An LT- ready and economically feasible renovation façade design.

Stamatia Kounaki

An LT- ready and economically feasible renovation façade design.

Master of Science (MSc) thesis
Msc Architecture, Urbanism & Building Sciences
Master Track: Building Technology
31st October 2019

Name
Stamatia Kounaki
Student Number: 4748751

Mentors
Dr.ing. Thaleia Konstantinou
Ir. Eric van de Ham

Delegate of the Board of Examiners
Dr. ir. Martijn Stellingwerff

Delft University of Technology
Faculty of Architecture and the Built Environment
Julianalaan 134
2628 BL Delft The Netherlands

ABSTRACT

The refurbishment of the Dutch post- war residential building stock provides a great potential for energy and CO_2 emissions savings, since a large number of buildings were built before 1975 and under low or no energy standards. However, their refurbishment and especially zero-on-the-meter, is too expensive and it is not possible to find the required funding. Following the guidelines of the Project MVI-Energie, which proposes disconnecting from the gas and decreasing the heating demand (that can reach up to 70% of energy demand) by insulating as such to be able to change to low temperature heating. This study focused on portiekapartments and proposed a refurbishment strategy to achieve LT-ready, while lowering the costs, time and nuisance to the residents. The facade criteria regarding the energy efficiency are the results of a parametric simulation, which includes every significant facade variable and the innovative process of applying external insulation at the optimal percentage to achieve LT-ready. The results of this simulation - diagram of solutions- can be used to upscale the research and as a guideline to quickly and easily understand if this strategy can be applied to other buildings and what it will need, based on their facade characteristics. For the technical solution a prefabricated small size insulating panel is used, that reinforces the economically feasible and fast refurbishment idea. An important aspect of the solution is to be adaptive (for example provide different cladding options) and can be part of a two-step refurbishment by providing the opportunity in the future to be continued to deeper refurbishment if needed.

Keywords: Facade refurbishment strategy, Dutch post -war portiekapartments, LT-ready, economically feasible refurbishment, innovative insulation process, prefabricated, parametric multi objective simulation.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my mentors, Thaleia Konstantinou and Eric van de Ham for their contribution. I would like to thank them for always guiding my focus on the most relevant and important aspects of this study and imparting their knowledge on the issues where I needed help.

I would like to also thank my amazing family who have been so supportive in every possible way. Special thanks to my friends the ones far away and the ones in Delft, for the support and the so needed breaks.

Stamatia Kounaki

00 Contents

01 INTRODUCTION

1.1 Background information

Energy reduction and the Building sector

Monday February 25th 2019 is being written down in the record books as both the warmest February day ever measured in the Netherlands, as well as the highest measured temperature in the meteorological winter (Weerplaza,2019). The planet's average surface temperature has risen about 0.9 degrees Celsius since the late 19th century (NOAA, 2019). The five warmest years were recorded in the last nine years.

There are more examples of the changing climate. It is not only the increase in average surface temperatures but also the sea level rising, the melting of glasier, the change in weather patterns and other natural systems. According to R. Lindsey (2016) the global sea level has risen with 6,7cm between 2014-1993 and will continue to rise with a yearly rate of 3,2mm. Especially for the Netherlands the rise of the sea level is of great importance. The change is driven largely by the increased carbon dioxide and other human-made emissions into the atmosphere which leads to an unwanted change in the fundamentals of the physics that keeps the earth habitable. The concentration of CO_2 and other greenhouses gases in the atmosphere is largely the result of the production of energy through the burning of fossil fuels and the long-term deforestation, with energy use producing 59,8% of GHG, followed by transport (19.5%), agriculture (9.2%) and waste (2.8%), as seen in figure 1.

The building sector (residential and building sector) is a key sector in reducing the energy use since it is the biggest energy user. It accounts for 35.8% of final energy consumption in the EU. Thus there is an urgent need to reduce this energy demand if EU wants to meet the long-term commitment of decarbonization with a target of 80 to 95% decrease in emissions by 2050.

Especially, residential buildings provide considerable potential for energy saving. The household sector is one of the largest energy consumers, accounting for approximately 1/4 of the final energy use in the European Union (Konstantinou, 2014) (Figure 2). As far as the residential stock is concerned, there are the new buildings that are currently being build following the existing energy standards (only 1% building stock is added each year) and the existing stock and was built under far lower energy and sustainability standards.

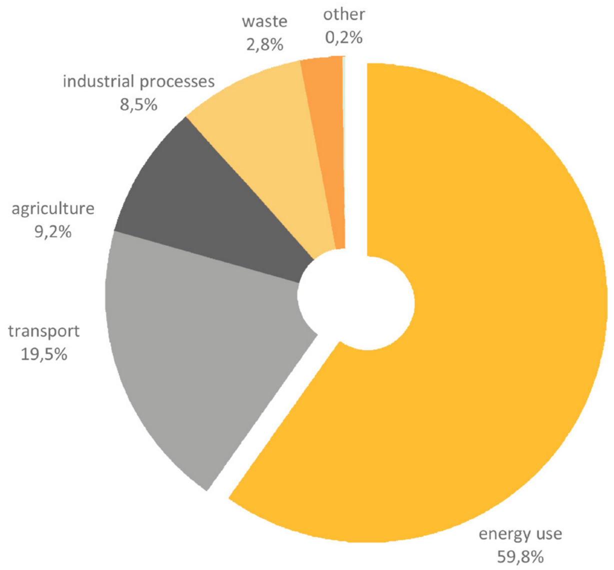


Fig 1 Greenhouse gas emissions by sector in EU, (EU-27, 2007).

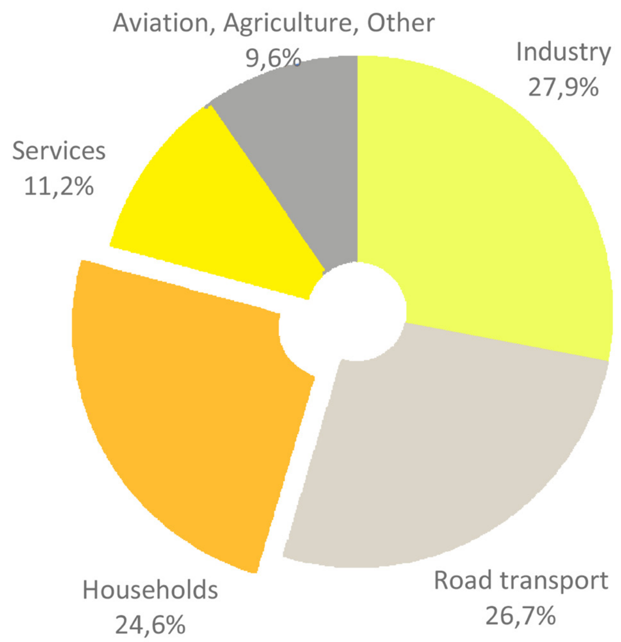


Fig 2 Energy Consumption in EU, (EU-27, 2006).

So, since the renewal rate is too slow addressing the problem of the existing stock has two answers: demolition or extension of life. Taking into account materials and waste and the embodied energy, studies show that the environmental impact of life cycle extension of a building is definitely less than demolition and new construction (Thomsen and Van der Flier,2008). Refurbishment constitutes a necessary action to meet the energy targets for the coming decades (Konstantinou, 2014).

So, as mentioned already, a start is to reduce the energy demand by reducing the energy demand of the residential sector. A great saving potential lies in the existing housing and especially in the post-war housing stock, built between 1945 and 1975. These dwellings account for one third of the total housing stock and they were built in the time that there were no or very limited energy measures since until the oil crisis in 1973 houses were hardly insulated.

1.2 Problem statement

Lack of funding and refurbishment solutions

A very efficient way to reduce the energy demand of the old houses is to refurbish them, by insulating and updating the installations. However, the market intake of such renovation is currently very slow, as housing associations are reluctant to invest the increased cost of a zero-energy refurbishment, despite the energy saving and the benefits for the occupants (2nd skin, 2016). It is estimated that 6.000.000 houses in the Netherlands still need to reduce their energy demand and the available budget for energy neutral renovation of these homes is limited.

Since it was realised how important for the energy reduction their refurbishment is, this has drawn some attention and there are projects being developed trying to achieve a more cost efficient refurbishment. However there is still a lack in refurbishment strategies and techniques.

Also, the traditional approaches are very disturbing to the residents, who have to be relocated during the process, causing extra costs. This leads to a no affordable and acceptable solution for residents in many cases, who despite the financial benefit of the energy saving, they often don't want to renovate due to the time consuming and disturbing construction work.

Moreover, most of the production still takes place on location. This leads to handcrafted, unique and customer-specific buildings. This usually leads to high costs as a result of which renovation is considered expensive and complex (Stutvoet, 2018).

1.3 MVI Energie

One project being developed currently trying to answer the lack of refurbishment strategies is called MVI Energie (Maatschappelijk Verantwoord Innoveren Energie). Acknowledging that zero on the meter is often too ambitious and expensive, the project is based on the knowledge that more than half of the final energy consumption of residential buildings in the EU is used for space heating, reaching up to 70% (BPIE, 2011). In average it is 57% (Figure 3). Naturally that accounts as the largest percentage of energy consumption in residential buildings. So, heating demand is the most significant criterion for energy efficiency.

Given that the consumption for heating is directly related to losses (due to transmission, ventilation and infiltration) through the building envelope, according to the “projectplan MVI energie” it is necessary to insulate the houses in such a way that heating with low temperature heating (<55 ° C) can be achieved. This makes sustainable generation (eg with a heat pump) feasible. However, this also proves difficult for a large group of houses for technical and financial reasons. There are few affordable alternatives to insulate a home, and there is not enough knowledge about what is needed for LT-ready renovation (MVI Energie, 2018).

1.4 Focus
Portiek apartments

The focus is the post war apartments in the years 1945 until 1975 (although the solution could be applied to houses up to 1991), because it is the largest Dutch residential part numerically and offer the most important capability for energy reduction. More specifically, the focus of this project is the low-rise, multi-family residential buildings, accessed by separate stairwells per 6-8 apartments called portiek apartments. As seen in figure 4, this type of building represents almost 380.000 houses built in the years 1945-1975(Voorbeeldwoningen, 2011).

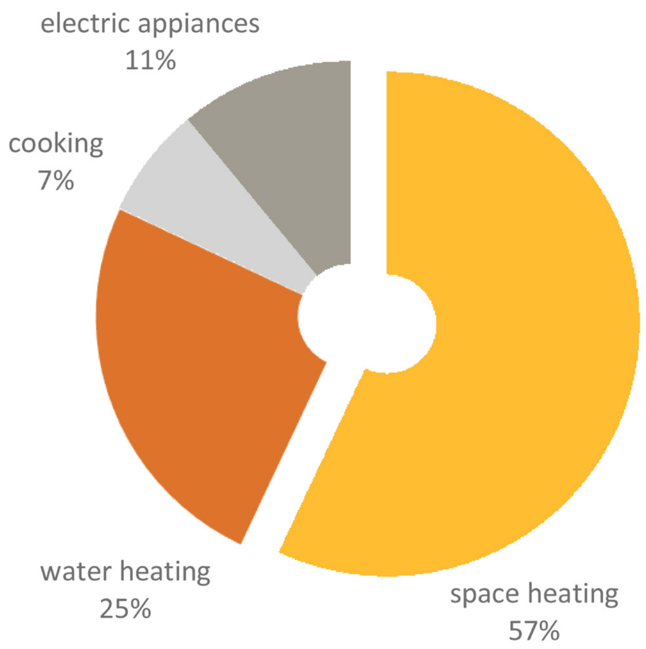


Fig 3 Energy consumption in residential buildings in EU, (EU-27, 2006)

A second reason that this type is chosen is that it is a difficult type of building because of its variance in shape, design and quality. Due to this reason there are not viable renovation concepts still been developed for this type of building. The focus will be on refurbishment of the building envelope, of the portiek apartments as it is very crucial for the heating demand and in particular the façade.

TYPE	TIMEPERIOD			
	UNTIL 1945	1946-1964	1965-1974	1975-1991
GALERIJ	69000		174000	109000
PORTIEK	256000	267000	112000	142000
GENERAL	99000		125000	125000

Fig 4 Post war Portiek apartments: 380.000 houses from 1945 until 1975 (Adapted from Voorbeeldwoningen, 2011).

1.5 Objective

There have been three major problems identified. Firstly, the lack of funds for the amount of the refurbishment needed and secondly the lack of solutions that can be pre-fabricated and suitable for a lot of buildings. A third point is that the refurbishment has to be fast and as little as possible disturbing to the tenants so that is accepted easier.

The refurbishment strategy that is the solution to the three problems consists of:

1. Adaption of the MVI- Energie project’s principles. In order to reduce the energy demand the first step is reducing the heat loss enough so the building can operate on low temperature heating using the existing installations. A way to achieve that is by applying insulation in an optimal way, following an innovative process to reduce the costs.

2. Transition from burning natural gas for heating with an input water temperature of 60°C- 80°C, to low or medium temperature of 40-55°C by insulating correctly.

3. The use of low or medium temperature heating offers the advantage of disconnecting from natural gas for heating and using instead heat district or a heat pump.

4. To achieve minimum disturbance and installation speed, the facade elements could be prefabricated. Also, to achieve minimum disturbance for the residents cavity and external insulation are chosen, and internal insulation is rejected.

5. A flexible modular facade system which will aim at saving in cost, energy and time in various stages of the refurbishment such as production process, transport and application.

6. The facade system should be adjusted to the existing structure without any major construction adjustments of the existing building taking into account the portiekapartment's characteristics.

1.6 Research question

Subsequently the research question is formed as such:

Which design strategy is needed in order to achieve a faster, economically feasible and LT-ready refurbishment for post-war portiek apartments?

Sub-questions

In order to answer the main question, first some sub-questions have to be answered:

What are the condition and construction of existing residential building stock?

What strategies and retrofitting measures are currently applied in refurbishment practice?

How much does a renovation cost today, what makes a renovation expensive and how could it be lowered to a more feasible amount?

How does the change to low temperature heating affect the renovation concept?

1.7 Methodology

The research methodology is divided in the following steps and methods:

Following the introduction of the project and after stating the problem and forming the research ques-

tion , a literature study is conducted in order to understand the building stock of the Netherlands. Analysis and evaluation of the existing building stock is an essential first step in every refurbishment project. The literature study of the building stock provides also the essential information needed in order to decide the focus of the research and the choice of the case study. The case study is used in every step of the research, for the calculations and for the design.

Secondly, understanding the current renovation techniques is very important in order to determine what is currently done and what costs the most in today's renovations in order to be able to form a cheaper solution. The cases studies analysis is useful to enrich the knowledge over prefabrication, structure, materials, application, detailing and innovative refurbishment approaches.

Next with a study of the MVI- ENERGIE project, important information for the reason and the way to an LT-ready building are derived.

Using the information from the literature study a list of simple insulation measures is formed, including traditional ways and an innovative approach. The cost assessment of the measures is done.

The current situation of the case study and the measures (that are applied on the case study) are then simulated in Design Builder. The results of the simulation of the current situation are validated with reference numbers for the gas and energy consumption. Every measure is tested separately, being the only parameter that is changed in order to see the effect. For maximum heating power the simulation is done in room level. In order to validate the results a steady state heat balance calculation is done for every concept and every room.

The measures are compared in terms of cost and annual energy savings. Then the maximum heating power results of the dynamic simulations for every room are compared to the heat output of the building's radiators. The 8 measures are the first step to check if the innovative way to insulate makes sense to further develop cost and energy wise.

To upscale the research and also explore more options for the case study, simulations in Grasshoper are done. The results are discussed and early-stage facade design of the case study is optimized in terms of cost and energy. After that it is clear how much, where, and what material the insulation should be. At this stage an additional heat loss and a condensation check is performed using the programme Therm.

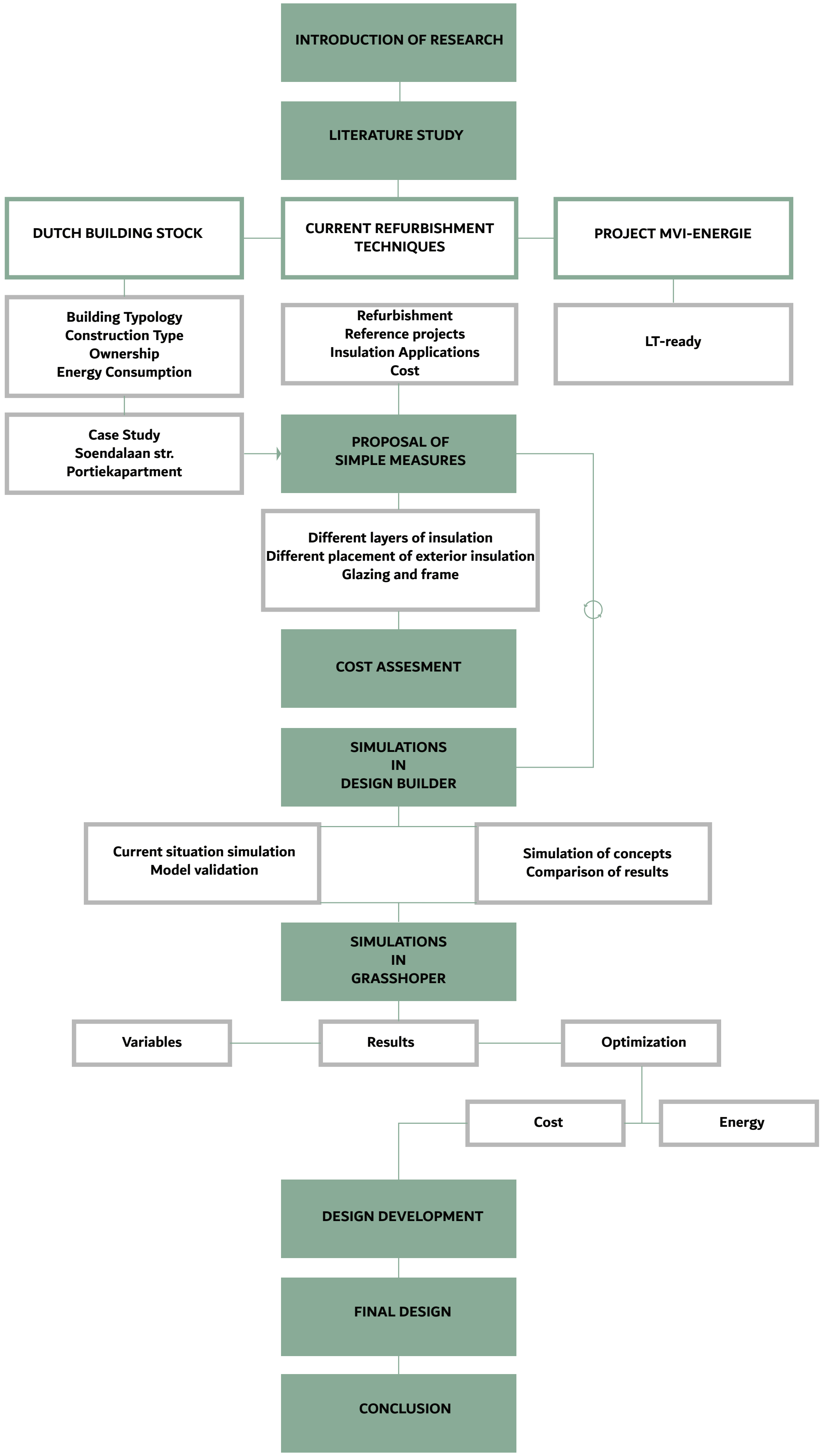
The two different silulation methods occured as a result of the flow of the reseach and the limitations and advantages of the two programmes. In fact the grasshoper part could be done in Design Builder but it would be extremelly time consuming to simulate over 2000 iterations. On the other hand there was no need to resimulate the 8 measures in grasshoper since, it was already done and due to the way its built, it was easier and faster to simulate one measure in Design Builder. So, Design Builder suimulations is the analysis needed as an input for the parametric simulation.

In design development the design criteria to achieve a low cost, fast and less disturbing for the tenants refurbishment are stated. The possibilities over the size, the layers, the way of connecting and the outside cladding are explored and discussed in terms of cost and other criteria that apply for each category. The chosen design is the optimal choice based on these criteria and needs to be validated again in terms of LT-ready. Then the drawings and details of the facade elements are made and the final design is then complete. The final step is to write the conclusions, the reflection and the relevance of the project.

Conclusion

In order to reach the energy goals of 2050, a big potential for energy saving lies in the post war residential buildings. The problem is that there are not enough funds or interest yet to refurbish these buildings, especially when it comes to zero on the meter refurbishment. There is need of solutions that will answer to these problem and include the way and the technology that currently is not available for a fast and cost-efficient refurbishment of post war apartments. In this research by design, the first step to a cost- efficinet refurbishment is to follow the principles of MVI- Energie project of changing to low temperature heating to reduce the heating demand, which can reach up to 70% of the total demand. This can be achieved by the optimal insulation and an innovative process with aims at achieving the balance between energy savings and cost. The third step is to use prefabrication for a faster and easier application of the facade elements. The issue of refurbishment is very complex as it includes energy efficiency, construction, architectural design, tenants acceptance and cost effectiveness.

Methodology Scheme



02 THE DUTCH BUILDING STOCK

2.1 The importance of the knowledge of the building stock

As a first step in every refurbishment project it is essential to analyse the building stock. The time of construction and age of the building can give relevant information about its original situation which could have been altered through the years. Combined with the current situation, an insight for the future of the building can be formed.

In order to be able to analyze properly the building it is important to get familiar with the typical forms of construction of the past years, especially the ones applied in the time period that the building belongs. Understanding the way of building and materials is an essential process in order to point out the physical condition of the building and the problems that have to be addressed. The buildings constructed in the post war years are old, counting a life from 35 to 50 years. Not only do buildings suffer from a variety of physical problems, but also most of the existing buildings were built under far lower energy and sustainability standards (Konstantinou, 2014).

The building stock consists of a variety of building types but the focus of this project is residential. For the analysis of the building stock there are three important main aspects: constructive characteristics, energy performance and type of ownership/residents.

According to the Nezer report (2014):

1. The constructive characteristics will gather data related to the structural condition, the façade, windows and roof typology used for the construction of the building,
2. the energy performance will compile information regarding the existing HVAC system and the current heating, DHW and electricity consumption.
3. In relation with type of ownership, it will be distinguished among private, tenants and social housing or specifying any other possible ownership type so that we can identify the profile of the residents/owners.

2.2 Constructive characteristics

The construction period is a very important parameter because depending on the different construction date, every building exhibits typical characteristics as a result of the new innovations of the time, the available materials, the regulations that applied and the construction techniques that were popular at that specific period. The constructive characteristics are depended not only on the time period but also on the location, since the different climate conditions and historic events also play an important role. The constructive characteristics that are needed in this project are of North Europe and particularly of the Netherlands, after the second World War, in the years 1945- 1975, and especially for portiekapartments.

The pre-war residential stock is reasonably homogeneous in terms of constructive characteristics. Dwellings were build with the so-called traditional way. In the post-war years and before the oil-crisis there was a wide variety of construction types. During the period 1946-1974 more than 2 million dwellings were constructed in the Netherlands (2nd skin, 2016), a result of the extreme need for housing after the destructive war. Thus new ways had to be invented to build faster and cheaper. They were characterized as non-traditional and industrialised systems, because prefabrication, new materials and ways of constructions were predominant. Those systems usually were developed and named after the construction companies that invented them and applied them and they are quite well documented in the literature (Bouwhulpgroep, 2013).

The need for a dwelling resulted in a rapid buildings construction which was not demanding and, therefore, with low quality (Nezer, 2014). The buildings of that period have various physical and functional problems, like the aging and maybe out of date building envelope. The industrialized systems were constructing element buildings (Figure 1). Element building means that large concrete wall and floor elements are made in the factory, transported to the building site on large trucks and assembled on the spot with a large building crane (2nd Skin, 2016). Figure 2 includes an overview of most building systems used in the Netherlands, with the respective number of dwelling and characteristics (2nd Skin, 2016).

Fig 1 Example of the systeem construction, (Bouwhulpgroep, 2013).

2.3 Energy performance

In the period up to 1965, there were no demands on the energy efficiency of homes. The houses were therefore not insulated. At that time the

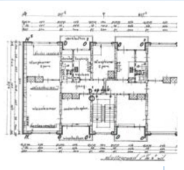
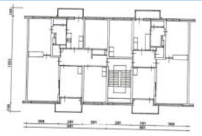
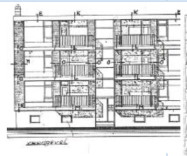
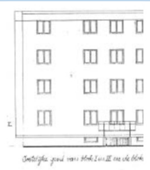
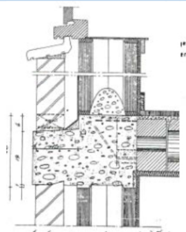
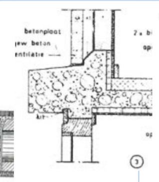
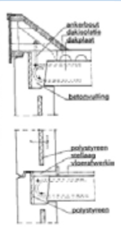
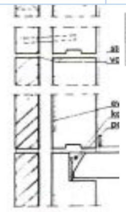
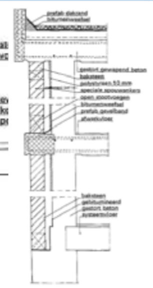
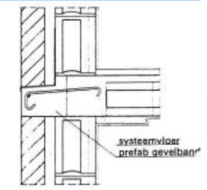
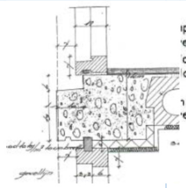
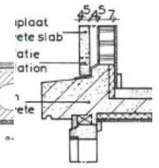
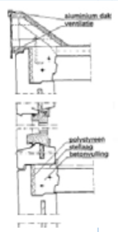
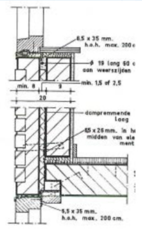
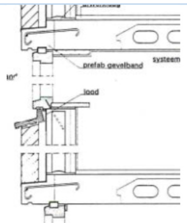
	MUWI	R.B.M.	Coignet-groep	B.M.B.	EBA-gietbouw	Pronto
						
Nr of dwellings	37831	32292	31378	29369	19291	17836
Percentage of post-war systems	11%	9%	9%	9%	6%	5%
Typical floorplan						
Typical façade						
Utility rooms position/ distance from facade	Kitchen on façade. Bathroom adjacent (appx.1-2m from façade)	In the middle of apartment (appx. 2m from the façade)	In the middle of apartment (appx. 3-4m from the façade)	Kitchen on façade. Bathroom adjacent (appx.1-2m from façade)	In the middle of apartment (appx. 3-4m from the façade)	Kitchen on façade. Bathroom adjacent (appx. 1m from façade)
Balcony type	Half-loggia	Cantilever	Loggia	Loggias and cantilever	Cantilever	Mostly cantilever
Façade detail Wall						
Façade detail Window						
Percentage of openings (Approximation)	60% (Parapet in the façade panel)	30-60 % (Varies significantly between portiek and gallery flats	30%	30%		60%
Wall construction	Cavity wall: MUWI wall (Stacked concrete blocks with poured in-situ concrete) Brick wall exterior	Cavity wall: Lightweight concrete and Brick wall exterior	Sandwich concrete panels with 2-2,5 cm polystyrene	Cavity wall: prefab beton, prefab baksteen	"Cavity: Siporex, 1cm polystyreen, baksteen"	Cality wall: Prefab concrete elements Brick wall exterior
Slab extension	No	Yes	No	No	No	No

Fig 2 Overview of layout and construction characteristics of the six most popular non-traditional systems (2nd skin, 2016).

houses were heated by collective conventional central heating boilers. For the preparation of hot water, the homes were equipped mainly with electric boilers. Since 1965 requirements have been set for the energetic quality of homes. Nevertheless, the houses were not very well insulated by current new building standards. To ventilate these houses, natural ventilation was used. Many houses were heated at that time by collective central heating boilers. This system was also used for the preparation of hot water.

The requirements for the energetic quality of new homes were increased in 1975 and in 1992 the insulation requirements were increased even more, as a result of which double glazing and insulation of the façade, floor and roof became common property. After 1992 the houses were often equipped with central heating with a VR boiler and mechanical ventilation.

Some of the post war homes have been energetically improved over the years with the emphasis being on placing double glazing but still remain poorly insulated and in need of refurbishment. According to AgentschapNL (2011), in the Netherlands almost all houses build before 1975 have an energy label class between D and F (Figure 3), approximately 350-400 kWh/m2/year primary energy), and energy consumption of almost 20.000 kWh/dwelling/year.

Houses before 1965	A	B	C	D	E	F	G
Original level					X	X	X
Current level			X	X	X	X	X
Saving Packages	X	X					

Houses 1965- 1974	A	B	C	D	E	F	G
Original level					X	X	X
Current level			X	X	X	X	
Saving Packages	X	X	X				

Fig 3 Energy labels of the Dutch building stock, (Adapted from AgentschapNL, 2011).

2.4 Type of ownership

The market in terms of ownership and tenure status determines who initiates and makes the decisions for the refurbishment, who is investing and who profits. In terms of ownership status the residential building stock is divided into three main categories: owner-occupied, social rented (reduced price), and private rented (Konstantinou, 2014). In the Netherlands 60% is privately owned, 31% is social rented and 11.5% is privately rented. In terms of owner-occupied, if there is enough funds the one who invests is the one who profits. The problem with the other two categories is that the renting company or person is investing but the residents (and of course the planet) are profiting from the investment. The investment can be paid back by an increase in the rent and by rising the value of the property. However, in the social sector this is sometimes not possible due to regulations that confine the rent increase.

Conclusion

A large part of the post- war residential Dutch stock in the years 1945-1975 was built under the pressure of housing need after the war and also with no or very low energy standards. That led to prefabricated, cheap low quality constructions and very high energy consumption. Added to these problems, these buildings are approximately 50 years old and their envelope has reached end of life. These reasons prove the urgency to refurbish and improve the energy labels of these houses for the benefit of the environment but also to increase their value, extend their life time and offer better living conditions for the residents.

03 CURRENT REFURBISHMENT TECHNIQUES

3.1 Refurbishment

The first step is to define refurbishment and the levels of refurbishment. Refurbishment does not include major changes in the load-bearing structure. In refurbishment not only the defective building components are repaired or replaced, but also the out-dated components or surfaces (Giebeler, 2009). Upgrade of fire protection, acoustics and thermal performance can be, thus, achieved through refurbishment (Konstantinou, 2014). In this project the aim is to replace the outdated facade and achieve the upgrade of the thermal performance.

There are three levels of refurbishment, the low ambition or partial where usually one component is the main focus, usually the building envelope/facade. Secondly, a building can be improved by refurbishing parts of the building envelope and upgrading the building services. Thirdly, there is the high ambition refurbishment, an integrated approach which usually aims for zero on the meter. According to BPIE (2011) the refurbishment depth is related to the level of energy or greenhouse gas emission savings that are achieved when refurbishing a building. Expert opinions suggest that deep energy renovation equals to a reduction in energy consumption for heating, cooling, ventilation and hot water in a range between 60-90%(0-30% shallow, 30-60% moderate). Superficial renovations, as opposing to deep renovation, significantly increase the risk to miss the climate targets and huge absolute savings to remain untapped (Konstantinou, 2014).

An approach is to apply the three steps technique: Reduce, Reuse, Produce. The reduction of energy consumption of the building is an important first step using passive measures such as thermal insulation, change of windows, sun shading, upgrade of old installations. Secondly is to reuse any waste energy or materials, reusing the grey water or a heat exchanger to recover the lost heat through ventilation. Thirdly, to produce the remaining energy demand using renewable energy sources. Non renewable types of energy generation if needed, should be used as efficiently as possible. This integrated approach usually leads to zero on the meter refurbishment.

3.2 Reference projects

A wide variety of refurbishment projects were studied and a selection of them are presented here. The aim of studying them is first of all to enrich the knowledge over similar projects, understand the different techniques as they are currently done and levels of refurbishment, their advantages and disadvantages and finally how much they have costed and why.

The subjects to learn from this literature study are:

1. Levels of refurbishment (zero on the meter or lower)
2. Prefabricated techniques (level of prefabrication, size of the element, layers of materials, connections, the outer cladding materials)
3. Innovative approaches

The levels of refurbishment has already been explained in de definition of refurbishment.

Regarding the use of prefabricated elements, according to the BPIE report (2011), the industrialisation of the construction process will lead to lower costs for holistic energy renovations, and lower renovation costs, combined with enabling measures, will lead to a higher renovation rate and depth. Pilot projects in the Netherlands are showing a potential cost decrease from €130.000 (2010) to €60.000 (2014) (BPIE, 2011). These cost reductions are achieved by implementing the following actions:

1. reduced person-hours (labour has always been a bigger cost than materials and equipment)
2. Limiting conventional wharf costs significantly since scaffolding, crane, construction site infrastructure are no longer needed.
3. Economy of scale to reuse models and limit the time spent on individual projects
4. Decreased transportation and logistics needs.

So, retrofitting buildings as much as possible off-site and reducing the amount of labour on-site will decrease the longer construction times and will lead to better quality and cheaper refurbishment.

3.2.1 Project Stroomversnelling

Stroomversnelling is a platform created by the Dutch ministry of housing to bring together all the corporations, companies and different experts in refurbishment with the aim to accelerate this process by exchanging knowledge. The aim is to renovate 4.5 million post-war dwellings by 2050 (Stutvoet, 2018), to zero-on-the-meter. There were seven projects in this scheme in Noordwijkerhout, Rijswijk outside, Nieuw Leusen, Maurik, Oosterhout, Arnhem and Grijpskerke.

In the Presikhaaf district of Arnhem, the Portaal housing corporation renovated 96 homes. The social rental properties are from the 1960s. The houses were given a new, very well-insulated exterior with a new pre-fabricated facade. It is system of ultra-tight envelope panels that are attached to the building's existing facade, and a new, panelised roof with built-in solar panels. The retrofit can be applied in less than 10 days with minimal tenant disruption. These houses are also disconnected from the gas supply and equipped with a new roof with solar panels. Mechanical ventilation with heat exchange was installed, to recover the lost heat form the ventilation and preheat the incoming outside air. There were openable windows but natural ventilation was mostly replaced by mechanical. Similar refurbishment techniques were applied also to the other locations (Figure 1).

Figure 1 The prototypes in Arnhem (top), Heerhugowaard (bottom), (Stutvoet, 2018).

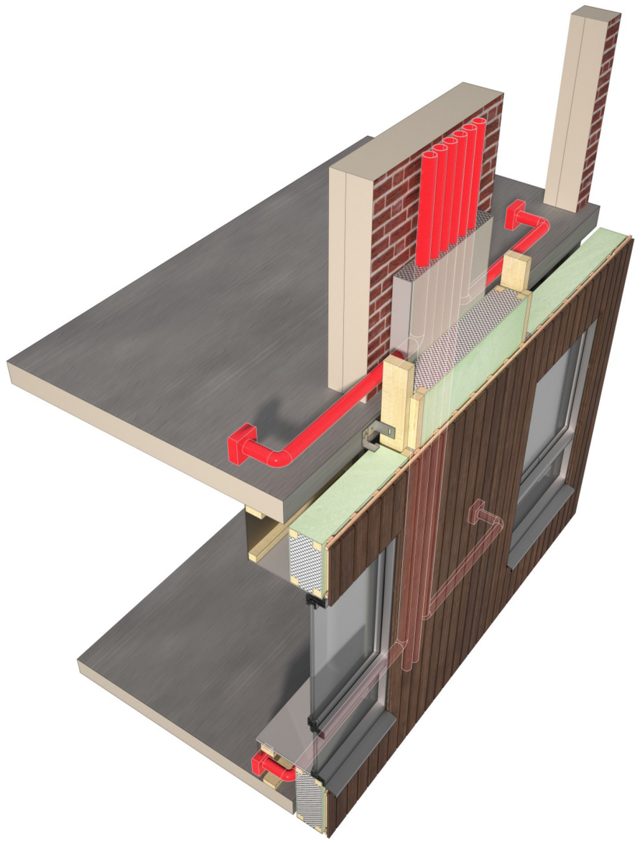


Figure 2 The prefabricated panels of the 2nd skin (2nd skin, 2016).

3.2.2 2nd skin

A zero-on the meter concept is the 2ndSKIN. The goals of the renovation project is to : 1. improve the current energy performance up to zero energy by upgrading the building envelope, using efficient building systems and the generation of energy 2. produce a prefabricated and integrated façade module 3. ensure minimum disturbance for the occupants, during and after the renovation, 4. take possible behavioural changes into account.

The design of the renovation solution focuses on a reference post-war building in Rotterdam-Zuid. Its construction characteristics are massive concrete wall and brick cladding with an intervening, non-insulated cavity, reinforced concrete slabs, continuous to the balconies, and large windows.

During the renovation process, the building envelope is insulated with floor-height, prefabricated sandwich panels. Heating and ventilation are integrated in the building's skin (Figure 2). As described in the project's report (2nd Skin, 2016),: The suggested construction process differs from conventional renovation process in the fact that the technology is seen as independent from the underlying structure of the building, and integrated into the facade. The prefabricated, floor-height, sandwich panels, featuring new windows and integrated services pipes, are attached to the substructure that consists of wooden posts connected to the external facet of the existing structure through steel U profiles. The panels containing the windows are connected to the wooden posts subsequently.

The energy demand of the 2ndSkin technical solution (i.e. only renovation without behavioural change or change for more efficient appliances) is reduced by 66%. If the scenario is considered with improved appliances and behaviours, a reduction on energy demand of 78% is reached. If considering the heating demand alone, which accounts for the largest percentage of energy consumption in the building stock, it is minimised, with a reduction of 93% after the refurbishment solution (2nd skin, 2016).

Cost assessment of the 2ndSKIN concept showed that costs are still a 160% of the targeted k€ 60 per dwelling.

