Czech Technical University in Prague
Faculty of Civil Engineering

Department of Building Structures

DIPLOMA THESIS

# Prefabricated Retrofitting Solutions for Building Envelope Refurbishment

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I declare that I have written the enclosed Master's Thesis completely by myself under the supervision of Ing. Jan Růžička, Ph.D.

I have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked.

Prague, 28. 6. 2018

……………………………………
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# ZADÁNÍ DIPLOMOVÉ PRÁCE

## I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Pokyny pro vypracování:
Práce se bude zabývat využitím prefabrikace v rekonstrukcích obálky budovy. Bude tedy obsahovat vysvětlění motivace k těmto metodám, obecné porovnání prefabrikovaných a ETICS sysémů v kontextu rekonstrukce a nahlédnutí do celého procesu tohoto typu rekonstrukce.Dále představí dva rozdílné typy tohoto řešení a porovná je v různých aspektech. Tato řešení budou teoreticky aplikována na konkrétní budovu a budou popsány rozdíly v chování této budovy zejména z hlediska energetické bilance a environmentálního dopadu.

Seznam doporučené literatury:
G. Salvalai, M.M. Sesana, G. Iannaccone: Deep renovation of multi-storey multi-owner existing residential buildings: A pilot case studdy in Italy, 2017
IEA ECBCS Annex 50: Prefab Systems for Low Energy/High Comfort Building Renewal
A. Lupisek, INTRODUCTION OF A METHODOLOGY FOR DEEP ENERGY RETROFITTING OF POST-WAR RESIDENTIAL BUILDINGS IN CENTRAL EUROPE TO ZERO ENERGY LEVEL

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## III. PŘEVZETÍ ZADÁNÍ

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## Abstract

Current situation of the European building stock is no longer sustainable. Buildings account for 40% off all consumed energy in Europe. The renovation of the building stock is therefore a priority and the only way of achieving it in sufficient time is to speed up the whole refurbishing process, while making it more efficient at the same time. This however cannot be done with dated refurbishing methods and for this reason, many new and unorthodox refurbishing strategies have been developed in recent years.

The purpose of this thesis is to examine firstly the background of the European building stock, its age and ways of refurbishment. Next task is to introduce and summarize the off-site prefabrication process in relation with building envelope refurbishment. In contrast with traditional ETICS insulating strategy, the prefabrication process brings many new approaches, solutions, but also problems to the table. These need to be point out in order to successfully assess the state-of-the-art solutions.

Second part of this thesis consists of thorough comparison of two off-site refurbishment strategies. These were consciously chosen as solutions with very different methodology of the retrofitting process. Both have holistic approach, focusing not only on the production of the retrofitting elements, but on the process from A to Z. This includes energy analysis, 3D scanning, BIM modelling custom production and a construction. Comparison of two solutions with similar holistic approach but very different execution of it will provide an interesting data and an insight into the fast-growing prefabrication field.



## Keywords

Retrofitting, refurbishment, off-site, prefabrication, energy efficient buildings, ETICS, residential building, European building stock

# Abstrakt

Současná situace Evropského bytového fondu je dlouhodobě neudržitelná. Budovy jsou zodpovědné až za 40% celkové spotřeby energie v Evropě. Rekonstrukce těchto domů se proto stala prioritou posledních let a jediný způsob, jak jejího úspěchu dosáhnout v požadovaném časovém horizontu, je urychlit celý proces rekonstrukcí a zvýšit i jeho efektivitu. Toho ale nelze dosáhnout typickými metodami zateplování obálky budovy. Z tohoto důvodu jsou v posledních letech představovány a testovány inovativní způsoby a strategie zateplení obálek budov.

Tato práce se v prvé řadě věnuje pozadí celého problému, tedy stavu staveb v Evropě, jejich věku a ostatním okolnostem. Dalším krokem bude představení a shrnutí procesu prefabrikace v kontextu rekonstrukce obálky budovy. Naproti typickému ETICS systému přináší prefabrikace nový pohled na celý proces, nová řešení ale také mnoho nedořešených problémů. Všechny tyto aspekty je třeba pojmenovat, aby bylo možné hlubší porozumění celé problematice.

Druhá část diplomové práce se věnuje porovnání dvou prefabrikovaných řešení pro zateplení obálky budovy. Tyto dvě řešení jsou si podobná svým prvotním přístupem, ale naprosto rozdílná konkrétními výstupy. Obě pojímají proces zateplení budovy a zejména její obálky jako komplexní problém, ale s zcela odlišnými výsledky. Porovnání těchto dvou přístupů poskytne užitečný a zajímavý náhled do celé problematiky prefabrikace pomocí multi-kriteriálního hodnocení.



# Klíčová slova

Rekonstrukce, bytový dům, prefabrikace, energetická náročnost budov, zateplení, ETICS

# Obsah

# 1 Foreword

# 2 Living in Europe

## 2.1 EU targets and energy conversations commitments

Global temperature rise has been recognised as one of the greatest problems of 20th and 21st [1] century. In last decades, this issue has been addressed by several institutions, but mostly by the UN. Following the Kyoto Protocol, Paris Agreement (an agreement within the United Nations Framework Convention on Climate Change) has set specific goals to mitigate the greenhouse gas emissions. The major goal is to hold the global temperature increase below 2°C, compared to the pre-industrial levels, or better yet, keep the increase below 1.5°C [1]. Under the *Europe 2020 strategy* climate change and energy part, another goal has been set;

- Greenhouse gas emissions 20% lower than 1990 levels
- 20% of energy from renewable sources
- 20% increase in energy efficiency

This agenda has since been extended to year 2050, when the greenhouse gas emissions should be reduced by 80%. Most recent legislation covering this issue is the *Energy Efficiency Directive* (EED) from 2012. [2]

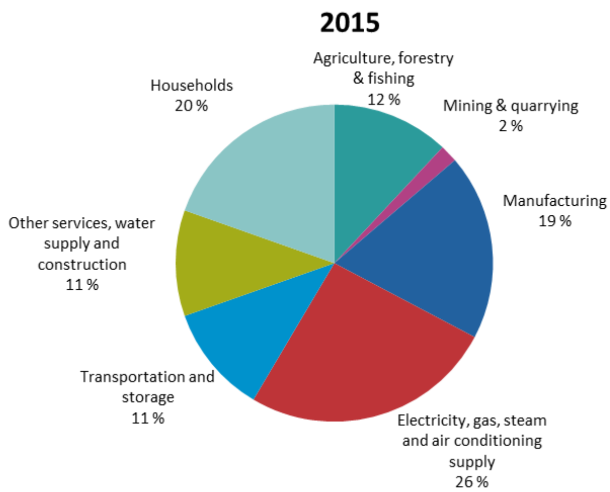



*Figure 1: Greenhouse gas emissions by economic activity. Source: Eurostat 2015*

Building sector has a key role in energy consumption, since it accounts for 16-50% of total worldwide energy. When focusing on Europe, 40% of total energy is building-related, as well as 36% of $CO_2$ emissions [3]. This gives the building sector a pivotal role in energy consumption saving and gives a reason for exploring energy-efficiency buildings from all the aspects.

## 2.2 European building stock

The need for highly energy-efficient buildings has already been established. Next step is the analysis of the current building stock, from which we can assess the specific methodology for most efficient refurbishing methods.

In order to deliver a concrete outcome from this assessment, we need to set a set of constraints. The variety of building in Europe is evidently wide, with lots of variables. For this reason, the thesis will consider only residential buildings. This decision comes from the assessment of building floor area, from which we can see residential buildings, as the major type of all building stock, representing almost three quarters of the total building stock in Europe. Potential for $CO_2$ emission reduction is

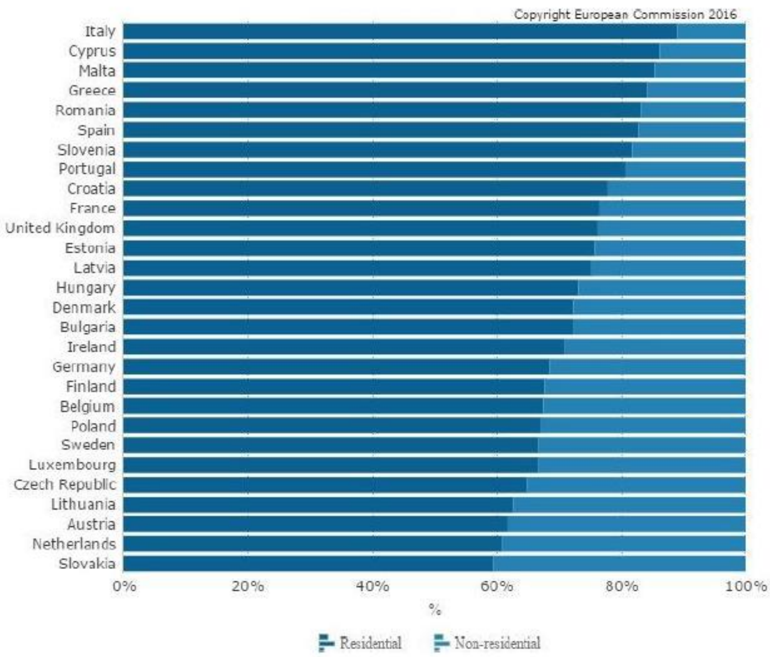



*Figure 2: Breakdown of building floor area. Source: European Comission, 2016*

therefore much greater for this category. Another aspect for Europe-wide comparison of energy efficiency is the construction age of the buildings stock. Since we established the potential of residential buildings, a general assessment of the construction age must be addressed also. Almost every EU country's building stock consist of dwellings constructed before 1980, with some countries such as Germany, UK or Italy with even 70% of total residential stock [4]. The table shows the exact age distribution of residential buildings across Europe. It can be stated, that there was no or little consciousness about energy efficiency regarding building before 1980s, therefore all of the dwellings have potential for big energy savings from contemporary point of view.

### 2.2.1 Construction age

The age of the building is another factor that has to be considered if we deal with renovation. Buildings in Europe are on average old, vast majority of member states has got a share of dwellings built before 1980 greater than 50%, while some populated countries such as Germany, Italy or United Kingdom exceed 70% of the total residential stock [5].

