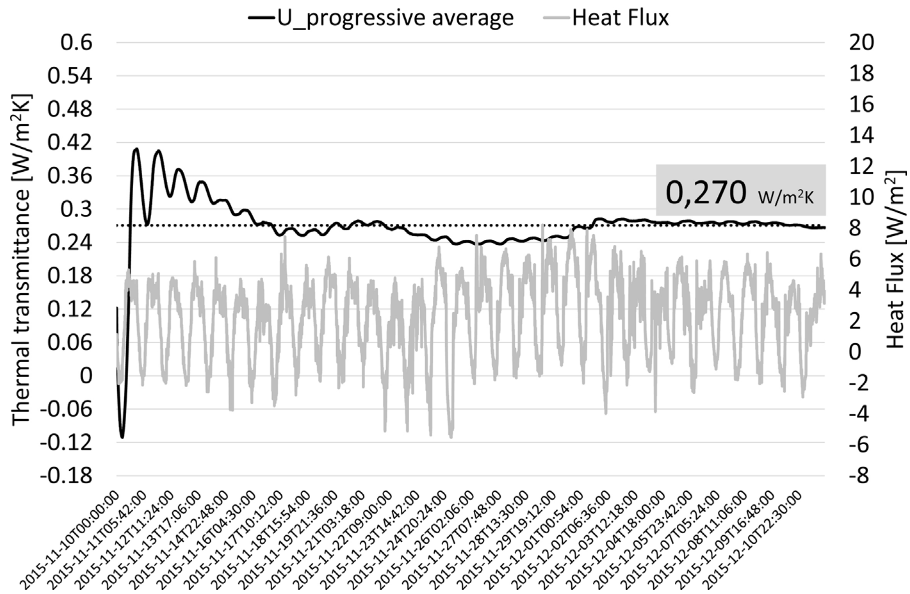


Fig. 14. Thermal transmittance measurement.

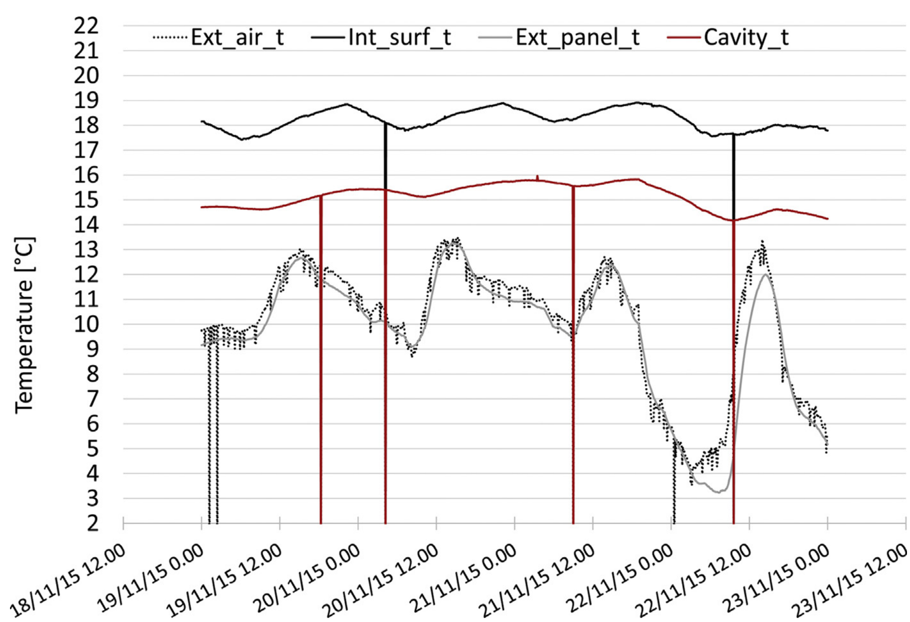


Fig. 15. Temperature levels of the outer and inner wall surfaces compared with the cavity temperature level.

perature level is not influenced by the external air temperature confirming that no air leakages has been detected during the monitoring campaign. This prove that the adopted joints solution between the panels and between the panels and the wall allow to create an air proof cavity that works as further insulation layer reducing the energy losses.

The general quality of the envelope after retrofitting is shown in Fig. 17 and Fig. 18. The thermal imaging of the south-west façade shows an homogenous surface temperature level with absent thermal bridge over the renovated façade.

6. Conclusion

The deep renovation of existing buildings plays a major role for the reduction of the greenhouse gas emissions, as foreseen in the energy policy both at European, national and at local level. At this regard, the Italian pilot action of the EASEE project, concerning the outer façade renovation solution, has been presented in the article.