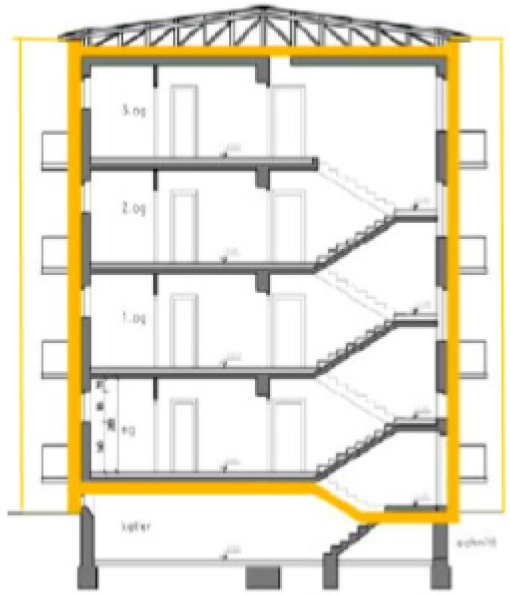
3.2.3 MeeFS

The MeeFS (Multifunctional energy efficient façade system for building retrofitting), aims to develop an innovative energy efficient multifunctional façade system and a flexible and modular solution. Flexible as it could be adapted to different architectonic configurations and typologies. And modular as a system that combines different technological solutions.

The facade has active and passive components. The composite panels can host various technological units to minimise energy demand but also generate energy on-site. The façade system (the pultruded profiles
)will be manufactured of composite materials (FRP - Fibre Reinforced Polymer) for improved lightness. Several modules can be incorporated in the facade system such as insulation modules with aluminium cladding, green facade modules, photovoltaic modules and more.

For the installation of the facade, first the facade is cleaned and any unevenness is equalled out. Then the trays are mounted on the walls were the panels are installed. The panels have been pre-assembled in a nearby workshop and transported on-site using a dedicated lifting beam. The pre-assembled panels were then hoisted directly into their definitive position and securely attached to the supporting trays.
The MeeFS project is aiming to save 30% on heating bills and up to 10% on air conditioning costs. The project is installed in one Building in Spain and being tested (figure 3). All information were found on the projects website Meefs.com.

Figure 3 TThe MeeFS solution on a real building in Extremadura, Spain (meefs.com).



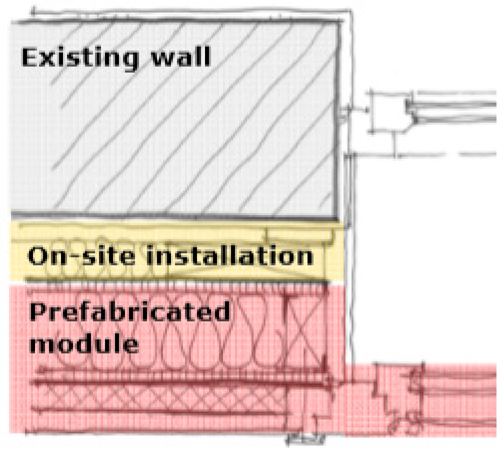


Figure 4 Cross section of new thermal envelope (top). Figure 5 Prefabricated facade module (middle). Figure 6 A view of the facade (bottom), (IEA , 2011).

3.2.4 Residential area Dieselweg 4 / Graz

The residential area Dieselweg is located in t he south of Graz (Styria, Austria). The buildings were built in the 1960's.

Due to the fact that since the time of construction no improvement measures have been carried out the building stock showed a very energy inefficient and poor situation. The most challenging circumstance was the fact that it was considered to be impossible to resettle the tenants during constructions works.

The renovation concept (figure 6) for the "Dieselweg" was mainly based on two facts: 1. The essential improvement of the thermal envelope with prefabricated façade modules (figure 4), 2. The implementation of a new and innovative solar -active energy concept.

The basic principle of the solar façade is the solar comb. It is arranged on the OSB board, covered by a glass panel. In between is a rear ventilated air space. Sunlight falls through the glass and leads to an increased temperature in the airspace and the solar comb . This in creased temperatures lowers the difference between inside and outside temperature in winter and leads therefore to red used heat losses and an improved effective U-value. The onsite installation has steel-bearing angles on the plinth, a wooden substructure mounted on the facade and covered with XPS boards (figure 5).

It should lead to a significant reduction of the heat demand (about 93%). All information was found in the IEA ECBCS Annex 50, 2011.

3.2.5 Modular façade panels -Belgium

The idea behind this project (fig.7) developed in Belgium is that a prefabricated modular facade system. The panels cover part of the facade. “Only those parts of the building envelope where the return on investment is the highest , are insulated with the panels. All the work is done on the exterior so there is no need to move out during the works, which saves costs as well. Each panel installation exists on its own, so a step by step approach is possible.” (Peeters, L. 2017)

The Rc-value of the panels is minimum 7 m2K/W. The cost of the facade panel is around 100 euros per square meter and a payback period of 7 years is expected. The project aims to increase the comfort at a reasonable price and increase the ROI of renovations. A disadvantage related to society is the looks of the building, that it is changes than what the residents are used to and favour. Less materials are needed for the insulation.

Challenges involve the uneven surface of the existing facade where the panels need to be mounted. “ A challenge may also be the module size and the mounting (and transporting) of big panels.” (Peeters, L. 2017). All information were found on the projects pdf in city zen website.

Figure 7 Project’s front facade. (cityzen-smartcity.eu)

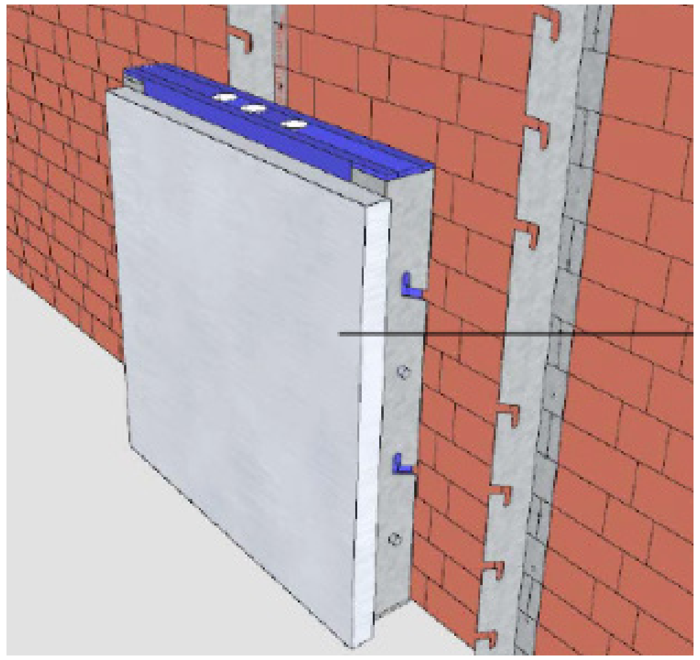


Figure 8 The prefabricated panel. (Annex 50, 2011)

3.2.6 Thermal Rehabilitation of Buildings-Portugal

Portuguese Science and Technology Foundation Programme funded a project aiming at energy efficiency with prefabricated panels within the scope of IEA ECBCS Annex 50 “Prefab Systems for Low Energy / High Comfort Building
Renewal”.

As descripted in the Annex:
The developed retrofit module aims to:

- *Increase multi-family and single-family buildings energy efficiency through the application of insulation materials contributing to the achievement of final energy consumptions lower than 50 kWh/(m²·y).*
- *Be an integrated solution.*
- *Apply materials with high potentiality of reuse/recycle, and incorporate materials with low embodied energy (energy needed for production, transport and application of the material), minimizing the environmental impacts of the modules production;*
- *Be an effective solution capable of reducing the execution/application time, reducing the inconvenience caused to the occupants and involving lower financial investment, leading to a greater acceptance of this type of solutions by users.*

The dimensions of each module (fig 8)are of about 1 m x 1 m and its weight is of 12 kg/m². These dimensions were selected in order to ease their transportation and on site application. The mounting system allows a simple application and withdrawal of the modules, based on two steel U-profiles on each side of the modules, with a system of pins and holes to be fitted into a support structure that is bolted to the existing wall. Reduction of total energy demand is up to 69%. It can be scalable to other regions and countries with changing the materials. All information were derived of IEA ECBCS Annex 50 - Prefab Retrofit of Buildings Retrofit Strategies Design Guide – Part D 117.

3.2.7 Comparison of reference projects

Project	Size of the element	Prefabrication level	Flexibility	Scalable	Fast	Integrated	Heating demand reduction	Cost	Innovative
Dieselweg Austria	Large	Medium	Low	Low	No	Yes	93%	High	Yes
2nd Skin Netherlands	Medium	Medium	Medium	Medium	Medium	Yes	93%	Medium	Yes
Arnhem Netherlands	Medium	High	Medium	High	Yes	No	85%	Low	No
MeeFs Spain	Small	Low	High	Medium	No	Yes	30%	High	Yes
Modular Belgium	Large	High	High	High	Yes	No	unknown	Low	Yes
Panel Portugal	Small	High	High	High	Yes	Yes	68%	Medium	Yes

Table 1 Comparison of the refference projects.

Figure 10 Cavity insulation in the cavity through a hole.

3.3 Economically feasible and Insulation Applications

The first step to this economically feasible refurbishment strategy is to accept the principles of the MVI- Energie project. The next step is to identify the ways of insulating and compare them regarding their cost. As already mentioned insulating the houses in such a way that heating with low temperature heating (<55 ° C) can be achieved, is the most important factor for the MVI- Energie project to be applied. Insulating is a passive measure that can be done in many ways depending on the situation and the objectives of every project. The most common ones will be discussed in this chapter. The cost is affected by the type of insulation and the materials. Thus a range of price from minimum to maximum cost will be given, based on the literature finds.

3.3.1 Cavity Wall Insulation

Cavity wall insulation is interesting for houses that were built between 1920 and 1975 : they have not been given cavity wall insulation during construction. Homes from before 1920 usually do not have a cavity wall at all. A specialized cavity wall insulation company fills that space with, for example, polystyrene balls or glass wool flakes. The most commonly used insulation materials are glass wool, rock wool or EPS pearls (polystyrene balls, minimum depth of 5cm). Less commonly used are PUR foam, UF foam or siliconized perlite beads. In some situations (for example with a narrow cavity) not all materials are suitable. Holes are drilled on the outside brick layer in the joints of the facade (figure 10). The holes come about a meter apart, always at the intersection of a horizontal and vertical joint. The insulation material is blown through the holes into the cavity. The last step is the holes to be sealed. This is a very fast procedure (usually takes one day) and it is not disruptive to the residents. This job cannot be DIY. No maintenance is required.

The insulation value mainly depends on the width of the cavity and less on the insulation material used. A cavity of 3cm could be filled, but it is better if the cavity is above 5cm. The insulation value of the façade as a whole - the bricks plus the insulation material - (Rc value) comes to 1.7 (m2*K)/W after insulation of a cavity 6 cm wide. That is much better than the insulation value of an uninsulated cavity wall (0,4(m2*K)/W). For an average house it provides an improvement in energy performance of 15 to 20% (toolkitduurzaamerfgoed.nl).

The cavity needs to be checked (Fig 11) and cleaned of debris before applying the insulation. The condition of the cavity can be checked with an endoscope (a special camera) (Fig 12). Also the walls should be checked to avoid moisture developing.

Cavity wall insulation is the most economical way to insulate. The average price for cavity insulation is €15,- to €30,- per m2 (milieucentraal.nl).

3.3.2 External wall insulation

The cavity wall insulation can be combined with insulation on the inside or outside of your facade. If the house must be made energy-neutral, that can be hardly avoided: an Rc of at least 4.5 is needed for this and it can not be achieved with cavity wall insulation alone. Then a less thick layer on the outside is needed for the same insulation value: the outside wall only becomes 10 cm thicker, instead of 16 cm for example. Adjustments to window frames and eaves are also easier.

Exterior wall insulation is more expensive than cavity wall insulation, but has important advantages: you can apply a much thicker layer of insulation (if there is no or suitable cavity) and there are no more cold bridges, where condensation can occur that can lead to damp spots and mold formation. Also the exterior walls get a new appearance. There are three types of finish: brick strips, stucco (decorative plaster) or cladding (wood, plastic, cement panels). Another way is the construction of an almost new facade. The outer layer of the cavity wall is demolished (the inner layer remains), the insulation material is placed against the inner layer and finished with a material of choice. An advantage of this method is that the outer wall does not get much thicker. A disadvantage is that it is more expensive. This technique can be used especially with detached houses or when a whole row of houses is being adjusted at the same time.

Some types of finishing of the facade require more maintenance than others. A wooden cladding has to be painted regularly, unless a type of wood is chosen that can remain untreated. Plastic boards or plates can look like wood, but hardly need maintenance. With the exterior stucco (plastering), any cracks or damage must be repaired so that the underlying insulation layer remains intact. Brick strips

Figure 11 Inspection for debris in the cavity.

Figure 12 Endoscope in the cavity.

Figure 13 External Wall insulation application.

Figure 14 Internal wall insulation application.

require hardly any maintenance, just like a standard brick exterior wall. In the Netherlands were people are used to brick veneers find it hard to maintain a plaster outer wall. However, finishing with a brick veneer is more expensive than with decorative plaster. A permit is required because the exterior insulation ensures that the building will look slightly different.

Regarding the insulation materials, plastic insulation boards made of polystyrene hard foam (XPS) are usually used as insulation material. This material has a high insulation value and is resistant to moisture. The insulation boards are applied to the existing façade with the help of an adhesive grout (possibly supported by a light metal frame). The panels can then be plastered or a wooden structure is applied to the panels on which the facade cladding can be screwed.

Directly on the existing façade is the quickest way to insulate your exterior façades. The insulation is directly attached to the exterior wall with screws. The window frames can usually stay the same. There are special thinner strips to ensure that the insulation fits well to the window frames or roof edge. That is also the way not to get cold bridges around the windows, by grinding off the edges (dagkanten in Dutch) and finishing with insulating plates.

For external insulation professionals have to be hired to apply it. The price depends on the insulation material and its thickness and the cladding material, if its applied in the traditional way. For a Rc-value of 4(m2*K)/W the price is 100-150€/m2 (isolatie-weetjes.nl). On average an energy saving of 25% is achieved with exterior wall insulation.

3.3.3 Internal insulation

There is also the option of internal insulation, in cases where external insulation cannot be applied (not enough space, buildings to be preserved). Insulation material is applied to the inside of the wall. This can be done directly against the wall or an air cavity can be used in combination with a retention wall. The cavity must be ventilated with outside air. This is often difficult to realize in practice as it requires holes in the outer wall. Moisture accumulation may then result. That is why the use of an air cavity is usually discouraged.

In addition to a retention wall, there is also the system with a 'box in a box principle'. A completely new room will then be built in a room in which the new walls, ceilings and floors are insulated. This construction must be ventilated on all sides with outside air. For the average building, this is usually not a realistic option due to the loss of space and scope of the intervention (and high costs).

Overall, the insulation of massive external walls on the inside leads to many problems. The buildings has 'thermal leakage', meaning that thermal bridges are almost impossible to prevent and the insulation level will have to be kept a little lower.

Applying insulation material on the inside means for an average building an energy improvement of only 10 to 15% (depending on the surface of the outside wall). This is even lower for terraced houses with a relatively large amount of glass in the front and rear facades (toolkitduurzaamerfgoed.nl). Without insulating the outer walls, your home loses a lot of heat through the facades. This means that the heating system has to work harder to keep the inside temperature constant, and burns much more energy for heating than in a comparable home with external walls insulated. Internal insulation can be placed by professions (the average cost is 90€/m2 for Rc-value 2,5(m2*K)/W) or it can be DIY (on average 40€/m2) (isolatie-weetjes. nl).

3.3.4 Roof Insulation

More than 80 percent of the homes already have an insulated roof, but most are moderately insulated. A well insulated roof has an Rc- value of 4(m2*K)/W and a thickness of 13cm in most materials is required to achieve that. There are also legal requirements for roof insulation. For new construction this is an Rc of 6.0 or more, for existing construction or renovation at least 2.0.

Insulating the roof is an easy and very efficient way to decrease heat losses. For pitched roofs it depends if the attic is used and needs to be heated or not. For attics that are heated, insulating the roof can make a big difference. However, insulation is also useful if the attic is not heated. A lot of heat loss occurs through such a cold attic or loft. In this case only the attic floor can be insulated: that is easier , cheaper, needs less material and has the same result.

A vapor-proof layer is placed on the warm side under the insulation material to prevent moisture problems. If the floor needs to be walkable, the easiest way is to install walkable insulation boards. The insulation material can also be laid between the floor beams (Fig. 15) and then floorboards can be applied on top. The hatch has to insulated as well and the gaps between the hatch and the attic floor are sealed with insulating tape. Another choice is to insulate the ceiling directly under the attic floor.

Figure 15 Insulation between the wooden beams.

Figure 16 Layers of insulation for a pitched roof.

Figure 17 Preparing the frames for the thicker glass.

Figure 18 Insulating frames with triple glazing.

In case of an open attic that cannot be closed with a door or hatch, then insulation of the attic floor makes no sense. In that case the inside or outside of the roof should be insulated. The same applies if the attic is used as a living space. There are three ways to insulate a pitched roof: 1. insulate the inside of the roof, 2. remove the tiles, insulate on the outside and replace the tiles, 3. Spray or blow insulation under the roof tiles. Insulating the inside of a sloping roof provides good to very good insulation. The external insulation provides the best insulation value, because the insulation material is not interrupted by the beams of the roof and because there is room for sufficient insulation material. The insulation material makes the roof higher and the connection with the gutter has to be made again. It is a job for a professional company. When insulating the outside of the roof, the entire roof structure is protected against moisture and cold. The third option is to spray or blow insulation material under the roof tiles by an insulation company, for example PUR foam, glass wool or rock wool flakes, or EPS thermo-beads (polystyrene balls). The process is done from the outside. This type of roof insulation is only recommended if there are no other options. It provides only moderate insulation.

The exact costs of roof insulation depend, among other things, on the roof construction of the house and the method used. In average, the cost for insulating the attic floor or internally a pitched roof is 20- 50€/ m2, not including the finish. Cost for external insulation is 40-60€/m2, without the cladding material (isolatie-weetjes. nl).

3.3.5 Windows and frames

HR ++ glass and triple glass insulates much better than single glass or regular double glass and is an efficient measure to reduce the heating demand of a house. Installing new windows and frames doesn't take long, in average 5 working days for a house. However it is one of the most expensive measures.

Triple glass and HR ++ glass are now the standard when the windows are replaced as it saves much more energy than with ordinary double glass. With older frames it can occur that the construction is not suitable for the heavier double or triple glazing. When replacing single glazing with double or HR++ glass, the frames can be adapted but it is cheaper to install new frames at the same time as the glass. Triple glass however is much often requiring new frames, due to weight or thickness. In case of need to replace the frames it is better to opt for triple glazing, as installing new frames with triple glass costs around 20% more than with HR ++ glass. New window frames with ordinary double glazing are just as expensive as with HR ++ glazing. With triple glazing it is advised the U-value of the frames to be 1,3 W / m2K or lower, to avoid condensation in or on the frame. Insulating frames and doors have air chambers or a hard insulation layer between the outside and inside.

3.4 Ventilation

Regarding the ventilation, if the facade and the rest of the building are well insulated, then probably the seams and cracks are sealed. The supply of fresh air and the removal of pollutants is then no longer automatic. If seams and cracks are closed, it is therefore necessary to actively refresh the air in the house. When re-insulating the cavity, the ventilation of any crawl space must be guaranteed.

Good ventilation of the spaces is vital for the health of the users. Polluted air in the home reinforces allergies, respiratory problems and irritation of mucous membranes, especially in the elderly and people who are already sick. Lack of sufficient ventilation also leads to developing of moisture. Although ventilation (mechanical) uses energy and due to ventilation there is heat loss, it is essential for the health reasons mentioned.

The way to actively refresh the air in the house is ensuring constant ventilation. This can be done using natural or mechanical ventilation or even better a hybrid system of the two. For example natural ventilation can be done via a grille above the window or a folding window. It must be ensured that air can flow through the house through space under the interior doors or grilles in interior doors and walls. If the layout of the house/apartment allows it, it is possible to cross or stack ventilate. If not the ventilation is done single sided (Fig 14).

Mechanical ventilation in houses like portieka-

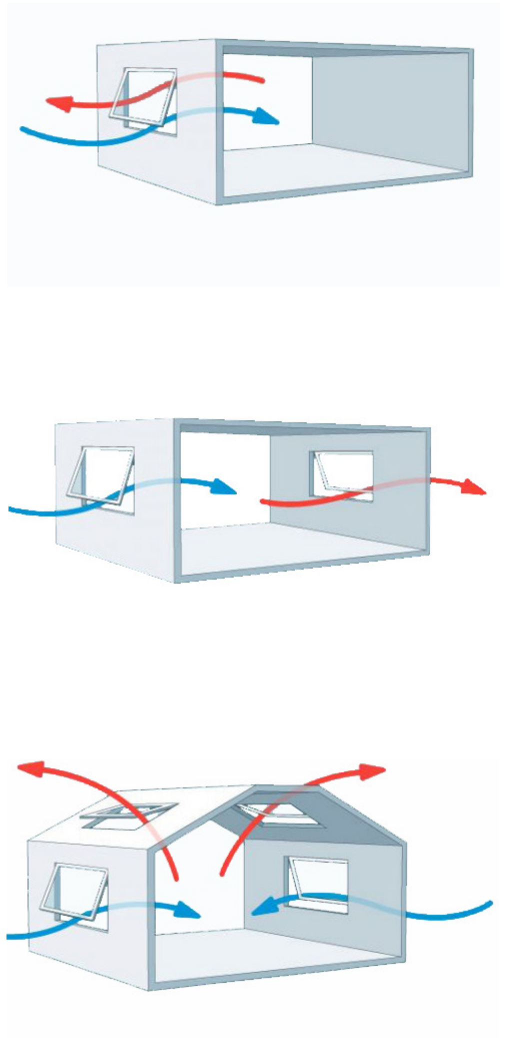


Figure 30 Natural single-sided/ corss/stack ventilation.

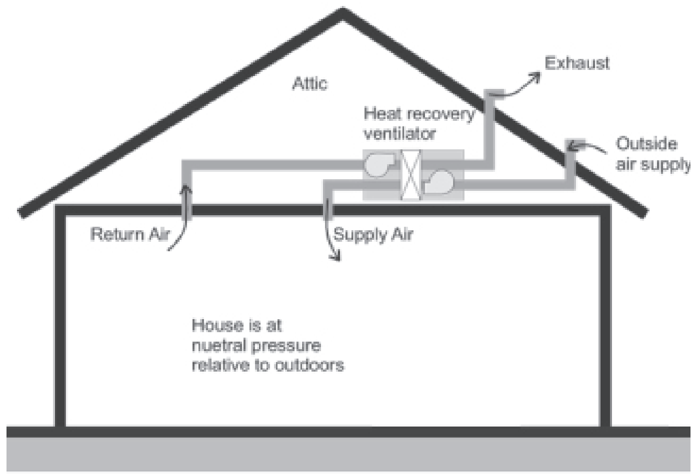
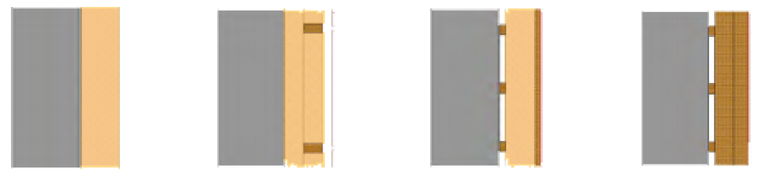


Figure 31 Mechanical ventialtion with heat recovery.

partment blocks is obligatory in Dutch regulations in the form of exhaust in the kitchen, toilet and the bathroom. In order to minimize the heat loss due to ventilation a unit could be installed for heat recovery, by pre-heating the incoming air (Fig 15).

3.5 Prefabrication level

Schwehr, Fischer, & Geier has shown the differences in prefabrication vs in-situ in ten steps. Below the five(Fig. 32) more relevant steps to this research are presented. they are parameters concernig the construction time and cost. Based on this method and the design criteria described in the design development the level of prefabrication will be decided.



External thermal insulation composite system (ETICS)*	Rear ventilated façade system	Façade system – partly prefab	Prefab 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 prefabricated substructure, filled with blown-in insulation. Cladding whether integrated in prefabricated system or manually brought up afterwards.*	*Fully prefabricated modules, assembled in fabrication hall, transported on-site and mounted on prepared sub-structure onto façade. Serial production possible.*	
Truck - Standard	Truck - Standard	Lorry or truck - dependent on module size	Lorry or truck - dependent on module size	**Delivery**
Area for scaffolding necessary	Area for scaffolding necessary	Building, mobile or truck-mounted crane	Building, mobile or truck-mounted crane	**Areas for set-up and mounting**
Renovation work depends on dry weather, moderate sun-shine and temperatures over 5°C	Renovation work only partly dependent on weather	Renovation work only partly dependent on weather	Renovation work nearly independent of weather	**Weather**
Vast restrictions and discomfort for occupancy	Restrictions concerning long time span	Shorter construction time with minimized influences for occupancy	Very short construction time and minimized restrictions and discomfort for occupancy	**Occupancy during renovation works**
Long construction time-span and time for desiccation	Long construction time-span	Shorter construction time, note manual bringing of insulation	Very short construction time-span on-site	**Construction time**

Figure 32 In sity vs prefabricated. Adapted by Schwehr, Fischer, & Geiern 2011.

3.6 Insulation materials

The advantages and disadvantages of the thermal building insulation materials are discussed in this chapter.

The most important attribute of an insulation material is the factor lambda (λ), the thermal conductivity (W/(mK)). The lowest the λ of the insulation material, the highest is the Rc- value of the solution and the lowest the U-value.

A low thermal conductivity means that in order to reach the recommended Rc-value in the refurbishment with one material, the thickness has to be increased. However, very thick building envelopes are not desirable due to several reasons, e.g. considering space issues with respect to both economy, floor area, transport volumes, architectural restrictions and other limitations, material usage and existing building techniques (Jelle, 2011). A second way to reach the Rc-value is opt for another material with lower λ. New materials that are currently being developed have a lower thermal conductivity. This innovative materials are not massively used yet, are considerably more expensive and have not been tested in the long term.

The insulation materials can be categorized in mineral, synthetic(plastic) and natural (Fig. 19) and will be described in terms of thermal conductivity (source: greenspek.co.uk), environmental impact, application and cost (the prices are calculated on the basis of 8 cm of insulation material and the source is isolatie-weetjes. nl). The European market of insulating materials is characterised by the domination of glass wool and stone (or rock) wool, which account for 60% of the market, and expanded and extruded polystyrene and to a lesser extent polyurethane, which account for some 27% of the market [Papadopoulos, 2004]. The information for the materials (if not sited otherwise) is gathered from the websites greenspek.co.uk and isolatie-weetjes. nl.

PUR insulation
Thermal conductivity/ λ (lambda) W/ m.K = 0.023–0.026
Price € 25 per m2
Pur is made of foam that consists of 2 components. Within a few seconds after the foam has been applied, it hardens. By applying foam, the seams and cracks are also sealed immediately, making it a very effective insulation material. A distinction is made between fast-acting PUR foam, which can be used well for floor and crawl space insulation and slow-acting PUR, which can be used for filling a cavity wall. In a number of cases, residents reported health problems after applying PUR foam for floor insulation. An important disadvantage of PUR (and PIR) is that during a fire, the chemicals (HCN, isocyanates) that have been used in the production are released and are poisonous. Embodied energy MJ/kg = 101

PIR insulation
Thermal conductivity/ λ (lambda) W/ m.K = 0.023–0.026
Price € 12 per m2
PIR is a development of PUR, but is available in plates. It can be used well as floor, flat roof, cavity wall and wall insulation. PIR sheets can be cut easily and are easy to process because they are light. PIR has a very high insulation value and does not absorb moisture. In addition, it is more fire-resistant than PUR. The disadvantages of isolating with PIR are that, in contrast to PUR, chemical substances have been used to make the material and that unusable residues can arise during cutting. Embodied energy MJ/kg = 101

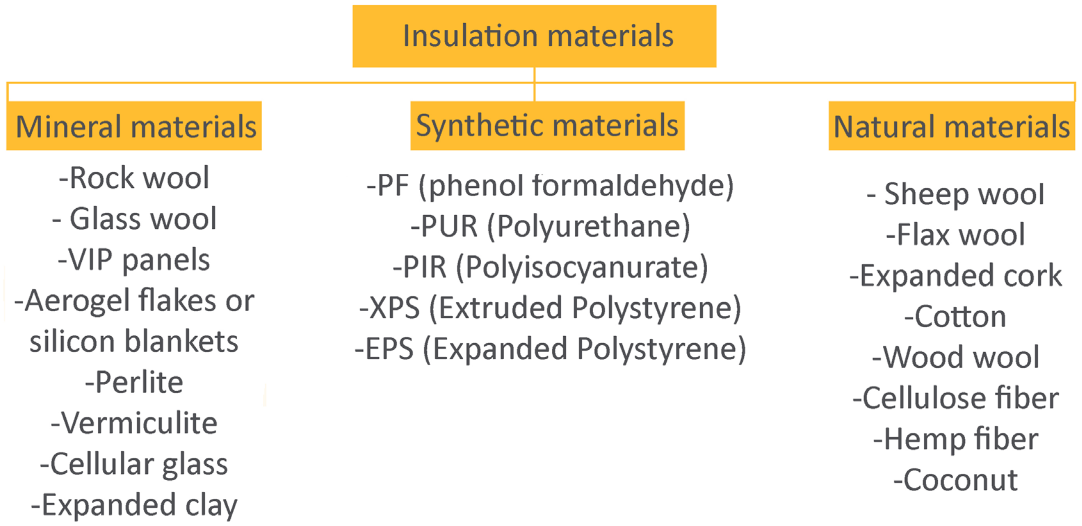


Figure 19 Insulation materials in three categories.

Figure 20 PUR inside the pitched roof.

Figure 21 PIR.

Figure 22 Rock wool.

Figure 23 Glass wool.

Rock wool
Thermal conductivity/ λ (lambda) W/ m.K = 0.032–0.044
Price € 8 per m2
Rock wool consists of fibres of volcanic rock. Rock wool has a good insulation value and is also sound-insulating. This makes it widely used in cavity walls. Because rock wool has an open structure, the temperature at the surface to be insulated is better distributed. An important advantage of rock wool is that the material does not age and it is not susceptible to mold. Because rock wool is a natural product, it is very durable. Embodied energy MJ/kg = 16.60

Glass wool
Thermal conductivity/ λ (lambda) W/ m.K = 0.035
Price € 7.50 per m2
Glass wool is made from sand and recycled glass and is mainly produced in blankets. It has an open structure and has a very high insulation value, making it suitable for use as roof insulation and wall insulation. Glass wool is used a lot because it costs and weighs little, it is also fire-resistant and sound-insulating. A disadvantage of glass wool is that when the blankets are cut to size, fibres are released that can cause skin irritation. Embodied energy MJ/kg = 26

Cellulose
Thermal conductivity/ λ (lambda) W/ m.K = 0.035 in lofts; 0.038 - 0.040 in walls.
Price € 13 per m2
Cellulose is paper (recycled newspaper) that is ground into small flakes. These flakes are mainly used for floor, wall and roof insulation. It is a relatively inexpensive insulation material, because it costs around € 13 per m2. The material can be blown in, sprayed or distributed manually over the surface. Cellulose ensures good heat and sound insulation in your home and is very environmentally friendly due to the ener-

gy-efficient process of making the flakes. Embodied energy MJ/kg = 0.45

EPS

Thermal conductivity/ λ (lambda) W/ m.K = 0.040
Price € 10-15 per m2 for 10 cm of material
Unlike many other insulation materials, EPS is available cut to size. This means that little material is lost. Due to the hard structure, it can also be properly reused and can be recycled up to 5 times. However, discarded polystyrene is not biodegradable. It can be used for floor roof and façade insulation. EPS is also suitable for cavity wall insulation, it can be blown into small cavity foam balls in the cavity wall. It is a closed-cell foam but is not 100% waterproof or vaporproof. EPS can be cut at the building site and adjusted at the projects needs, without any loss of thermal resistance. Embodied energy MJ/kg = 88.60

XPS

Thermal conductivity/ λ (lambda) W/ m.K = 0.030–0.035
Price € 15- € 20 per m2.
XPS is available in boards and consists of closed cells. Comparing to EPS it has higher density which makes it somewhat stronger. It has lower thermal conductivity. It is more waterproof and vaporproof than EPS and more suitable for application in wet environments. Also XPS can be cut at the building site and adjusted at the projects needs, without any loss of thermal resistance. Embodied energy MJ/kg = 88.6

BioFoam

Thermal conductivity/ λ (lambda) W/ m.K = 0,034
Price € 15- € 25 per m2.
BioFoam can be compared with EPS in terms of properties. What is special about BioFoam is that it is produced using vegetable raw materials. This makes the material the first foam insulation made from organic or infinite material. It is a very durable insulation material and biodegradable. The material can be used for various insulation methods such as cavity wall filling, attic floor insulation and roof insulation.

VIP

Thermal conductivity/ λ (lambda) W/ m.K =0.0042
Vacuum insulation panels (VIP) consist of an open porous core of fumed silica enveloped of several metallized polymer laminate layers. A risk with VIP is that it is fragile and can be easily punctured (destroying the vacuum) which leads to loosing a large part of thermal insulation capability. That means that VIP material cannot be cut in the desirable size at the building site, or punctured by any mean (nail it). Another major

Figure 24 Cellulose.

Figure 25 EPS board.

Figure 26 XPS board.

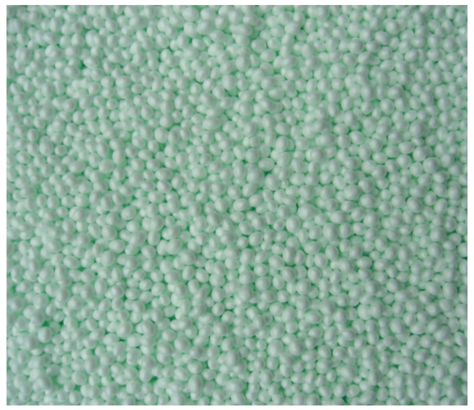


Figure 27 Biofoam.

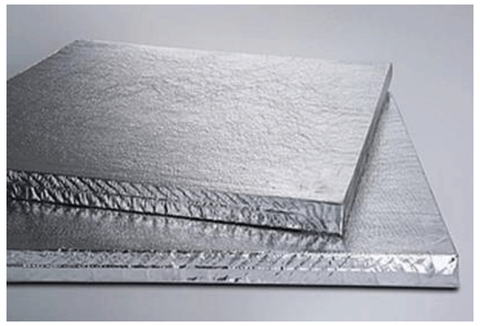


Figure 28 VIP.

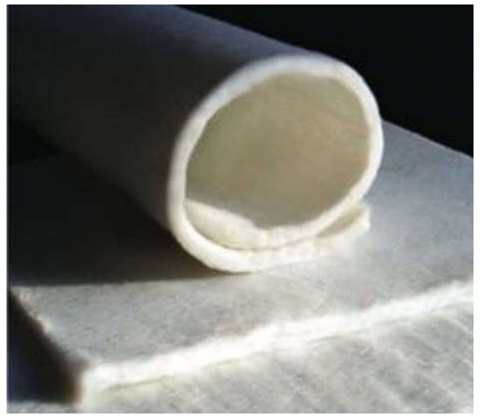


Figure 29 Aerogel.

disadvantage is the relatively high production cost.

Aerogels

Thermal conductivity/ λ (lambda) W/ m.K = 0,014
Aerogels is a synthetic porous ultralight material derived from a gel, in which the liquid component of the gel has been replaced with a gas. The result is a solid with extremely low density, low tensile strength but also low thermal conductivity. Aerogels are considered as an insulation solution that has great potential for the future. An innovative aspect that is being developed is that aerogels can be produced to be translucent. However, the production costs of aerogels, translucent or opaque are still very high.
Embodied energy = 5.4kgs / CO_2 per m^2

Conclusion

The refurbishment can be done in various levels and ambitions, which are ranked in three levels based on the reduction of energy and other resources. For a deep renovation the aim is over 60% reduction. For lower renovation costs, industrialization is necessary, so the prefabrication as much as possible of the facade elements is necessary. The cost of insulation depends on many factors. The way of insulation, the choice of material, the surface to be insulated, the accessibility and humidity in the house are important. There are many insulation materials and ways on the market today that could be used for this renovation concept. These will be compared with one another on their cost perspective and efficiency. Special attention should be given also in the replacement of the windows, so the right type of glazing and frames will be chosen.

04 CASE STUDY ANALYSIS

4.1 Context

The case study is a multi-family apartment block from the year 1952, at the Soendalaan in Vlaardingen. The building is situated in a neighbourhood with similar apartment blocks. It is North- South oriented. This apartment block was renovated through the 2ndSkin project, but for this thesis it is assumed that the apartment block is still in its unrenovated state.

This case study was chosen as a good representative of the type (post- war portiekapartment) and the condition (poor thermal quality of the construction) of the number of units in the Netherlands which offer a good energy reduction opportunity. A second reason was the availability of information and drawings of the building since it has been used in the 2nd skin project. On-site investigation was not possible since the building has already been renovated, but there are plenty of pictures in the previous state.

To continue the research the case study will be the prototype and it will be analysed in terms of context, plan layout, construction and facade. It will be used as is for the design builder simulation but in order to upscale the research some facade characteristics will be changed in the Grasshopper simulation.