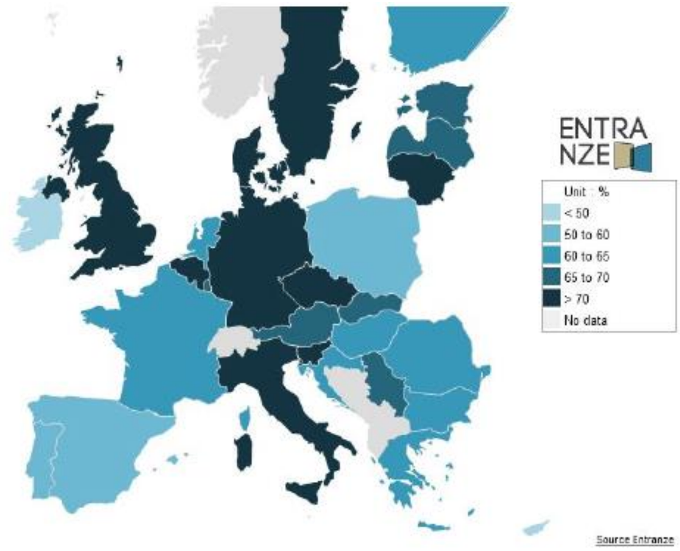



*Figure 3: Share of dwellings built before 1980. Source: Entranze, 2016*

### 2.2.2 Geoclusters

What differs for almost each country in regards of energy efficiency is, of course, the climate, which differs drastically across from Norway to Spain. Since the climate is influenced not only by latitude, but also closeness to the sea shore, occurrence of mountain ranges etc., there is no way of fairly comparing all countries with one set of variables. However, this does not mean that each country requires a specific approach. For partial comparison of all European countries a general category system has been developed that puts countries with comparable climate and general weather conditions together. Selected countries then form so called "geoclusters". These were not formed only on climate basis, but also after local culture and behaviour, construction techniques, GDP etc. were taken into considerations. Geoclusters, namely [6]:

1. Southern Dry (ES, PT)

2. Mediterranean (IT, EL, CY, MT)

3. Southern continental (FR, BG, HR, SI)

4. Oceanic (UK, IE, BE)

5. Continental (DE, NL, AT, HU, CZ, LU)

6. Northern continental (PL, DK, RO, SK, LT)

7. Nordic (SE, FI, LV, EE)

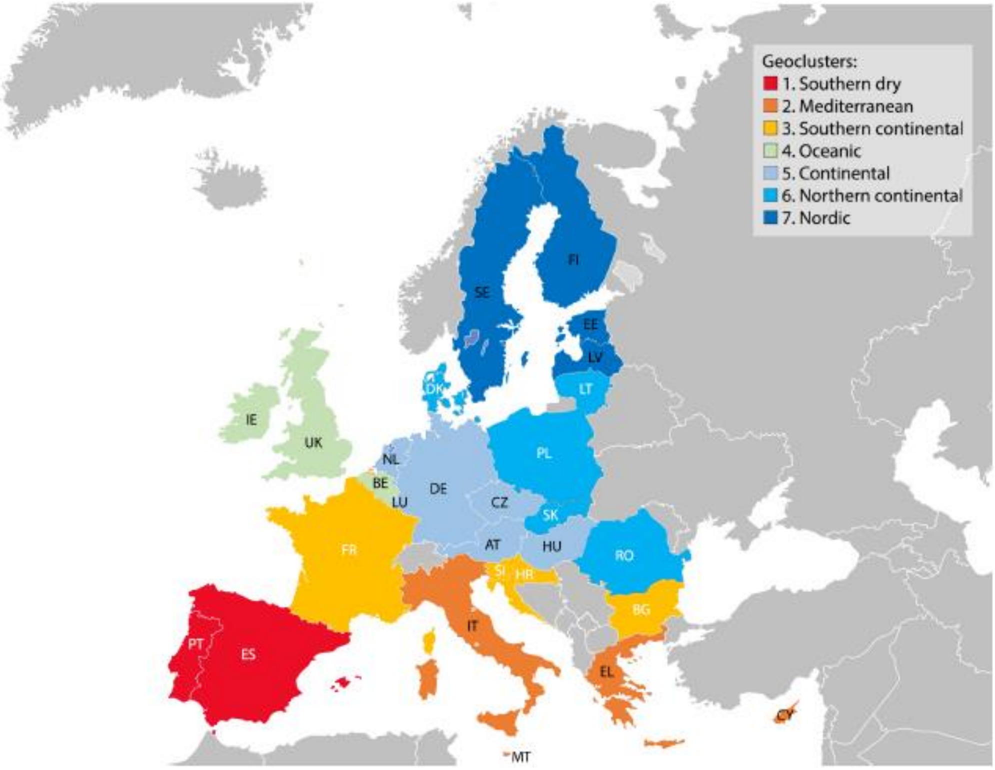



*Figure 4: Mapping of Geoclusters. Source: Birchall, 2014*

### 2.2.3 Residential building stock characteristics

The overall residential building stock in Europe accounts for 22.6 billion $m^2$ of floor area divided in 250 million of dwellings (a physical structure, a house, an apartment, a group of rooms, intended for occupancy by a member of a household) (EU Buildings Database) distributed among the geoclusters as shown in table. [4]

| | <'45 $[Mm^2]$ | 45-'69 $[Mm^2]$ | 70-'79 $[Mm^2]$ | 80-'89 $[Mm^2]$ | 90-'99 $[Mm^2]$ | >'99 $[Mm^2]$ | TOT $[Mm^2]$ |
|---|---|---|---|---|---|---|---|
| #1_(ES) | 421 | 594 | 517 | 423 | 450 | 689 | 3095 |
| #2_(IT) | 640 | 1086 | 660 | 495 | 321 | 461 | 3664 |
| #3_(FR) | 939 | 728 | 583 | 461 | 348 | 622 | 3681 |
| #4_(UK) | 1183 | 829 | 432 | 304 | 231 | 387 | 3366 |
| #5_(DE) | 1445 | 1815 | 895 | 709 | 535 | 576 | 5974 |
| #6_(PL) | 397 | 556 | 345 | 298 | 179 | 226 | 2001 |
| #7_(SE) | 182 | 253 | 157 | 120 | 69 | 90 | 871 |
| EU-28 | 5140 | 5932 | 3620 | 2841 | 2116 | 3004 | 22652 |

*Figure 5: Share of dwellings built in different periods. Source: European Commission, 2016*

## 2.3 Building renovation rates

### 2.3.1 Equivalent major renovation

Article 2 of EPBD (EU, 2010) defines the major renovation as follows:

> 10. 'major renovation' means the renovation of a building where: (a) the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building, excluding the value of the land upon which the building is situated; or (b) more than 25 % of the surface of the building envelope undergoes renovation; Member States may choose to apply option (a) or (b).

Member states obviously have some discretion in the construction of the term 'major renovation' both in terms of monitoring and definition. Because of that, we have to sort out these different interpretations.

by Zebra 2020 (2014) defines the 'major renovation equivalent accordingly:

> The ZEBRA consortium assumes that with major renovations, a building's final energy demand for heating can be reduced by 50 to 80% (range depending on the country defined by national experts according to the current efficiency of the building stock).

A common indicator has been found for a good comparison. Major renovation rate by geoclusters can be seen in table.

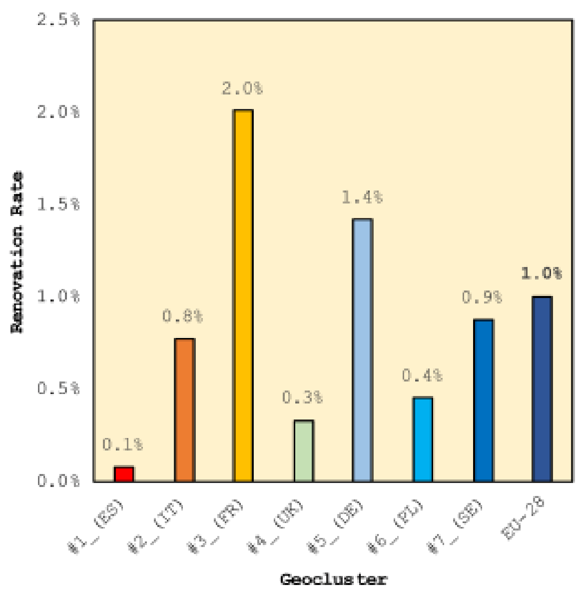



*Figure 6: Renovation rate by Geoclusters. In order to consider a normalized type of intervention, equivalent major renovation has been considered. Source: Zebra2020, 2014*

### 2.3.2 Current rates

The todays renovation rate in Europe is almost 1.0% [2], which tells us that after the first year, 99% of the building stock still accounts for large sum of fossil fuel for operational energy, and after second year 98%, and so on. If we take a look at this value within the framework of the transition, it is an surprisingly low number.

Also, 1.0% is a community average, but actually among the cluster we detect values which significantly differ and which range from 0.1% to 2%. Looking at this non-uniformity it is easy to acknowledge the importance of pushing towards a unified common policy.

Renovation rate is a fundamental parameter, because the share of energy intensive buildings is far too high (87%) and every year it claims a significant portion of budgets which could be invested instead of depleted on paying the energy bill. Hence, qualitatively, it would be better to have absurdly high renovation rates at the beginning (start of our analysis 1st January 2018), when it matters, and then decrease it when the share of consumer buildings has been drastically reduced. Obviously, this scenario is purely theoretical, as renovation rate is actually a parameter that suffers from big inertia, because the construction sector by definition is not flexible and very low to incorporate changing.

### 2.3.3 Time-span for completing renovation

It is important to keep renovation rates separate, at least by geocluster, because this way it is possible to keep track of the differing speeds. In a certain moment, each cluster will experience the 'saturation'; the ones with high renovation rates, while others will keep going forward with their low rates even beyond thousand years; namely within the 200 years of our projection only some of the cluster will have used up all the building stock to under analysis, while others will had got still a considerable share of energy consumer buildings.

# 3 Building envelope refurbishment methods and strategies

## 3.1 Introduction

The need for lowering the greenhouse gas emission levels has already been established. We know by how much and what timeframe is set for achieving such goal. We need to answer the next crucial question – by what means? Several case studies have been conducted on the topic of most efficient refurbishing methods for existing building stock e.g. *the IEA_EBC_Annex_50 _Prefabricated Systems for Low Energy Renovation of Residential Buildings*. This study is devoted to refurbishing of a typical apartment building while targeting the primary energy as the most important value using prefabricated modular retrofitting panels.

