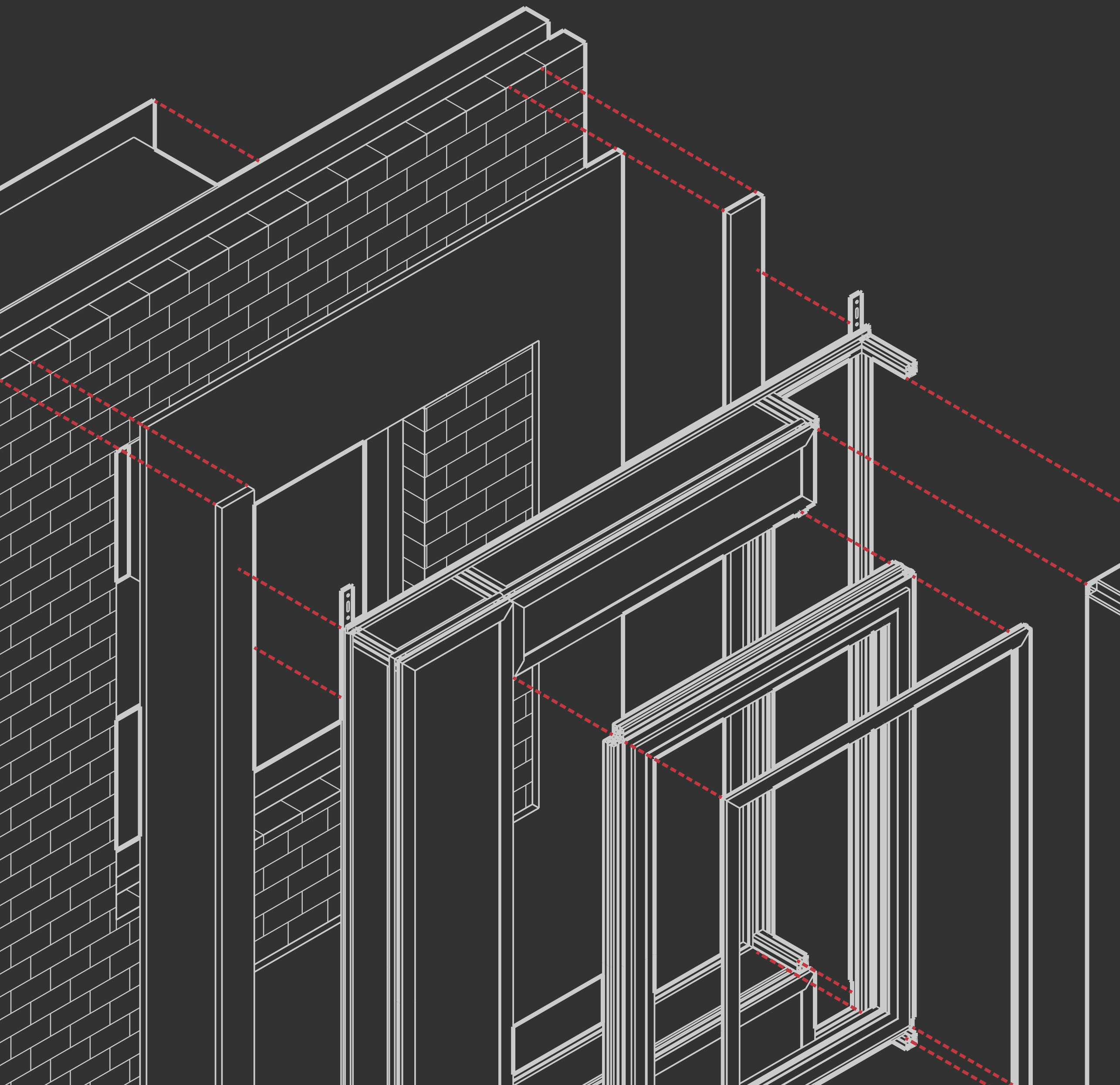
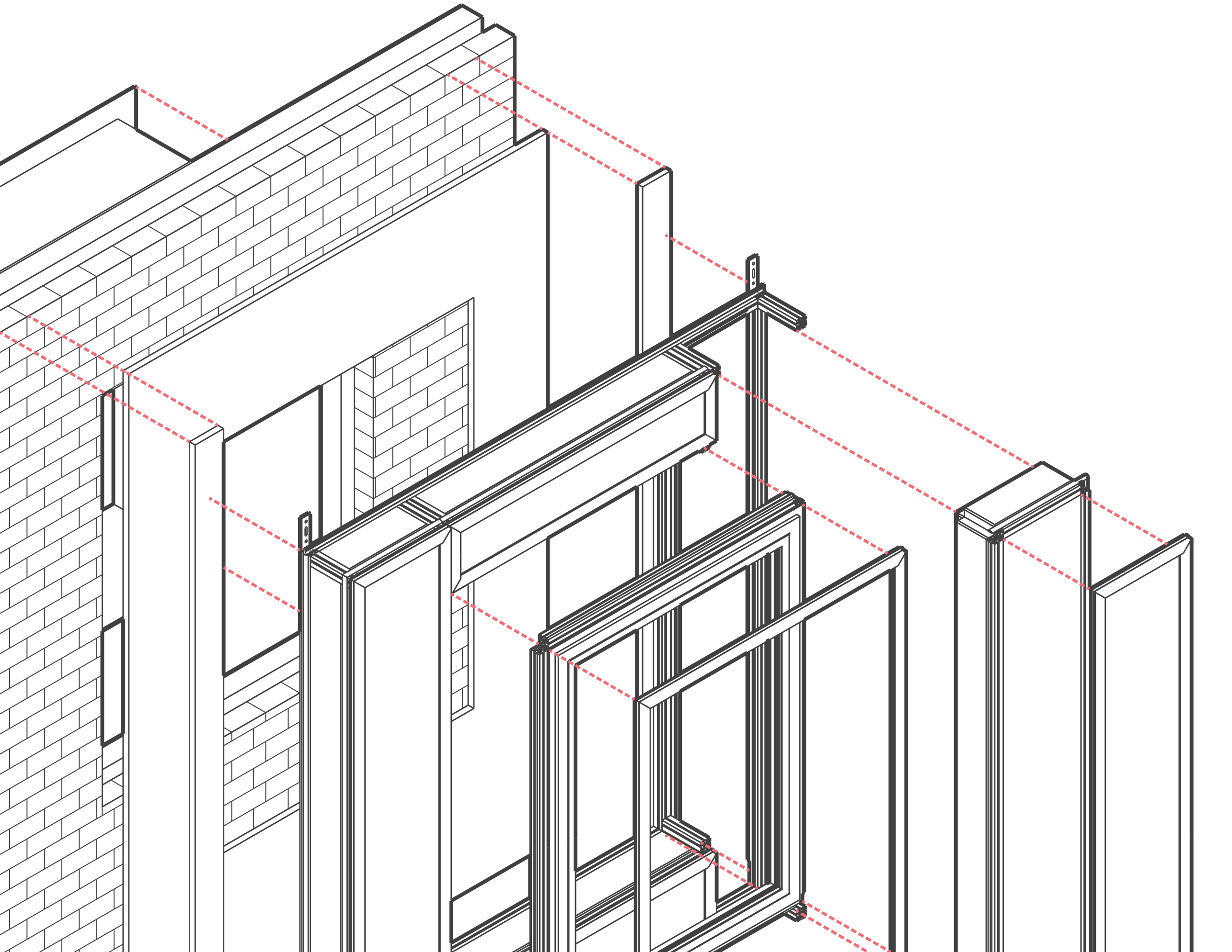
RE∞NOVATE