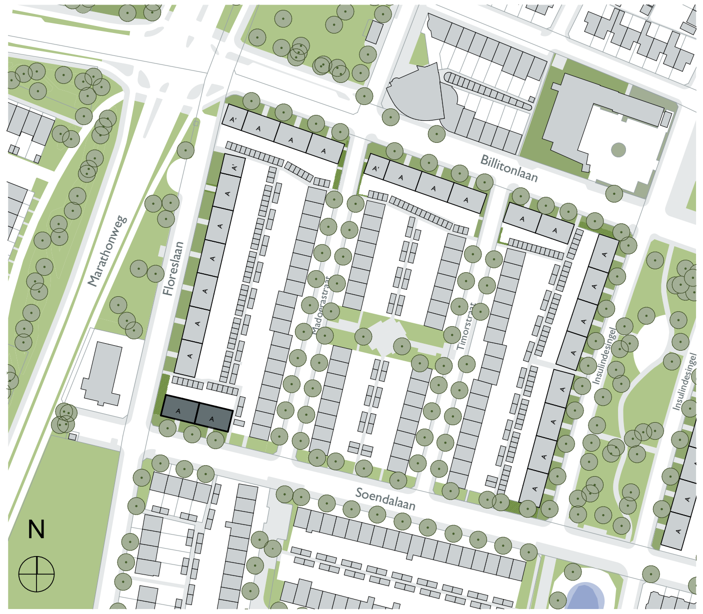


Figure 2 The site plan. (Source: KAW, 2017)

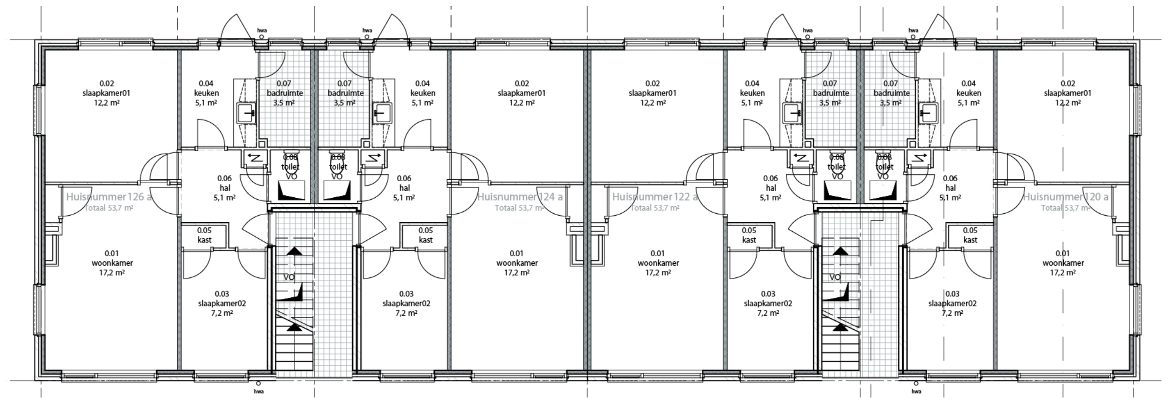


Figure 1 The typical floor plan. (Source: KAW, 2017.)

4.2 Plan layout

The building consists of three stories with an attic that was intended to remain vacant and therefore there is no need to insulate it. Every floor has four apartments, absolutely symmetrical in the middle, and the identical apartments in each side are mirrored. It consists of four apartments per floor that are orientated south to north. The entrance to the house is done by a a semi-public entrance. The staircases are considered to be a semi-exterior space.

All apartments are exactly the same size at 53.7 m2 ,consisting of a living room, two bedrooms, a kitchen and a bathroom with an additional separate toilet. There are balconies on the north facade. The kitchen, bathroom and the large bedroom are placed on the north facade, and the living room and second bedroom on the south facade. The WC, storage and hall are placed in the center and have no connection to the outside air.

4.3 Construction

The apartment block is build with Simplex construction system. The building has a cavity wall, with concrete in the inside and brick on the outside. The cavity is relatively large 70mm and it is assumed that it is uninsulated (by observing the pictures of the building, there are no obvious holes). The floors are 15 cm concrete with continuous slabs to the balconies of the north facade. The roof is pitched with an inclination of 28° and is uninsulated. The crawl space is 35 cm, uninsulated.

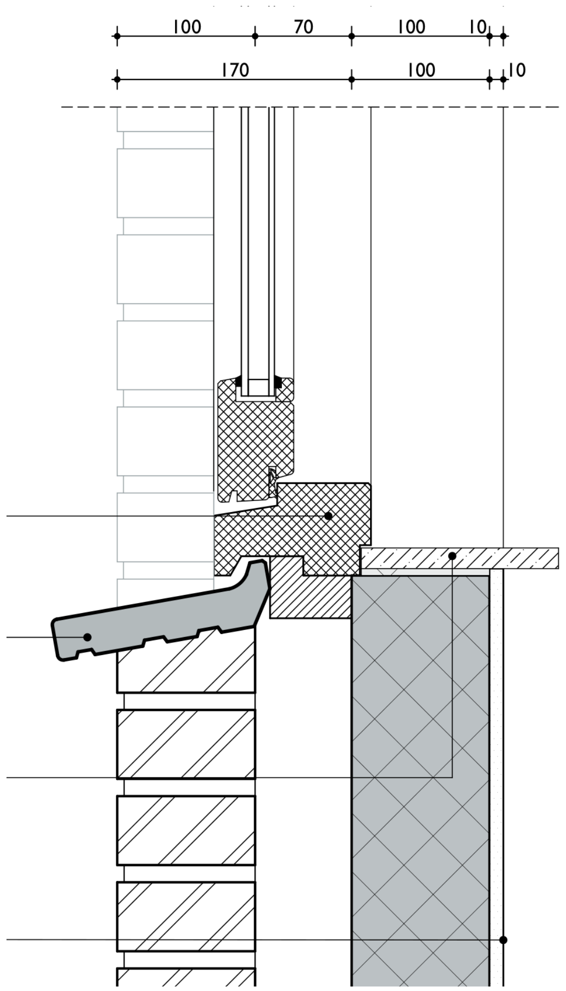


Figure 3 Detail of the cavity wall. (Source: KAW, 2017)

4.4 Facade

Regarding the facade, as described in 4.3 it is a cavity wall with masonry facade. The facade is not load-bearing construction, its carrying only its own weight.

The windows are large, approximately an average of window to wall ratio of 40%, have been replaced in the past and now are double glazing with wooden frames. There are also windows in the staircases that are single glazing with concrete framing. There is no shading system.

In the north and south facade are placed the gutters and the drain pipes, extending from the roof to the ground floor.

Figure 4 Picture of the case study. (Source: KAW, 2017)

Facade percentage calculation

In chapter 5, in the measures proposal certain parts of the facade will be used and some percentages will be needed. The facade was separated in window (glazing and frames together) and wall (closed space). The general measurements for all four facades can be found in Appendix A. Below there is an overview of the options for the facade percentages that are going to be used later in the research.

CLOSED PARTS: 432 m^2

NORTH FAÇADE WALL + WINDOWS, DOORS	239,13
WINDOWS TOTAL	92,71
WALLS	146,42
PERCENTAGE	34%

Figure 5 Percentage of North facade.

BEDROOM (HALF BUILDING)	
(3.72 x 2.75) - 4.72 =	5.51
(3.65 x 2.75)- 4.72=	5.32
(9.00 x 2.75) - 4.00=	24.75
TOTAL WALL	35.58 X 2= 71.16 x3= 213.48
WALLS TOTAL	432,31
PERCENTAGE	49%

Figure 6 Percentage of living room and one bedroom walls.

LIVING ROOM (HALF BUILDING)	
(3.72 x 2.75) - 4.72 =	5.51
(5.20 x 2.75) - 2.00 =	12.3
(3.65 x 2.75)- 4.72=	5.32
TOTAL WALL	23.13 X 2= 46.25 x3= 138.78
WALLS TOTAL	432,31
PERCENTAGE	32%

Figure 7 Percentage of living room walls.

4.5 Input list- Case study current situation

To make the simulation workflow easier, the information that is used as input in the Design Builder simulation is summarized.

Weather data

The weaher data provided by Design Builder for Rotterdam is used as an input.

North

The building is oriented 14 degrees of north.

Window to Wall ratio

The window to wall ratio of the case study is 40%, the window sill height is 0.575m and the window height is 1.875m.

Ventilation rates

Following the Dutch regulations demand, ventilation is done by natural air supply through windows and air grilles and by mechanical exhaust in the WC, bathroom, and kitchen.
For ventilation, the exchange rate per hour proposed by NEN 1087, article 3.29 is:

- A residential area has a facility for ventilation with a capacity determined in accordance with NEN 1087 of at least 0.9 dm³ / s per m² floor space with a minimum of 7 dm³ / s.
- A living room has a provision for ventilation with a capacity determined in accordance with NEN 8087 of at least 0.7 dm³ / s per m² floor space with a minimum of 7 dm³ / s.
- ...a residential area with an installation location for a cooking appliance ... has a ventilation facility with a capacity determined in accordance with NEN 8087 of at least 21 dm³/ s.
- A bathroom has a ventilation facility with a capacity of at least 14 dm³ / s, determined in accordance with NEN 8087.
- A toilet room has a ventilation facility with a capacity of at least 7 dm³ / s.

Infiltration rate

For non insulated, not airtight buildings where there are supposed to be a lot of cracks an infiltration rate (ac/h) of 0.6 is used.

Heating

The apartments are heated with double plate radiators. The water is heated by a HR_combi boiler operating with natural gas. The heating system CoP is 0.9 .

Heating set point temperature: 21 °C.
Heating set back: 12 °C.

Equipment loads

Liv_room: 3.90 W/m²
Bedroom_1: 3.58 W/m²
Bathroom: 1.61 W/m²
Kitchen: 30.28 W/m²
WC: 1.61 W/m²
Bedroom_2: 3.58W/m²
Storage:1.57 W/m²
Hal: 1.57 W/m²

Lighting

For the loads resulting form lighting 3,4 W/m² is considered.

Occupancy

One person every 20m2 is considered for the whole apartment. For each room there is a different occupancy schedule part of the default apartment schedule.

Construction

With hand calculations and literature study the Rc-values and U-values were calculated (Table 1).

Construction	Structure type	Rc value m2*K/W	U value W/ m2*K
External Wall	Brick- concrete cavity wall (no insulation)	0,54	1,85
Ground Floor	Concrete Floor	0.68	1,48
Pitched roof	Wooden roof structure with ceramic tiles	0,79	1,26
Glazing	Double glazing		2,60
Frames	Wooden frames		2,63
Doors	Low standard doors		2,82
Installations			
Ventilation		Natural ventilation	
Heating and HW installation	HR combi-boiler operating with gas, Double plate radiators		
Infiltration rate (ac/h)		0,6	

Table 1 The R and U-values of the current situation.

4.6 Heat capacity of radiators

Ideally the change to medium or low temperature heating will be able to be achieved without the need to change the radiators that are installed in the building currently (figure 11).

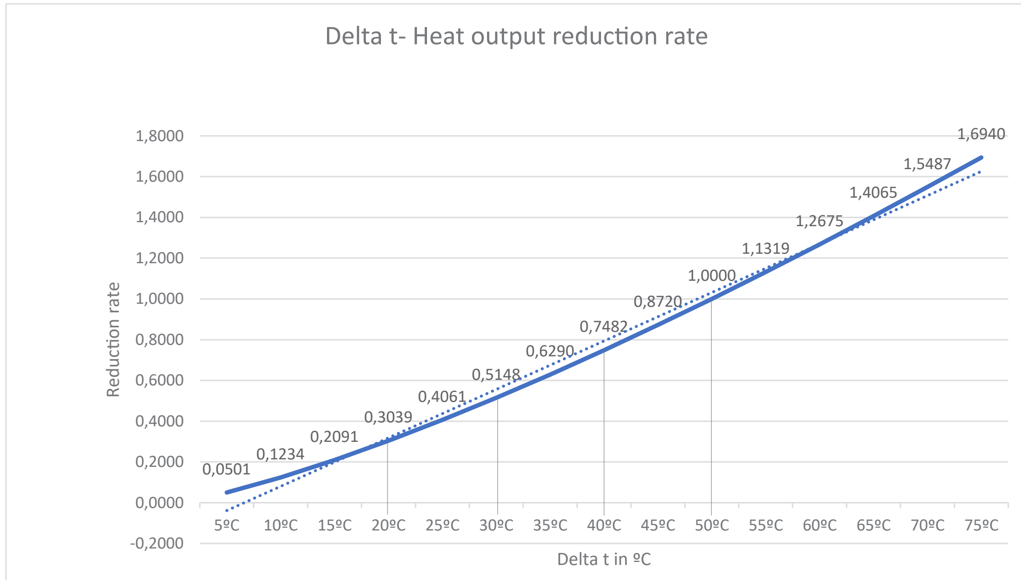
The research is done in room level. The way to figure out if a building is LT-ready is to compare the capacity of the radiators with the maximum heating power of every room. The first step is to find the capacity of the radiators by searching online information from manufacturers (two sources were compared to ensure that the numbers are valid). Secondly, the building is simulated and one of the results is the maximum heating power for every room.

The first objective is the building to become LT-ready and the second how far low temperature heating can it be. The current situation is assumed to be a Delta T factor of 50°C with a flow water temperature (75°C) and the return water temperature (65°C). The capacity of the radiator for a Delta T factor of 30°C is reduced by 0.5148 and for 20°C 0.3039 (between 30°C and 20°C the low temperature heating temperature will work).

A second assumption is that there is one radiator in the kitchen, bathroom and bedrooms of the same size.

Figure 8 The radiator installed currently.(Source: KAW, 2017)

5ºC	0,0501
10ºC	0,1234
15ºC	0,2091
20ºC	0,3039
25ºC	0,4061
30ºC	0,5148
35ºC	0,6290
40ºC	0,7482
45ºC	0,8720
50ºC	1,0000
55ºC	1,1319
60ºC	1,2675
65ºC	1,4065
70ºC	1,5487
75ºC	1,6940



Delta T factors in ºC other than 50ºC, Exponent n=1.3		Watts				
	5ºC	140	30ºC	1443	55ºC	3174
	10ºC	346	35ºC	1764	60ºC	3554
	15ºC	586	40ºC	2098	65ºC	3944
	20ºC	852	45ºC	2445	70ºC	4343
	25ºC	1139	50ºC	2804	75ºC	4750

Table 2 Delta T factors in ºC and heat output in Watts in other than 50 ºC as given by "Quinn raditors".

		Heat Outputs @ ΔT 50°C		Heat Outputs @ ΔT 30°C	
		Watts	Btu/h	Watts	Btu/h
600mm	400	539	1839	277	944
	500	681	2324	350	1193
	600	823	2809	423	1442
	700	964	3289	495	1688
	800	1106	3774	568	1937
	900	1247	4254	640	2183
	1000	1389	4739	713	2432
	1100	1531	5223	786	2681
	1200	1672	5703	858	2927
	1400	1954	6668	1003	3423
	1600	2239	7638	1149	3920
	1800	2521	8603	1294	4415
	2000	2804	9568	1439	4911
	2200				
	2400				
	2600				
	2800				
	3000				

Table 3 Heat output in Watts in Delta T 50 ºC and 30 ºC as given by "Myson".

05 PROPOSAL OF SIMPLE MEASURES

5.1 Innovative insulation approach

Since this project is looking for the balance between energy demand and cost, an innovative approach is tested where only critical parts of the building are insulated. The building is insulated enough so it can be changed into low temperature heating. It will be checked if it can be done and if it has a significant enough influence on the cost and regarding the facade insulation.

The first step is to insulate the cavity- as the cheapest and easiest measure, reaching a U-value of 0.7 W/ m2K. Then, to the parts of the building where extra insulation will be needed, exterior insulation is applied. In this way the transmission losses are decreased as much as needed for the low-temperature heating to work.

So, the two insulation measures are formed as such: from the literature study it makes sense to insulate the north facade, 34% of facade insulated externally as calculated in 4.4, since north oriented spaces distinctly have larger ratios of hours below comfort range (average 40-45%). The second is based on insulating the critical parts that need more comfort in a house such as the living room (figure 7, bottom), 32% of facade insulated, which is placed also in the corner of the building.

NORTH- 34%

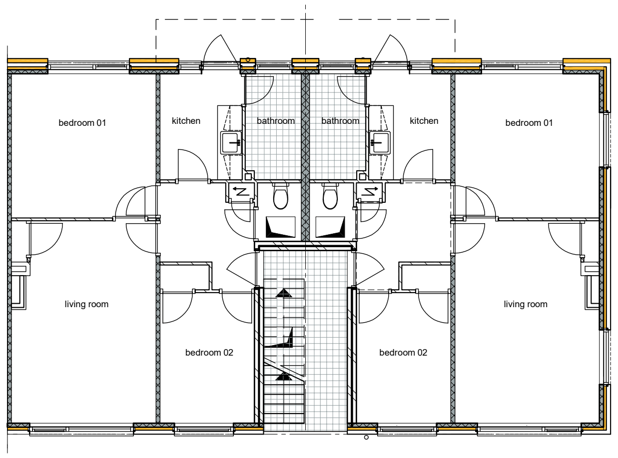


Figure 1 Insulation on the North facade.

LIVING ROOM- 32%

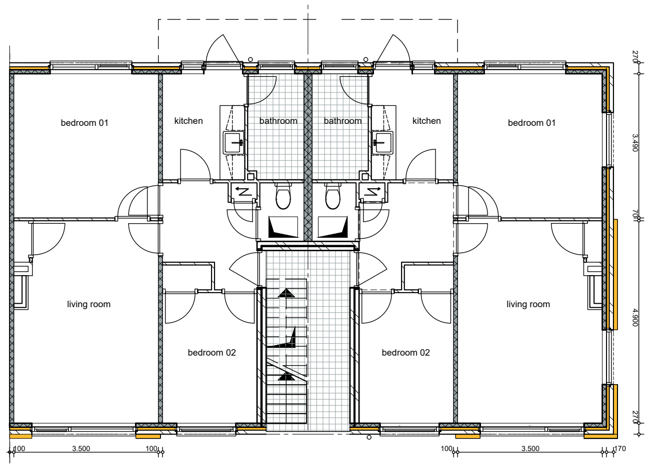


Figure 2 Insulation on the living room walls.

5.2 Simple Insulation measures

The energy analysis starts with the comparison of the two measures, in terms of energy savings and cost, with six simple insulation measures with the focus on the wall structure and the windows. Using the information from the literature study on ways to upgrade the building envelope a list of six simple measures is made. There are three regarding the wall and three the windows.

The measures about the wall are:

1. by filling the cavity with insulation
2. by insulating the exterior
3. the combination of the two above.

Regarding the windows:

1. replacing the double glazing with HR++ glazing and keeping the frames.
2. replacing the double glazing with HR++ glazing and the wooden frames for frames with a thermal brake.
3. it will also be tested if it makes sense to pay the extra amount and opt for triple glazing and insulated frames.

For all the measure the roof has to be insulated too. It could be insulated externally which is more expensive but also the attic floor could be insulated. In this case since the attic is meant to remain empty there is no reason the pay the extra cost to insulate externally.

06 COST ASSESEMENT

In this chapter the eight insulating measures are compared in the basis of costs. Information has been found online specifically for the Dutch market, in euro/m^2. At a first stage the measures will be compared for the cost for the materials and the production of the element. Then, using the program Archicalc the labour hours are calculated also.

Materials Cost

The costs for the materials are presented as:

- investment cost for the whole building
- investment cost per apartment
- payback time for the building's investment

DESCRIPTION	PRICE	INVESTMENT COST	INVESTMENT COST	PAYBACK TIME
	€/m2	€/ building	€/ apartment	
Wall				
Cavity wall insulation	15-30	9720	810	1 year 6 months
External wall insulation (no cavity insulation)	100-150	54000	4500	8 years 3 months
External wall insulation (with cavity insulation)	115-180	63720	5310	9 years 8 months
Windows				
HR ++ glass	75	15525	1293	2 years 3 months
Aluminum frame with HR++	120- 250	38295	3191	5 years 9 months
Aluminum frame with HR+++	225-450	69862	5821	10 years 7 months
% of external insulation scenarios				
Living room- 32%	(125*138)+ 9720	26970	2247	4 years 2 months
North- 34%	(125*146)+9720	27970	2330	4 years 3 months

Table 1 The concepts and their cost.

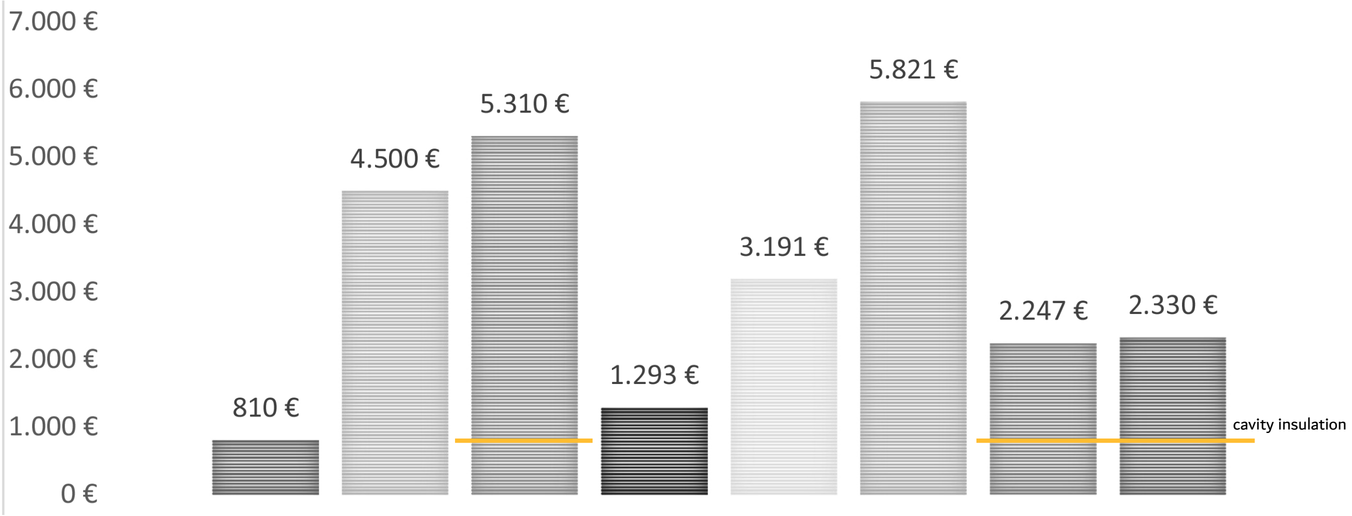


Figure 3 A comparison bar graph, investment per apartment.

The results are presented in table 2 and figure 8. The most expensive measure is the replacement of the windows with triple glazing and the cheapest the cavity insulation.

The two new insulation measures with 32% and 34% insulation are significantly cheaper than external insulation that would normally be used. Thus this method will be researched further.

Roof Insulation

DESCRIPTION	PRICE	INVESTMENT COST
Roof	€/m2	€
Internal pitched roof or attic floor insulation	30-70	7830
External pitched roof insulation	60-100	13920

Table 2 Roof insulation options and their cost.

Labour cost

The labour costs were given by the programme Archicalc. Also, the prices of the materials were compared to the ones found online and the differences are considered insignificant. The salary per hour for a construction worker in The Netherlands will be assumed to be 20 euros, based on the basic construction salary.

So, it is assumed that this complex details are also more expensive than the opaque closed wall parts. Especially for the case study the places where extra detailing is needed is around the windows, the small parts between the upper floor windows and the roof and the corners. These parts will be assumed that in labour costs they cost double as much as the opaque wall.

Omschrijving	Ee	Aantal	Prijs/1h	Bedrag	Manuren	Loon	Materiaal	Materieel	Oa
WERKTERREININRICHTING									
BUITENWANDEN		0,000	0,00	0,00	0,00	0,00	0,00	0,00	0,00
GEÏSOLEERD GEVELPANEEL [RC 1,38] MET VOORGEMONTEERDE STEENSTRIPS	m2	432,000	129,93	56131,50	287,57	0,00	50515,50	0,00	5616,00
geïsoleerd gevelpaneel [Rc 1,38] met voorgemonteerde steenstrips	m2	213,000	129,93	27675,95	141,79	0,00	24906,95	0,00	2769,00
geïsoleerd gevelpaneel [Rc 1,38] met voorgemonteerde steenstrips	m2	138,000	129,93	17930,90	91,86	0,00	16136,90	0,00	1794,00
BUITENWANDOPENINGEN									
HR++ beglazing 6-6	m2	207,000	75,08	15541,56	248,40	0,00	15541,56	0,00	0,00
HR++ beglazing 6-4-6	m2	207,000	153,73	31822,11	248,40	0,00	31822,11	0,00	0,00
aluminium kozijn merk A2, draairaam, buitendraaiend	m2	207,000	238,73	49417,11	647,91	0,00	49417,11	0,00	0,00

Figure 4 Material and labour costs from Archicalc.

To cover the building in exterior insulation 287 labour hours would be needed.

287 hours x 20 € = 5740 € plus cost

To cover the living room with exterior insulation (32% of the facade):

91 hours x 20 € = 1820 € plus cost

"Focal point of detailing"

In a Swiss retrofit module development (Kobler, R. , FHNW, 2011) they point out the completely different approach needed for the opaque wall section in contrast with the various details. "Only little time is used for discussing and detailing the opaque wall sections." and "Discussions are more clearly focused on the detailing at windows, reveals, junctions, fixings, ventilation, ducts, penetrations, blinds, fixtures".

07 DYNAMIC SIMULATIONS IN DESIGN BUILDER

7.1 Current Situation Simulation

The first step for the dynamic simulations in Design Builder is to simulate the current situation of the building. The information gathered in 4.5 is used as an input. In this case the simulations are made a bit easier by the repetitive situation in the building, since all 3 stories are identical and also the 4 apartments are exactly the same. So, only one needs to be modelled (figure 2). However, three types of apartment will be simulated since there is a difference between the middle and corner apartments but also the top and ground floor ones. The types are differentiated in design builder by setting the adjacency of the elements (walls, roof of floor) from auto to adiabatic. The three representative types that will be simulated are:

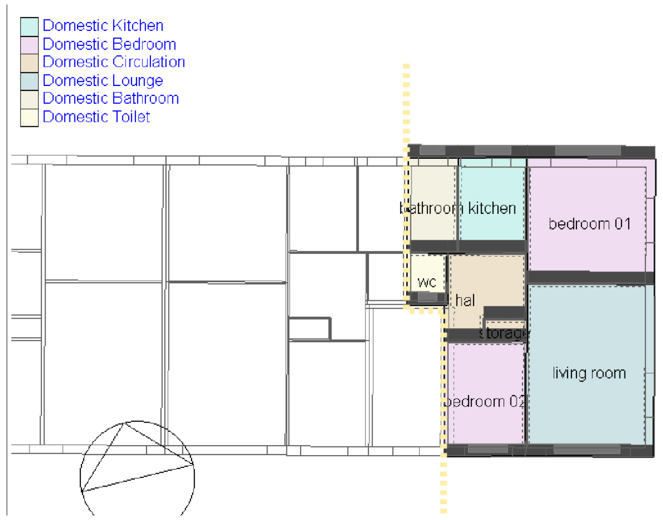


Figure 1 The apartment in Design Builder.

- T1 corner top
- T2 middle in the middle
- T3 corner ground floor

Figure 2 The three apartments types.

7.1.1 Current Situation Results

T1 Top corner

Annual energy demand: 13417 kWh
Annual heating demand: 9853 kWh

Room	Watts
Living room	2793
Kitchen	868
Bedroom1	2063
Bedroom2	1124
Bathroom	628

The heating demand reaches up to 74% of the total energy demand, which makes the building a good case to apply the MVI- ENERGIE project.

Except the living room, there is overcapacity for the rest of the rooms.

T2 MIDDLE MID

Annual energy demand: 7206 kWh
Annual heating demand: 4064 kWh

Room	Watts
Living room	1025
Kitchen	466
Bedroom1	875
Bedroom2	823
Bathroom	302

T3 BOTTOM CORNER

Annual energy demand: 9532 kWh
Annual heating demand: 6467 kWh

Room	Watts
Living room	2060
Kitchen	539
Bedroom1	1515
Bedroom2	847
Bathroom	326

So, T1 as expected has the higher energy demand and the highest maximum power for all rooms. The same result gives the simulation for cavity wall insulation. From now on type T1 will be further elaborated.

The results for every room are compared with a simple steady state calculation to validate the results. The steady state heat balance calculation is the sum of the transmission losses and the heat losses due to ventilation and infiltration. In that number an extra 20% is added for the heating surcharge for night or weekend reduction and the heat loss to the neighbours. The design builder results and the steady state calculation results are then compared and if there is not a difference bigger than 20%, it is considered valid. The steady state calculation can be found in Appendix B.

7.2 Simulation of measures - Input list for measures

In design builder the concepts had to be translated in data input for the programme approximating the U-values that I wanted to reach, found from the literature study and from simple hand calculations.

Heating

The proposition is to keep the existing double plate radiators to keep the costs as low as possible. The water is heated by electricity from the grid or a heat pump. The heating system CoP is 1.

Heating set point temperature: 21 °C.
Heating set back: 12 °C.

Construction

The cavity will be filled with 70mm EPS beads. The external wall is insulated with 100mm EPS boards.

DESCRIPTION	U VALUE	Rc VALUE
External Wall	W/ m2*K	m2*K/W
Cavity wall insulation 70 mm EPS	0.6	1.7
External wall insulation (no cavity insulation) 100mm EPS	0.31	3.2
External wall insulation (with cavity insulation) 70mm cavity + 100mm EPS exterior	0.24	4.2
Windows		
HR ++ glazing	1.1	
Change of frames and HR ++ glass	2.4 / 1.1	
Insulating frame / HR+++	1.3 / 0.77	

Table 1 The R and U-values of the measures.

Infiltration rate

For an average building that is not air-tight nor leaky a rate of 0.3 is used.

Roof insulation

The attic floor is insulated with a U-value of 0.346 W/m2K.

7.2.1 Simulation of measures results

Cavity Insulation
60% heating savings
46.7% total savings
Cannot achieve Low temperature heating only with cavity insulation

External Insulation 100mm EPS
66.7 % heating savings
52.3% total savings
LT-ready sufficient

Cavity and external Insulation (70+100mm EPS)
68.6% heating savings
53.7% total savings
LT-ready sufficient

HR++
Rejected due to findings form the literature study, as a very time consuming and disturbing to the residents measure.

HR++ and frames
73.8% heating savings
56.6% total savings
LT-ready sufficient

Triple glazing
75.6% heating savings
57.8% total savings
LT-ready sufficient

North 34% of external insulation (100mm EPS)

The concept that the insulation is on the North has no further perspective, since the rooms that are on the North already had overcapacity.

Living room 32% of external insulation (100mm EPS)
62% heating savings
48.6% total savings
LT-ready sufficient

Apartment type	T1 top corner					
DESCRIPTION	Total annual kWh	Energy savings kWh	Heating annual kWh	Heating Savings kWh	Max HP LR Watt	Max HP BR1 Watt
Current situation	13417	-	9853	-	2793	2063
Wall						
Cavity wall insulation	7143	6274	3883	5970	1465	1097
External wall insulation (no cavity insulation)	6396	7021	3280	6573	1289	961
External wall insulation (with cavity insulation)	6200	7217	3086	6767	1238	920
Windows						
Ordinary wooden frame with HR ++ glass	5948	7469	2696	7157	1107	805
Insulating frame with HR ++ glass	5818	7599	2573	7280	1019	721
Insulating frame with triple glass	5656	7761	2401	7452	996	703
% of external insulation scenarios						
32% Living room	6894	6523	3741	6112	1205	1061
34% North	7215	6202	4281	5572	1476	1261

Table 2 The comparison of the results for the 8 measures.

7.3 Energy Savings- Cost

Figure 3 demonstrates the final results for the simulation of the eight measures in terms of annual savings and cost per apartment.

All eight measures achieve heating savings between 60-75%. The worst energy wise is the cavity and the best the triple glazing. However, they are respectively the cheapest and most expensive measures. Triple glazing and HR++ although they have almost double the price, have the same energy savings. Comparing the exterior insulation with the combination of cavity and exterior insulation it seems that the cavity insulation in this case is extra cost and material wasted, since the difference in savings is small.

Regarding the innovative process both measures are very low in cost-wise but achieve satisfying enough energy savings. Which means that the entire facade does not need to be insulated. Almost the same results are reached by insulating parts.
(The costs include only the materials part, the labour costs are not taken into consideration in this part.)

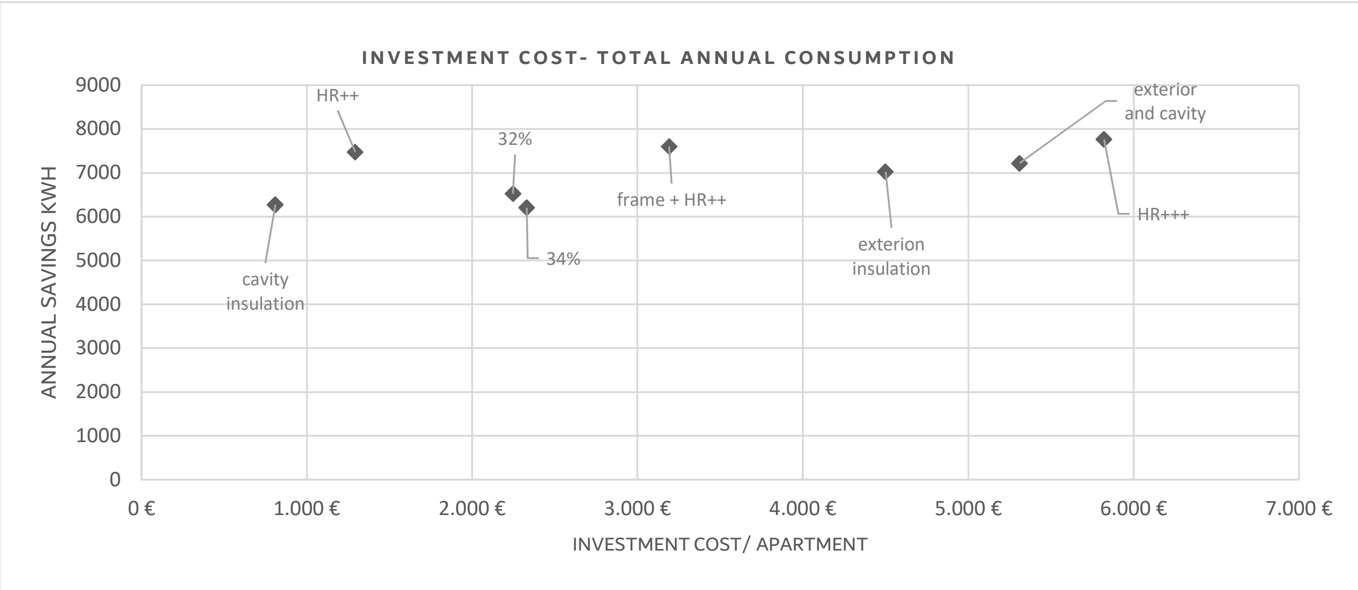


Figure 3 Graph of investment cost per apartment in Euros, and total annual energy consumption per apartment.

Conclusion

The simulation of all three types of apartments T1, T2 and T3 resulted that T1 has the highest energy demand for heating and the highest values for maximum heating power of all rooms. T1 will be used from now on.

The costs are seperated in materials costs and labour costs. The eight measures are compared in terms of material costs and energy savings. HR++ and “North” are rejected. The remaining measures vary significantly in price but not in energy savings. Meaning that there is sense in insulating the parts that will give payback and lowering the costs and material usage.

08 SIMULATION IN GRASSHOPPER

The simulation in Design Builder showed that there is potential in the insulation process but there are a lot of variables that could affect the results. In addition, it is important to test if it is a concept that can work in other apartment blocks that have different facade characteristics than the case study.

Repeating simulations in Design Builder can be very time consuming and prone to errors when transferring the results from DB to the excel sheets. To explore all the possibilities and achieve efficiency in the decision making, a method is created with predefined criteria. A “roadmap” that uses the case study as prototype and utilizes the analysis so far, includes the critical variables, the outputs and the economic- and energy-related objectives that will help with the optimization on an early stage of the facade design.

In order to shorten the time, parametric simulation is used. The parametric simulation is done in Grasshopper with the addition of other add-ons explained in chapter 8.3.

8.1 Preliminary Analysis

Simulations in Design Builder were used to decide the variables that can have a significant impact in the results.

Insulation material

The thermal conductivity of the insulation material can vary from 0,028 to 0,040 W/mK. The choice of the material can be of interest for environmental, health and practical reasons, however in this research there is not a significant difference in the results to consider the various lambda of the materials. So, two values are taken into conideration that of 0,030 and 0,040 as in some cases the lower lambda can make the difference in achieving the margin for low temperature heating.

Single glazing

Initially it was also tested the possibility of a building with single glazing and if it is possible to achieve the goals by maintaining it. Although, it would be a very cheap solution to keep single glazing in order to achieve heating temperature of 55°C an insulation of XPS 180mm or more should be used. Which doesn’t make sense to over insulate the building in order to keep the single glazing that will be replaced eventually in the future. For that reason, in this project it is takes as a limitation that the buildings already have at least simple double glazing.

Facade Typology

It is taken as a fixed parameter that the facade typology is a cavity wall, which is representative of the post was apartments to a great degree. Also, the construction of the cavity wall of the case study, which is 100mm concrete, then the cavity and 100mm brick as the exterior layer is also taken as a fixed parameter since it is again considered to be very common and also not as influential for the results. The cavity width however is considered a variable.

8.2 Variables

The facade of a building is a combination of components and parameters that influence its performance, the building’s energy performance and the indoor climate. There are fixed parameters on every building and variables that can be chosen during the refurbishment design. Their ideal combination will result in the optimal solution for every case. To run the parametric simulations, these variables are connected to the simulators as inputs and are:

Cavity wall

Cavity wall combines two possible inputs just to make the simulation faster and more efficient. It includes the cavity width and lambda of the insulation material used to fill the cavity, in the form of Rc-value of the whole wall. This input is used for the walls that have no exterior insulation.

The case study has a cavity width of 70mm, which is considered to be a large cavity, so two smaller cavities are taken as variables of 30 and 50mm. For the insulation material, as mentioned in the preliminary analysis, the lambda of 0,030 and 0,040 are used as needed. All Rc-values can be found in Appendix B.