Generally, two external insulation systems that provide the desired performance are used:

- On-site
- Off-site

There are many solutions standing between these categories, however, the prefabrication process essential for off-site solutions distinguishes it greatly from the typical on-site solutions.

| **Composite insulation system** | **Rear ventilated façade system** | **Façade system – partly pre-fab** | **Pre-fab module system** |
|---|---|---|---|
| Common insulation measure – manually brought up insulation panels, covered with reinforced priming material and a plaster coating, which is coloured. | Insulation brought up between laths or other substructure, fixed with mounting system, covered by various claddings. Entire assembling procedure carried out manually. | Assembly of pre-fabricated substructure, filled with blown-in insulation. Cladding whether integrated in pre-fabricted system or manually brought up afterwards. | Fully pre-fabricated modules, assembled in fabrication hall, transported on-site and mounted on prepared sub-structure onto façade. Serial production possible. |

## 3.2 Choosing the right renovation concept

First and arguably the most important step in the off-site refurbishment process is the decision to use this method itself. It is not only the lack of experience and methodology which are to be taken into account, but also real aspects of the considered building as its performance requirements and financing. For these reasons, we shall consider all the variables included in making the decision of opting for the off-site refurbishing.

### 3.2.1 Architecture and urban surroundings

Although the discussion up until now has been mostly concerned with energy efficiency and measurable variables included, there is one aspect of building refurbishment that precedes the process of retrofitting a building envelope – considering the recognised architecture quality and culture heritage of the original building and the context of the urban area, as well as its historical value.

Aesthetics and architectural design should obviously play a major role in the renovation process. Nonetheless, because of the demands on the speed of construction and the overall costs, it is often not taken into consideration to the extent deserved. It is less of a concern for contemporary buildings styles, however, in previous chapters we have already established that for the building stock renovation to be effective, mostly post war and between wars era buildings need to be refurbished.

It is typical for residential buildings of this age, that the detailing on the façade was done in a high decorative manner; namely ledges between the floors, decorative window frame bits, entrance portals etc.  These were usually done using a stucco or simple overhanging bricks. Since the decorative elements of building façade from these historical periods are among the most valuable historical and architectural properties of these building, it is advised to keep them in view when considering envelope refurbishment.

This can either be ensured by the local legislation, which often considers such decorative properties as valuable as to place them under legal protection, but more often it is solely on the conscience and decision of the owner. One of the reasons for this is that building envelope refurbishment is not always recognised by the municipality as a 'major renovation' and therefore no official project documentation is required. This way quite valuable decorative façade can disappear overnight by being refurbished by simple ETICS system with zero decorative qualities. See picture xx. as an example of a refurbishment of a school from 1900s resulting in such outcome.

*Figure 7: Unreasonably refurbished façade of a school, Source: iDnes.cz*

This should not imply that decorative facades pose as a constraint in refurbishing process. Many functioning refurbishing strategies have been developed, which allow the same level of decorative manner, see pic xx.

*Figure 8: Detail façade refurbishment with ETICS. Source: Peter Hofer*

### 3.2.2 Access points, delivery and mounting options

Every refurbishing method requires a certain operation space, delivery method and means. Whereas composite heat insulations methods and smaller off-site systems are installed manually, most of the modular off-site refurbishing systems require much larger operations. Standard ETICS systems therefore use almost exclusively scaffolding for mounting access and standard trucks for delivery. All material is stored on-site and used throughout the installation process.

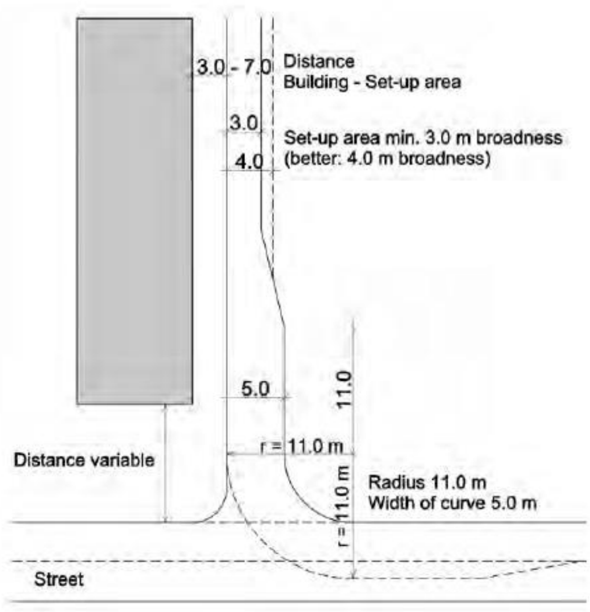



*Figure 9: Range for access by truck. Source: AEE INTEC*

Larger composites systems and all the modular off-site solutions requite crane-operated mounting process. Especially with larger dimensions of the modular pieces, the space required for the crane access can be quite large a must be included in the decision process. Same goes for delivery – generally off-site solutions require larger trucks and delivery means as well as storage space for them.

*Figure 10: Assembling procedure of prefabricated façade modules within Dieselweg, Graz-Liebenau. Source: gap-solution*

### 3.2.3 Weather conditions, construction time

All of the refurbishment methods have a specific way of dealing with difficult weather conditions. Most commonly accounting:

- low temperatures, usually below 5°C
- high temperatures, above 30 °C
- rain
- strong wind
- direct sunlight (UV radiation)

All of the listed weather conditions have a direct impact on the proper functionality of materials used. With the introduction of off-site technologies other issues arise. Since most of the retrofitting modules or parts are made in the safe environment of the manufacturer, there is much less actual labour needed on site. This results in a usually much faster installation process and therefore less impact on the labourers themselves.

The construction time also includes the amount of time the tenants have to deal with the construction being done. With some of the off-site technologies there is even the possibility of replacing the old windows from the inside, while the new window is already set at place as part of the whole modular retrofitting.

The difference between on-site and off-site retrofitting from the planning, research and analysis perspective will be developed in further chapters. With every chapter and every issue that is tackled it becomes more and more apparent, that this is one of the biggest issues of the new technologies to be handled.

### 3.2.4 Technical assessment of the building

Every retrofitting is based on actual condition and performance of the building. Not only it sets the scale and therefore the cost of the renovation, but it plays a paramount role in choice of the final retrofitting strategy. Although this thesis mainly focuses on residential building stock, there are some common aspects to it. Depending on the country where the renovation takes place, the residential buildings of the post war era generally share some similarities. It can be the prefabricated panel houses in the Eastern Europe region, or the masonry residential buildings in Italy. The similarities can be found not in the exact measurements, but rather similar joints, window positions, details etc. This creates at least some opportunity to standardize the production of retrofits and its parts.

Large scale technical analysis therefore allows for choosing the correct and most appropriate way of envelope retrofitting strategy. Load bearing capacity of the exterior walls and roof, airtightness and other properties must be examined.

Another aspect is the surface of the original façade, since the complexity of the new retrofitting always deals with it in a major way. Evenness and general technical condition are the most crucial. If the evenness does pass certain levels – depending on the specific retrofitting strategy – it may increase the original costs in a very significant way. Usually two approaches of uneven surface are taken:

1. leaving a cavity between the original façade and the new retrofitting
2. using an 'levelling layer' of insulation, that will even out the surface

The general shape and complexity of the façade are significant in retrofitting strategy decision-making. Every deviation from the basic cubic form of the building, every console component such as balconies, adds to the demands of the retrofit design and installation. Thus, we can assume that the simpler and cleaner the complex shape of the building is, the easier the design of an off-site retrofit will be and therefore the bigger reason for using it.

## 3.3 Off-site envelope refurbishment methodology

### 3.3.1 Introduction

Pre-fabrication offers a production process with a controlled quality standard. The majority of the construction phase is not dependent on weather conditions. This enables serial production of standardized modules, much shorter construction periods and less discomfort for tenants during the construction phase. The utilization for renovation concepts is not wide-spread at the moment. Currently, a common and economic renovation method – even to reach passive house standard – is to bring up a composite heat insulation system. Concerning this method, no further development or improvement is possible. Even if there are a lot of "best practice" projects for building-integration of solar thermal collectors within new buildings – the development of pre-fabricated modules is in an early stage of development. Advanced pre-fabricated module kits are able to contribute to economic feasible and sustainable renovation, which offers further advantages for builders and occupants.

Off-site refurbishment systems are still quite a new solution for the building industry. Many research studies and even specific products have been developed for this use so far, however majority of the remaining un-renovated building stock is still being renovated using on-site refurbishing solutions, mainly basic ETICS system. For off-site methods to become the new popular standard, it is of high importance that general guideline and methodology is introduced. In this chapter, a short proposal of this methodology is introduced.

### 3.3.2 Common methodology practice

**Assessment of the existing building**

As stated in the previous chapter, the technical conditions along with other aspects is the first step for the successful retrofitting process.

**Energy modelling of the building and defining the goals of the refurbishment process**

Since all the technical data about the building have been collected, the next step is to create an energy model, based not only on measurements, but also on actual energy consumptions of the building. Based on that, the specific thickness and properties of insulating materials used can be chosen.

Defining the goals of the whole refurbishment process is the first step that leads to specific solutions and retrofitting strategies. Not all strategies are suitable for general refurbishment process. Many things have a say in picking the correct one, including the scale of it (whether the investor plans to refurbish only the building envelope, including or non-including windows, roof etc.). Choosing the right strategy which fits the goal and scale of the process is key.

**Building 3D model based on an actual point cloud measuring**

Since the off-site process requires high level of accuracy for the components, only building plan-based measurements are not enough for detailed production (not mentioning that these plans might very often not even exist). Therefore, there is a need of creating a complete building model, based on on-site scanning techniques. For acquiring proper data, two methods are most often used – laser scanning and photogrammetry. Both methods allow us to create a building model with a millimetre precision and therefore the perfect tool for detailed envelope assessment. This model is later used not only for exact manufacturing of the retrofit parts, but also for the positioning the joints etc.

**Production design in BIM**

Many off-site refurbishment strategies work with BIM software throughout the whole process. The first model is based on the three-dimensional scanning with combination of the known measurements of the building. The model is then able to recognize any irregularities in the envelope important for the later design of the insulating panels. Depending on the retrofitting strategy and the scale of the panels, BIM software can be also very useful in parametric design of the specific dimension of the panels throughout the envelope. Since the dimensions of the panels are variable and also the buildings have all different proportions and window positions, parametric design is a convenient way of setting the ideal grid and final specifics before production of the panels.