The paper summarizes the results aimed at demonstrating the effectiveness of an innovative modular prefabricated system for the envelope retrofitting characterized by good insulation performances and durability and a wide variability of finishes for both color and textures, able to reproduce, whenever needed, the existing façade features. The implementation of the demonstration activities allowed verifying and testing on site the developed solutions, the materials, the installation method and the construction works scheduling. The lesson learned and the experimental investigations have demonstrated a high potential of the innovative system in terms of easy installation, performance, architectural quality and replicability. There are still some limitations regarding critical points (i.e. balconies, lodges, etc.) application of the EASEE outer solution, which might be solved within further research and application tests. Authors are currently studying some new

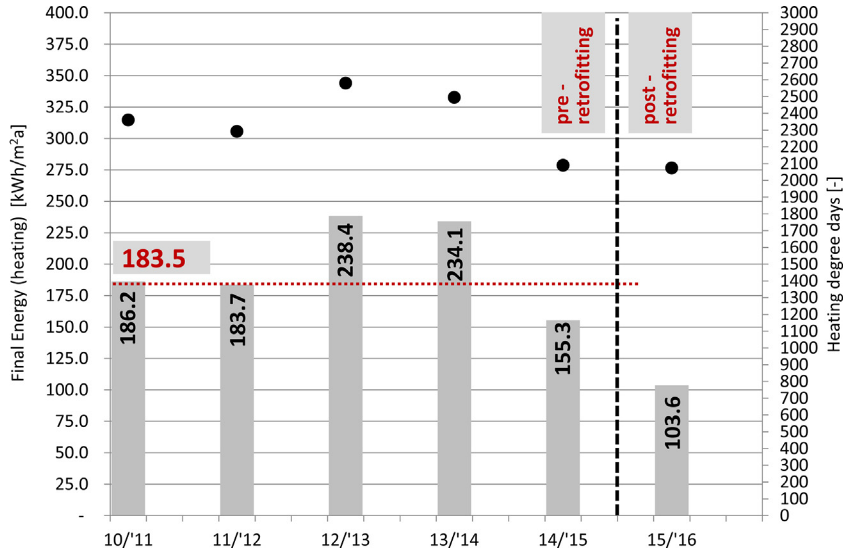
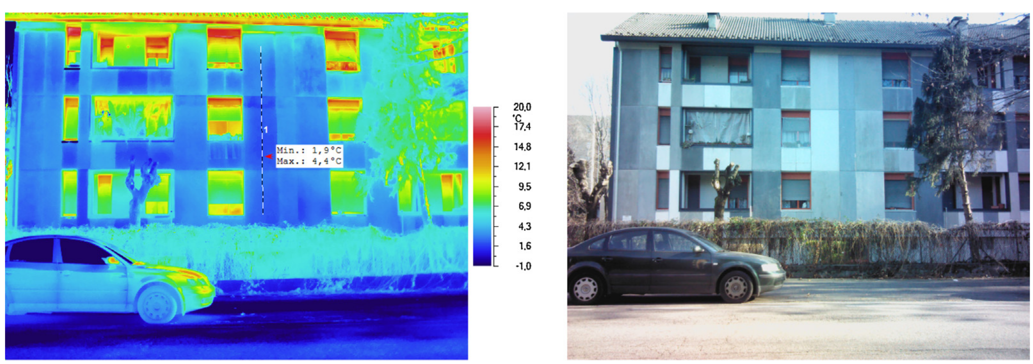


Fig. 16. Heating energy consumption overview before and after the energy renovation. The energy consumption data has been provided by the heat management company. The HDD has been calculated considering a base temperature of 20 °C with data from a local weather station provided by the Regional Environmental Protection Agency (ARPA) [40].



a) b)

Fig. 17. Italian demo building thermal imaging survey on South facade (Source. POLIMI Elaboration).

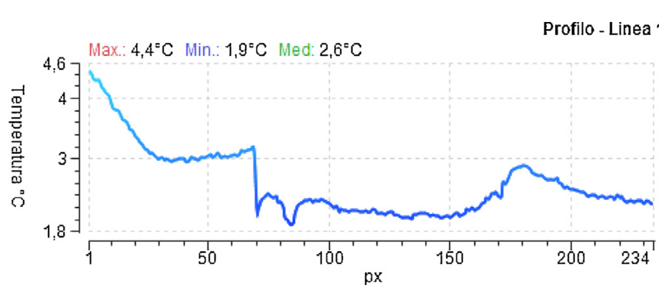


Fig. 18. Temperature profile line of the thermal survey on South façade – Ref. (Source. POLIMI Elaboration).

configuration of the panel with system or technological element integrated. From the economical point of view, it is still necessary, however, an optimization of the production process so as to make competitive the prefabricated panels against a traditional External Thermal Insulation Composite System.

Acknowledgments

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