Window to Wall Ratio

The windows are a major source of heat loss, as higher the window to wall ratio the higher the heat losses. The options of 20%, 40%, 60%, 80% are used as inputs that cover the most common rations and extreme situations.

Window Quality

Cost-wise the optimal solution is to maintain the existing windows. However, there should be the option to upgrade the windows in terms of glazing and frames. So, the three options are double glazing with wooden frames, HR++ with aluminium frames and HR+++ with aluminium frames with U-values of 2.6, 1.2, 0.9 respectively.

External Insulation Rc-value

For the external insulation the same logic applies as for the cavity wall. Wherever external insulation is applied, the total Rc-value of the wall is used as an input including the existing wall, cavity width of 30/50/70mm, exterior insulation thickness of 50/100/150mm, exterior insulation material λ of 0.030 or 0.040. All Rc-values can be found in Appendix B.

Facade Percentage Exterior Insulation

Regarding how much of the facade will be insulated externally, the measure of 32%- Living room will be one option and a second one will be 50%- Bedroom1. The second option derived from the results of the eight measures 7.2.1 since it seems that some solutions will need some insulation in the bedroom to reach the low temperature goals.

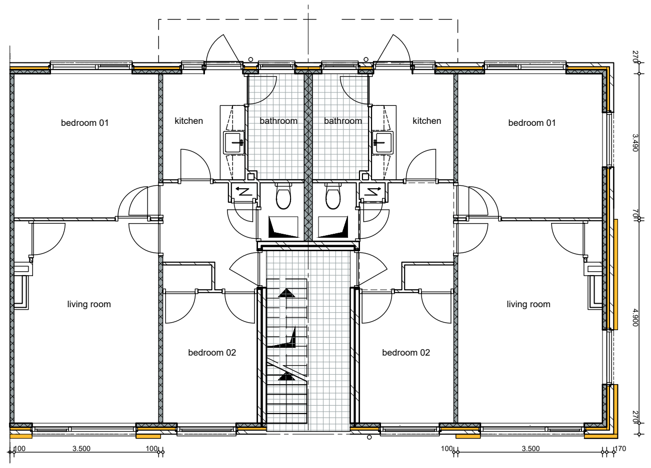


Figure 1 Insulation on the 32%

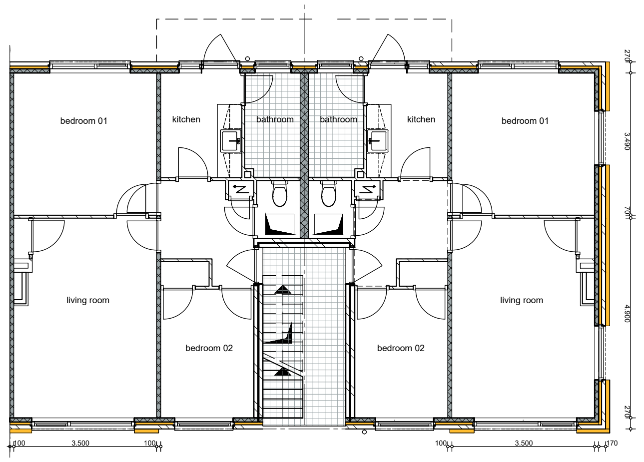


Figure 2 Insulation on 50%

8.3 Workflow

For the simulation Grasshopper and the plugins of Honeybee, Ladybug, Energy Plus are used for the energy simulation and Colibri for the iterations. The results are then shown in Design Explorer.

Geometry

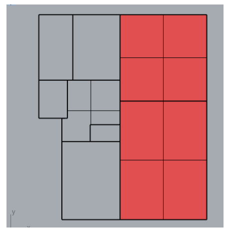
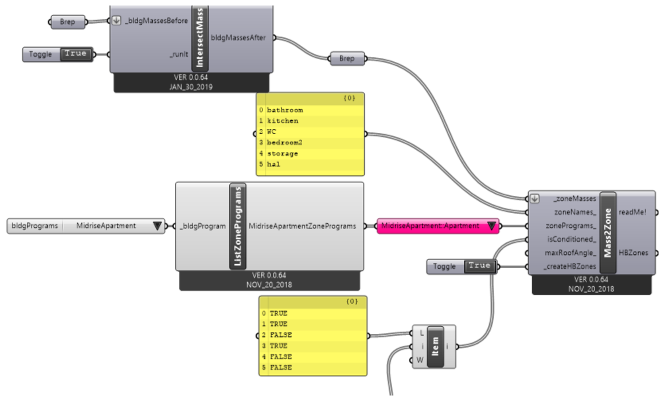


Figure 3 the apartment in zones in Rhino.

The apartment type T1 upper corner that was also used for the Design Builder simulations is modelled as simple boxes in Rhino. Every box represents a different room/zone. The boxes for the living room and bedroom1 need to be exploded and treated as surfaces since different materials will be applied to each surface.

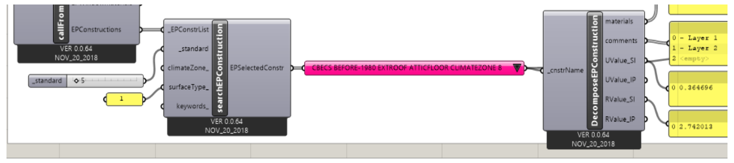
Zones and Program

After the geometry is internalised in Grasshopper the next step is to define the zones and apply the default programme for apartment. In this part we define which zones are conditioned and which not. WC, storage and hall are not conditioned.

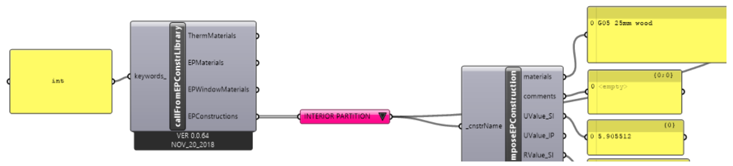


Set construction

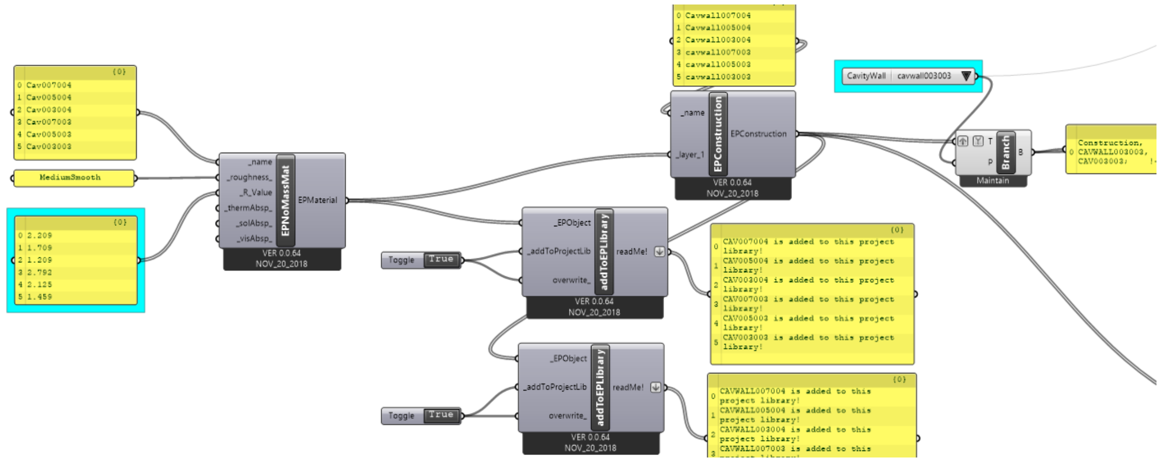
The construction for the roof and the internal wall are chosen.



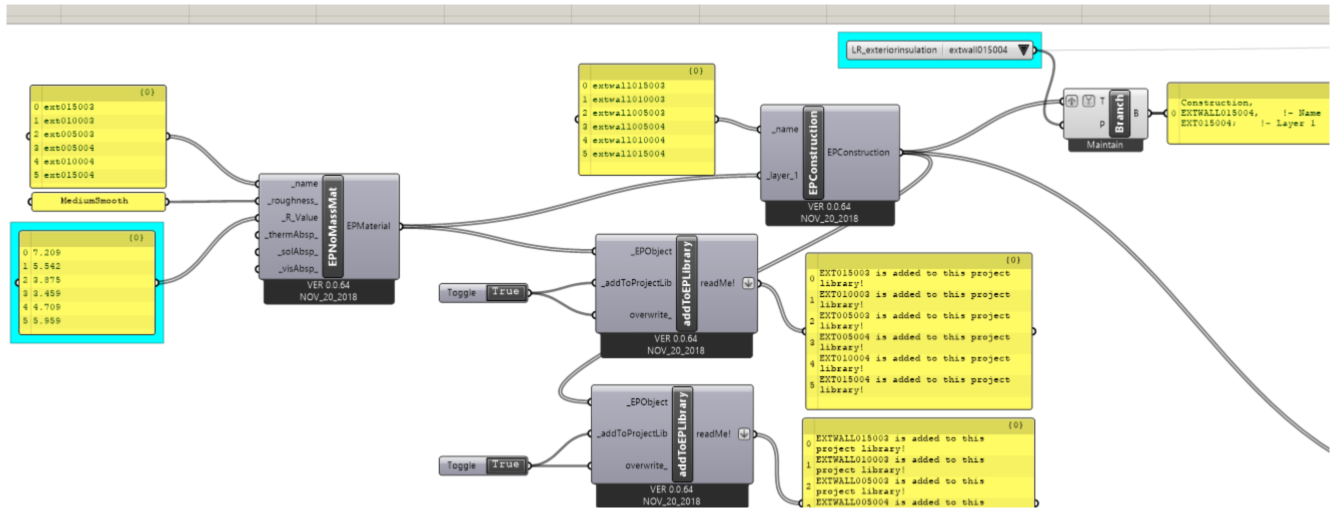
INTERIOR_WALL



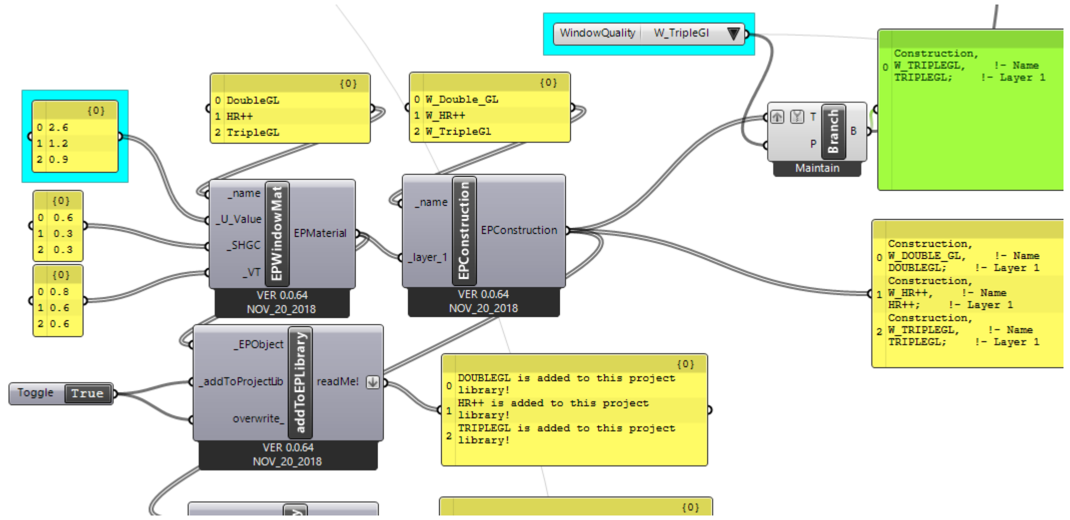
For the cavity wall the Rc-value of the wall is a variable (bright blue colour) and connected to Colibri.



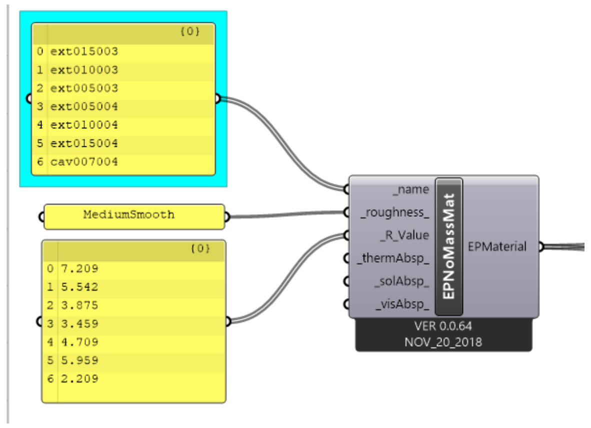
The exterior wall follows the same logic. Below the example of 70mm cavity is shown. Exactly the same was done for 50 and 30mm cavity.



For the windows the Uvalue is the variable.

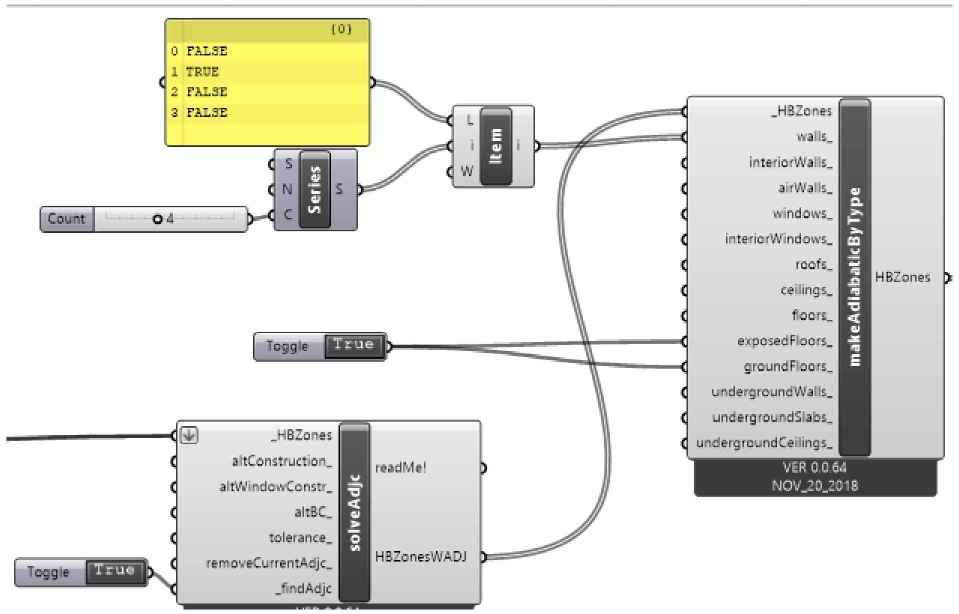


For the bedroom there is one more Rc- value option which corresponds to wall with cavity insulation only. So, all the combinations that have this option for the bedroom are the 32% exterior insulation, and the rest (where is also exterior insulation to the bedroom wall) is the 50%.



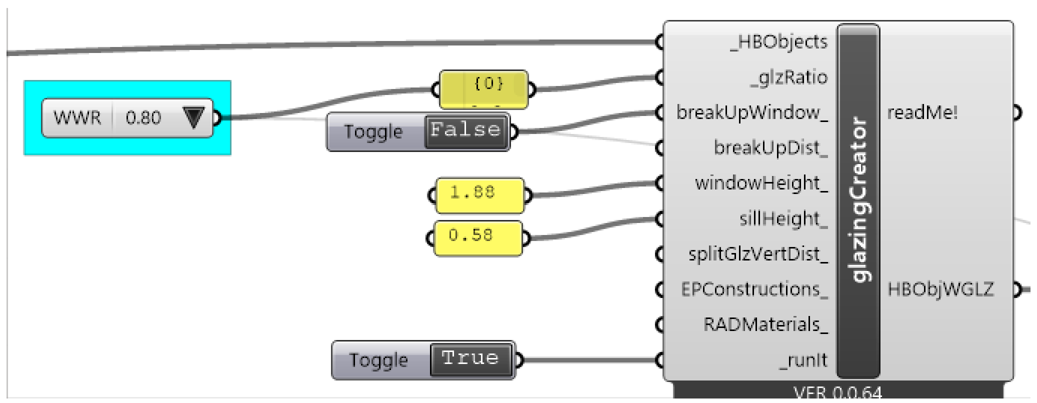
Adjacencies and Adiabatic

The adjacencies between the surfaces and three zones are solved so Grasshopper knows what is indoor and outdoor and the surfaces that are connected to the apartment next door are set based on the apartment type T1. The floor is also set adiabatic.



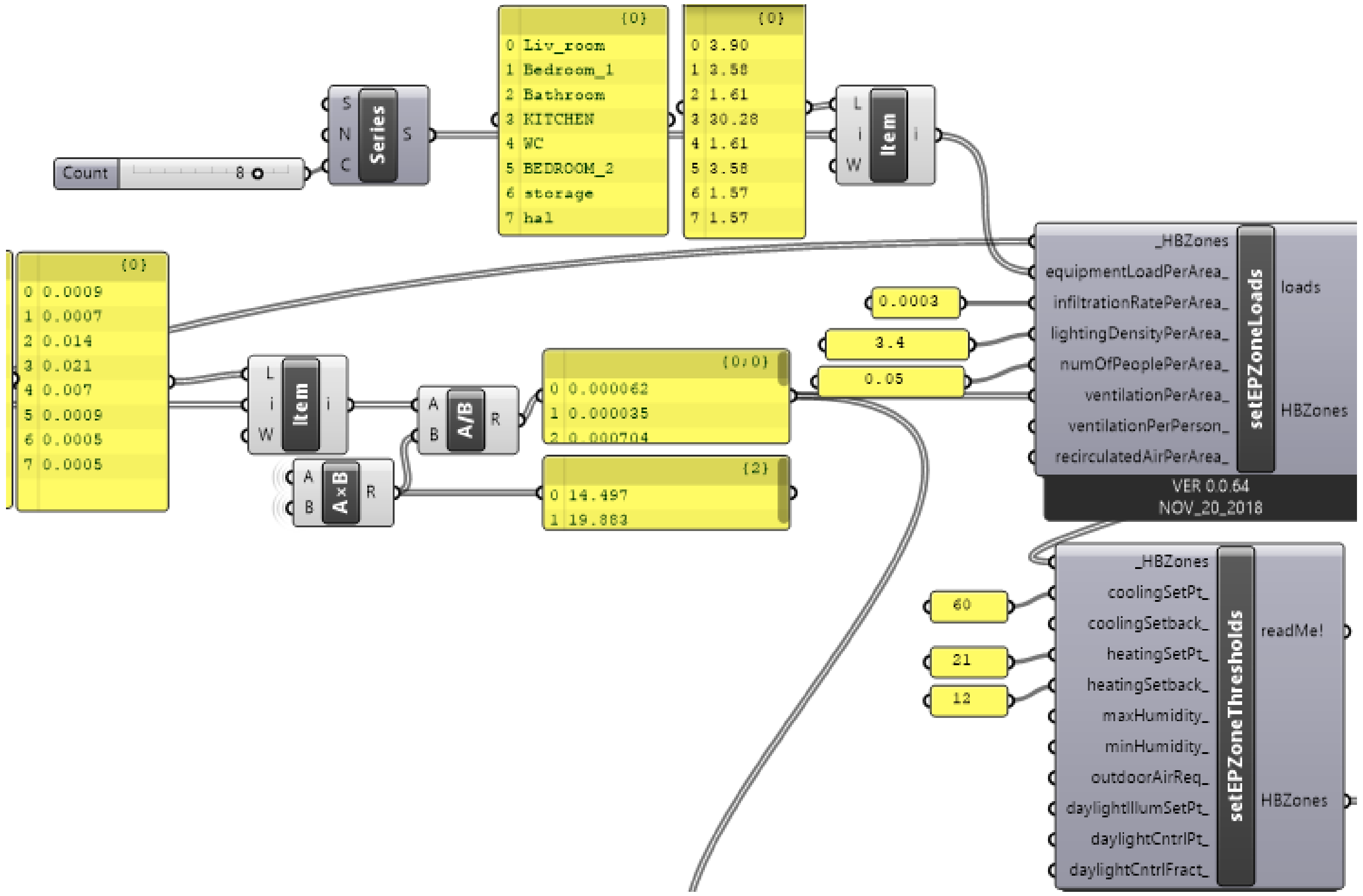
WWR

After the adjacencies and the adiabatic surfaces are set is time to have the WWR as an input. In the same component the height and sill height of the windows is determined and also the breakUpWindow is set to false so there is only one window in each surface as is in the case study.



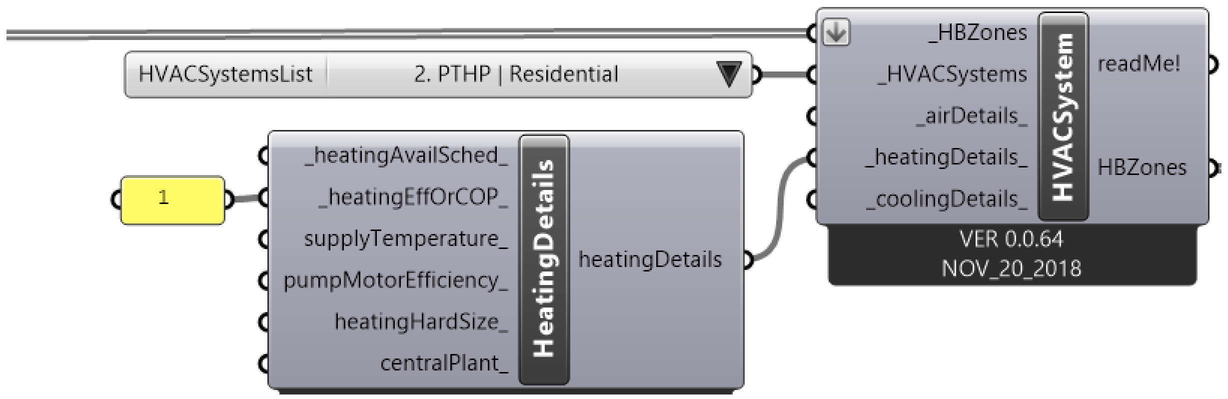
Loads and Ventilation rates

With these components the occupancy, the ventilation rates and the equipment loads are set for every zone. The heating set point is 21 and the cooling is 60, which is a way to tell the program that there is no cooling.



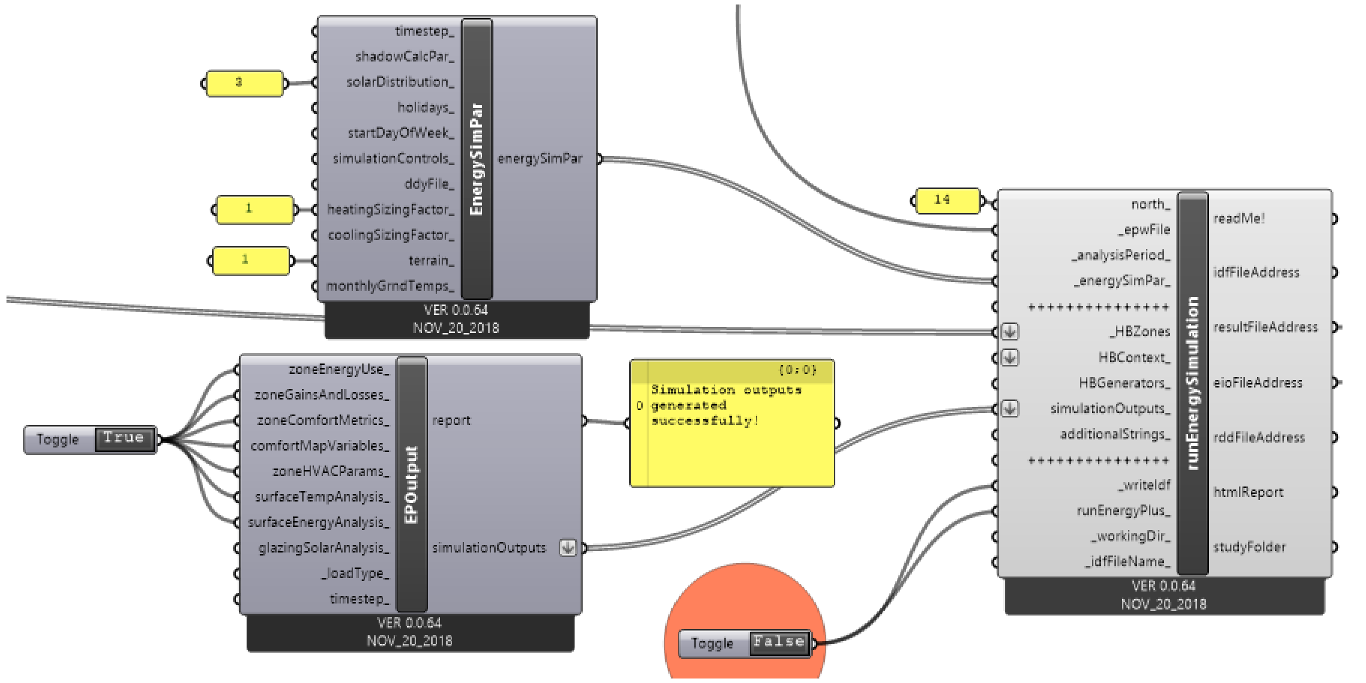
HVAC

The Hvac is the last input, PTHP is an all electric residential option with a CoP of 1.



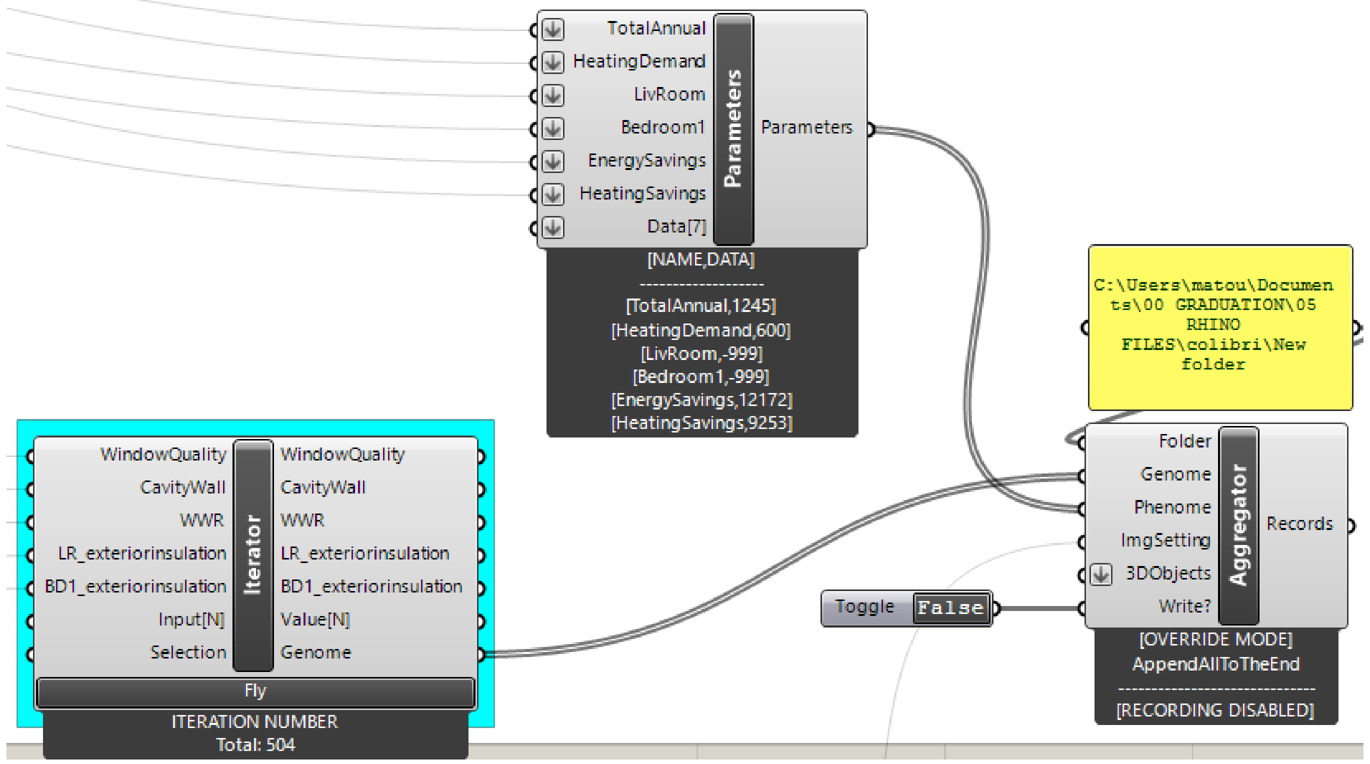
SIMULATION

In the simulation component the orientation is set and also the context information. The timestep is the default hourly.

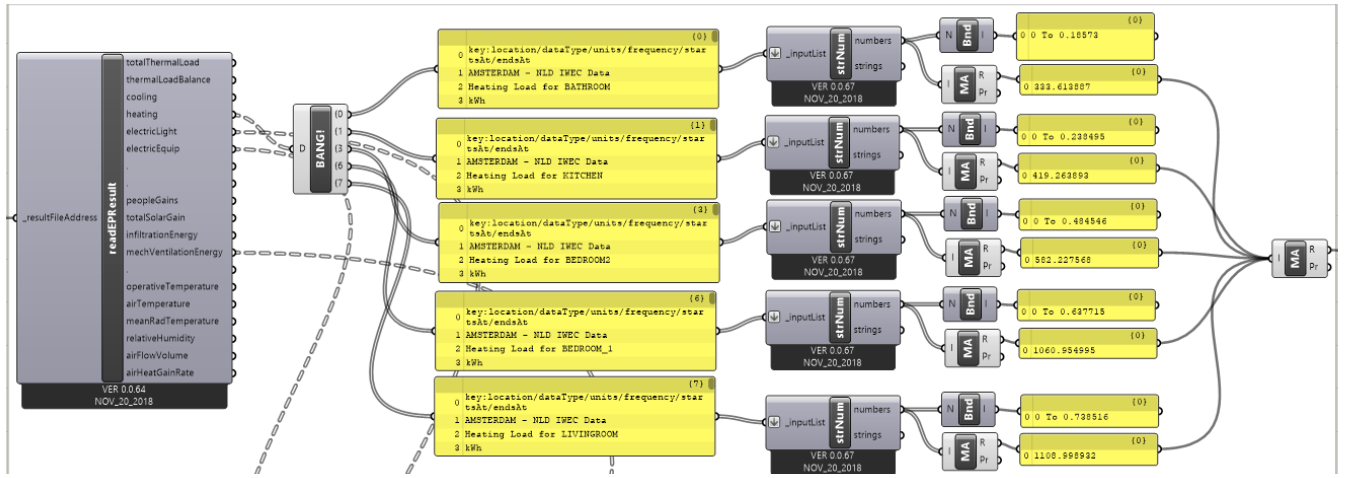


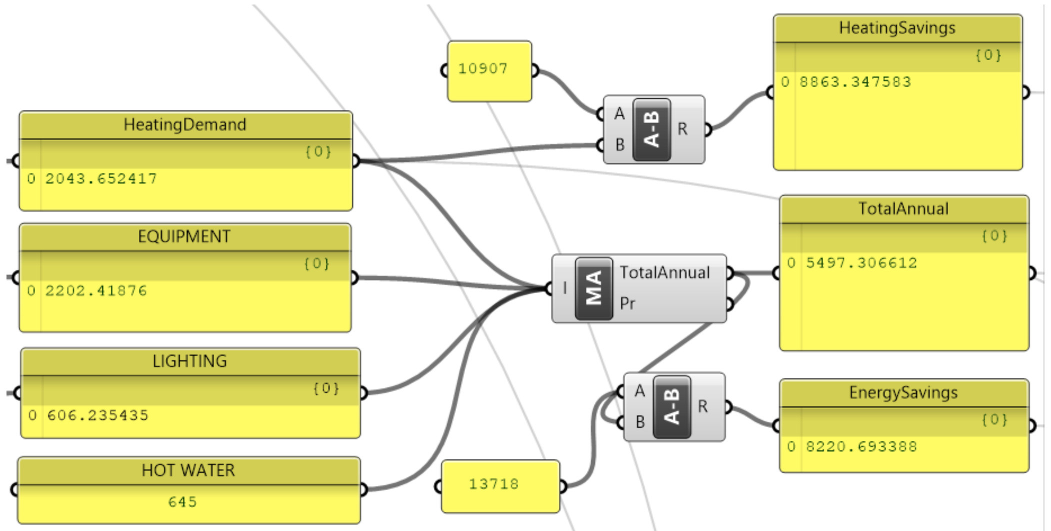
Colibri

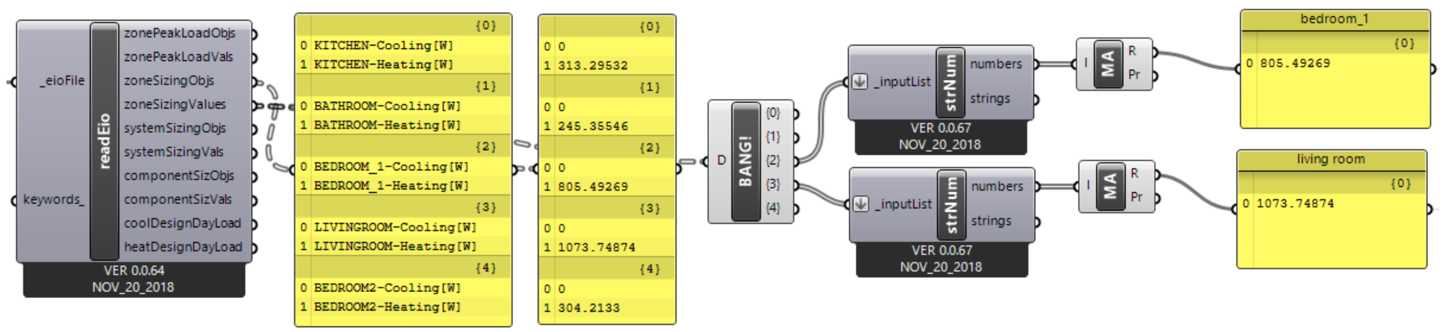
All the inputs are connected to the Colibri iterator and all the results to the parameters component. The aggregator rights the inputs and outputs in an excel file.



RESULTS







8.4 Outputs

The outputs are editable data lists which can be further analyzed through a variety of graphs and diagrams illustrated in Design Explorer and In Excel.

Annual energy demand

Annual energy demand in kWh includes the demand for heating, hot water, lighting, electricity for equipment, for the whole year.

Annual heating demand

The demand in kWh for heating.

Zone peak heating demand (LR-BR1)

The maximum heating power for the living room and bedroom1 in Watts. These results are important for tyhe LT-ready.

Investment cost per apartment

This value is not an output of the parametric simulation, but it comes from the literature study. Especially important for the optimization phase.

8.4 Objectives

Lt-ready yes or no?

The first objective is if the combination of variables can reach below the numbers for low or medium temperature heating. Either it does or not.

Energy savings

Energy savings objective is related to the LT aspect, it is important to see how energy efficient the solution is.

Cost per m2 and Payback period

As already explained the aim is to get a facade insulation as low in cost as possible.

8.5 Optimization

The optimization process with many iterations does not end up with one best solution but rather a set of solutions that can work. Using the objectives set above as weighting criteria, the solutions are filtered either in terms of cost or energy efficiency.

The whole process of the Grasshopper simulations is illustrated in figure 5.

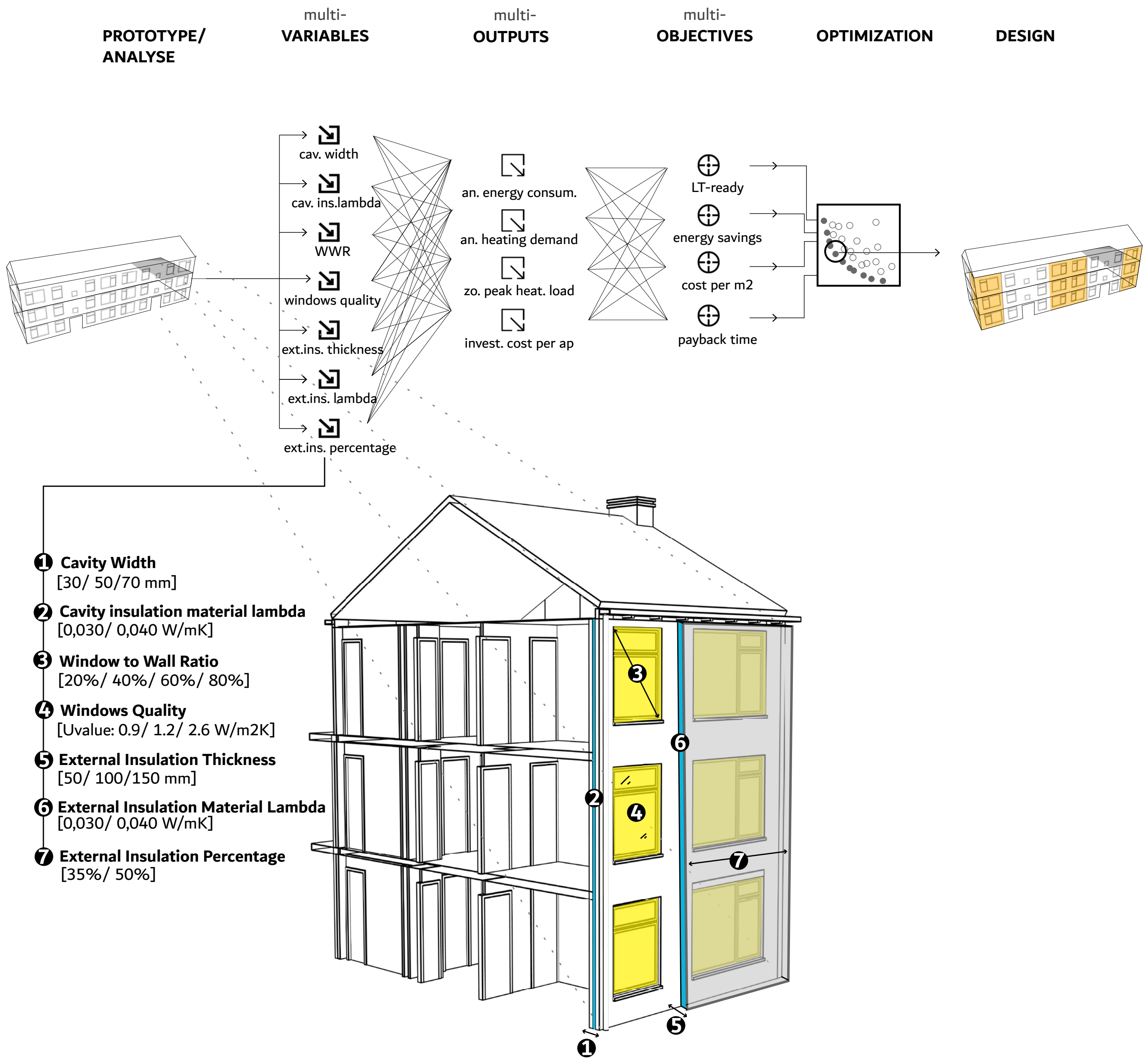


Figure 5 The grasshoper simulation in one picture, including the variables, outputs and objectives.