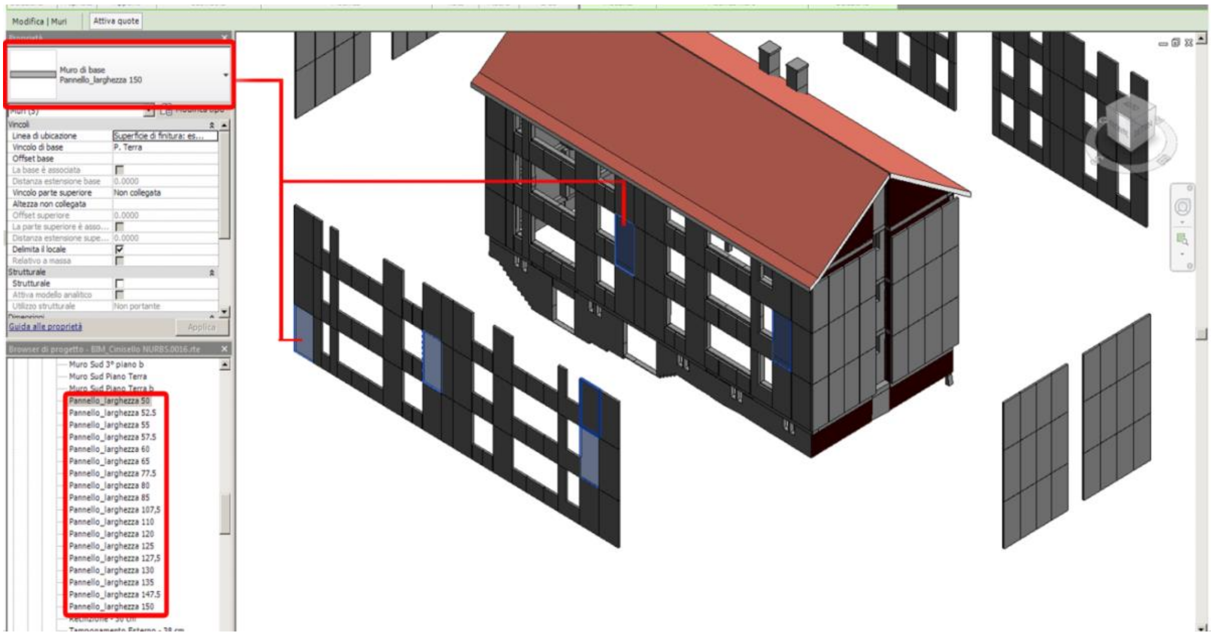


*Figure 11: BIM model of the EASEE panel façade. Source: POLIMI elaboration*

# 4. Off-site retrofitting systems – case studies

## 4.1 EASEE prefabricated panel system

### 4.1.1 Introduction

EASEE (Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-storey, multi-owner residential) project has been developed under the Department of Architecture, Built Environment and Construction on the Politecnico di Milano university. Its goal is to develop a modular retrofitting solution for building envelope with emphasis on simple construction, minimum discomfort for the occupants the maximal level of off-site prefabrication. It has been designed with specific Italian building stock in mind. This includes the fact, that retrofitting process is often divided into several phases. Old single-glass windows are being replaced as a first step, the façade itself comes usually later. For this reason, the EASEE retrofitting panels have been designed as ‘façade only’, not including the windows or any installations. Another aspect was to adjust the design and the construction process for non-skilled labourers and therefore prevent the escalation of the costs of the retrofitting process.

The whole retrofitting system has already been put into testing. First on a testing façade at the Politecnico di Milano campus in Milan, but later on an actual residential building with the need of façade refurbishment. The building correlates well with the intended approach – it is multi-storey, multi-owner and with some envelope details not so easy to handle [10]. This building is now in the process of being monitored for long-term results of the EASEE strategy.

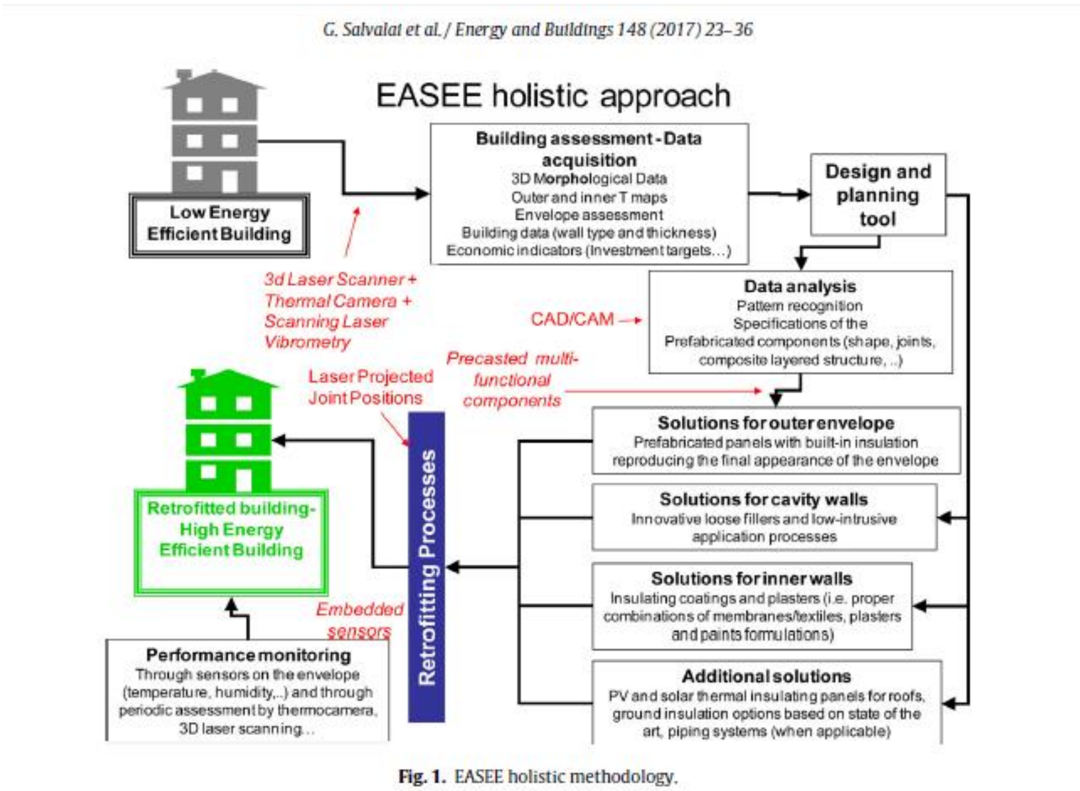



*Figure 12: EASEE holistic approach. Source: POLIMI elaboration.*


*Figure 13: EASEE design, vertical casting system. Source: POLIMI elaboration.*

The overall idea is therefore to provide a holistic solution and strategy to the whole retrofitting process, including building energy assessment, design of the retrofitting elements using BIM and, after construction itself, long-term monitoring of the building performance.

### 4.1.1 Module construction

The façade element solution was based on idea of combining finishing layer and insulation in one integrated panel. Several solutions were tested during the first stage of the project, all experimenting with different materials and finishes. The selected solution is a prefabricated sandwich panel with Expanded Polystyrene (EPS) as an insulating material, which is laminated between two external layers of Textile Reinforced Concrete (TRC). The dimensions of the panel can vary from 1.2 – 2.4 m in width, the height is a constant depending on the height of the regular floor of the building [11].

The panel has four anchoring points, which are implemented in the TRC from the inner side. Their construction has been designed in order to make placing procedure as easy and simple as possible while maintaining safety as a priority also. One of the key features of EASEE retrofitting system is also the option of monitoring, repairing and easy replacement of the panels themselves.

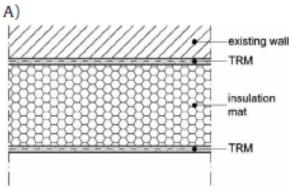
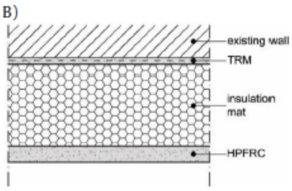
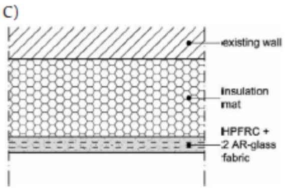
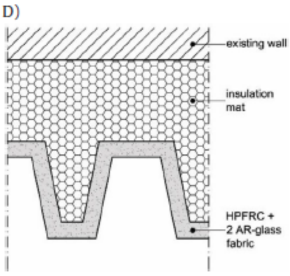
| Technological Solution | Advantages | Disadvantages |
|---|---|---|
| A)   | - weight minimization (30–50 kg/m$^2$ neglecting boundary details); - good dimensional stability and mechanical properties; - no problems related to differential shrinkage; - simultaneous casting of the two cementitious layers; - 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). |

*Figure 14: EASEE early stages designs, Source: POLIMI elaboration*

Including all these set boundaries and the general approach, EASEE system is the closest alternative to traditional ETICS retrofitting strategy, only with all the benefits of precise design and production that come from the off-site prefabrication process. It does not require specifically trained labourers, or technology. It is fast, cost-effective, well designed and sustainable.

*Figure 15, EASEE construction on the Italian demo building. Source: POLIMI elaboration*

## 4.2 MORE-CONNECT bio-based prefabricated panel system

### 4.2.1 Introduction

The MORE-CONNECT project is research under the Horizon 2020 framework programme which aims to *develop prefabricated, multifunctional renovation elements for the total building envelope (façade and roof) and installation/building services [12].* The research is now in the stage of testing the design façade elements on small scale test buildings in the Czech research centre UCEEB (University Centre for Energy Efficient Buildings), which operates under the Czech Technical University. In future there is already a plan for testing it on a larger residential building in Milevsko, Czech Republic.

As part of the research, MC also set a system dividing Europe into geoclusters [12], in order to cover all the performance demands, which differ across Europe. Based on these geoclusters, total of three variants of MC façade panels has been designed. For this thesis however, only one of these will be examined. MC also aims to design the full solution for building envelope refurbishment, including roof panels etc. For better comparison in upcoming chapters, this thesis will only focus on the façade modular panels.