8.6 Results

8.6.1 Cavity Insulation Results

The first set of results is focused on the combinations that can achieve medium or low temperature heating only by applying cavity insulation on the facade. This output is especially important since it is the cheapest and fastest solution.

To obtain the outputs the following variables as described in 8.2 where used:

- Window Quality
- WWR
- Cavity Wall

- Regarding the variable cavity wall, all three cavity widths and both lambdas are considered. All results are presented in Figure 6, which will be further analyzed to obtain conclusions.

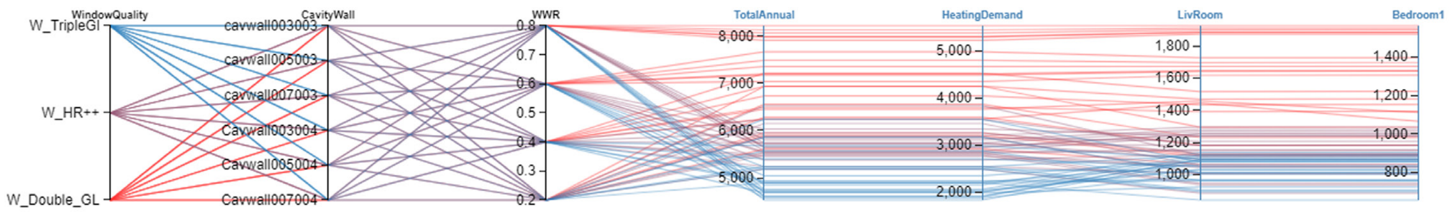


Figure 6 Diagram with the set of solutions for cavity insulation.

The indicative factor is the peak heating demand of the living room which is compared with the heat output of the radiators as described in chapter 4.6, which should be below 1443 Watts.

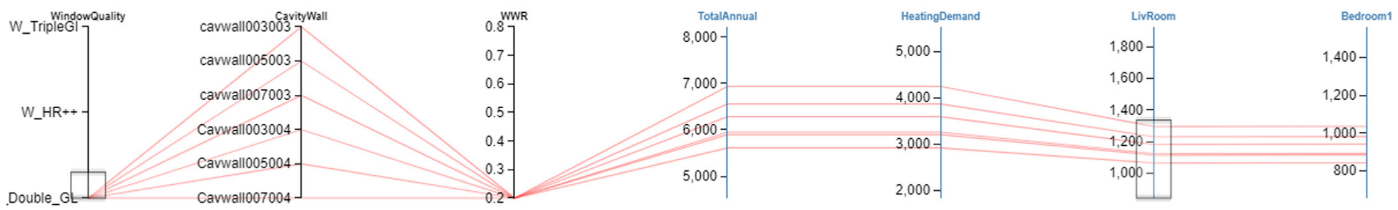


Figure 7 Diagram with the set of solutions for cavity insulation that achieve medium/low temperature heating without changing the glazing.

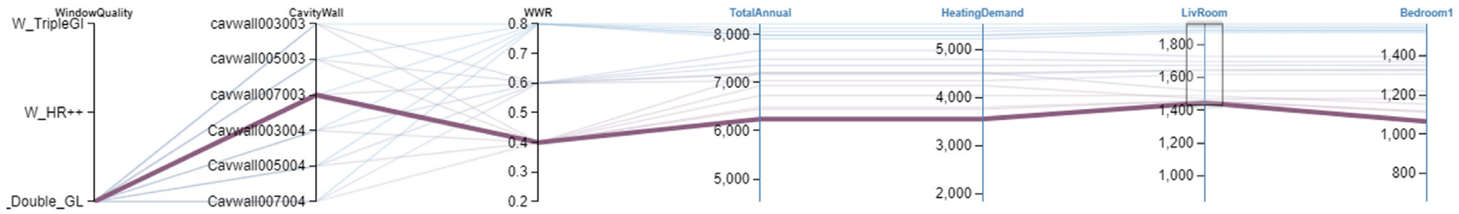


Figure 8 Diagram with the set of solutions for cavity insulation that fail to achieve medium/low temperature heating.

Conclusions form the graphs:

- Low temperature heating cannot be achieved only with cavity insulation if the building has a window to wall ratio of 40%, 60% or 80% in combiantion with double glazing. The only WWR that allows to maintain the same glazing is 20% which is not very common.
- With 80% window to wall ratio and double glazing not even the bedroom heating power is close to the value needed.
- The most influential parameter becomes the quality of the glazing as the window to wall ratio becomes bigger.

Figure 9 Graph with the reletion on the livingroom's maximum heating power to the WWR.

The full set of solutions in excel form andmore diagramms can be found in Appendix B.

8.6.2 Cavity and exterior insulation results

The second part is focused on the cases that need exterior insulation in the living room and/or bedroom. For every cavity option there were 504 combinations so in total there are 1512.

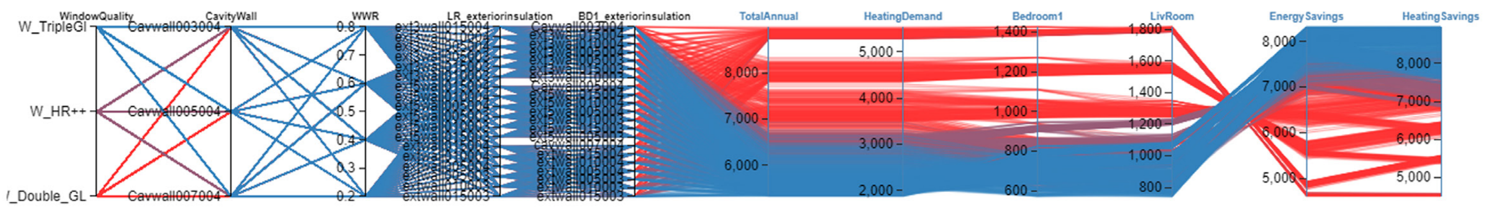


Figure 10 Diagram with the set of solutions for cavity insulation and exterior insulation in the living room/bedroom.

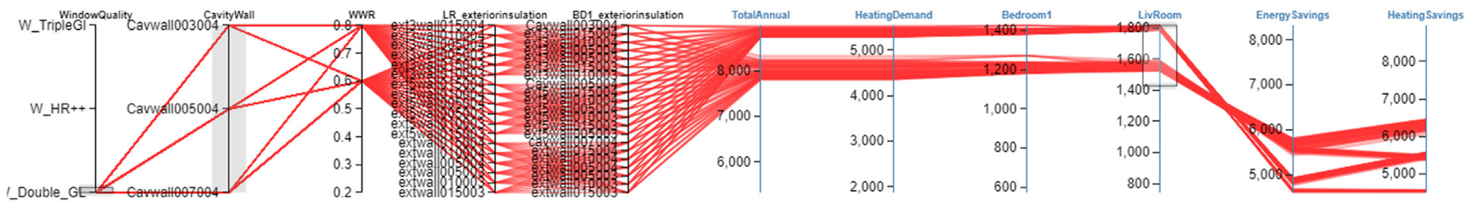
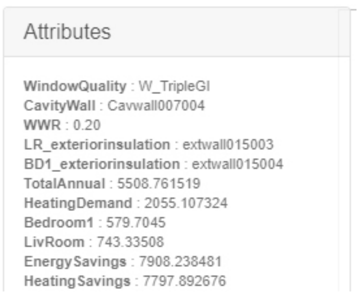


Figure 11 Diagram with the set of solutions for cavity insulation and exterior insulation in the living room/bedroom that fail to achieve low temperature heating.

Conclusions form the graphs:

- Low temperature heating cannot be achieved if maintaining the double glazing and a window to wall ratio of 60% or 80% with the insulation of max 150mm. However, it is possible now for the 40% ratio.
- The lowest the supply temperature can be is between 40 and 45 degrees, with a return temperature of 30-35.


Attributes

WindowQuality : W_TripleGl
CavityWall : Cavwall007004
WWR : 0.20
LR_exteriorinsulation : extwall015003
BD1_exteriorinsulation : extwall015004
TotalAnnual : 5508.761519
HeatingDemand : 2055.107324
Bedroom1 : 579.7045
LivRoom : 743.33508
EnergySavings : 7908.238481
HeatingSavings : 7797.892676

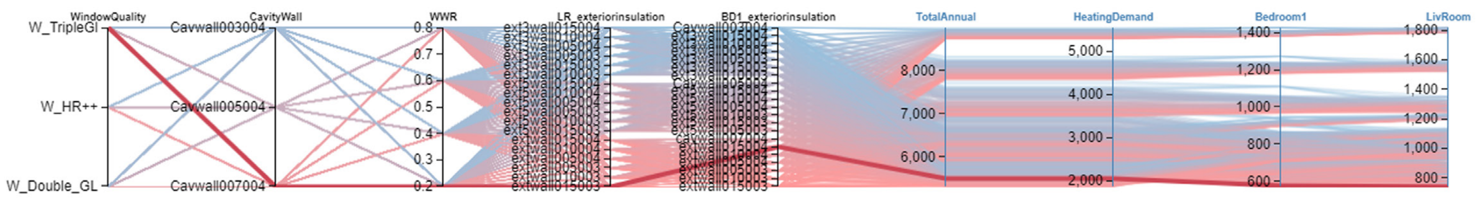


Figure 12 Diagram with the solution for cavity insulation and exterior insulation in the living room/bedroom that achieves the lowest temperature heating.

- The combination of the window quality and WWR plays the most important role compared to the other variables. The bigger the WWR, the largest is the impact of the window quality. For example ,in WWR of 20% the change from double to triple glazing doesn't have the significant result that has in a building with WWR of 80%. Meaning that different strategy will have to be followed having in mind also the cost of the solution.
- For the smallest WWR, then the Rc-value of the cavity insulation has a more important impact and finally the external insulation, which has a small impact but can make the difference in some solutions near the change from LT ready or not (not included as a variable but for example with a WWR of 50%), or change of temperature.

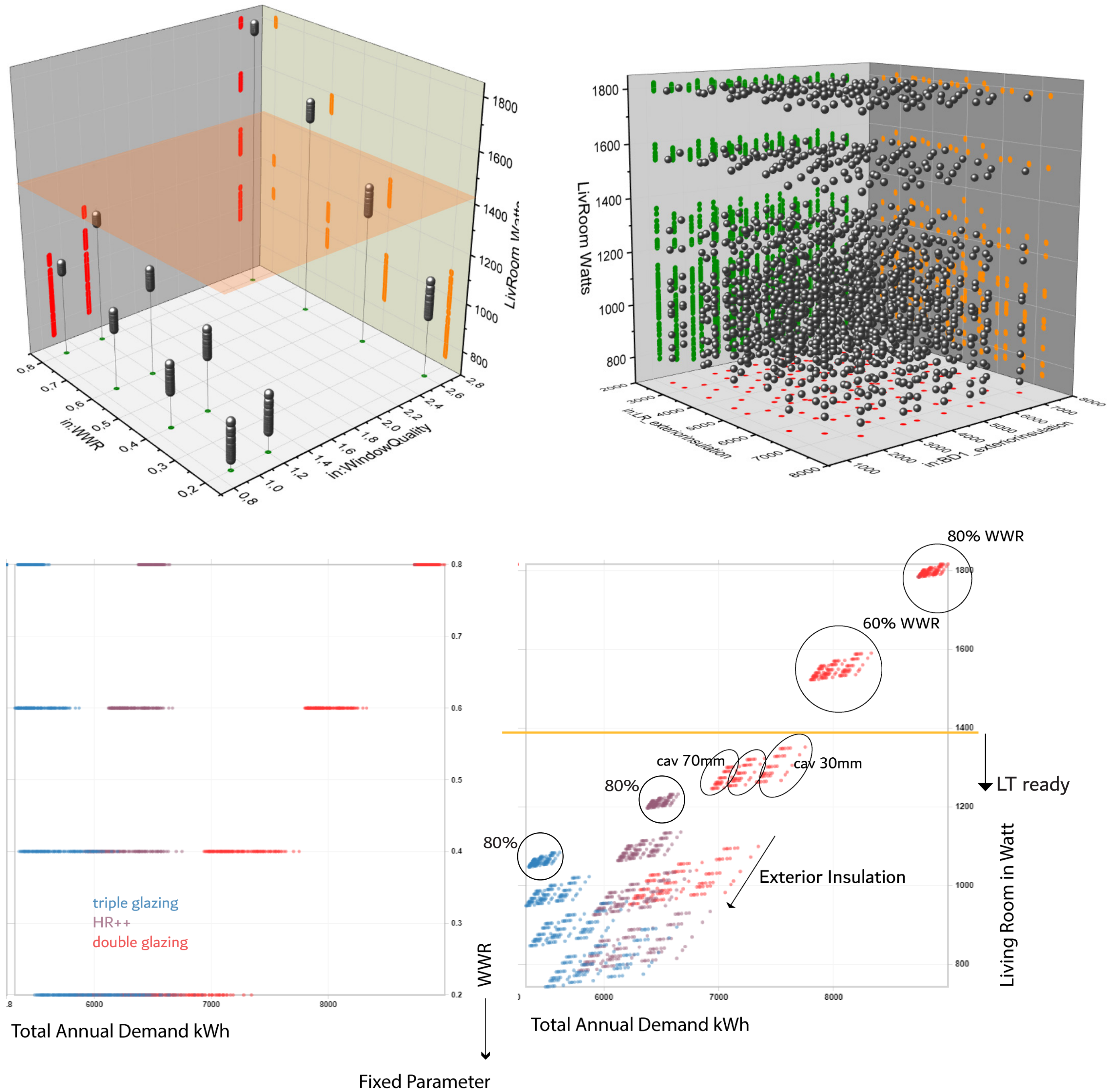


Figure 13 (Top left) 3dgraph with WWR, window quality and maximum heating power of the living room, (top right) 3graph with exterior insulation for the living room, exterior insulation for the bedroom and maximum heating power of the living room, graphs with Total Annual Demand kWh-WWR (bottom left), Total Annual Demand kWh- Living room maximum heating power in Watt (bottom right).

8.7 Applied on portiekapartments

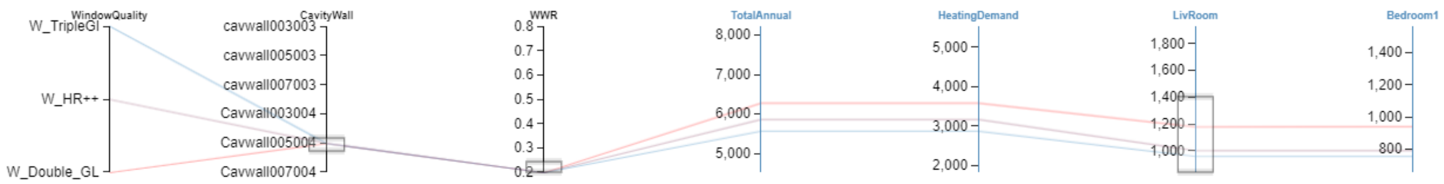
Bosleeuw Lucellestraat Amsterdam, Noord-Holland

Figure 14 The facade og the building in Amsterdam, (Source: rvo.nl)

Characteristics

Floor area of the house: 64.5 - 97.2 m²
Orientation: different
Cavity: 50mm uninsulated
Glazing: single and double
Frames: wooden
WWR: 20%

Information found on RVO.nl



No need for exterior insulation. Due to the low window to wall ratio the building can be heated with low temperature heating only with cavity insulation with EPS.

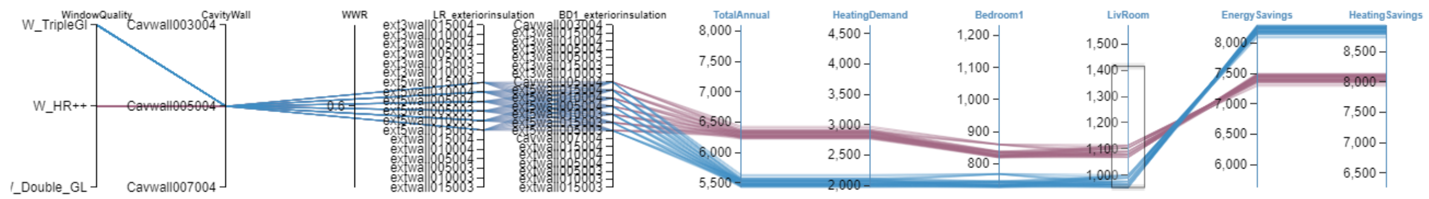
Rotterdam Zuid

Figure 15 The facade og the building in Rotterdam. (Source: 2nd Skin,2011)

Characteristics

Floor area of the house: 67 m²
Orientation: North-South
Cavity: unclear, propably 50mm uninsulated
Glazing: double
Frames: UPVC
WWR: 60%

Information found on 2skin project



In this building the windows would have to be changed to either HR++ or Triple glazing. The exterior insulation however could be at a percentage of 35%, depends on the floor plan.

8.8 Applied on the case study

Outputs

In order to continue to the design development the results for the case study will be analysed first. The set for solutions for the case study are presented. From the cavity results it is it is already ready clear that by maintaining the windows external insulation is needed. Also, all solutions for exterior insulation are below the benchmark for medium temperature heating.

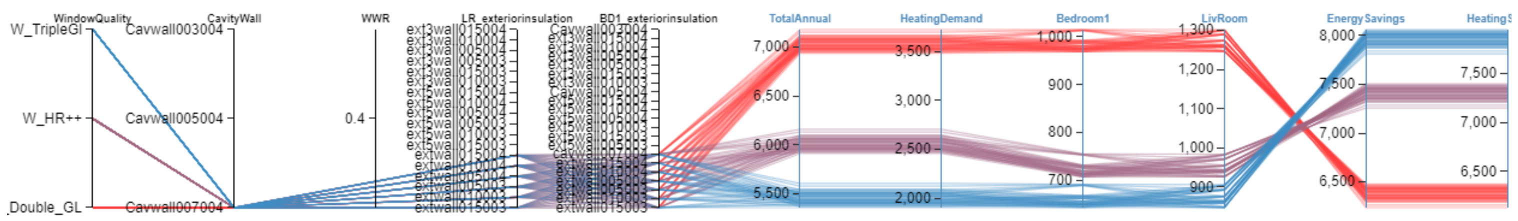


Figure 16 The set of solutions for the case study.

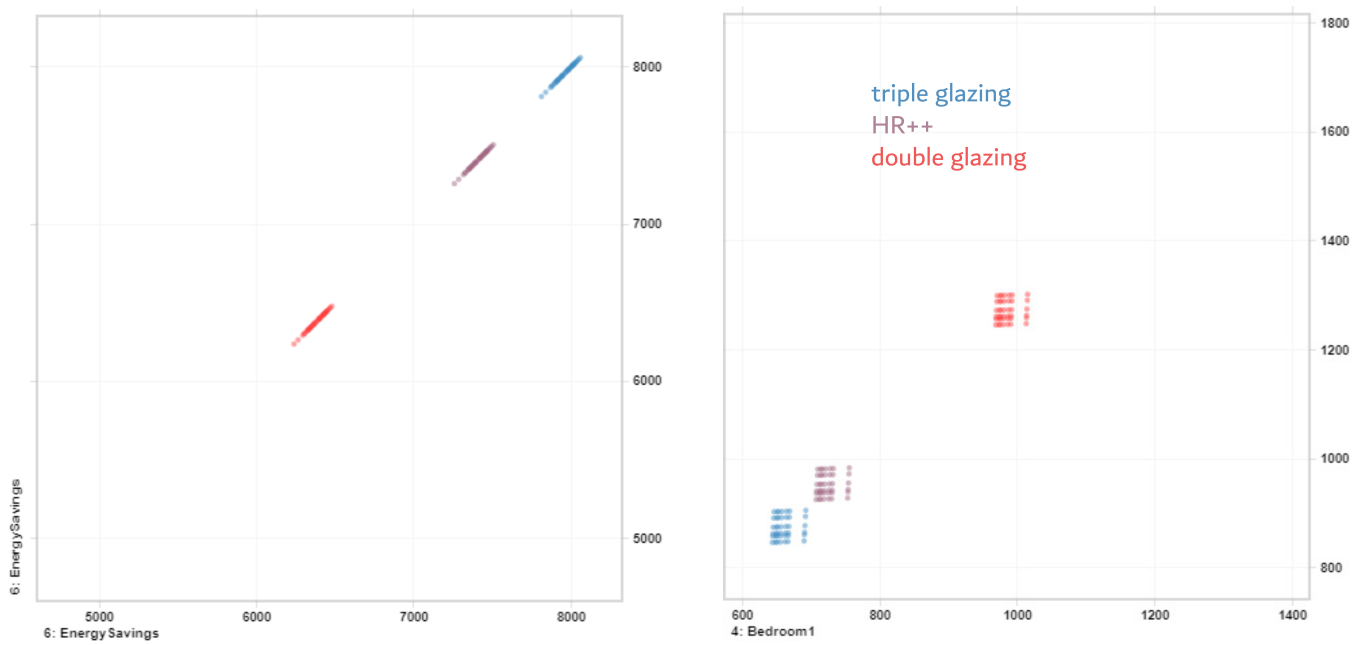


Figure 17 The energy savings kWh (left), bedroom- living room maximum heating power Watt (right).

Optimization

The objectives as described in 8.4 are :

- Lt- ready, which is achieved for all solutions.
- Energy savings
- Cost per m^2

The optimization can be done either for the most cost-efficient solution or the most energy efficient solution.

OPTIMIZED IN TERMS OF COSTS

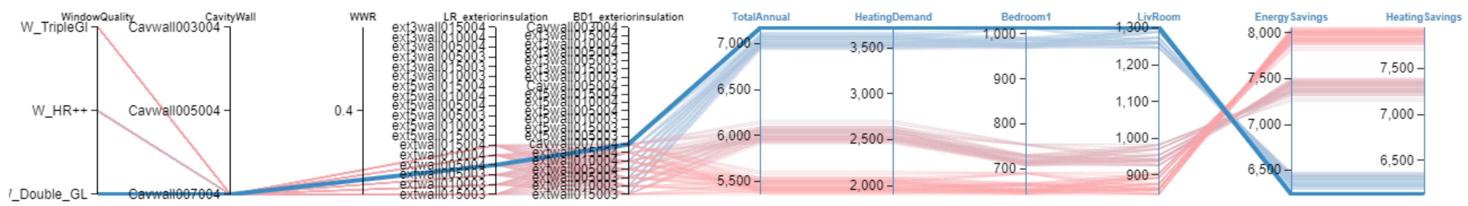


Figure 18 The low cost solution for the case study.

This is the cheapest solution, as the windows remain the same, external insulation is applied to 32% of the facade, there is EPS in the cavity and as exterior insulation and the thickness of the insulation is the smallest.

The input temperature of the flow for the radiators is 55 degrees which is medium temperature heating.

Materials cost = 62.4€/m2 < 100 €/m2.

Labour costs for the facade: 2760€

Heating savings up to 62%. Energy savings up to 46%.

Payback period for the facade insulation: 50 months

Rc-value of externally insulated parts: 3.5 m2K/W

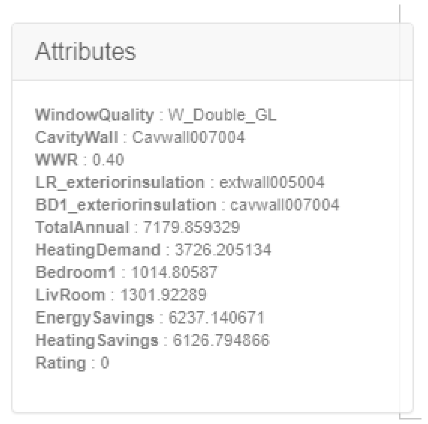


Figure 19 The low cost solution for the case study.

OPTIMIZED IN TERMS OF ENERGY

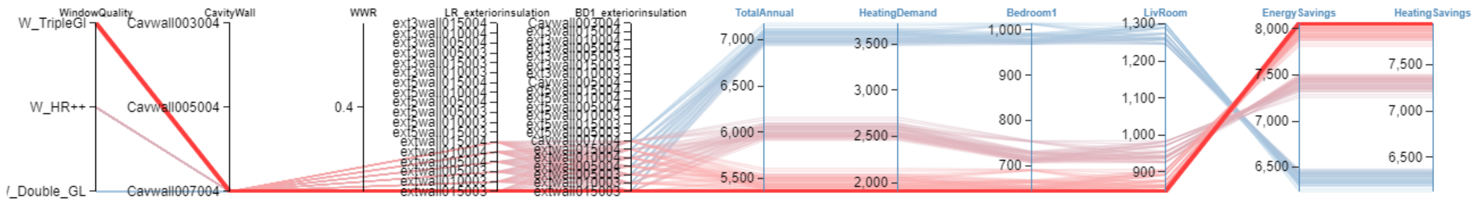
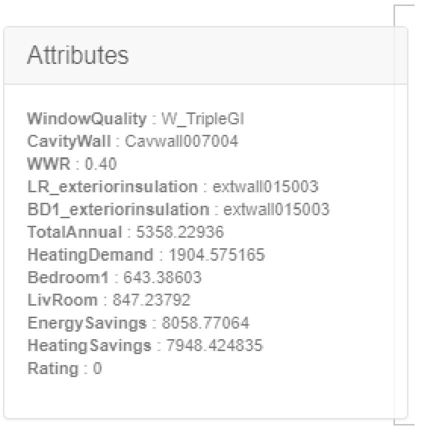


Figure 20 The solution with the best energy savings for the case study.

The best solution in terms of energy performance is the one with triple glazing, 50% external insulation of XPS 150mm. It has the highst energy savings and achieves the lowest heating temperature with water flow of 45 degrees.



The cost for 50% insulation is 36345 €/ building + 69862€ for triple glazing= 106207 €
Cost = 245 €/m2
Energy savings up to 60%.
Heating savings 80.5%
Rc-value of externally insulated parts: 7.2 m2K/W

Figure 21 The solution with the best energy savings for the case study.

Comparison of two solutions with 100% external insulation.

The two concepts are compared with each other and with a third basic concept of external insulation. The comparison is done for the costs for materials and labour hours and annual energy/ heating savings.

	Low cost	100 mm EPS external	High energy savings
Façade insulation materials			
	62,4 €/m2	100- 150 €/m2	245 €/m2
	2247 €/ apartment	4500 €/ apartment	8850 €/ apartment
	26970 €/building	54000 €/building	106207 €/building
Payback time for materials / building	50 months	99 months	196 months
Façade insulation labour (placing the panels)	91 hours x 20€=1820€/ building	287 hours x 20€= 5740€/ building	141 hours x 20€= 2820€/ building
(change windows)	_	_	647 hours x 20€= 5740€/ building
(cavity insulation)	24 hoursx 20= 480 €/ building	_	24 hoursx 20= 480 €/ building
Attic floor insulation/ building	7.830 €	7.830 €	7.830 €
Investment cost / building	37100 €/building	67570 €/building	123077 €/building
Payback time	68 months	125 months	228 months
Investment cost /apartment	3091 €/ apartment	5630 €/ apartment	10256 €/ apartment
Energy savings/ apartment	46%	52%	60%
Heating savings/ apartment	62%	66%	80%

Table 1 Comparison of the three insulation concepts for the case study.

8.9 Additional heat loss and condensation risk

Deatil 1- Additional Heat loss

By partly insulating a thermobridge forms in every place that the insulation stops. An extra calculation is performed in Therm, to calculate this additional heat loss and how much it affects the result. The details are drawn in Grasshoper's Honeybee and then opened in Therm for the calculation.

The detail is drawn in simple layers of 1 m without details but only the ones that affect the result. In this layers each material is assigned from the therm library. The next step is to set the boundary condition for outside and inside. The rest of the edges are set to adiabatic. The value that is the result of the calculation is thermal transmittance ψ for a linear thermal bridge.

BOUNDARY CONDITIONS
Rsi= 0.13 hi= 7.69 Ti= 18°C
Rse= 0.04 he= 25 Te= 0°C

So, $L_{2D} = U_1 A_1 + U_2 A_2 + \psi l$

$\psi = L_{2D}$ (found in therm)- ΣUA (calculated manually)

ΣUA = 0.38 x 1 + 0.42 x1 = 0.8

ψ= 0.35- 0.8 = - 0.45 x 2m= 0.9 W/mK (x 2.75m (h)= 2.47 Watt)

(The Uvalues were calculated using the conductivity values from therm for the materials).
So there is an additional heat loss added in the living room and bedroom, which is not a significant amount.

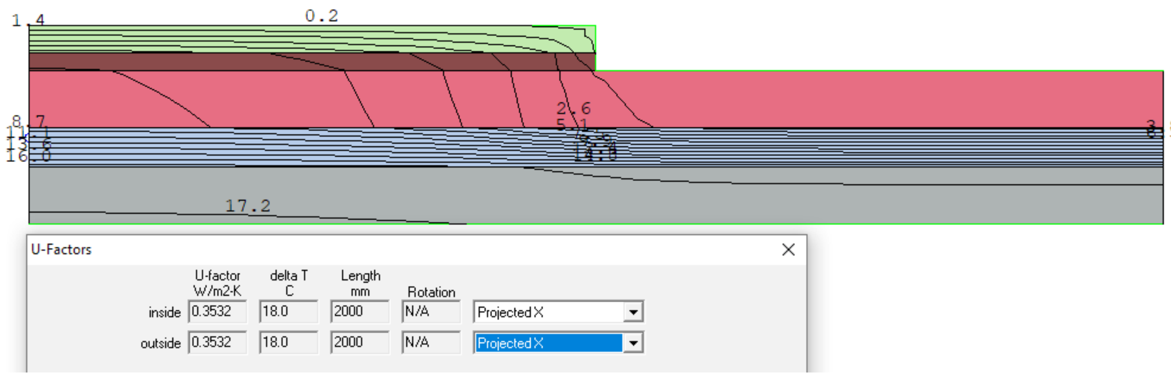


Figure 22 The results for the U-Factor of the simulation in Therm.

Detail 1- Condensation check

The same calculation is performed with a different hi to calculate the temperature factor f, to perform the condensation check. In this case hi=2.

f = Tismin- Te / Ti- Te= 15.8-0 /18- 0 = 0.87
f should be equal or bigger than 0.65. In this case, there is no condensation risk. More details, especially corner ones will be checked for condensation.

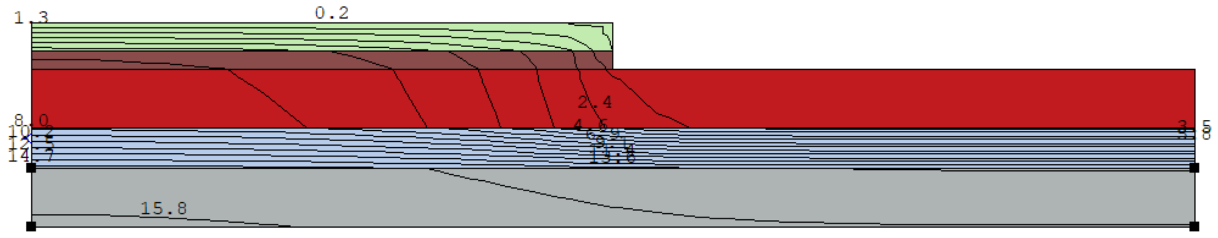


Figure 23 The results for the condensation check in Therm.

Detail 2- Condensation check

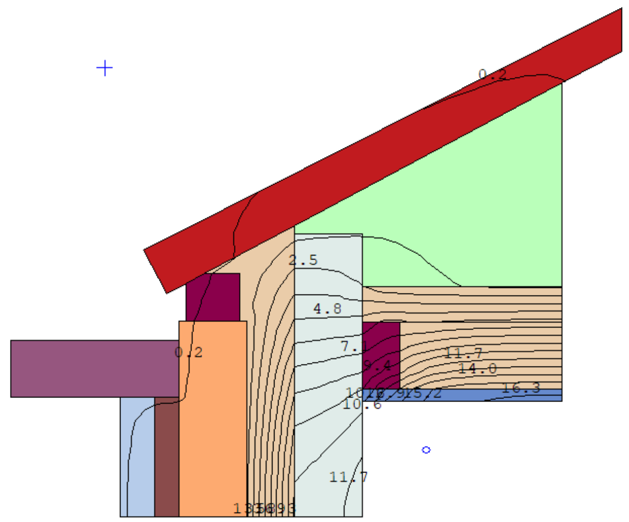


Figure 24 The results for the condensation check in Therm.

The most interesting detail for the condensation risk check is the corner where the wall and the roof in connected. Firstly it is checked with the Rc-values that are needed for the low temperature heating, according to the simulations. Since, the attic is a non heated space, the area is suimulated as a cavity material (the material with green colour in figure 24 and 25).

f = Tismin- Te / Ti- Te= 10.6-0 /18- 0 = 0.59 < 0.65

There is condensation risk. For this reason the insulation on the attic floor is increased from 150mm to 250mm.

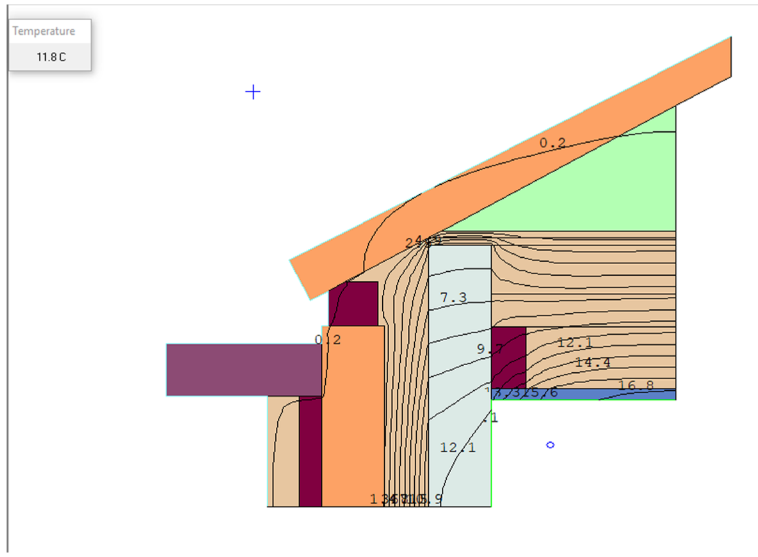


Figure 25 The results for the condensation check in Therm.

f = Tismin- Te / Ti- Te= 11.8-0 /18- 0 = 0.656> 0.65. With the increased inuslation there is no more condensation risk.

Deatil 2- Additional Heat loss

As described in Chapter 6, the insulation panel between the window and the roof, shown in this detail, it is one of the most complicated and expencive panels to place. Thus it will be checked if, from the building's physic point of view, it could not include it in the solution. The additional heat loss must be calculated in this case, in order to simplify the Therm calculation it will be done in two steps, since there are two heat loss paths (figure 26).

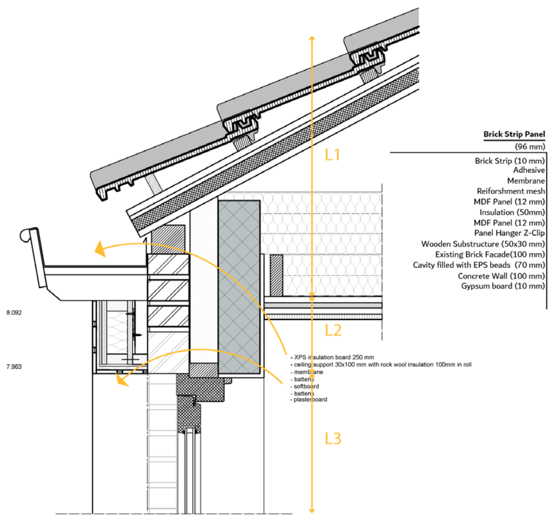
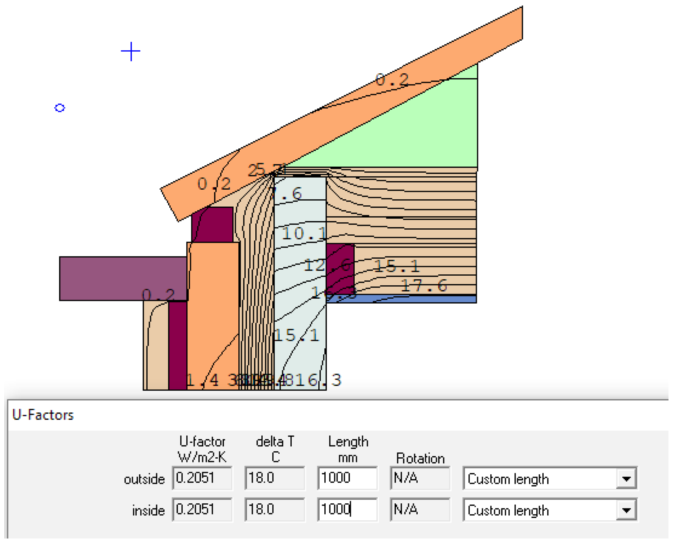


Figure 26 The two paths for heat loss.

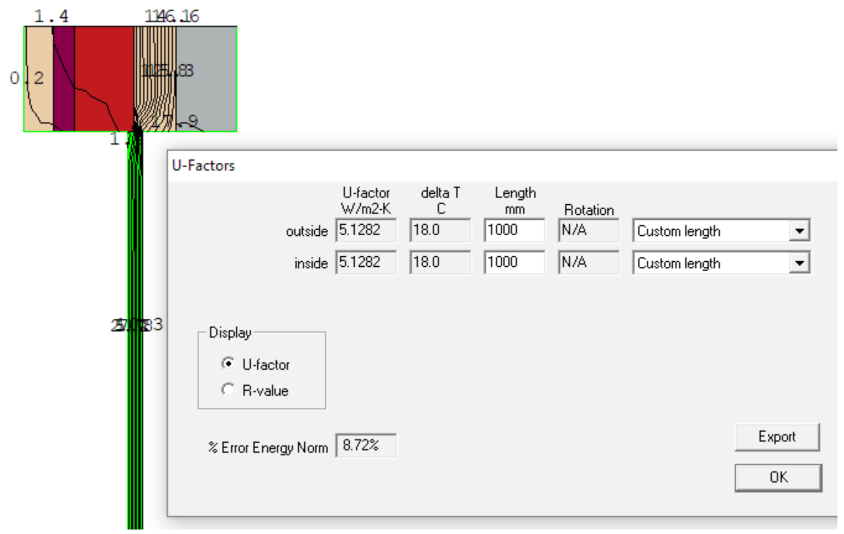


L1= 0.66m
U1= 0.1 W/m2K

L2= 0.2m
U2= 0.38 W/m2K

L_{2D} = U (L1+L2)= 0.2051 (0.66+ 0.2)= 0.1764

ψ = L_{2D} (found in therm)- ΣUA (calculated manually)= 0.1764- (0.66+ 0.076)= -0.56 x 2.5m (length of window)= 1.4 Watt



L2= 0.2m
U2= 0.38 W/m2K

L3= 1.9 m
U3= 2.6 W/m2K

L_{2D} = U (L1+L2)= 5.1282 (0.2+1.9)= 10.8
A new material is created in Therm to simulate the double glazing window with d= 25mm (the width for the double glazing) and λ = 1.12.

ψ = L_{2D} (found in therm)- ΣUA (calculated manually)= 10.8 - (4.94 + 0.076)= 5.8 x 2.5m (length of window)= 14.5 Watt

The sum for the additional heat loss is 14.5 + 1.4= 15.9 Watt for each window.
There are two windows (to simplify it is assumed of the same size) in the living room so 31.8 Watts.

In the selected low cost solution for the case study the living room has a maximum heating power of 1301 Watts. If 31.8 Watts is added = 1332,8 Watts < 1443Watts . Still possible to achieve the same results without placing this panels.

Conclusion

The simulations in Grasshopper helped to gain a new insight at the study and explore its potential and limits. The results show that WWR is a very significant factor. In conclusion low temperature heating can be achieved with cavity insulation with WWR of 20% even with the existing windows. For 40% WWR external insulation is needed, which depending in the end goal can vary in placement, thickness and material. A lot of solutions are viable. For 60% and 80%, the insulation thickness of 150mm is not sufficient, so in tis cases the windows have to be changed.

To move into design development for the case study, the optimization was done based on the best results for cost and the best for energy savings. The two options differe significantly in terms of costs. For the design the lower cost option is chosen.

09 DESIGN DEVELOPMENT

9.1 Design criteria

In this chapter the design criteria that are going to be used for the design development are determined. The criteria are separated in terms of energy performance, which derive from the simulations (chapter 8.8), approach from the literature study and architecture.
In regards of energy performance:

- External insulation is applied to 32% of the facade.
- An Rc- value of 2.2 m_2K/W is needed for the building, except for the living room that the Rc-value is 3.9 m_2K/W.
- The Rc-value of 2.2 m_2K/W can be reached by insulating the cavity using EPS beads.
- The Rc-value of 3.9 m_2K/W can be reached by insulating the cavity using EPS beads and 50 mm of external insulation with λ = 0.030 W/mK
- The windows can remain double glazing.
- The attic floor is insulated with a U-value of 0.346 W/m2K.
- The building services remain the same.

In regards of approach the criteria are:

- A solution that is effective and reduces the application time and the inconvenience caused to the residents. That means a prefabricated panel with the cladding already in place that needs to be fitted in place as fast as possible. Also it should be installed on top of the existing exterior layer.
- Is futureproof in the sense that the insulation could be continued or/and the windows could be changed if necessary in the future. The edges of the panel and the connection with the windows should be design in a way to allow that.
- Is a lower financial investment. That concerns the production process, transport and application. The connections and spots that are more labour intensive so more expensive are avoided.

In regards of architecture:

- Adaptable in various buildings. There is a standard solution in terms of layers, construction, and connections that can become a universal solution by adapting the size, insulation thickness and material.
- Multiple choices for the cladding.

The decisions to be made involve the size of the panel, the layers, the fixing and chaining method, the construction, connections to the windows and cladding options.

9.2 The layers of the insulation

In chapter 3.6 the level of prefabrication of the external insulation was categorized in the traditional in-situ way, semi-prefabricated and fully prefabricated, including the cladding. Especially in the categories of occupancy, construction time and delivery the fully prefabricated panel is compatible with the design criteria.

The next step is to determine the layers. For the case study 50mm of insulation is needed. However the solution should be able to adapt to up to 150mm. The choice is done between a sandwich or a framed panel.

The advantage of the frame panel (figure 1) is that it has already fixed edges, meaning that the detailing around the window would be made quite simple. However, it isn't adaptable in terms of sizing and the chaining between two panels has to be made weatherproof.

The sandwich panel (figure 2) is a better option in terms of adaptability and the chaining method between panels is easier and creates less thermo-bridges. the edges however have to be figured out. For this project the sandwich panel is chosen.

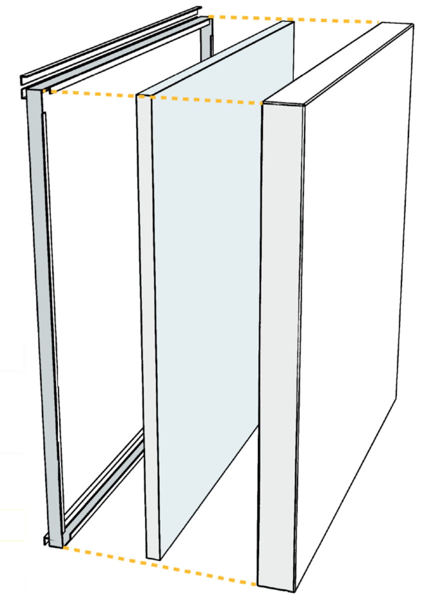


Fig. 1 Framed panel

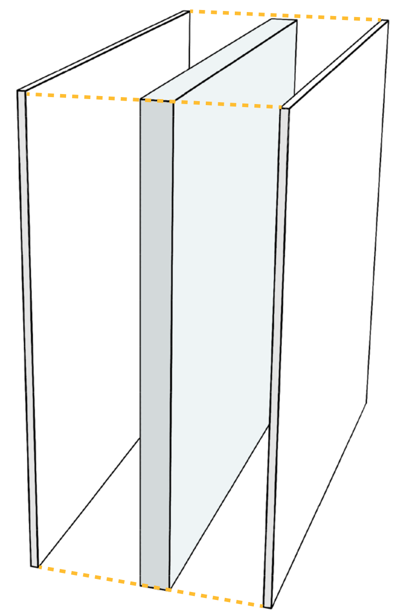


Fig. 2 Sandwich panel

9.3 Construction

The construction is depending on the ability of the facade to extra load and the weight and sizing of the prefabricated panel. It can be a suspended or a standing construction.

In case of a suspended construction (figure 3) the load is distributed upon existing substructure and is transmitted via the existing construction to the existing or reinforced foundations.

For a standing construction (figure 4) there is a substructure element that has several fixing over the facade and the load is transmitted through the substructure to a new foundation that can be connected to the old foundation.

To lower the costs and time the ideal choice will be to suspend on the facade. However, that requires for the structural analysis of the existing structure to figure out if it can take the extra load. Unfortunately, in this case it seems that the structure is not able to take the load so there will be a new metal foundation chemically anchored to the old foundation and a vertical substructure.

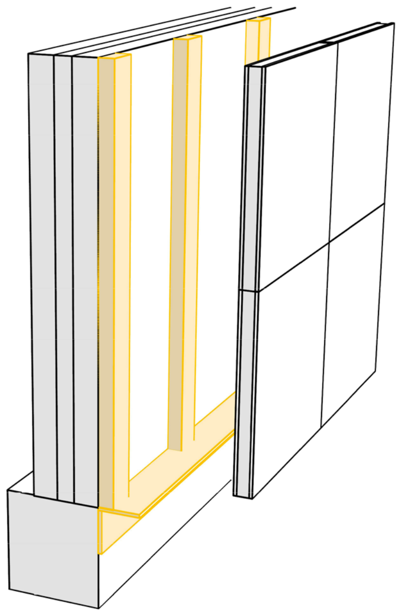


Fig. 3 Suspended Construction

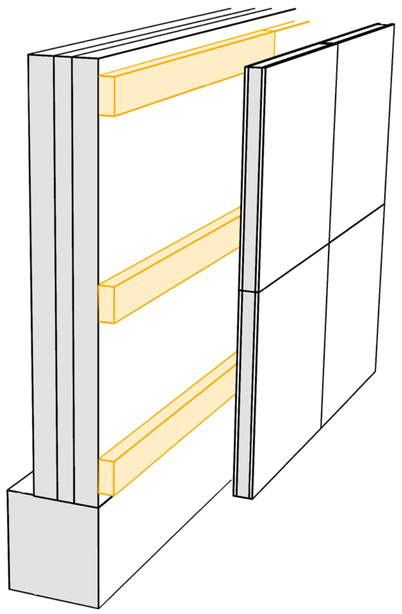


Fig. 4 Standing Construction

9.4 Size of the element

The prefabricated element can be as big as covering the whole height of a four level building or as small as a tile. The size affects the flexibility of the project, the costs for transportation and for on-site labour work, how difficult and fast it is to assemble and if the windows can be integrated or not.

The bigger sizes are faster to install on site but cost extra money and energy to transport. Also, the bigger the element the more complicated is the assemblage on-site due to the need of large machinery such as crane. The flexibility is also decreased as the size increases. In the largest elements the windows can be integrated, which for this project is indifferent since they will not be changed. With the smaller items the disturbance for the residents is more since the installation time is prolonged due to the number of pieces to mount. A smaller size of element serves better the purpose of this project, since the windows don't need to be changed and the costs for the heavy machinery and the transport can be saved.

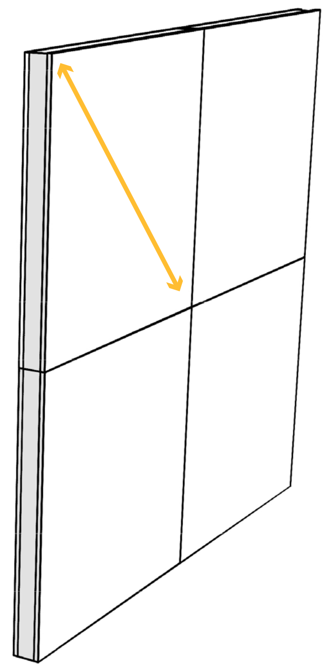


Fig. 5 Size of the panel

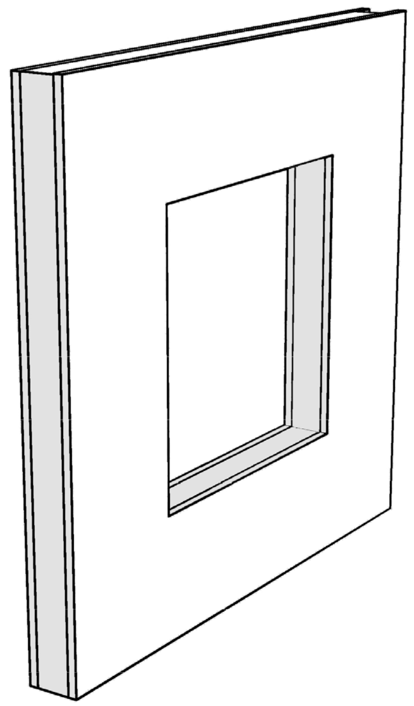


Fig. 6 Windows integrated or not.

9.5 Fixing method

Regarding connection between the prefabricated element and the existing facade there are a lot of traditional and innovative techniques which affect significantly the time of construction and the flexibility of the system (demountable or not, able to be improved in the future). In this project the massively used wooden substructure will be used. The substructure will be mounted on the facade using steel brackets and the pieces will be mounded on the wooden beams with zip clips. That way the substructure could remain in the future if the prefabricated pieces needed to be replaced. That way the pieces are put to place fast, in a secure way that allows tolerances.

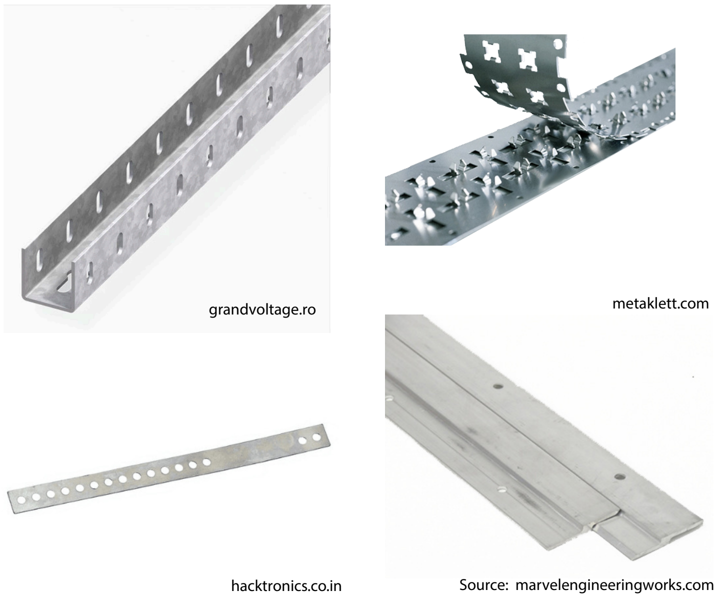


Fig. 7 different fixing methods.

9.6 Chaining method

The airtightness and weather protection of the system is dependent on the chaining method of the panels. In general a butt-to-butt is not satisfactory.

The joint between the panels could be a flush joint, a rebate or a tongue-in-groove joint. The connection of the panels is a rebate joint in this design. The chaining method affects also the edge where the insulation stops. An additional piece with the same method will be placed there to weatherproof the insulation system. this piece has to be demountable in case the insulation needs to be continued in the future.

This home contains wooden frame windows that will not be removed. A jamb extension will be installed on the exterior to accommodate the thickness of the insulating panels.

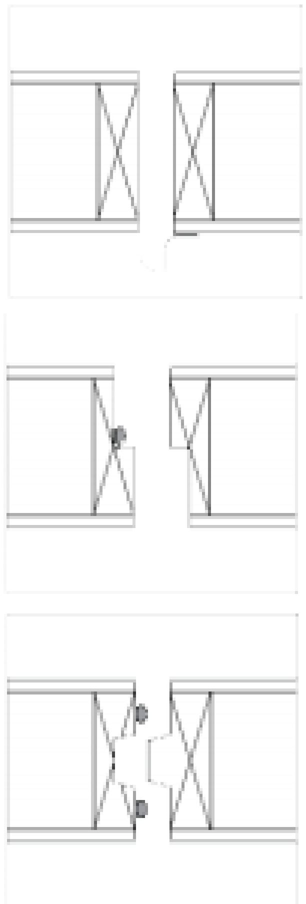


Fig. 8 Different chaining methods of the panels.

9.7 Cladding options and renders

The last search is for the cheaper, easier to apply and architecturally interesting options for the cladding of the outer layer. One option is the brick strips which is considered a cheap solution. Other option could be wood, plaster or metal. The weight of the cladding also has to be considered. Cladding is also chosen based on design preferences, context of the building and requirements (cultural heritage protection). For every cladding the strength and design of the insulation panel has to be designed accordingly.

Fig. 9 Cladding options. (Source: textures.com)

10 FINAL DESIGN

The first step after the design development is to place the wooden substructure and divide the isulated parts in panels. The panel , will come in eight different sizes to fit right. The largest size is 1.0x1.2m. The are a lot of options for the placement. In this option the panels under and above the windows are divided in two.

The panel is a sandwich panel with 50mm insulation between two 12mm MDF panels. It is covered in a reiforshment mesh, a weatherproof membrane, adhesive and as cladding brick strips. One piece of the Z-clips is placed on the substructure and its pair is bolted along the panel’s back face.

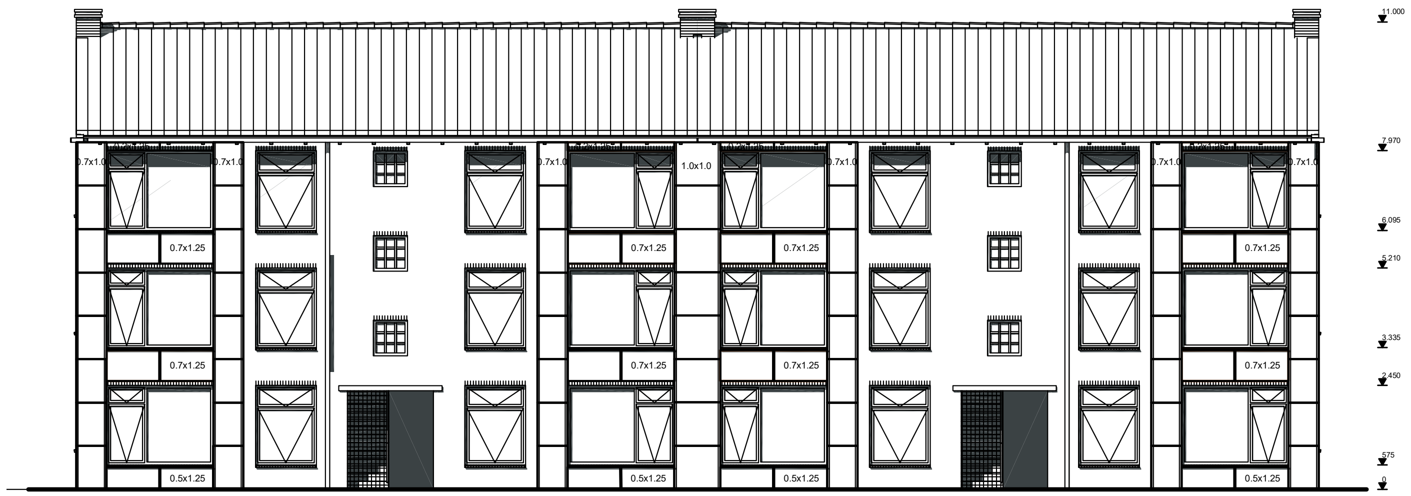


Fig. 1 The placement of the panels on the facade.

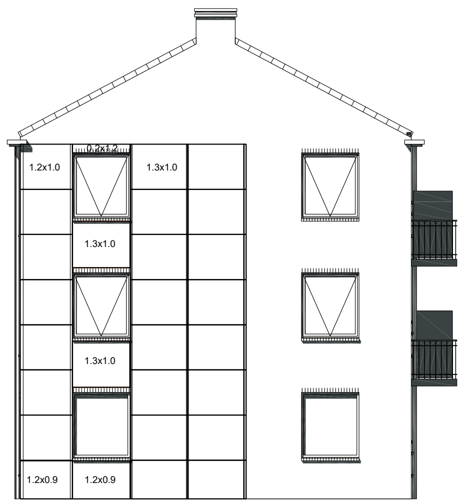
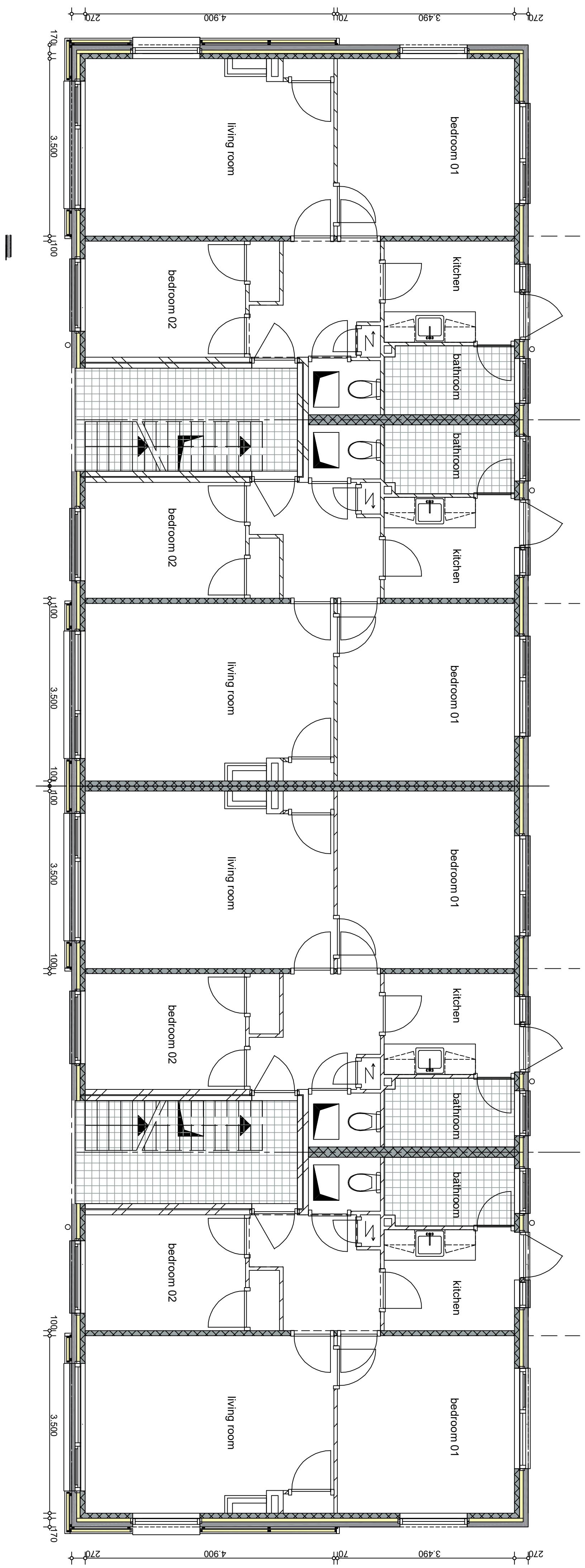
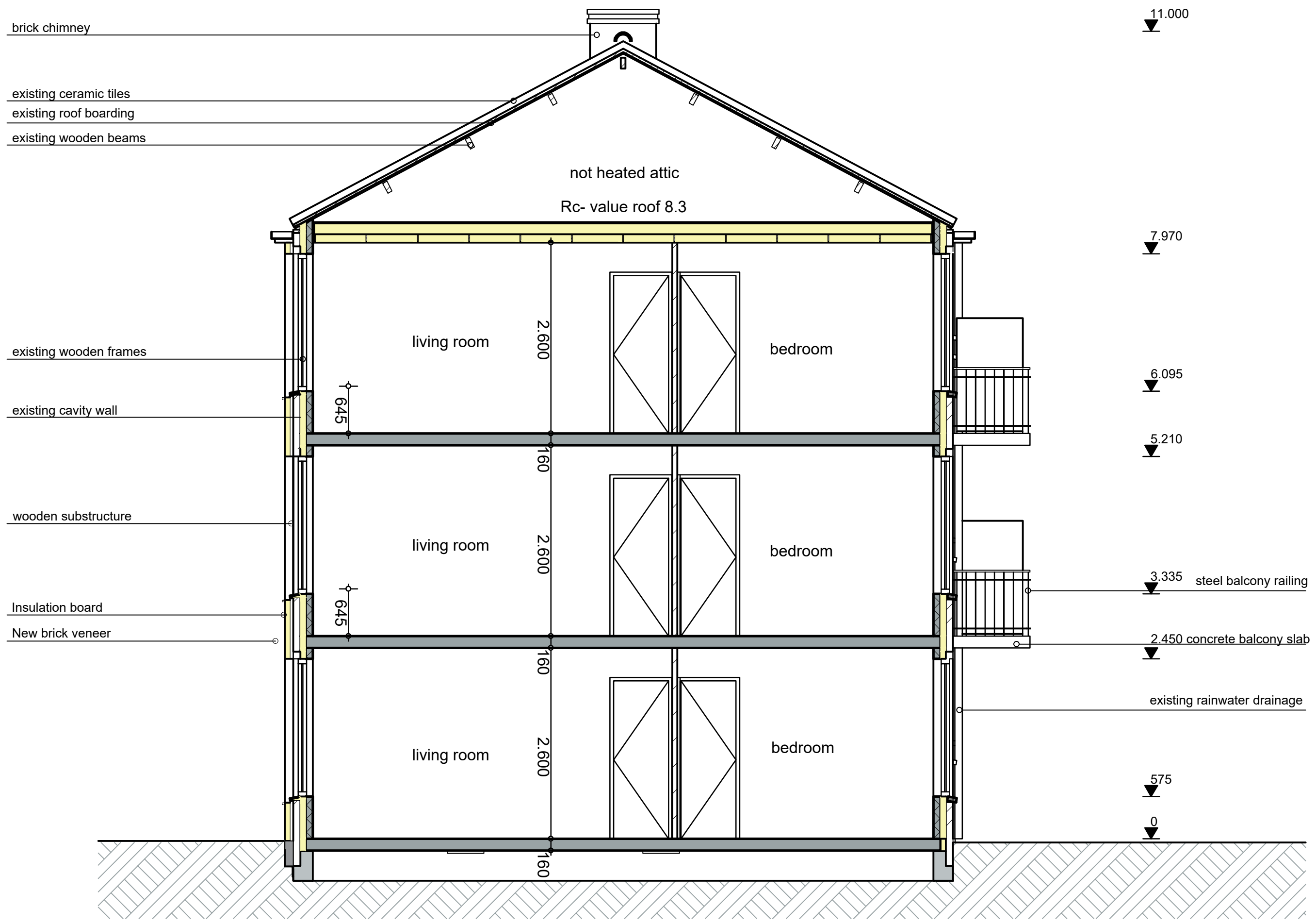


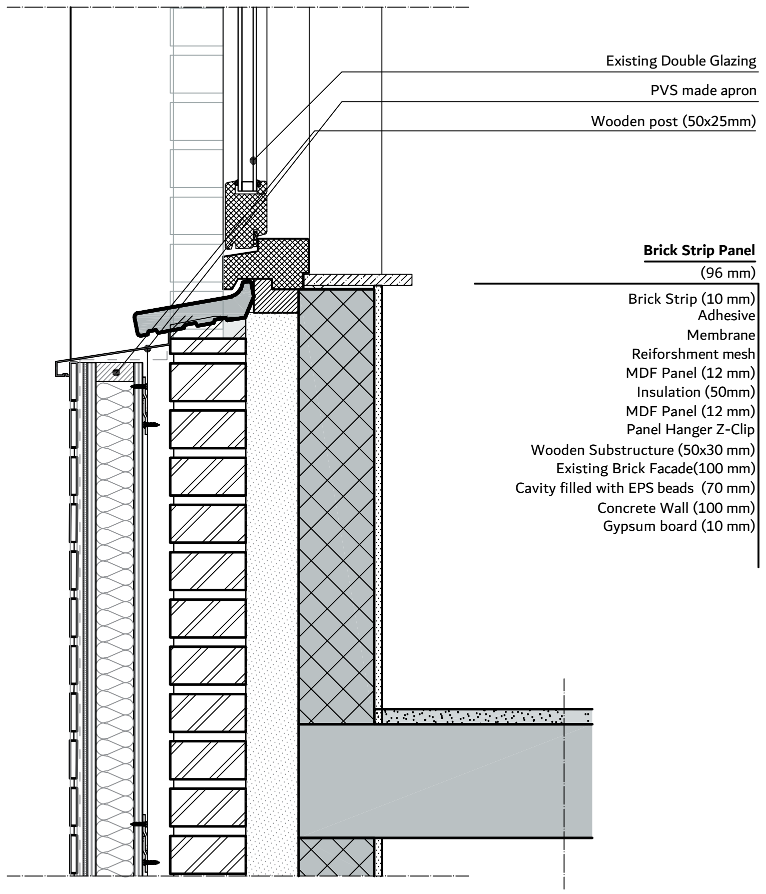
Fig. 2 3d represantation of the placement.