*Figure 16: MORE-CONNECT demo building. Source: UCEEB*

### 4.2.2 Approach and concept

In previous chapters there has been established the fact, that there are several different approaches for designing an off-site refurbishing concept. MORE-CONNECT (MC) system is being designed as a Near Zero-Energy Building (NZEB) renovation system, which aims to find the perfect solution combining production costs, installation time and effort and environmental quality. To achieve this, following objectives has been set:

- Product innovation
- Process innovation
- Cost optimization
- Quality optimization
- Performance optimization

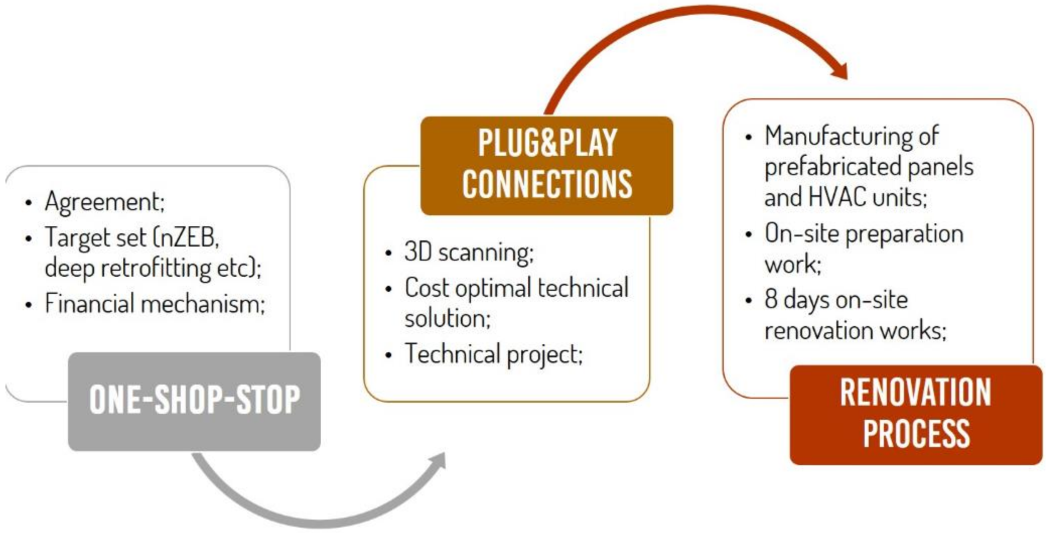



*Figure 17: MORE-CONNECT approach. Source: UCEEB*

### 4.2.3 Wall construction modules

MC façade modules are designed as large, modular facade elements. One module has the height of the specific construction height of the building it's used on and 7 m length, again depending on the design of the façade [13]. It is attached to the original building envelope with six anchoring points, which must be located at the rim of the wall. The load-bearing construction consists of wooden, or wooden based frame structure with high density mineral wood boards. Frame itself is filled with insulating material, where the specific material depends on thermal performance requirements. Generally mineral wool is used. The cavity between the original wall and MC module is also filled with mineral wool, thus serving both as an equalizing layer and an extra insulation. The finishing layer is a classic thin plaster, mainly for costs reason.

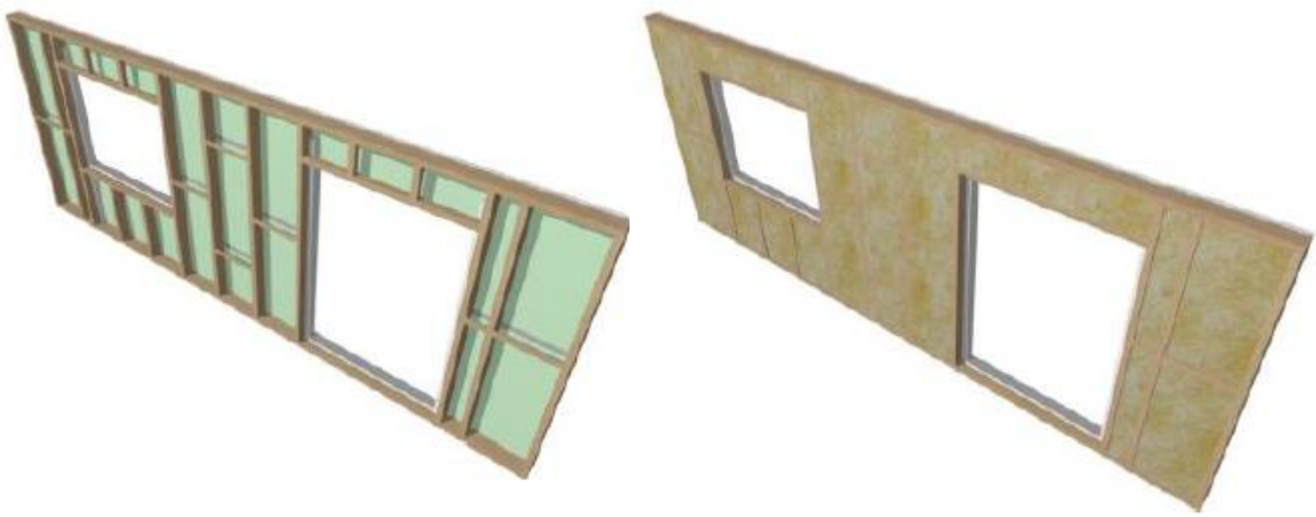


*Figure 18: MORE-CONNECT module panel. Source: [13]*

Windows are also included as a part of the module, specific type again dependant on investor and performance requirements.

Figure 19: MORE-CONNECT demo panel. Source: UCEEB

Since façade refurbishment is usually just a part of a total refurbishment of the building, it has been decided to include the installations such as air ventilation pipes into the module. Reason for that being, that quite often it is very technically challenging to refurbish interior of the building with air distribution piping, for their considerable size. Using the façade elements however doesn't require much interior changes and therefore is much easier solution.

The modules include an air distribution elements placed by the windows, air distribution piping and electrical wiring. The air piping is located in the main insulating layer, potentially creating a thermal bridge. For this reason, different insulating material is used to cover these pipes. This material should have much greater thermal insulation properties, such as PIR foam.

*Figure 20: MORE-CONNECT demo panel. Source: UCEEB*

## 4.3 EASEE and MORE-CONNECT Comparison

### 4.3.1 General properties comparison

**Concept and approach**

- **General approach**

While both off-site retrofitting systems can be considered ‘holistic’ in the meaning of their concept, there are significant differences in the overall approach to the retrofitting process. Firstly, MC system aims for sustainable materials from the beginning, using wood and wooden based materials for both the structural frame and the boarding. The only non-bio elements are the anchoring points and obviously the instalments included. EASEE system doesn’t use only bio-based materials, since its concept is formed under different approach – the goal is simplicity. Especially in the meaning of delivering a final and rigid product to the construction site, where even less skilled labourers are able of finishing the construction.

Another basic concept difference can be found in the scale of the modular elements. While EASEE works with small scale insulating panels, MC concept is based on big scale module that not only differ in their size from EASEE, but mostly in the scale of completion. With windows and air vents already included in them, they offer much bigger step in the process of refurbishment of the whole building. MC is therefore more suitable for this exact investor’s intent – overall refurbishment with the added positives of air ventilation. On the other hand that is not always the case of building refurbishment. Very often it is a long process divided into stages, where envelope refurbishment is only on part of the whole process. In this case, EASEE system can offer much easier and flexible solution, with no need of replacing windows in the same stage of refurbishment.

- **Scale of building refurbishment**

Building refurbishment can be done in many stages and with many approaches. It can only include window replacement, façade refurbishment or changing the heat source. In this aspect there is a big difference between EASEE and MC. While EASEE, with its goal for simplicity and limitation set by the materials, aims for façade refurbishment, MC goes much further. Not only it's offering the installation included in the modules, as well as the windows, but most importantly it introduces refurbishing solution for the whole building envelope with roof elements included. That can be considered a significant difference for the reason, that when properly designed, MC system is capable of delivering the whole refurbishing process off-site. All the elements and modules needed can be done outside the construction site. EASEE at this stage does offer 'only' the façade elements, which in the refurbishing process will always lead to the necessity of using the standard ETICS systems in some parts of the refurbishing process, such as roof. That being said, it cannot provide the full off-site solution.

**Architectural integration and quality, surface finishes**

- **Finishing detail options**

Detailed and well-executed solutions of specific façade points are quintessential part of any retrofitting strategy. Not only from the thermal-bridge point of view, but firstly in the possibilities of architectural detailing. Both retrofitting strategies were developed with specific building stock in mind, as was described in previous chapters. Most of the building stock considered for both strategies is post-war dated and its major part was built before 1980s. From this information we can make a preliminary assessment of the aesthetic façade detailing on the buildings. In most of Europe, the pre-1950s buildings have quite different level of façade finish. After the second half of the century, the facades became simpler, less detailed and less decorative. Therefore it can be said, that for the majority of the considered building stock the façade detailing is not the main issue. It is arguable, that for the pre 1950s buildings with highly decorative facades it is still simpler to use ETICS insulating solutions with specific decorative elements designs. There is no way of standardizing these elements and therefore there is not that many options of off-site production of it.

EASEE system keeps simplicity as the major goal in this category also. Since production of the modular elements is based on one type of panel, there is not many options of detail solution on the façade. All non-standard façade points are solved with ETICS systems, using EPS with plaster

*Figure 21: EASEE Italian demo building*

finishing. This includes all balconies, consoles, awnings, and simply every façade point other than plain element. Reason for this is also quite fragile construction of the sandwich panel itself. Thin concrete layers would be unable to bear any decorative elements, whole other design of the panel would have to be developed for that. On the other hand, the way EASEE deals with joints of the individual panels offer a very interesting 'grid' on the façade. The joints are not levelled to the level of the surface of the panel itself, they are sunk a bit deeper This creates a depth and structure of the façade as a whole, not being completely flat.

MORE-CONNECT retrofitting system however offers more variable options of finishing details. Thanks to the timber-frame construction, which is generally sturdier the EASEE, there are possibilities of including more decorative elements on the façade. Main advantage is however once again in the complexity of the design. When used with also MC developed roof elements, it can offer more holistic solution for the envelope refurbishment. Quite similar situation as EASEE has the MC system with balconies and other console-based façade elements. These thermal bridges however are a weak point of any envelope retrofitting strategy and therefore cannot be concluded as a disadvantage per se.

- **Surface finish options**

Surface finish is an aspect where the two systems are maybe the most different from all the criteria. EASEE system has one surface finish option – the textile reinforced concrete (CRT) from which it's made from. However this fact includes two aspects;

Firstly, it does not mean, that there is only one colour option for the façade. The basic CRT used for the testing building is in the grey scale, which is and will be the most common option. There is however possibility of additives to the concrete formula, which will turn it into colour scale of any other shade.

Secondly, the biggest problem arising from off-site production of the concrete surface is the lack of control of the exact properties and shade of the basic colour. While the CRT formula is still being improved, the production company hasn't been able to produce panels of the exact same colour finish. Also the aging process is not the same for all the panels, therefore it can be assumed, that in future the shade of the individual panels will also be slightly changing.

All of these issues are production and design development based. In reality it is absolutely possible to produce panels of the same shade and once the production testing is in that state, these issues will cease to exist.