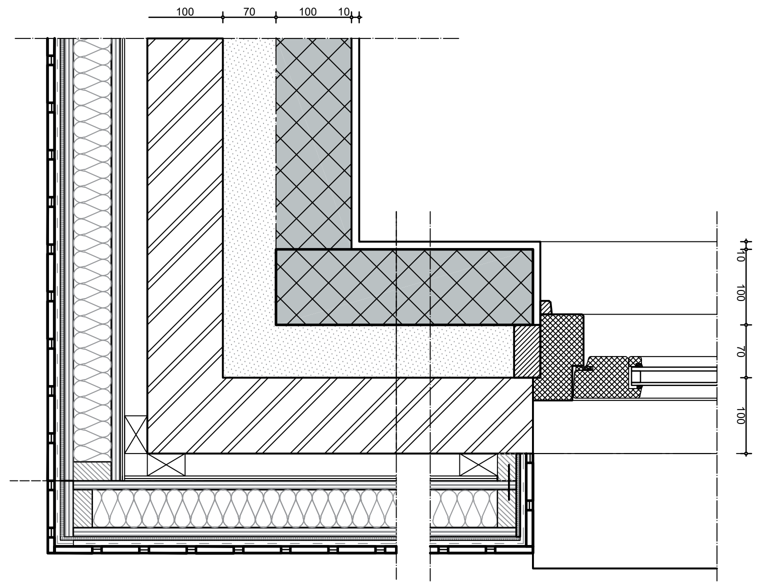
Floor Plan 1: 100



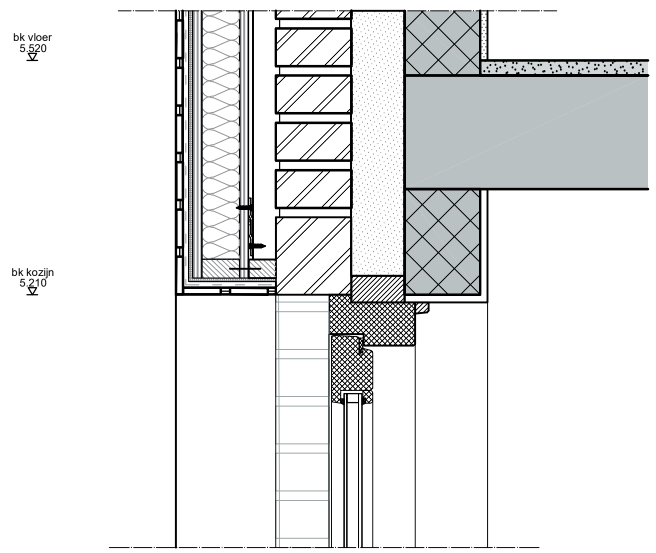
Section 1: 100



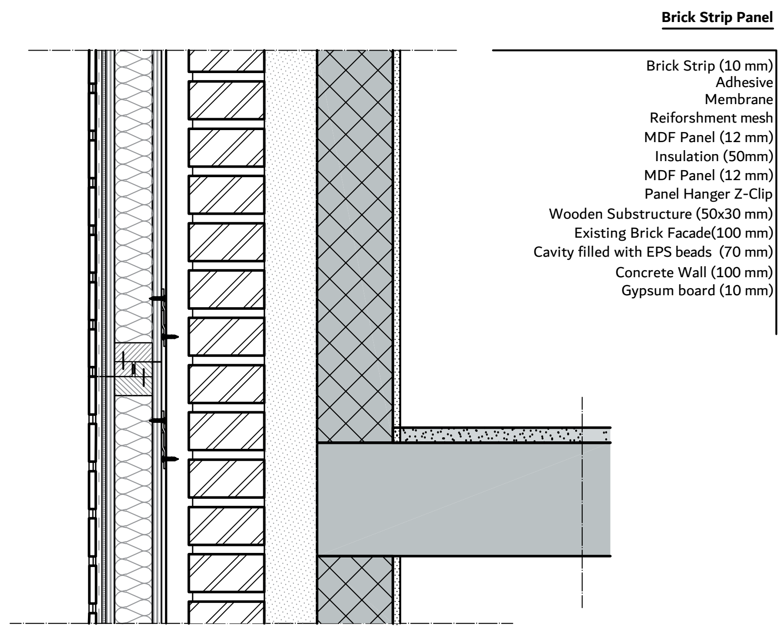
Detail 01 1: 10



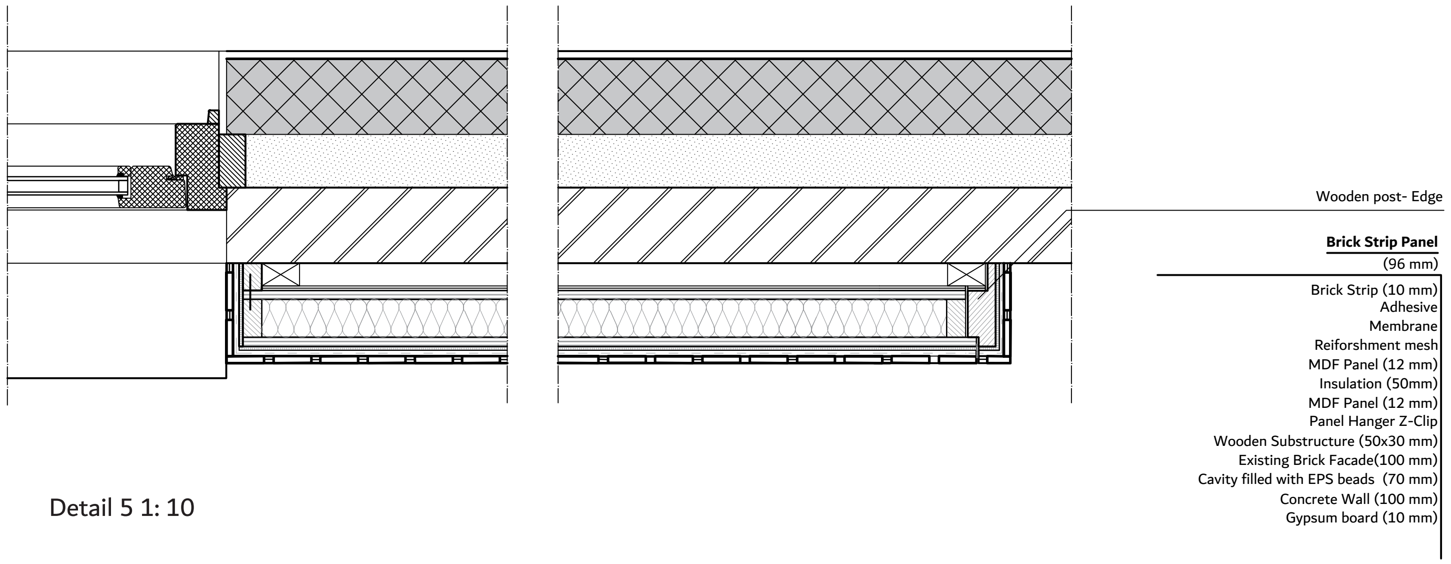
Detail 3 1: 10



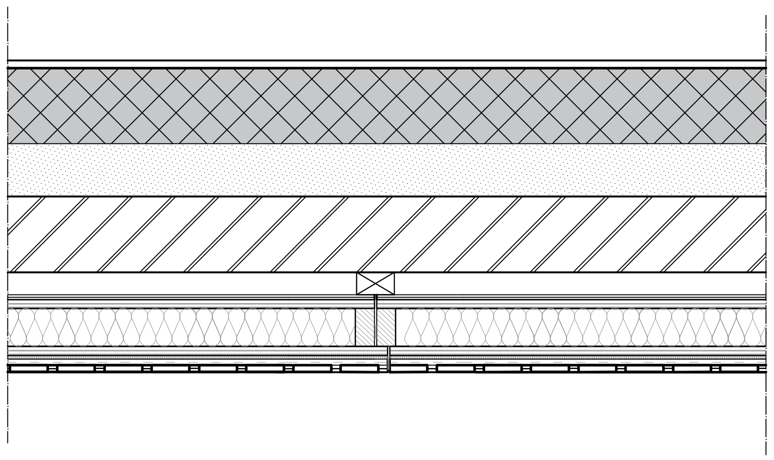
Detail 2 1: 10



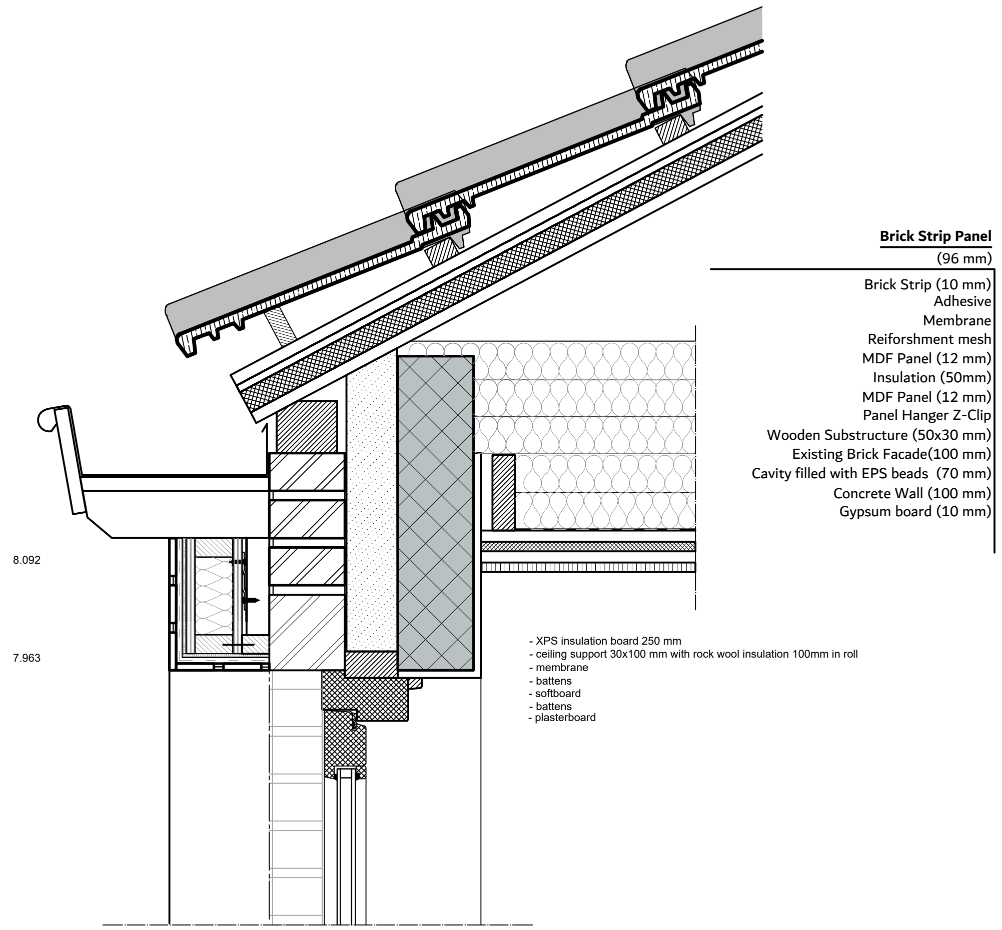
Detail 4 1: 10



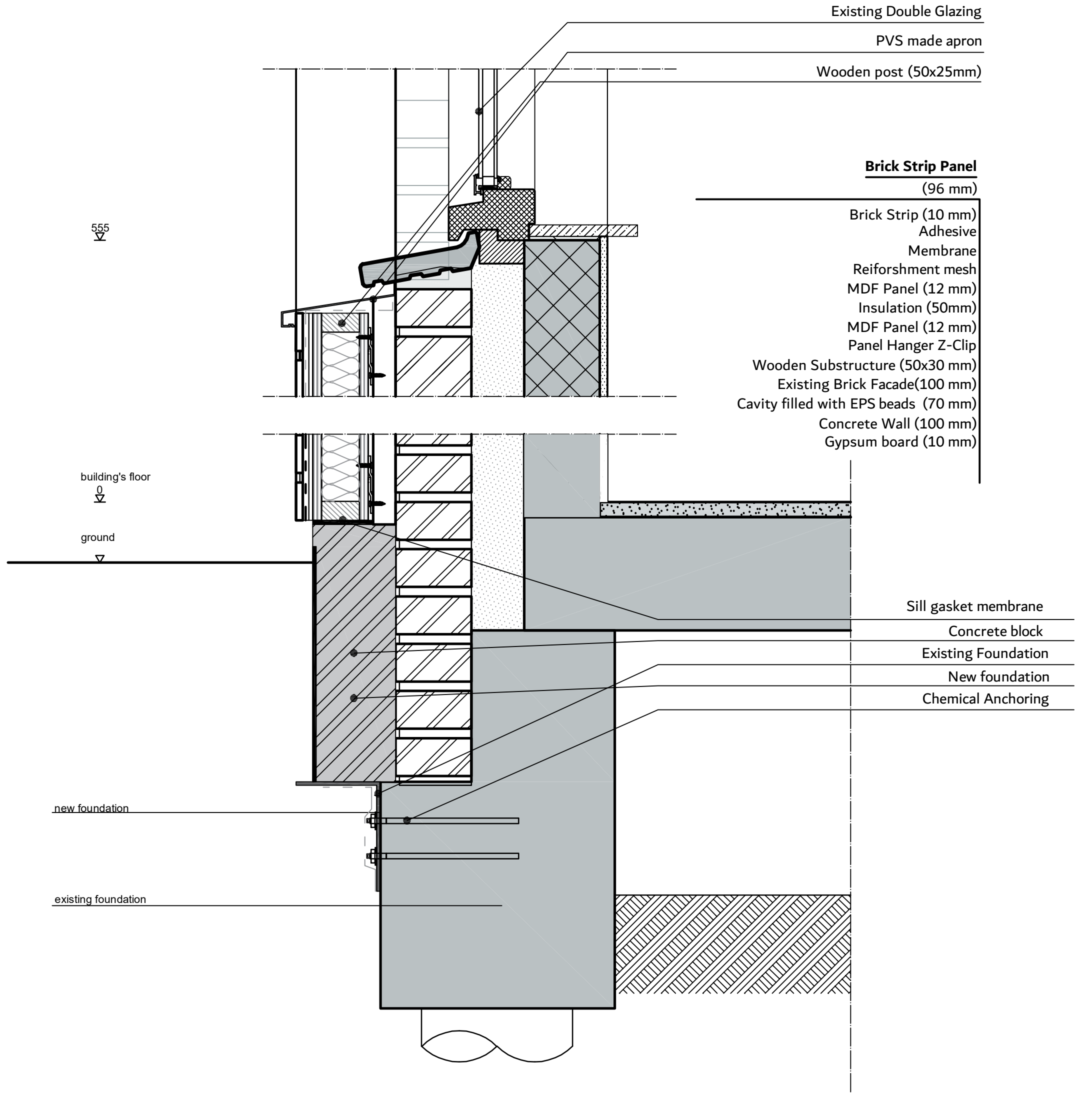
Detail 5 1: 10



Detail 6 1: 10



Detail 7 1: 10



Detail 8 1: 10

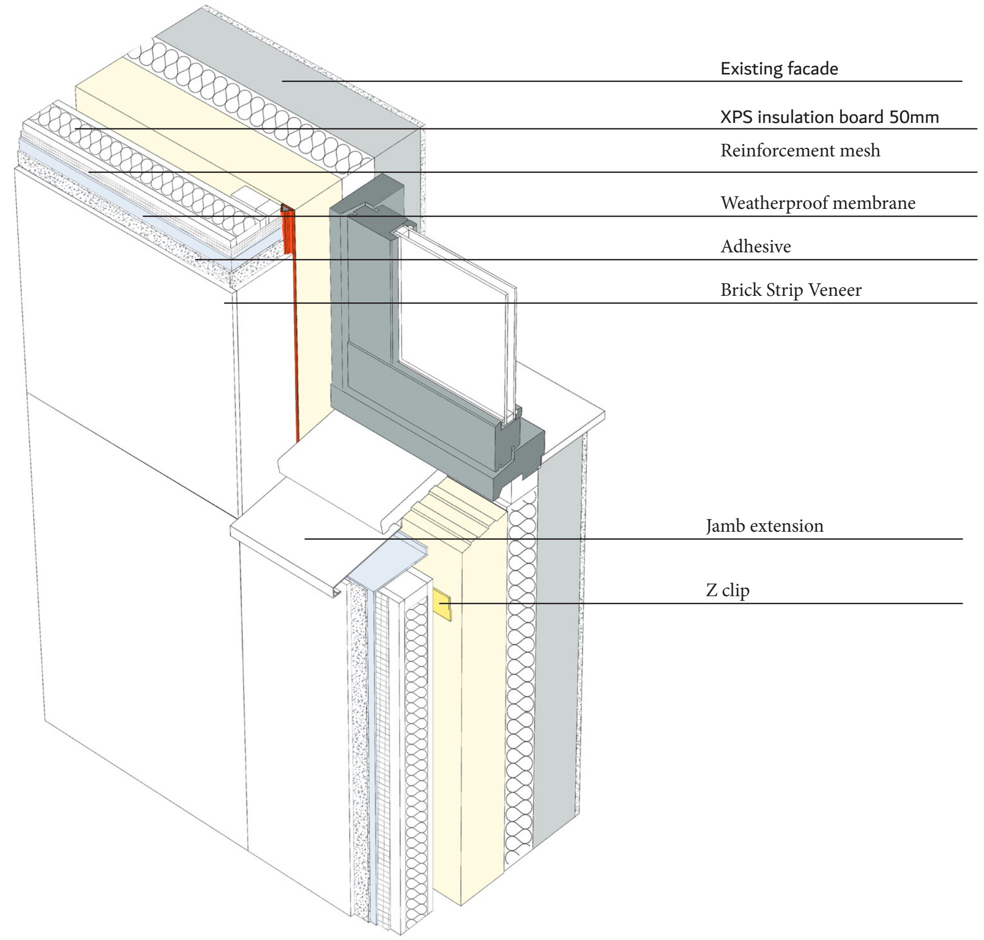
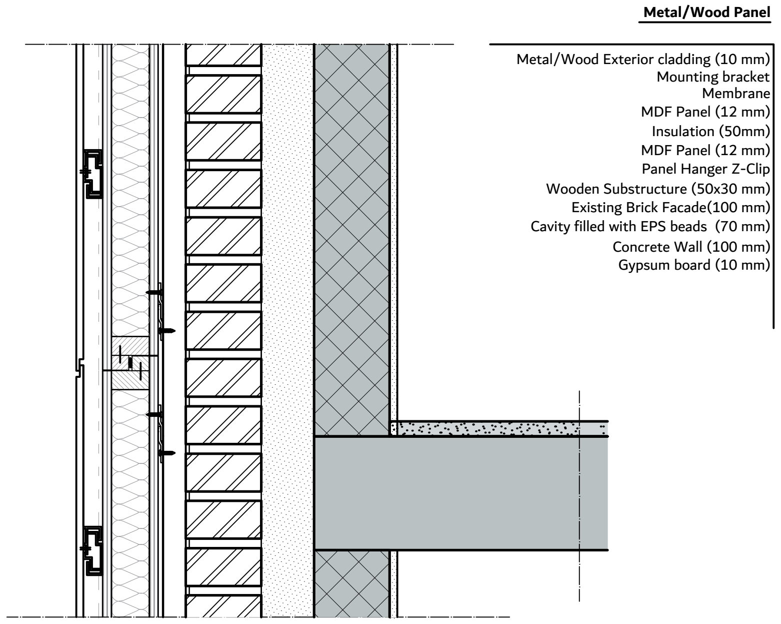
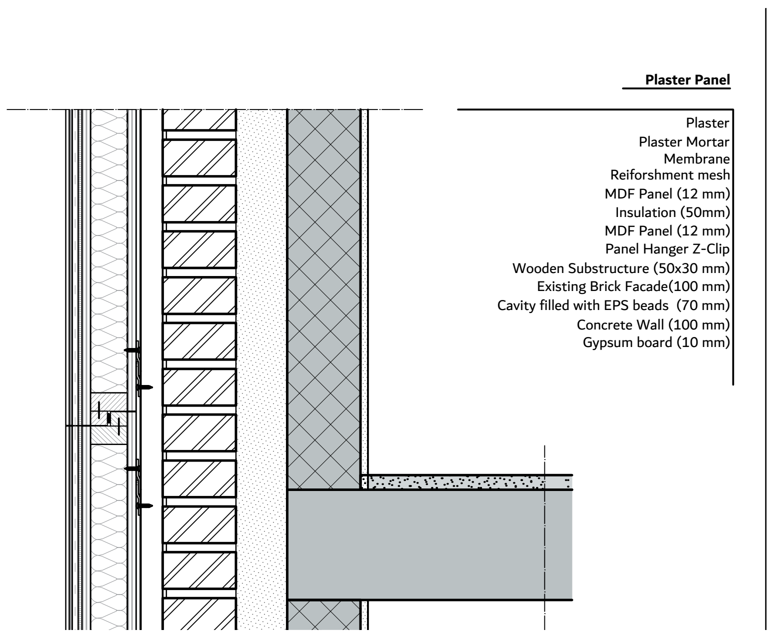


Fig. 3 3D Represantation of the solution for the window connection.

CLADDING OPTIONS

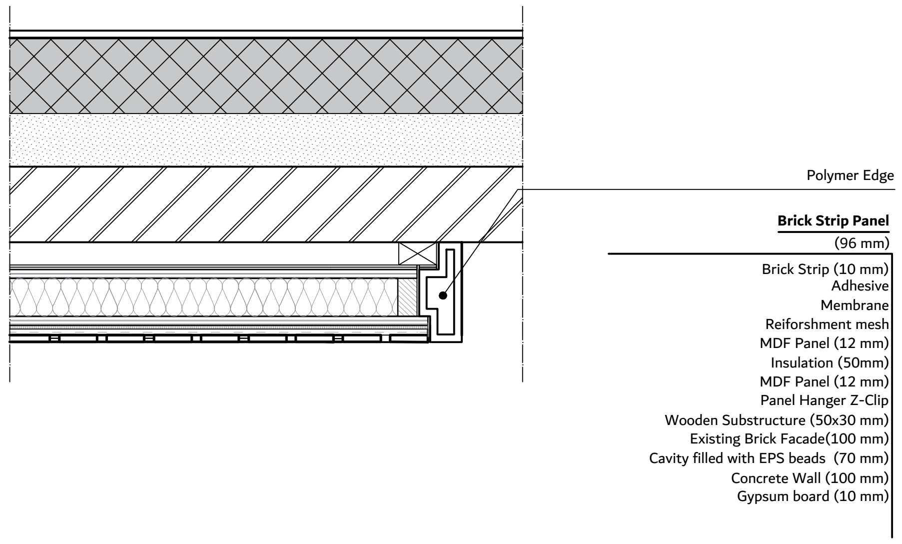


Detail 9 1: 10



Detail 10 1: 10

OPTION FOR EDGE PIECE



CONSTRUCTION SEQUENCE

The panels are assembled off site and arrive in the construction site fully prefabricated. To lower the cost assembly the amount of labour, parts and unique parts were decreased. Wood was used as a cheap and common material.

The chosen insulation, which has been defined by the calculations, is produced and moved to the panel's factory. The first step there is to assemble the wooden frame of the panel and fit the back mdf panel, in the right dimensions according to the position of the panels. The frame is then rotated and the insulation and front mdf is placed. The next step is to place the wooden parts that are needed for the connections. Then the layers according to the chosen cladding is placed. The last step is to size, cut and place the Z clips. The panels are stacked and shipped to site. The same procedure is followed to produce the edge pieces. Off-site also the wooden substructure is produced, and the z clips are placed in the right spots.

The parts that are prefabricated and produced off-site are transferred to the construction site and the rest of the work is done on-site.

DAY 1
The first job is to dig and make the new foundation if it is needed. The substructure is then mounted on the existing facade. The attic floor is insulated.

DAY 2
The cavity wall is insulated. The next step is to place the jamb extensions under the windows and fix the prefabricated insulation panels under the windows.

DAY 3
The rest of the prefabricated panels are placed, and the edge pieces are fixed on place.

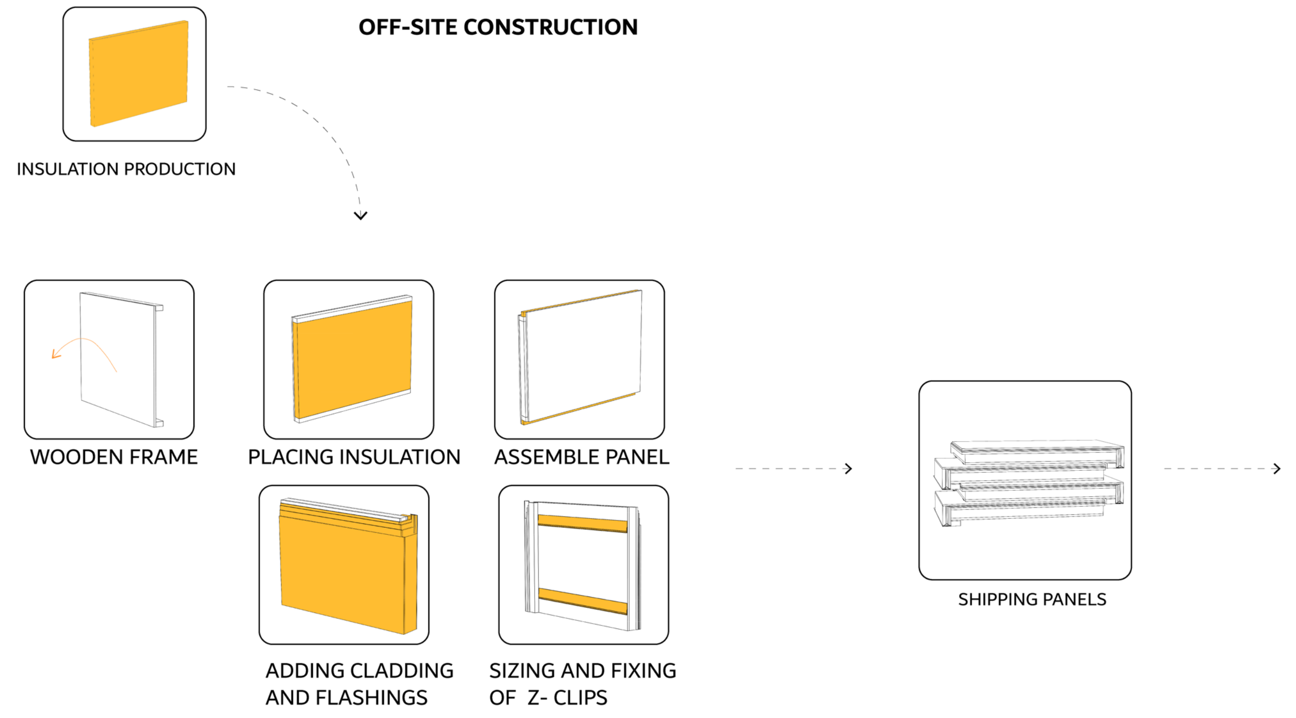


Fig. 4 Production process of the panel.

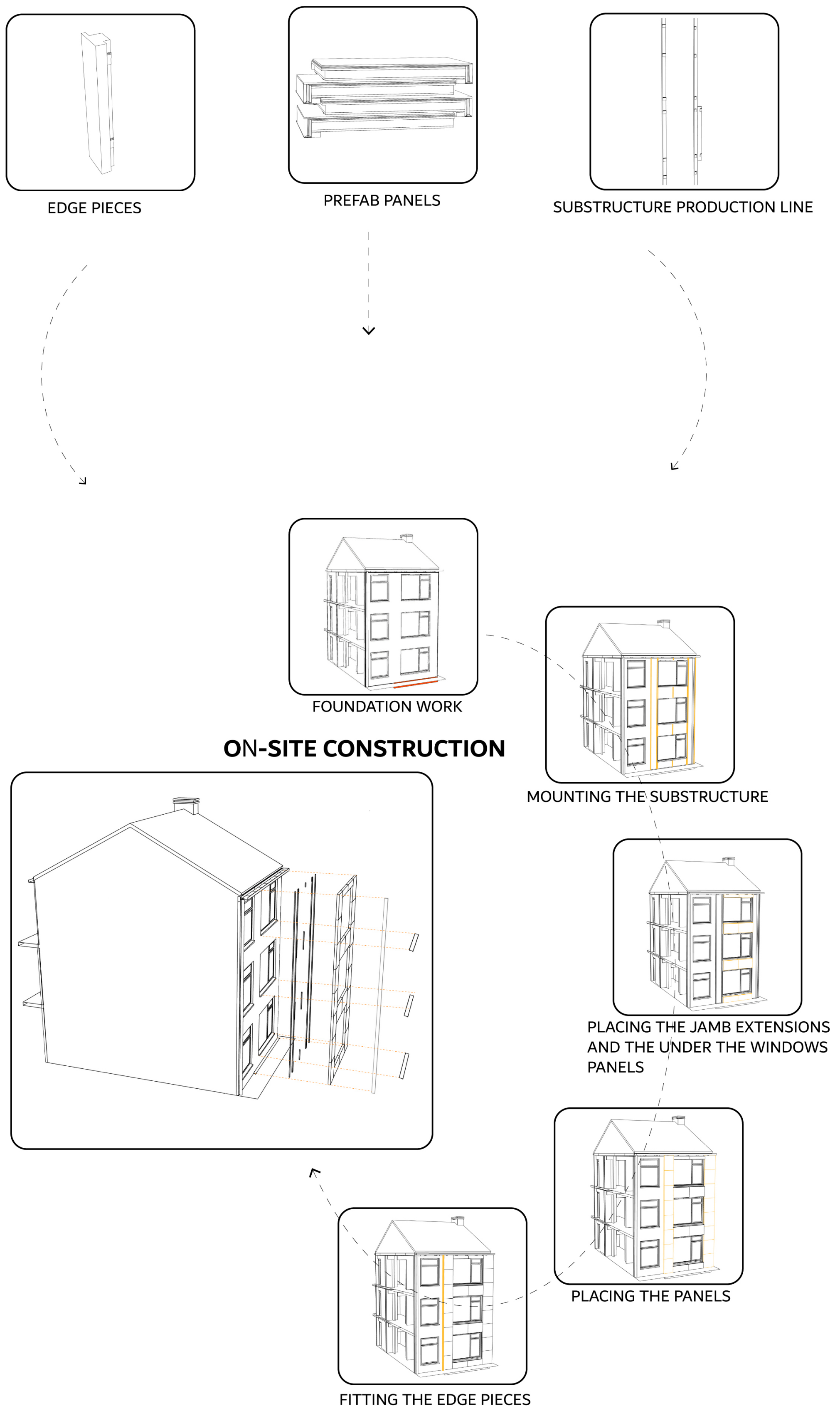


Fig. 5 Construction sequence.

Fig. 4 3d represantations of the facade with the different claddings, brick and plaster page 104, metal and wood page 105.

The next step is to establish a strategy for the application of the refurbishment method that has been developed through this study to a larger portion of the portiekapartments and based on the results for the case study, reflect on the contribution of the refurbishments to the problem in the bigger picture.

BPIE (2013) has prepared a guide to form a strategy in five key phases, which will be used as a base to form this strategy. The five steps are:

1. Identifying Key Stakeholders & Information Sources
2. Technical & Economic Appraisal
3. Policy Appraisal
4. Drafting & Consulting on the Renovation Strategy
5. Publication & Delivery

In step 1 the strategy must engage building owners and the investment community. Step 2 includes the identification of the building stocks characteristics, economic appraisal of renovation potential, identification of energy and non-energy benefits. This step is the result of this study. Step 3 includes the comprehensive appraisal of barriers and the assessment of range of policy measures that affect this strategy. Step 4 is a draft refurbishment strategy and improving based on feedback and step 5 is the publication of the final strategy for the building stock.

After the completion of the strategy it is assumed that the refurbishment method is applied to half of the 380000 portiekapartments in the Netherlands, so 190000 buildings, based on the lower energy scenario, which means maintaining the existing windows, insulating the cavity and up to 35% of the facade.

In a very simple manner that would mean energy-wise that a reduction of energy consumption up to 50% and of heating demand up to 62%, with all these buildings heated with a medium temperature heating and disconnecting from the gas reducing the CO_2 emissions. Cost wise, assuming that otherwise the buildings' facades would have been 100% insulated and that the buildings are similar to the case study in size, an investment cost of 37100€ corresponds to each building rather than 67570€, with savings of 30470€/ building and 5.789.300.000€ cumulatively.

There is another factor which is the cost reductions that can be achieved through scaling up activity levels. Costs can vary depending on whether measures are installed individually or as a package, and whether improvements are being undertaken at the same time as maintenance, repair or building upgrade/modernisation (BPIE, 2011).

Regarding the CO_2 emissions savings, the embodied CO_2 is already reduced by 65% since only 35% of the facade required to insulate the facade is being used. As for the Operations-related CO_2 emissions savings, one apartment saves per year 6221 kWh, 74652 kWh per building per year which is equal to 21132 $kgCO_2e$ saved. Multiplied with 190000 equals 4.08 megatons CO_2 emissions saved per year. This amount is equal to 850.393 passenger vehicles driven for one year or one coal-fired power plant CO_2 emissions in one year.

Fig Building stock. (BPIE, 2013)

The impact of different renovation pathways on the resulting energy and carbon savings was modelled by BPIE in its 2011 publication "Europe's buildings under the microscope". This showed that only in those scenarios where both the rate and the depth of renovation were substantially increased, alongside rapid decarbonisation of the energy supply system, could the carbon saving ambition for the building sector set out in the Commission's 2050 Low Carbon Economy Roadmap be achieved. (BPIE, 2013)

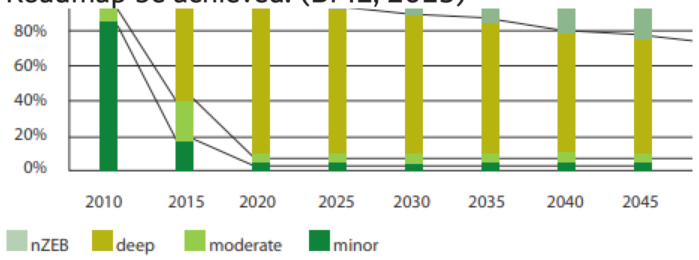


Fig. 1 Required increase in renovation depth to achieve 90% CO2 saving. (Source: BPIE ,2011)

The refurbishment strategy of this study would be considered moderate. Combined with a medium rate of growth forms scenario 2- medium in the BPIE publication. This scenario results in 48% of energy saved and 53-84% of CO_2 saved by 2050.

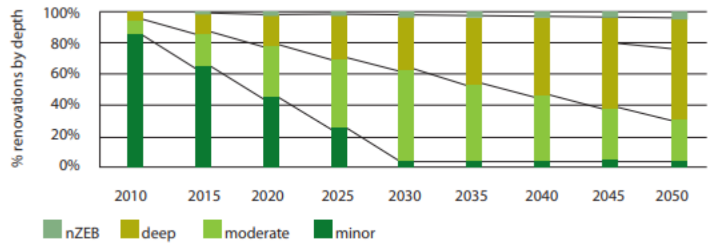


Fig. 2 Intermidiate renovation path (Source: BPIE ,2011)

However it could be part of a fourth renovation path depicts the case in which some properties are renovated twice, though with different measures. Properties that undergo minor or moderate renovation between 2011 and 2030, are then upgraded 20 years later, to deep and nZEB standards respectively. These second round of renovations occur in addition to first time renovations, which follow the Medium scenario. This scenario leads to 71% energy saved and 73-91% CO_2 saved by 2050.

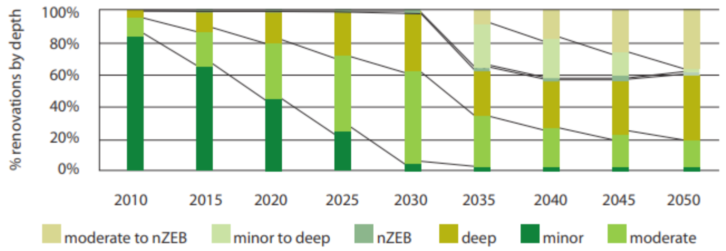


Fig. 3 Two-stage renovation path (Source: BPIE ,2011)

While both the deep and the two-stage scenario achieve broadly the same level of CO2 reduction, the deep scenario requires a significantly higher absolute investment level. In return, it also generates higher energy cost savings; however, the net savings are smaller than in the two-stage scenario. The high investment needs of the deep scenario are caused by a fast increase in deep renovation measures in the first decade.

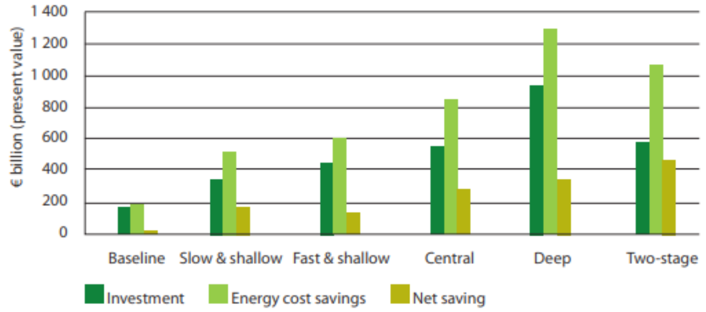


Fig. 4 Lifetime financial impact for consumers (present value) (Source: BPIE ,2011)

12 CONCLUSION

12.1 Discussion

There are two main points of discussion. The first is about the method followed of obtaining and presenting the results for a multi variable optimization. The second is the applicability of the design.

A facade design is a complex task with many variables to be considered and a lot of conflicting objectives. In this research, objectives that are related to the facade design such as shading, daylight distribution are not taken into account due to the nature of the research and the limitation of costs. However, still there were many possibilities to be explored, and although the results are not surprising, a small change in the variables in some cases- such as changing the material of the insulation, could make the difference in achieving low temperature heating or not. All the options could not be simulated manually. That lead to 1512 combinations that had to be presented in one graph. Design explorer offers the possibility to view the results in a very straightforward and easy way and the main advantage is that all the options are displayed at once and it is very easy to compare two cases. However, the disadvantage is that whatever is displayed has to be the result of the parametric simulation and needs to be done in a way to be a numerical value. It is not possible, due to the way the outputs are organized to add- in my case the cost. A lot of extra time and work is then needed. A second disadvantage is that it is a 2d display, which means that there is no possibility to view the relation between two variables and the result.

The second point of discussion is the applicability of the design. Should it be a step in the right direction to achieve intermediate goals or is it a permanent solution. As stated in the beginning of the research there is not enough funding to make all the buildings zero energy. It already achieves an energy reduction of up to 60% and saves costs, but for the remaining 40% it has to rely on external sources. It is important that the remaining energy is produced in a sustainable manner. Most renovation activity at the moment achieves only modest energy savings, perhaps 20-30%, but this needs to increase to deep renovations of at least 60% if the full economic potential is to be realised (BPIE, 2013). Meaning that it is an alternative option in cases of limited funding but the option to continue to zero energy must be given, if needed.

12.2 Limitations

The limitations of the research are listed below:

- The most important limitation in this study is the lack of information regarding the costs. It was not possible to find detailed cost assessments online or in any reference text. Especially for the costs regarding the different parts of the facade application. Assumptions had to be made in order for the study to progress.
- There was a lack of information for the original form of the case study, such as the radiators installed, the cavity's condition, if there is already insulation in the crawl space, the ventilation system.
- Time is also a limitation in such optimization process with a lot of iterations. There needs to be a very good preliminary analysis and good planning of the variables to be able to make a safe conclusion. Still even with 1512 iterations there are a lot of variables not tested and options that are left out.
- In the process of the study simplifications were made such as the orientation and plan layout of the case study were taken as a fixed parameter for all iterations. Also the context of the case study was not taken into consideration.
- Also, the need to have a functional cavity and at least double glazing is also a limitation of the research.
- The behaviour of the users has not been taken into consideration in any part of the study.

12.3 Recommendations

There is still room for improvement as already stated and recommendations for further research and development.

The circularity of the design is one point. The whole insulation system and especially the panel and the chaining method could be made demountable. It is important in order to be upgradable in the future or reused on another building. However, since this is an exterior application and needs to be weatherproof, it becomes a difficult task.

The embodied energy of the materials and their impact on the environment. In the literature study, the insulation materials were also described regarding to their environmental impact briefly, however in order to obtain satisfactory results that aspect was not further developed.

More research on the edges of the panel, where the insulation stops and to the connection on the windows to ensure that it is futureproof.

Investigation on how the design works with different energy systems.

Extra research on the buildings services and especially the ventilation system. As of now it was simplified to natural ventilation with mechanical exhaust where needed, and the rates where taken as the ones proposed by the Dutch low. However, it is a simplification because it was not researched if the existing windows and installed grills of the case study can provide that.

The advantages and disadvantages of mass application, in terms of costs and energy in more detail with actual facts. It is already a focal point of this study to be up-scalable and the design to be able to be adapted to other buildings easily and a rough estimation has been made. However, it is a learning curve and it needs further development. The more it would be applied, the cheaper and easier it would get.

12.4 Conclusion

After the simulations and the development of the technical solution the research question

"Which design strategy is needed in order to achieve a faster, economically feasible and LT-ready refurbishment for post-war portiek apartments?"

can be answered.

For the case study, the strategy is:

Maintain the existing windows with double glazing and wooden frames.

Maintain the building's services and radiators.

Insulate the attic floor.

Fill the cavity with insulation material.

Insulate 32% of the facade externally with an Rc-value of 3.5 m2K/W, to the parts where it is needed (living room walls) so that heating 55 degrees can be done and disconnect from the gas.

Insulate externally with small size fully prefabricated sandwich panels, with the cladding and the connections to the windows integrated. To place them use zip-clips.

The study's goal is to answer to the problem of limited funding and practical reasons that prevent a large number of refurbishments. The parametric simulations in Grasshoper proved that for a large portion of the portiekapartments heating can be done with 55 degrees by insulating parts of the facade. To reach lower temperature heating in buildings with window to wall ratio below 60% there is the need to replace the windows which keeps the costs very low. For higher window to wall ratios the window have to be changed or thicker insulation applied. Most of the times if there is the funding for triple glazing, there would be the funding also to insulate airtightly. However, if the goal is to reach LT-ready there is the advantage of saving the materials, which also has environmental impact.

The annual total energy demand is reduced by 46% and the heating demand by 62%. The result is an insulation strategy that will cost 62€/m^2 for the facade insulation. Compared to the lowest price found from literature study of 100€/ m2 for exterior insulation (without cavity insulation), it is almost half saved.

The construction and application of the exterior facade was kept as fast and cost-efficient as possible, avoiding complicated solutions. The easiest and possibly cheapest way to apply the insulation would be completely on- site with the traditional way. However, this project is meant to be scalable and as less disturbing to the tenants as possible. In order to be able to be applied in a large amount of buildings in the future, prefabrication for the facade element is chosen. By adding the demountable edge piece the insulation could be continued in the future.

The opportunities of the project is that there are multiple insulation options reaching up to a Rc-value of 7.2 m2K/W. Depending on the needs and wishes of the corporation or individual client the choice can be done for a cheaper or more energy efficient solution. The step by step approach can give the opportunity to the owners to gather funding and continue with the refurbishment while already having lowered the energy use and disconnected from the gas. As mentioned already, less material is used in the process.

Possible barriers might be the legislation in some regions that will not allow for this partially insulated method. Also, the investment although lowered there is still the need of funding, even if decreased.

Finally, the architectural side of the design is of importance. A challenge is to make it aesthetically pleasing with different claddings and optimal placement of the panels. The solution has to look good in order to be accepted by the residents of the buildings.

13 RELEVANCE AND REFLECTION

Relevance to the master track and programme

The graduation topic is very relevant to the master track Building technology since, the first aim is reducing the energy demand which is a sustainability issue, combined with climate and facade design. Knowledge taught and acquired during the master's courses, in energy transition, building physics, climate and façade design, are all needed and put in use. In my opinion, the theme is in tune with the overall direction of the track, to investigate new ways (even small changes) of doing with proper validation and with sustainability always in mind. A proof is the increasing number of papers and projects relative to energy efficient refurbishment the last years. As of the master programme MSc AUBS, the project is of great importance for the building environment and architecture as it is an energy refurbishment which aims to balance energy efficient and costs, but at the same time reach an aesthetically pleasing result suitable in the Dutch building context.

Relevance to society

The financial motives of the project are very important. An energy efficient refurbishment leads to reduced energy bills and the calculation of the payback time is easily calculated. As this project aims in a cheaper refurbishment solution the payback time will be, also, shorter. The refurbishment is going to also repair some of the physical problems of the old envelope and upgrade its performance and appearance. The aging houses are less attractive socially and their economic value is steadily decreasing. Thus, the refurbishment will increase the property's value. As scalable cheaper refurbishment strategy, it could become part of a plan in order to increase the value of other properties, the rent prices or even the gentrification and upgrade of now not so attractive areas. Thus, the refurbishment project is also relevant in the social framework. If successful it could be used in many apartment blocks to reform problematic areas and their socio-economic group of renters. Along with better housing for the residents, the renewed image of a sustainable building or neighbourhood adds value to the context. The social benefits include also the employment opportunities in the residential sector through the refurbishment market development. Last but not least, as the starting point of this project, the Co2 reduction and energy savings are a direct benefit for the society.

Reflection

The project is a research by design to create a fast and economically feasible refurbishment strategy, that potentially could be applied to many buildings. The relationship between research and design is translated as a constant flow of using alternately the information found through literature study and created by the simulations and the designing process (initially the concepts and then a less costly and complicated facade element design).

So far in the process, I have made and accepted logical assumptions either to serve the purpose of the project or because of lack of information, for example for the case study building. The innovative insulation process is an assumption based on building physics rules and by following the methodology and with dynamic simulations I try to understand if the assumption could prove correct. That was a process of trial and error. In that process I have already found two obstacles in this research approach. The first one is the lack or difficulty to find information online regarding the costs of the facade elements. There is the same, repetitive information about the general prices but not in depth and in detail as my project needs to validate the final product. Thus, after discussing with my main mentor, the cost evaluation of the facade element will not be done with providing an exact number but as a discussion in a more general level. The second difficulty has to do with the limitations of the simulation program design builder, and the lack of knowledge on some pre- defined by the program options, which needed to be clarified. That was solved by contacting the Design Builder Help, that answered to my questions and by trying different options and comparing the results.

The project's aim is to be feasible and applicable in real life, keeping it not expensive and complicated. The strategy for the refurbishment of the facade, following the traditional ways of insulating or the proposed prefabricated solution, is applicable easily. The changing to low or medium temperature heating is the part, that although proved to be working, still needs to be tested and thought thoroughly. So far, the innovation process seems to be efficient and the project contributes to the sustainable development.

Ethical issues

Regarding the ethical issues or dilemma's, every decision and step has been made based on my current state of knowledge and arguments but has consequences and possibly it could have been done in a better way. Ideally as architects we opt for no regret design, but the solution might prove obsolete in a few years. And that is a price paid when there are steps taken in the process that are innovative and have not been tested in the past. For example, this is categorized as a moderate refurbishment and it might be proven in the future that is not enough to reach the energy goals of EU in 2050. A second point is the issue of providing less comfort in return for lower environmental impact. This is a very important point in this project as it is a search for balance between making the solution feasible economically while decreasing the energy use but also not compromise on the residents comfort (a couple of examples: making the refurbishment less disturbing for them, keep the indoor temperature and ventilation rates in normal levels). Also, in the facade element design, in order to reach the Rc- value, I chose materials that have the properties needed but a bigger environmental impact. Using the insulation material itself is harmful for the environment because it costs raw materials and energy to produce, energy to transport, install and process it after demolition. But it is used because the energy required will be earned back in months or a couple of years by the energy saved. So, the fact that the building is insulated in such a way with the right material that is applied properly to achieve the goals is more important than choosing a less sustainable material.