*Figure 22: EASEE shades of grey on different panels of the facade*

*Figure 23: Window corner detail.*

**Modular shapes and sizes issues, window placement**

- **Window positioning**

Window replacement plays obviously a huge role in the process of building envelope retrofitting. Depending on the window/façade ratio, it can often be a major heat transfer element in the scope of the whole envelope. In the off-site retrofitting strategy there are several options of dealing with this issue. The two retrofitting strategies discussed in this thesis are on the opposite sides of the approach.

As was already mentioned, EASEE system only includes the sandwich panels. This means that not only it doesn't include the windows, but it doesn't really offer the option of including the windows in the level of the new insulation. The new windows therefore keep the same position after being placed, while the whole façade is extended by the thickness of the EASEE panel. As with most of the retrofitting aspects, the outcome of this fact is not strictly negative nor positive. On the positive side, this fact offers the option of scheduling envelope retrofitting and window replacement in two different stages, with those two operations being separate. This is quite fitting for the reality in retrofitting process – not always is the whole building envelope being refurbished, for financial or other reasons. EASEE offers the option of replacing the windows first (being the major heat loss element, as mentioned above) and retrofitting the rest of the façade later. There are also several negative aspects of this solution. Not including windows into the panels themselves means more difficult panel-window detail, bigger and more complicated thermal bridges. And generally longer construction time on site.

As already mentioned, MORE-CONNECT approach is quite different in this aspect. Windows are integral part of the module design, since MC offers generally modules of much bigger scale than EASEE. The advantages of this strategy are the exact opposite from EASEE approach – very well constructed thermal bridges, much faster construction time and overall complexity of the design.

- **Shapes options**

The shape of the panels is mainly defined by the construction method of the strategy and the variability that it offers. EASEE panels, being mostly based on a TRC load bearing structure have quite difficult starting point for custom shaping. While there was a research for custom shapes of the panels, due to lack of time and funding it was not possible to develop a suitable production for this process. For this reason, the EASEE panels can only be designed in rectangular shape, with a 'standard' side ratio. This fact of course denies the possibility of covering the whole building envelope, specifically triangle shaped elements by the roof.

Since the MC system is based on a load bearing timber frame, it is much more variable in shapes and sizes. Timber frame offers much easier design options for triangular shapes then TRC and is therefore more suitable for design of the whole building envelope retrofitting.

**Material, construction and insulating properties and options**

- **Material and insulation options**

The choice of material has been the major difference between EASEE and MC since the first approach phase. While MC aims for using as much bio-based materials as possible, the goal of EASEE is to provide quick and sustainable solution for building envelope retrofitting. The choice of material is derived from this approach. Using EPS as the insulation material is a logical step for its self-bearing properties, general accessibility and rigidity. Using TRC as the surface and load-bearing material is then based on several factors. TRC was used for its excellent resistance to compression and high tensile strength. The combination of these materials delivers the desired result – very light panel with integrated anchoring points and good thermal resistance properties, which is also easy to operate with. The choice of material for EASEE sandwich panel is therefore set exactly for the intended and designed purpose and cannot be changed without rethinking the whole concept.

MORE-CONNECT timber frame system is more variable compared to EASEE. Firstly it consists of more layers and materials in general, but most of them are optional and can be changed depending on the requirements of the investor and building. The main insulating layer as well as the cavity filling and the final insulating layer have several options of material. Low density mineral wool is the basic one, however especially for the final insulating layer even vacuum insulating panel have been considered for their thermal resistance properties.

- **Air cavity solutions**

Dealing with air cavity between the existing façade and new retrofitting elements is a common problem to be solved for all the off-site retrofitting strategies. It is based on the simple fact, that all off-site retrofitting strategies are based on modular elements, that most often sit on some kind of anchoring system on the existing façade. The existing façade is always considered more or less uneven and for that reason the anchoring system creates the air cavity. This fact might be considered an advantage, when included in the retrofitting strategy correctly – after all, vacuum (or air cavity with zero air flow) has thermal resistance comparable to some insulating materials. There are two approaches to dealing with the cavity:

1. Filling it with soft insulating material, most commonly mineral wool, which will even the surface of the existing façade and fill the entire cavity. This approach adds another insulating layer to the whole design and should insure air-tightness of the cavity. Clear disadvantage is however, that construction process becomes more intricate and prone to mistakes. This is the approach of MORE-CONNECT retrofitting. The inner insulating layer (mineral wool) is attached to the panel and can be therefore be included in the off-site manufacturing process.
2. Creating an air cavity. EASEE retrofitting system includes the air cavity between the panel and an existing wall. Reason for this being once more the fastest process of construction and as little complications during the whole process as possible. One major issue needs to be dealt with in this case though – the airtightness of the cavity. The insulating properties of still air are only true if there is no circulation in the cavity whatsoever. With the scale of the whole façade in mind, there is a big demand finishing works of the retrofitting process. The airtightness of the EASEE system is based on perfect execution of the joins, corners and generally all construction details that would allow any non-airtight spots.

**Production and construction and its requirements**

- **Production difficulties and requirements**

Since all off-site retrofitting strategies are based on the high-level production process, it is also a phase which needs to be executed perfectly. Both retrofitting strategies rely on the high-level detail execution, however that is not the only aspect accounting to the success of the overall strategy. The production and construction heavily relies on the first phase of the process – the scanning of the building itself. It is not only important for getting the actual dimensions of it, but for exact production and placement of the anchoring system – in order to even the usually uneven existing façade, it is a common practice to place the anchoring system one by one using a total station and setting the exact dimension form the existing wall to even out the new façade surface perfectly.

The production differences are based mainly on the quite different complexity of the two strategies. While MORE-CONNECT offers a large scale modular panels with included air ducts and windows, EASEE production consist mainly of the proper casting process. It must be said that the TRC casting process is much trickier then the MC timber frame construction, however once designed properly, the chance of fault production is rapidly lowered.

### 4.3.2 Façade points assessment

**Anchoring elements and options**

The anchoring elements are derived from two basic aspects – the scale of the retrofitting elements (the dimensions) and the weight which is carried by one anchor. Based on that two different anchoring systems were developed for EASEE and MORE-CONNECT. The scale of the anchoring elements is not only important for the load bearing ability, but also plays an important role as a thermal bridge between the retrofitting panel and existing façade. This is where the major difference is between the two strategies. EASEE panels, being as light as the materials offer and being carried by four anchoring points can afford to have the anchors quite minimalistic. The thermal bridge they create is as little as it can be thanks to that.

Compared to that, MORE-CONNECT uses much more substantial anchors, which require higher consistency of the existing wall, but most importantly create much more significant thermal bridges.

*Figure 24: EASEE façade anchor. Source: POLIMI elaboration*

*Figure 25: MORE-CONNECT facade anchor. Source:UCEEB*

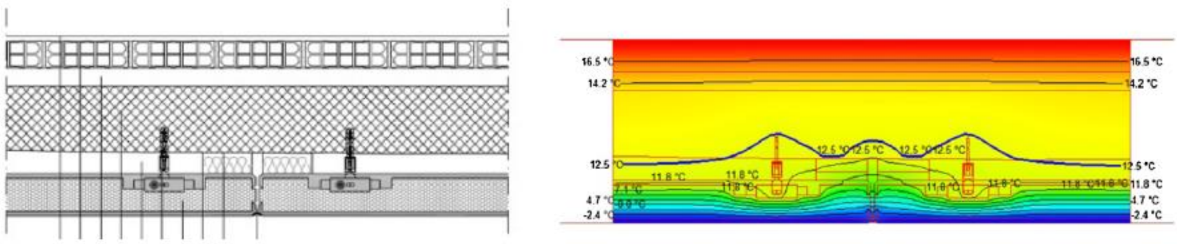


*Figure 26: EASEE join design and heat transfer analysis. Source: POLIMI elaboration*

**Critical facade points**

A great emphasis has been put on designing the critical details of both retrofitting systems. Unlike traditional ETICS insulating strategy, off-site retrofitting systems consist of several elements, usually panels, which are put together on the construction site. Although the production of the panels themselves is done under better supervision in controlled environment, it still creates much more opportunities for construction errors being done in joints, corners and other critical and challenging façade points.

Corners are typical critical façade points, which are prone to failures in both design and production/construction. In typical ETICS systems, the EPS panels are simply put together in the correct pattern and the only failure that can occur is the coherence of their joint and therefore the glue that holds them together. However with off-site panels, the situation is more complicated. Both EASEE and MC panels do not offer a specific design for a corner element, instead they use a standard façade element, with additional corner construction solution. Thanks to the layered timber structure of MC design, this fact is not an obstacle. The corner is therefore design with similar detail construction as normal timber frame wall. However EASEE strategy, with only on design of precast sandwich panels has to deal with more intricate issue. The corner design is solved with an insulating insert between the two panels in right angle. This insert eliminates the thermal bridge to a certain point, however it is not able to get rid of it perfectly.

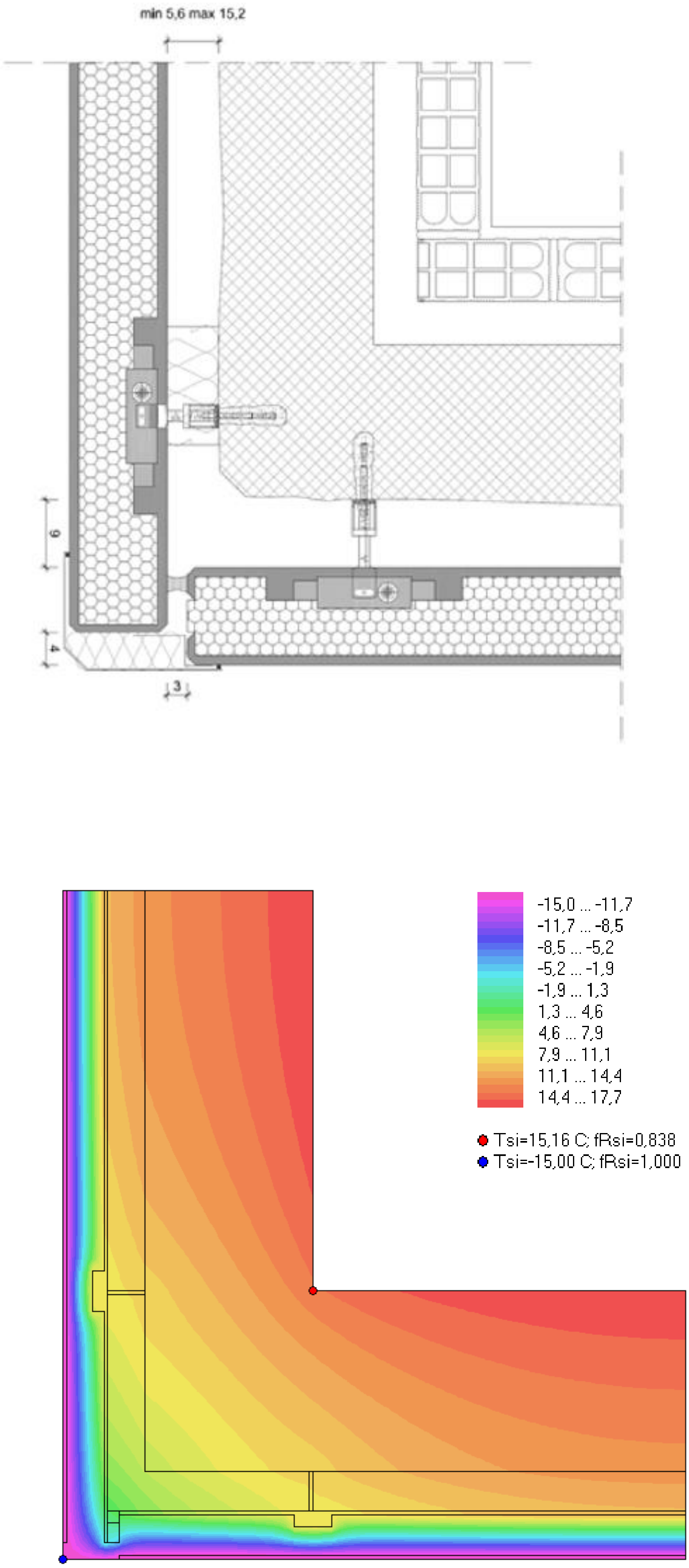



*Figure 27: EASEE corner design and heat transfer analysis*

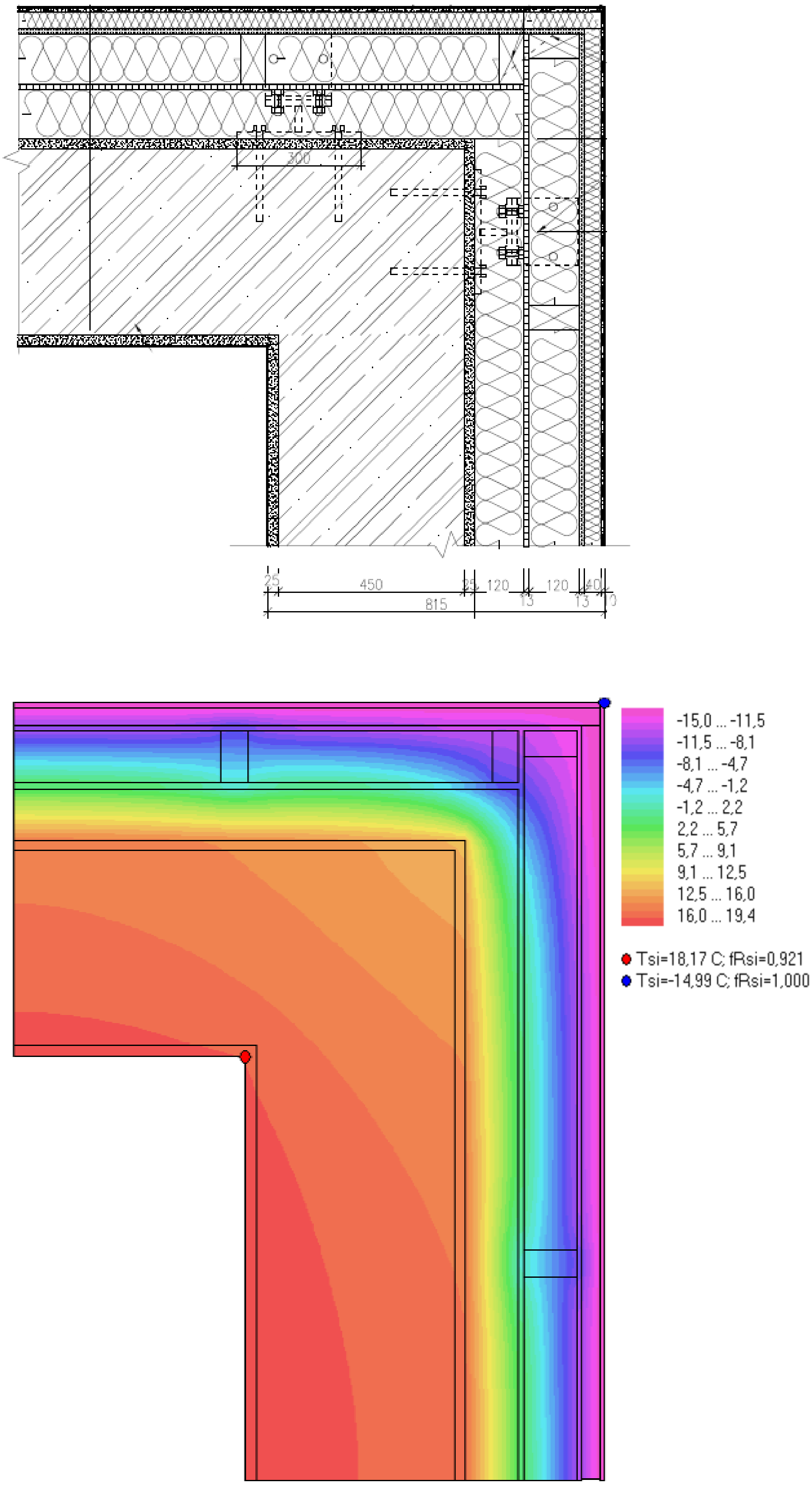



*Figure 28: MORE-CONNECT corner design and heat transfer analysis*

### 4.3.3 Environmental impact assessment

Since the whole point of all the retrofitting strategies is to be more conscious towards the environment, an environmental impact assessment of both retrofitting strategies is an important comparison aspect also.The functioning unit chosen is 1 $m^2$ of plain panel, not including installations or windows in the MORE-CONNECT panel. Primary data were gathered from the Envimat material database. For a proper comparison, both panels needed to be standardized to the same heat transfer performance. For this case, EASEE panel has been assumed with insulation layer of 210 mm, instead of 100 mm.

| **MORE-CONNECT REFURBISHED WALL** | | **thickness d** | **heat conductivity λ** | **thermal resistance R** | **thermal transmittance U** |
|---|---|---|---|---|---|
| | | mm | $W.m^{-1}.K^{-1}$ | $m^2.K.W^{-1}$ | $W.m^{-2}.K^{-1}$ |
| **material** | **note** | | | | |
| interior plaster | *existing wall* | 25 | 0,99 | 0,03 | |
| masonry | | 450 | 0,86 | 0,52 | |
| exterior plaster | | 25 | 0,99 | 0,03 | |
| low density mineral wool | *MORE-CONNECT* | 120 | 0,039 | 3,08 | |
| cement fibre board | | 12,5 | 0,32 | 0,04 | |
| low density mineral wool | | 120 | 0,052 | 2,31 | |
| high density fibre board | | 13 | 0,1 | 0,13 | |
| high density facade mineral wood board | | 40 | 0,05 | 0,8 | |
| plaster | | 5 | 0,47 | 0,01 | |
| **Boundary condition** | *interior Rsi* | | | 0,13 | |
| | *exterior Rse* | | | 0,04 | |
| **Total module** | | 311,5 | | 6,54 | 0,15 |
| **Total structure** | | **810,5** | | **7,12** | **0,14** |

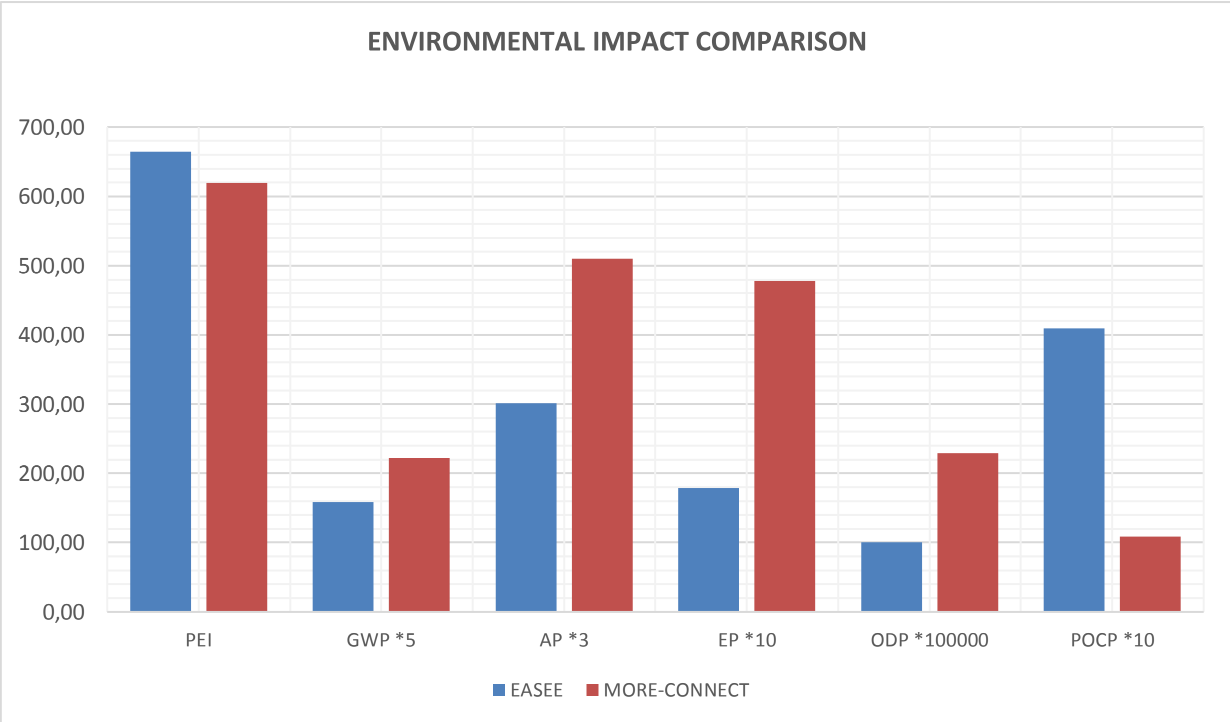
| **EASEE REFURBISHED WALL** | | **thickness d** | **heat conductivity λ** | **thermal resistance R** | **thermal transmittance U** |
|---|---|---|---|---|---|
| | | mm | $W.m^{-1}.K^{-1}$ | $m^2.K.W^{-1}$ | $W.m^{-2}.K^{-1}$ |
| **material** | **note** | | | | |
| interior plaster | *existing wall* | 25 | 0,99 | 0,03 | |
| masonry | | 450 | 0,86 | 0,52 | |
| exterior plaster | | 25 | 0,99 | 0,03 | |
| air cavity | *EASEE* | 100 | 0,588 | 0,17 | |
| TRC | | 10 | 1,43 | 0,01 | |
| EPS | | **210** | 0,034 | 6,18 | |
| TRC | | 10 | 1,43 | 0,01 | |
| **Boundary condition** | *interior Rsi* | | | 0,13 | |
| | *exterior Rse* | | | 0,04 | |
| **Total module** | | 330 | | 6,53 | 0,15 |
| **Total structure** | | **830** | | **7,11** | **0,14** |