APPENDIX A

FACADE AREA

DESCRIPTION	m^2
WEST/ EAST FACADES WALL + WINDOWS	85,69
WINDOW [1] : (1,325*1,495=1,981m2)*6 windows/facade	11,89
WALLS	73,8
SOUTH FAÇADE WALL + WINDOWS (NO ENTRANCES)	229,72
WINDOWS:	
[2] (2,515*1,875= 4,7156 m2)* 12	56,58
[3] (1,430*1,875= 2,681 m2)* 12	32,18
[8] (0,800*0,835= 0,668M2)*4	2,67
WINDOWS TOTAL	91,43
WALLS	138,29
NORTH FAÇADE WALL + WINDOWS, DOORS	239,13
WINDOWS:	
[4] (1,977*1,875= 3,706)*12	44,48
[5] (0.551*1,352= 0,745)*12	8,94
[7] (0,884*1,095= 0,968)*12	11,61
(2,449*0,942= 2,306)*12	27,68
WINDOWS TOTAL	92,71
WALLS	146,42

WALLS TOTAL	432,31
WINDOWS TOTAL	207,92
FAÇADE TOTAL	**640,23**
PITCHED ROOF (29,22*5,153=150,57*2)	301,14
FLAT ROOF/ ATTIC FLOOR (29,22*9)	262,98

STEADY STATE CALCULATION EXAMPLE

Steady state heat balance calculation — cavity wall insulation

Steps		Input	Results	
1	Living room			
2	Area		**17,20** m^2	
3	Volume		**45** m^3	
	Height of floor	**2,6** m		
4	Inside and outside temperature			
	Tinside =	**20** °C		
	Toutside =	**-10** °C		
5	Transmission Losses			
	Surface of closed parts of the building skin			
	Aclosed =	**18,5** m^2		
	U-value of closed parts of the building skin			
	Uclosed =	**0,6** W/m^2K		
	Surface of windows (glass and frame)			
	Awindow =	**6,7** m^2		
	U-value of window			
	U_{window} =	**2,6** W/m^2K		
	Transmission losses = (A_{closed} * U_{closed} + A_{window} * Uwindo		**856** W	**50** W/m^2
6	Ventilation losses			
	Ventilation air change rate			Bouwbesluit
	n =	**1**	**45** m^3/h	**0,7** dm^3/sm^2
			0,012 m^3/s	
	Ventilation losses= (n*V/3)*(Tin- Tout)		**447** W	
	Infiltration			
	n =	**0,3**		
	Infiltration= n_{inf}*V/3*(Tin-Tout)		**134**	
7	Total heat losses		**1437** W	**84** W/m^2
	Heating surcharge for night or weekend reduction + 20%		**1724** W	
	Heat loss to the neighbors			
	According to design builder		**1465** W	

Bedragen in euro's

Omschrijving	Aantal	1h	Kop	Norm	Loon/1h	Materiaal/1h	Materieel/1h	Oa/1h	Prijs/1h		Uren	Loon	Materiaal	Materieel	Oa	Bedrag
BUITENWANDEN																
BUITENWANDEN	**0,00**															
Totaal	**0,00**															
GEÏSOLEERD GEVELPANEEL [RC 1,38] MET VOORGEMONTEERDE STEENSTRIPS	**432,00**	**m2**														
platvolle voeg 20-50m2	432,00	m2	1,00					13,00	13,00						5.616,00	5.616,00
pur geïsoleerd gevelpaneel [Rc 1,38] met voorgemonteerde steenstrips	432,00	m2	1,00	0,400		88,70			88,70	172,80	172,80		38.318,40			38.318,40
gevelhoek 85/200 incl. steenstrips plakken	283,82	m1	0,66	0,400		40,00			40,00	113,53	113,53		11.352,96			11.352,96
aluminium startprofiel	49,66	m1	0,11	0,025		17,00			17,00	1,24	1,24		844,14			844,14
Totaal	**432,00**	**m2**		**0,666**		**116,93**		**13,00**	**129,93**	**287,57**	**287,57**		**50.515,50**		**5.616,00**	**56.131,50**
geïsoleerd gevelpaneel [Rc 1,38] met voorgemonteerde steenstrips	**213,00**	**m2**														
platvolle voeg 20-50m2	213,00	m2	1,00					13,00	13,00						2.769,00	2.769,00
pur geïsoleerd gevelpaneel [Rc 1,38] met voorgemonteerde steenstrips	213,00	m2	1,00	0,400		88,70			88,70	85,20	85,20		18.893,10			18.893,10
gevelhoek 85/200 incl. steenstrips plakken	139,94	m1	0,66	0,400		40,00			40,00	55,98	55,98		5.597,64			5.597,64
aluminium startprofiel	24,48	m1	0,11	0,025		17,00			17,00	0,61	0,61		416,21			416,21
Totaal	**213,00**	**m2**		**0,666**		**116,93**		**13,00**	**129,93**	**141,79**	**141,79**		**24.906,95**		**2.769,00**	**27.675,95**
geïsoleerd gevelpaneel [Rc 1,38] met voorgemonteerde steenstrips	**138,00**	**m2**														
platvolle voeg 20-50m2	138,00	m2	1,00					13,00	13,00						1.794,00	1.794,00
pur geïsoleerd gevelpaneel [Rc 1,38] met voorgemonteerde steenstrips	138,00	m2	1,00	0,400		88,70			88,70	55,20	55,20		12.240,60			12.240,60
gevelhoek 85/200 incl. steenstrips plakken	90,67	m1	0,66	0,400		40,00			40,00	36,27	36,27		3.626,64			3.626,64
aluminium startprofiel	15,86	m1	0,11	0,025		17,00			17,00	0,40	0,40		269,66			269,66
Totaal	**138,00**	**m2**		**0,666**		**116,93**		**13,00**	**129,93**	**91,86**	**91,86**		**16.136,90**		**1.794,00**	**17.930,90**
TOTAAL BUITENWANDEN										**521,22**	**521,22**		**91.559,35**		**10.179,00**	**101.738,35**
BUITENWANDOPENINGEN																
HR++ beglazing 6-6	**207,00**	**m2**														
HR++ beglazing 6-6, gas gevuld [HR coating]	207,00	m2	1,00	1,200		75,08			75,08	248,40	248,40		15.541,56			15.541,56
meranti glaslat 15x17mm, GL5	0,00	m1		0,080		1,30			1,30							
meranti ventilatie glaslat 17x25,5mm, GLV1	0,00	m1		0,080		2,98			2,98							
Totaal	**207,00**	**m2**		**1,200**		**75,08**			**75,08**	**248,40**	**248,40**		**15.541,56**			**15.541,56**
HR++ beglazing 6-4-6	**207,00**	**m2**														
HR++ beglazing 6-4-6, gas gevuld [HR coating]	207,00	m2	1,00	1,200		153,73			153,73	248,40	248,40		31.822,11			31.822,11
meranti glaslat 15x17mm, GL5	0,00	m1		0,080		1,30			1,30							
meranti ventilatie glaslat 17x25,5mm, GLV1	0,00	m1		0,080		2,98			2,98							
Totaal	**207,00**	**m2**		**1,200**		**153,73**			**153,73**	**248,40**	**248,40**		**31.822,11**			**31.822,11**
aluminium kozijn merk A2, draairaam, buitendraaiend incl. standaard hang- en sluitwerk	**207,00**	**m2**														
aluminium kozijn merk A2, draairaam, buitendraaiend	207,00	m2	1,00	1,930		174,38			174,38	399,51	399,51		36.096,66			36.096,66
HR++ beglazing 5-4, gas gevuld [HR coating]	207,00	m2	1,00	1,200		64,35			64,35	248,40	248,40		13.320,45			13.320,45
Totaal	**207,00**	**m2**		**3,130**		**238,73**			**238,73**	**647,91**	**647,91**		**49.417,11**			**49.417,11**
TOTAAL BUITENWANDOPENINGEN										**1.144,71**	**1.144,71**		**96.780,78**			**96.780,78**

APPENDIX B

LIST WITH THE Rc-values FOR GRASSHOPPER

Name	Rc-value m2K/W	cavity width mm	cavity λ	external insulation thickness mm	external insulation λ
ext3wall015004	4,959	30	0,04	150	0,04
ext3wall010004	3,709	30	0,04	100	0,04
ext3wall005004	2,459	30	0,04	50	0,04
ext3wall015003	6,209	30	0,04	150	0,03
ext3wall010003	4,542	30	0,04	100	0,03
ext3wall005003	2,875	30	0,04	50	0,03
ext5wall015004	5,459	50	0,04	150	0,04
ext5wall010004	4,209	50	0,04	100	0,04
ext5wall005004	2,959	50	0,04	50	0,04
ext5wall015003	6,709	50	0,04	150	0,03
ext5wall010003	5,042	50	0,04	100	0,03
ext5wall005003	3,375	50	0,04	50	0,03
ext7wall015004	5,959	70	0,04	150	0,04
ext7wall010004	4,709	70	0,04	100	0,04
ext7wall005004	3,459	70	0,04	50	0,04
ext7wall015003	7,209	70	0,04	150	0,03
ext7wall010003	5,542	70	0,04	100	0,03
ext7wall005003	3,875	70	0,04	50	0,03
Cavwall003003	1,459	30	0,03	0	0
Cavwall005003	2,125	50	0,03	0	0
Cavwall007003	2,792	70	0,03	0	0
Cavwall003004	1,209	30	0,04	0	0
Cavwall005004	1,709	50	0,04	0	0
Cavwall007004	2,209	70	0,04	0	0

SET OF RESULTS FOR CAVITY INSULATION

Window Quality	Cavity Wall	WWR	I L I Total Annual (kWh)	Heating Demand (kWh)	LivRoom (Watt)	Bedroom1 (Watt)
W_Double_GL	Cavwall007004	0.20	5897	3204	1115	885
W_HR++	Cavwall007004	0.20	5476	2783	936	735
W_TripleGl	Cavwall007004	0.20	5183	2489	893	699
W_Double_GL	Cavwall005004	0.20	6282	3588	1182	941
W_HR++	Cavwall005004	0.20	5867	3173	1005	793
W_TripleGl	Cavwall005004	0.20	5575	2881	962	757
W_Double_GL	Cavwall003004	0.20	6936	4242	1295	1036
W_HR++	Cavwall003004	0.20	6529	3835	1121	889
W_TripleGl	Cavwall003004	0.20	6239	3545	1079	854
W_Double_GL	cavwall007003	0.20	5610	2916	1064	843
W_HR++	cavwall007003	0.20	5184	2490	884	692
W_TripleGl	cavwall007003	0.20	4890	2196	841	656
W_Double_GL	cavwall005003	0.20	5951	3257	1124	893
W_HR++	cavwall005003	0.20	5530	2837	946	743
W_TripleGl	cavwall005003	0.20	5237	2544	903	707
W_Double_GL	cavwall003003	0.20	6560	3867	1230	982
W_HR++	cavwall003003	0.20	6149	3455	1054	834
W_TripleGl	cavwall003003	0.20	5858	3164	1012	799
W_Double_GL	Cavwall007004	0.40	6454	3761	1458	1112
W_HR++	Cavwall007004	0.40	5455	2761	1045	826
W_TripleGl	Cavwall007004	0.40	4896	2202	962	756
W_Double_GL	Cavwall005004	0.40	6735	4041	1489	1153
W_HR++	Cavwall005004	0.40	5744	3050	1096	869
W_TripleGl	Cavwall005004	0.40	5186	2492	1013	799
W_Double_GL	Cavwall003004	0.40	7213	4519	1518	1222
W_HR++	Cavwall003004	0.40	6235	3541	1182	940
W_TripleGl	Cavwall003004	0.40	5678	2985	1100	872
W_Double_GL	cavwall007003	0.40	6245	3551	1446	1066
W_HR++	cavwall007003	0.40	5239	2546	1007	794
W_TripleGl	cavwall007003	0.40	4679	1986	923	724
W_Double_GL	cavwall005003	0.40	6493	3799	1458	1118
W_HR++	cavwall005003	0.40	5495	2801	1052	832
W_TripleGl	cavwall005003	0.40	4936	2242	969	762
W_Double_GL	cavwall003003	0.40	6938	4245	1470	1182

W_HR++	cavwall003003	0.40	5953	3259	1133	899
W_TripleGl	cavwall003003	0.40	5395	2702	1050	830
W_Double_GL	Cavwall007004	0.60	7174	4481	1643	1326
W_HR++	Cavwall007004	0.60	5522	2828	1151	914
W_TripleGl	Cavwall007004	0.60	4713	2020	1028	812
W_Double_GL	Cavwall005004	0.60	7357	4663	1674	1352
W_HR++	Cavwall005004	0.60	5711	3017	1184	942
W_TripleGl	Cavwall005004	0.60	4904	2210	1062	840
W_Double_GL	Cavwall003004	0.60	7668	4974	1728	1397
W_HR++	Cavwall003004	0.60	6034	3340	1241	989
W_TripleGl	Cavwall003004	0.60	5228	2534	1120	888
W_Double_GL	cavwall007003	0.60	7038	4344	1619	1307
W_HR++	cavwall007003	0.60	5380	2687	1126	893
W_TripleGl	cavwall007003	0.60	4571	1878	1003	791
W_Double_GL	cavwall005003	0.60	7199	4506	1647	1330
W_HR++	cavwall005003	0.60	5548	2854	1155	918
W_TripleGl	cavwall005003	0.60	4740	2046	1033	816
W_Double_GL	cavwall003003	0.60	7489	4795	1697	1371
W_HR++	cavwall003003	0.60	5848	3155	1208	962
W_TripleGl	cavwall003003	0.60	5041	2348	1087	860
W_Double_GL	Cavwall007004	0.80	7979	5285	1886	1529
W_HR++	Cavwall007004	0.80	5641	2948	1253	999
W_TripleGl	Cavwall007004	0.80	4597	1904	1093	866
W_Double_GL	Cavwall005004	0.80	8068	5375	1902	1541
W_HR++	Cavwall005004	0.80	5735	3041	1269	1013
W_TripleGl	Cavwall005004	0.80	4691	1997	1110	880
W_Double_GL	Cavwall003004	0.80	8221	5527	1928	1563
W_HR++	Cavwall003004	0.80	5894	3200	1297	1036
W_TripleGl	Cavwall003004	0.80	4850	2156	1139	903
W_Double_GL	cavwall007003	0.80	7913	5219	1875	1519
W_HR++	cavwall007003	0.80	5572	2878	1241	989
W_TripleGl	cavwall007003	0.80	4528	1834	1081	855
W_Double_GL	cavwall005003	0.80	7991	5298	1889	1531
W_HR++	cavwall005003	0.80	5654	2960	1255	1001
W_TripleGl	cavwall005003	0.80	4610	1916	1096	868
W_Double_GL	cavwall003003	0.80	8133	5440	1913	1551
W_HR++	cavwall003003	0.80	5802	3108	1281	1023
W_TripleGl	cavwall003003	0.80	4759	2065	1122	890

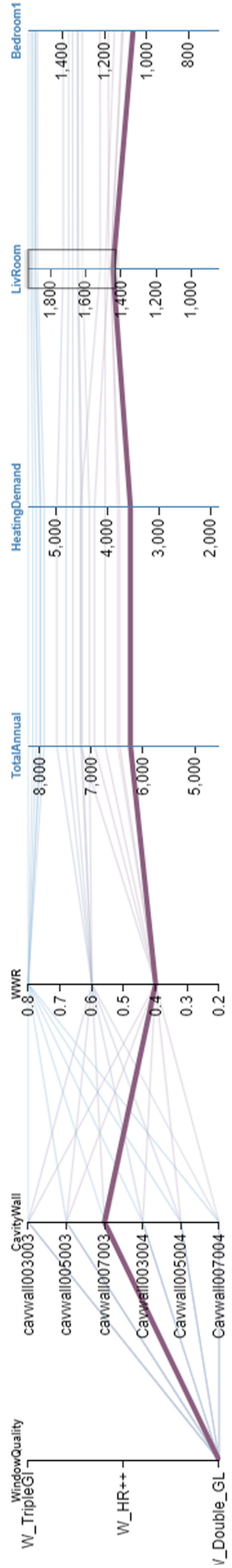


Figure 3 Diagram with the set of solutions for cavity insulation that fail to achieve medium/low temperature heating.

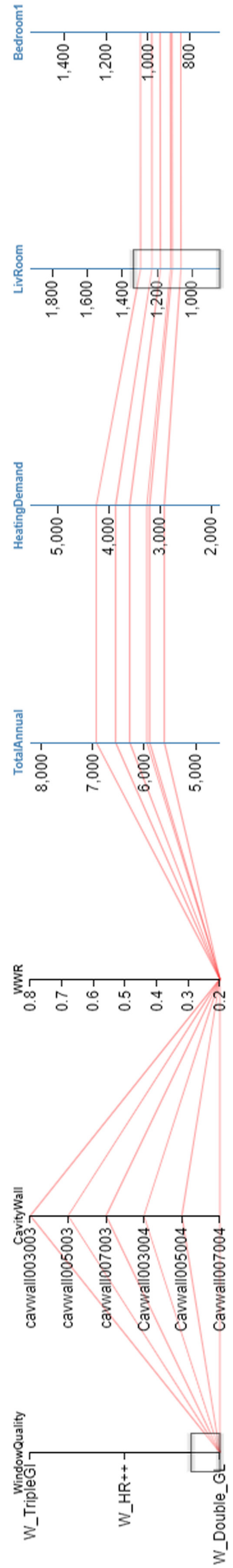


Figure 3 Diagram with the set of solutions for cavity insulation that achieve medium/low temperature heating without changing the glazing.

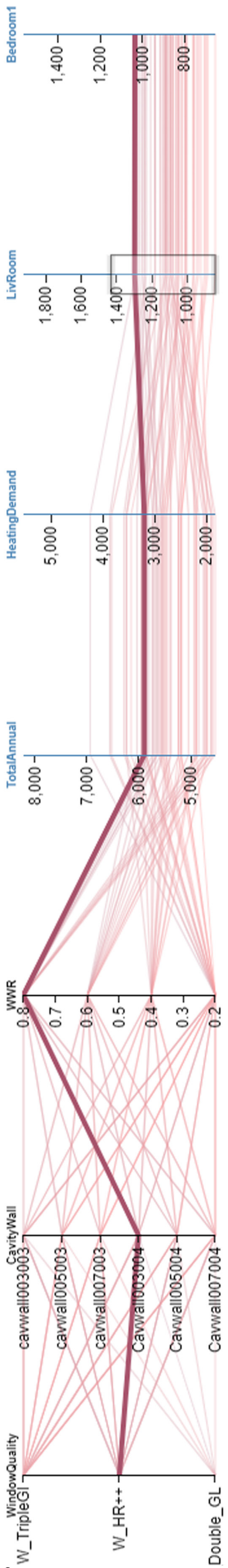
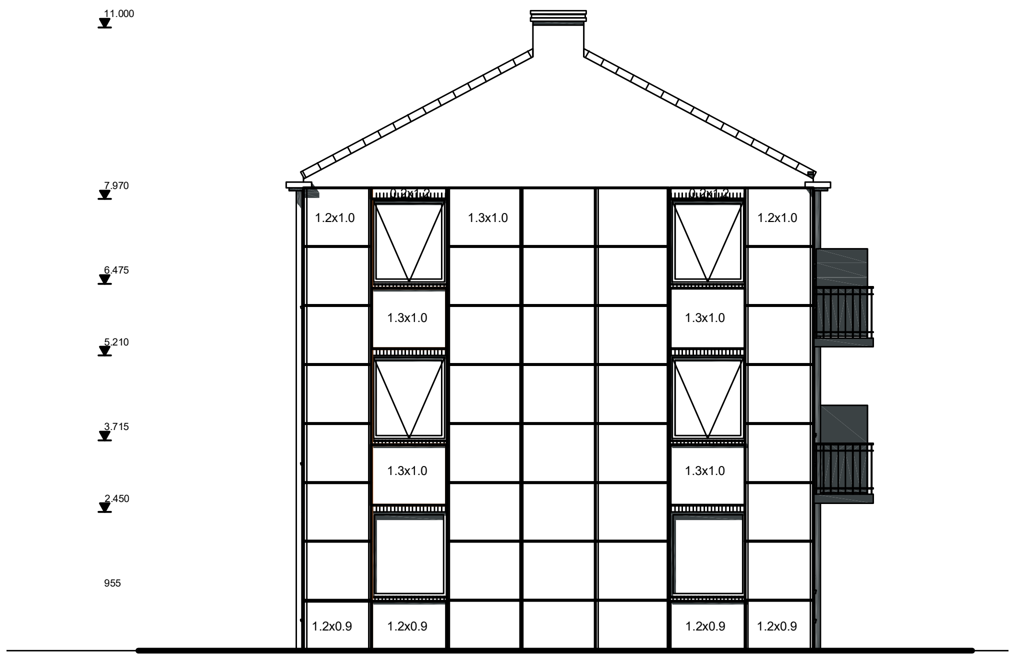


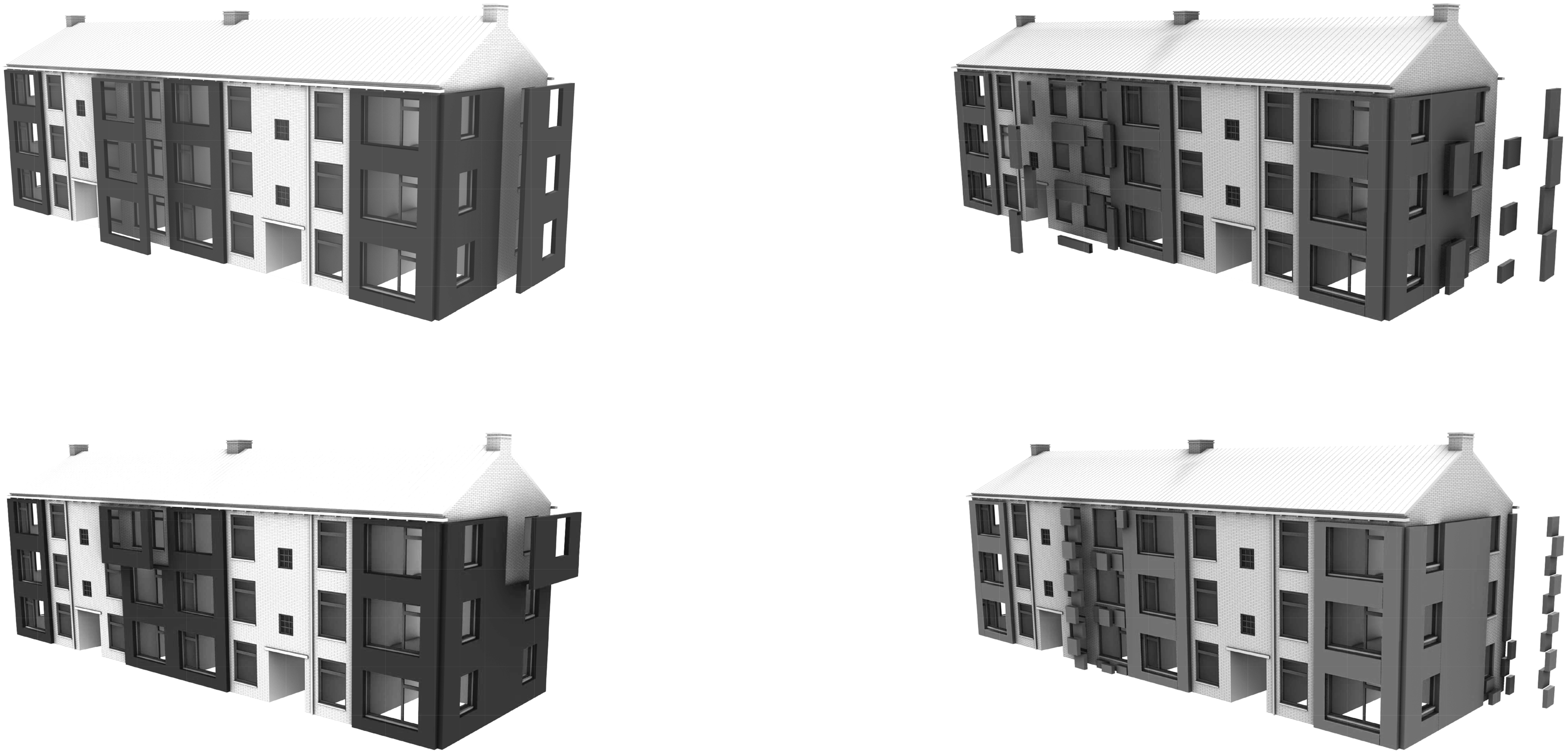
Figure 3 Diagram with the set of solutions for cavity insulation that achieve medium/low temperature heating.

Heating system	Supply flow, °C	Return flow, °C
High temperature (HT)	90	70
Medium temperature (MT)	55	35-45
Low temperatures (LT)	45	25-35
Very low temperatures (VLT)	35	25

PLACEMENT OF THE PANELS FOR 50% INSULATED CONCEPT



The case study and the refabricated elements in different size.



REFERENCES

01

Agentschap NL - Ministerie van Economische Zaken. (2011). Voorbeeldwoningen 2011: Bestaande bouw. Chapter (Vol. 6). Sittard, The Netherlands.

BAM Woningbouw NV, ENECO installatiebedrijven Zuidwest BV, Hogeschool Rotterdam, T. U. D. (2016). 2nd SKIN zero energy apartment renovation via an integrated façade approach. TU Delft, Delft, The Nehterlands.

Buildings performance institute Europe (BPIE). (2017). Prefabricated systems for deep energy retrofits of residential buildings. Brussels, Belgium.

Konstantinou, T. (2014). Facade Refurbishment Toolbox: Supporting the Design of Residential Energy Upgrades. TU Delft, Delft, The Netherlands.

Lindsey, R. (2016). Climate Change: Global Sea Level. Retrieved from: https://www.climate.gov/news-features/understanding-climate/climate change-global-sea-level

MVI Energie 2018. (2018). LT- Ready: Realistisch en betaal baar isoleren voor lage temperatuur verwarming. Delft, The Netherlands.

Stutvoet, E. (2018). Energietransitie: omarm de complexiteit. Technische Universiteit Delft, Faculteit Bouwkunde, Afdeling Management in the Built Environment, Delft, the Netherlands.

Thomsen, A. F., & van der Flier, C. L. (2008). Replacement or reuse? The choice between demolition and life cycle extension from a sustainable viewpoin Shrinking Cities, Sprawling Suburbs, Changing Countrysides (Vol. 1): Centre for Housing Research, UCD.

Websites

Weerplaza,2019. Information retrieved from https://www. weerplaza.nl/

NOAA, 2019. Information retrieved from https://www.cpc.ncep.noaa.gov/

Picture Sources

Figure 1: Greenhouse gas emissions by sector, EU_27, 2007. Source: Eurostat 2010, fig. 11.6 @European Union, 1995-2011

Figure 2: Energy consumption, EU_27, 2006. Source: Eurostat 2010, fig. 11.20 @European Union, 1995-2011

Figure 3: Energy consumption in residential buildings in EU. Source: Eurostat 2010, @European Union, 1995-2011

Figure 4: Post war Portiek apartments: 380.000 houses from 1945 until 1975, 2011. Source: Agentschap NL - Ministerie van Economische Zaken, (2011). Voorbeeldwoningen 2011: Bestaandebouw. Chapter (Vol. 6). Sittard, The Netherlands.

02

Agentschap NL - Ministerie van Economische Zaken. (2011). Voorbeeldwoningen 2011: Bestaande bouw. Chapter (Vol. 6). Sittard, The Netherlands.

BAM Woningbouw NV, ENECO installatiebedrijven Zuidwest BV, Hogeschool Rotterdam, T. U. D. (2016). 2nd SKIN zero energy apartment renovation via an integrated façade approach. TU Delft, The Nehterlands.

Bouwhulpgroep. (2013). Documentatie Systeemwoningen ’50-’75. Eindhoven, The Netherlands.

Giebeler, G. (2009). Refurbishment manual: maintenance, conversions, extentions. Basel: Birkhäuser.

Konstantinou, T. (2014). Facade Refurbishment Toolbox: Supporting the Design of Residential Energy Upgrades. TU Delft, The Netherlands.

Technalia, 2014. Nezer: Technical solutions for energy reduced and renewable energy sources for optimal energy efficient renovation. E.U.

Picture Sources

Figure 1 Example of the systeem construction. Source:Bouwhulpgroep. (2013). Documentatie Systeemwoningen ’50-’75. Eindhoven, The Netherlands.

Figure 2 Overview of layout and construction characteristics of the six most popular non-traditional systems. Source: BAM Woningbouw NV, ENECO installatiebedrijven Zuidwest BV, Hogeschool Rotterdam, T. U. D. (2016). 2nd SKIN zero energy apartment renovation via an integrated façade approach. TU Delft, Delft, The Nehterlands.

Figure 3 Energy labels of the Dutch building stock, AgentschapNL, 2011. Source: Agentschap NL - Ministerie van Economische Zaken. (2011). Voorbeeldwoningen 2011: Bestaande bouw. Chapter (Vol. 6). Sittard, The Netherlands.

03

BAM Woningbouw NV, ENECO installatiebedrijven Zuidwest BV, Hogeschool Rotterdam, T. U. D. (2016). 2nd SKIN zero energy apartment renovation via an integrated façade approach. TU Delft, Delft, The Nehterlands.

Buildings performance institute Europe (BPIE). (2017). Prefabricated systems for deep energy retrofits of residential buildings. Brussels, Belgium.

Jelle, B. P. (2011). Traditional, state-of-the-art and future thermal building insulation materials and solutions - Properties, requirements and possibilities. Energy and Buildings, 43(10), 2549–2563. https://doi.org/10.1016/j.enbuild.2011.05.015

IEA ECBCS Annex 50 (2011). Prefabricated Systems for Low Energy Renovation of Residential Buildings. Switzerland.

IEA ECBCS Annex 50 - Prefab Retrofit of Buildings Retrofit Strategies Design Guide – Part D 117.

Konstantinou, T. (2014). Facade Refurbishment Toolbox: Supporting the Design of Residential Energy Upgrades. TU Delft, Delft, The Netherlands.

Papadopoulos, A. M. (2005). State of the art in thermal insulation materials and aims for future developments. Energy and Buildings (Vol. 37). Aristotle University Thessaloniki, Thessaloniki, Greece.

Stutvoet, E. (2018). Energietransitie: omarm de complexiteit. Technische Universiteit Delft, Faculteit Bouwkunde, Afdeling Management in the Built Environment, Delft, the Netherlands.

Websites:

Milieucentraal. Information retrieved from: https://www.milieucentraal.nl/

Isolatie-Weetjes. Information retrieved form: https://www.isolatie-weetjes.nl/

MEEFS retrofitting. Information retrieved from: http://www.meefs-retrofitting.eu/project/retrofitting-facade-concept.html

Toolkit DUURZAAM ERFGOED. Information retrieved from: http://www.toolkitduurzaamerfgoed.nl/

Greenspec. Information retrieved from: http://www.greenspec.co.uk/building-design/insulation-materials-thermal-properties/

City-zen. Information retrieved from: http://www.cityzen-smartcity.eu/wp-content/uploads/2016/01/cityzen-kif-thnk-facade-panels.pdf

Picture Source

Figure 1 The prototypes in Arnhem, Heerhugowaard, Stadskanaal. Source: Stutvoet, E. (2018). Figures 2.20, 2.21, 2.22. Energietransitie: omarm de complexiteit. Technische Universiteit Delft, Faculteit Bouwkunde, Afdeling Management in the Built Environment, Delft, the Netherlands.

Figure 2 A piece of the prefabricated facade. Source: https://www.residentialproductsonline.com/rocky-mountain-institute-works-toward-scalable-net-zero-multifamily-retrofits

Figure 3 The 2nd skin project. Source: BAM Woningbouw NV, ENECO installatiebedrijven Zuidwest BV, Hogeschool Rotterdam, T. U. D. (2016). 2nd SKIN zero energy apartment renovation via an integrated façade approach. TU Delft, Delft, The Nehterlands.

Figure 4 The prefabricted panel of the 2nd skin project. Source: BAM Woningbouw NV, ENECO installatiebedrijven Zuidwest BV, Hogeschool Rotterdam, T. U. D. (2016). 2nd SKIN zero energy apartment renovation via an integrated façade approach. TU Delft, Delft, The Nehterlands.

Figure 5 The MeeFS solution on a real building in Extremadura, Spain. Source: https://www.meefs-retrofitting.eu/demonstration.html

Figure 6 The MEEFS facade system. Source: https://www.meefs-retrofitting.eu/demonstration.html

Figure 7 Cross section of new thermal envelope (top), Figure 8 Prefabricated facade module (middle), Figure 9 A view of the facade (bottom). Source: - IEA ECBCS Annex 50 (2011). Prefabricated Systems for Low Energy Renovation of Residential Buildings. Switzerland.

Figure 9A Project's front facade. (cityzen-smartcity.eu)

Figure 9B The prefabricated panel. (Annex 50, 2011)

Figure 10 Cavity insulation in the cavity through a hole. Source:https://www.sdi-insulation.com/sdi-insulation-spray-foam-insulation-blown-insulation-batt-insulation-installers-bay-area/cavity-wall-insulation-1/

Figure 11 Inspection for debris in the cavity. Source: https://blog.completepreservation.co.uk/2016/08/08/suspected-rising-damp-on-a-cavity-wall/

Figure 12 Endoscope in the cavity. Source: https://twitter.com/btpreservation

Figure 13 External Wall insulation application. Source: https://www.helifix.co.uk/applications/external-wall-insulation-programmes/

Figure 14 Internal wall insulation application. Source: http://www.ces-limited.com/project/solid-wall-insulation/

Figure 15 Insulation between the wooden beams. Source:https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/isoleren-en-besparen/dakisolatie/

Figure 16 Layers of insulation for a pitched roof. Source: https://www.isolatie-weetjes.nl/dakisolatie/

Figure 17 Preparing the frames for the thicker glass. Source:https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/isoleren-en-besparen/dubbel-glas-hr-glas-en-triple-glas/

Figure 18 Insulating frames with triple glazing. Source: https://www.google.com/search?q=insulating+-frames&source=lnms&tbm=isch&sa=X&ved=0ahUKEwiq4dLHnY_iAhVIZVAKHfDyBT4Q_AUIDigB&biw=1366&bih=625#imgdii=s-HyzxEDi1faeM:&imgrc=jY70RiX73VSAZM

Figure 19 The three categories of insulation materials. Produced by me.

Figure 20 PUR inside the pitched roof. Source: https://www.isolatie-weetjes.nl/isolatiematerialen/

Figure 21 PIR. Source: https://www.isolatie-weetjes.nl/isolatiematerialen/

Figure 22 Rock wool. Source: https://www.isolatie-weetjes.nl/isolatiematerialen/

Figure 23 Glass wool. Source: https://www.isolatie-weetjes.nl/isolatiematerialen/

Figure 24 Cellulose. Source: https://www.thetrusolutions.com/different-types-insulation/

Figure 25 EPS board. Source: https://www.alibaba.com/product-detail/-EPS-sandwich-panel-board-for_60029160254.html

Figure 26 XPS board. Source: https://www.alibaba.com/product-detail/Extruded-polystyrene-XPS-insulation-foam-board_60684705254.html

Figure 27 Biofoam. Source: https://www.isobouw.nl/nl/producten/algemene-isolatie/biofoam-isolatiemateriaal/

Figure 28 VIP. Source: https://www.nuclear-power.net/nuclear-engineering/heat-transfer/heat-losses/insulation-materials/vacuum-insulation-panels/

Figure 29 Aerogel. Source: https://www.insulation4less.co.uk/aerogel-spaceloft-blanket-9mm-10-sheets

Figure 30 Natural Ventilation. Source: https://www.tealproducts.com/natural-ventilation-control

Figure 31 Mechanical ventilation with heat recovery. Source: https://gavinlowe.co.nz/energy-solutions/ventilation-heat-recovery/

Figure 32 In sity vs prefabricated. Adapted by Schwehr, Fischer, & Geiern 2011.

04

Websites

Rijksoverheid. Information retrieved from: https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012%5b12%5d/hfd3/afd3-6/par3-6-2?tableid=docs/wet/bb2012%5b12%5d/hfd3/afd3-6/par3-6-2&articleid=3.38&fragid=art3.38#art3.38/lid4

Myson. Information retrieved from: https://www.myson.co.uk/publisher/online-view.php?doc=/static_files/my/media/downloads/31420%20Product%20Range%20Bro%2004-17%20Ed1%20-%20Radiators%20NEW.pdf&locale=en-GB#page=28

Quinn radiators. Information retrieved from: http://www.quinn-radiators.com/wp-content/uploads/2013/08/PanelBrochure_low-res.pdf

Picture Sources

Figure 1 Typical floor plan. Figure 2 Site plan. Figure 3 Detail of the cavity wall. Figure 4 Picture of the case study. Source for all 4 figures: KAW. (2017). Drawings Soendalaan Vlaardingen.

Figure 8 Radiator installed currently. Source: KAW. (2017). Drawings Soendalaan Vlaardingen.

08

Websites

https://www.rvo.nl/initiatieven/energiezuiniggebouwd/renovatie-bosleeuw-lucellestraat

11

BPIE. (2011). Europe's Buildings under the Microscope: A country-by-country review of the energy performance of buildings. Buildings Performance Institue Europe (BPIE)

BPIE. (2013). A Guide to developing strategies for bulding energy renovation. Buildings Performance Institue Europe (BPIE)