*Table 1: MORE-CONNECT and EASEE construction layers.*

Following aspect were compared between the two retrofitting strategies:

- PEI (Primary Energy Input)
- GWP (Global Warming Potential)
- AP (Acidification Potential)
- EP (Eutrophication Potential)
- ODP (Ozone Depletion Potential)
- POCP (Photochemical Ozone Creation Potential)

| | | EASEE | MORE-CONNECT |
|---|---|---|---|
| **PEI** | [MJ/m2] | 664,15 | 619,52 |
| **GWP *5** | [kg CO2 ekv./m2] | 158,85 | 222,18 |
| **AP *3** | [g SO2 ekv./m2] | 300,66 | 509,86 |
| **EP *10** | [g (PO4)3- ekv./m2] | 179,29 | 477,43 |
| **ODP *100000** | [g R-11 ekv./m2] | 100,60 | 229,26 |
| **POCP *10** | [g C2H4 ekv./m2] | 409,29 | 108,81 |




The individual indicators were then multiplied by a factor that helps the overall scale of comparison.

From the final comparison table we can conclude, that the result are not strictly one sided. Although EASEE panels have bigger Primary Energy Input, in other indicators it is MC with the better results. We can also see how big of a role the individual choice of materials plays in the scale of the whole panel. The EPS insulation in EASEE dominates in all the indicators, while in MORE-CONNECT the impacts of the individual materials are much more even.

| MATERIAL | PEI [MJ/kg] | GWP [kg CO2 ekv./kg] | AP [g SO2 ekv./kg] | EP [g (PO4)3- ekv./kg] | ODP [g R-11 ekv./kg] | POCP [g C2H4 ekv./kg] |
|---|---|---|---|---|---|---|
| textile reinforced concrete | 0,69079 | 0,13316 | 0,22171 | 0,05400 | 0,00000 | 0,00824 |
| EPS | 105,07300 | 4,21210 | 14,90000 | 2,54900 | 0,00013 | 6,75450 |
| low density mineral wool | 20,19230 | 1,13310 | 8,35830 | 1,83000 | 0,00006 | 0,44541 |
| cement fibre board | 11,77070 | 1,09090 | 2,45310 | 0,80900 | 0,00006 | 0,14217 |
| high density fibre board | 12,50570 | 0,48132 | 2,03708 | 0,91700 | 0,00002 | 0,29519 |
| high density facade mineral wood board | 20,19230 | 1,13310 | 8,35830 | 1,83000 | 0,00006 | 0,44541 |
| exterior plaster | 1,45966 | 0,21317 | 0,35407 | 0,08700 | 0,00001 | 0,01641 |

| EASEE | d[m] | ρ [kg/m3] | kg/m2 | PEI [MJ/m2] | GWP [kg CO2 ekv./m2] | AP [g SO2 ekv./m2] | EP [g (PO4)3- ekv./m2] | ODP [g R-11 ekv./m2] | POCP [g C2H4 ekv./m2] |
|---|---|---|---|---|---|---|---|---|---|
| textile reinforced concrete | 0,010 | 2440 | 24,4 | 16,85535 | 3,24901 | 5,40980 | 1,31760 | 0,00011 | 0,20110 |
| EPS | 0,200 | 30 | 6 | 630,43800 | 25,27260 | 89,40000 | 15,29400 | 0,00079 | 40,52700 |
| textile reinforced concrete | 0,010 | 2440 | 24,4 | 16,85535 | 3,24901 | 5,40980 | 1,31760 | 0,00011 | 0,20110 |
| | | | **SUM** | **664,14870** | **31,77061** | **100,21959** | **17,92920** | **0,00101** | **40,92920** |

| MORE-CONNECT | d[m] | ρ [kg/m3] | kg/m2 | PEI [MJ/m2] | GWP [kg CO2 ekv./m2] | AP [g SO2 ekv./m2] | EP [g (PO4)3- ekv./m2] | ODP [g R-11 ekv./m2] | POCP [g C2H4 ekv./m2] |
|---|---|---|---|---|---|---|---|---|---|
| low density mineral wool | 0,120 | 32 | 3,84 | 77,53843 | 4,35110 | 32,09587 | 7,02720 | 0,00021 | 1,71037 |
| cement fibre board | 0,013 | 1900 | 23,75 | 279,55413 | 25,90888 | 58,26113 | 19,21375 | 0,00139 | 3,37654 |
| low density mineral wool | 0,120 | 32 | 3,84 | 77,53843 | 4,35110 | 32,09587 | 7,02720 | 0,00021 | 1,71037 |
| high density fibre board | 0,013 | 650 | 8,45 | 105,67317 | 4,06718 | 17,21333 | 7,74865 | 0,00021 | 2,49431 |
| high density facade mineral wood board | 0,040 | 80 | 3,2 | 64,61536 | 3,62592 | 26,74656 | 5,85600 | 0,00018 | 1,42531 |
| exterior plaster | 0,005 | 2000 | 10 | 14,59660 | 2,13170 | 3,54070 | 0,87000 | 0,00010 | 0,16414 |
| | | | **SUM** | **619,51611** | **44,43588** | **169,95346** | **47,74280** | **0,00229** | **10,88105** |

### 4.3.4 Multi-criteria comparison

Since there is so many categories, indicators and aspect in which can off-site retrofitting strategies be compared, it is difficult to recognize the true weight of them in direct comparison. Following tables offer one multi-criteria comparison strategy, which allow better insight into the complex comparison.

| **MORE-CONNECT**<br><br>how much does the retrofitting strategy suits/is flexible to investor's requirements and building properties on scale 1 - 10: | | properties of the building and investor's requirements: | | |
|---|---|---|---|---|
| | | building volume | volume complexity | performance requirements |
| retrofitting strategy performance | Architecture quality | 4 | 6 | 4 |
| | Modular options | 3 | 5 | 6 |
| | Material, construction | 0 | 5 | 0 |
| | Production, construction | 0 | 5 | 4 |
| | Joints and corners | 0 | 4 | 7 |
| | environmental impact | 5 | 6 | 5 |
| | construction time | 2 | 9 | 5 |
| | detail related risk | 3 | 9 | 8 |

| **EASEE**<br><br>how much does the retrofitting strategy suits/is flexible to investor's requirements and building properties on scale 1 - 10: | | properties of the building | | |
|---|---|---|---|---|
| | | building volume | volume complexity | performance requirements |
| retrofitting strategy performance | Architecture quality | 3 | 7 | 7 |
| | Modular options | 3 | 9 | 4 |
| | Material, construction | 0 | 7 | 0 |
| | Production, construction | 0 | 7 | 3 |
| | Joints and corners | 0 | 6 | 7 |
| | environmental impact | 5 | 8 | 5 |
| | construction time | 2 | 9 | 5 |
| | detail related risk | 3 | 7 | 7 |

As a final outcome, these results have been fitted into one table with overall result of the comparison. In effort for better distribution of the indicators, each of the indicators have been adjusted accordingly. Before this adjustment the results were extremely similar, after the adjustment MORE-CONNECT system came out with slightly better result, being the more universal strategy.

| | MORE-CONNECT | EASEE | INDICATOR WEIGHT DISTRIBUTION | MORE-CONNECT after adjustment | EASEE after adjustment |
|---|---|---|---|---|---|
| Architecture quality | 14 | 17 | 0,8 | 11,2 | 13,6 |
| Modular options | 14 | 16 | 1 | 14 | 16 |
| Material, construction | 5 | 7 | 0,7 | 3,5 | 4,9 |
| Production, construction | 9 | 10 | 0,7 | 6,3 | 7 |
| Joints and corners | 11 | 13 | 0,8 | 8,8 | 10,4 |
| environmental impact | 16 | 18 | 0,9 | 14,4 | 16,2 |
| construction time | 16 | 16 | 1 | 16 | 16 |
| detail related risk | 20 | 17 | 0,9 | 18 | 15,3 |
| **SUM** | 105 | 114 | | **92,2** | **99,4** |

# 5. Conclusions

The goal of achieving all tasks set by the Paris Agreement is a bold and ambitious one. In order to make it reality, many measures have to be taken in the construction industry and legal systems in general. Embracing the off-site prefabrication process as a new standard seems to be one of these measures. The speed and precision in which the European residential building stock needs to be refurbished tells us that in near future it will be necessary to come to this decision.

This thesis offers an introduction to the whole off-site refurbishment process, including the established steps of prefabricated envelope panel design and production. It also summarizes the reasons and reality, that leads to innovative construction strategies and ideas.

In the second part, two very different refurbishment strategies have been selected for a multi-criteria comparison. First strategy, EASEE, focused on fast production, simple design and trouble-free construction using only a small crane, has been recognized as very effective strategy for specific residential buildings. Especially when the refurbishing process is divided into several phases. EASEE simply uses all the advantages of ETICS, while eliminating the disadvantages. MORE-CONNECT strategy stands on the other side of the prefabricated systems. It offers a complex, wide scale solution useful for major renovation projects. This approach has been found to be more universal and fitting, together with the choice of materials, which offer better construction solutions of difficult façade points. The choice of materials has been one of the deciding aspect in every compared category. While the textile reinforced concrete used in EASEE panels is light and durable, it turns out to be more unreliable then the traditional bio-based timber frame, from which MORE-CONNECT panels are constructed.

Prefabrication is certainly the right way of building refurbishment future. With high demand on speed and precision it is the only strategy capable of delivering it. In today's situation most of these strategies are still in process of testing, while most buildings are still being refurbished with ETICS solutions. It will take a great effort from the municipalities, construction companies and investors to make the off-site production the new standard.

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