Upgradable Building Envelope System for Energy Reduction Renovation of Dutch Post-war Apartments

Mick Simmering





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MSc thesis Delft University of Technology

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Master of Science (MSc) thesis
Re-novate- Upgradable Building Envelope System for Energy Reduction Renovation of Dutch Post-war Apartments

Part of series of graduation projects aligned with the 2ndSkin Project.

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Mick Simmering

Abstract

Problem Definition and main objective: Current prefabricated building envelope systems utilised for energy reduction renovations are expected to be a long-lasting solution. In practice, the building envelope systems are not adapted to facilitate future updates due to changing regulations or changing standards. Furthermore, in most renovation systems the material or component with the lowest service life dictates the service life of the complete system, leading to materials being disposed of before they reached the end of their potential service life. The goal of the thesis is to design a system that is adapted to these issues by being a flexible system that separates functionalities in separate boxes and layers, and therefore is able to upgrade or replace individual components when necessary to ensure the system's long-term functionality.

Study Design: Literature review, followed by the formulation of a strategy and a design. Design effectiveness is confirmed through application on a case study. Long-term functionality is confirmed through transformation of the case study application based on formulated scenarios.

Setting: The thesis is part of a series of ongoing research projects associated with the 2ndSkin project. The case study is an apartment block located at the Soendalaan in Vlaardingen.

Results: A design concept for an external building envelope system for energy reduction renovation of Dutch post-war apartments elaborated in a 1 to 5 detail scale. The final design incorporates an adaptable aluminium frame system with module boxes containing different functionalities, which can be slid into the main frame. The system is finished with a clamp system with cladding, functioning as the protecting layer for the system.

Keywords: Prefabricated, building envelope system, energy reduction renovation, Dutch post-war apartments, future proof, service life, changing standards.

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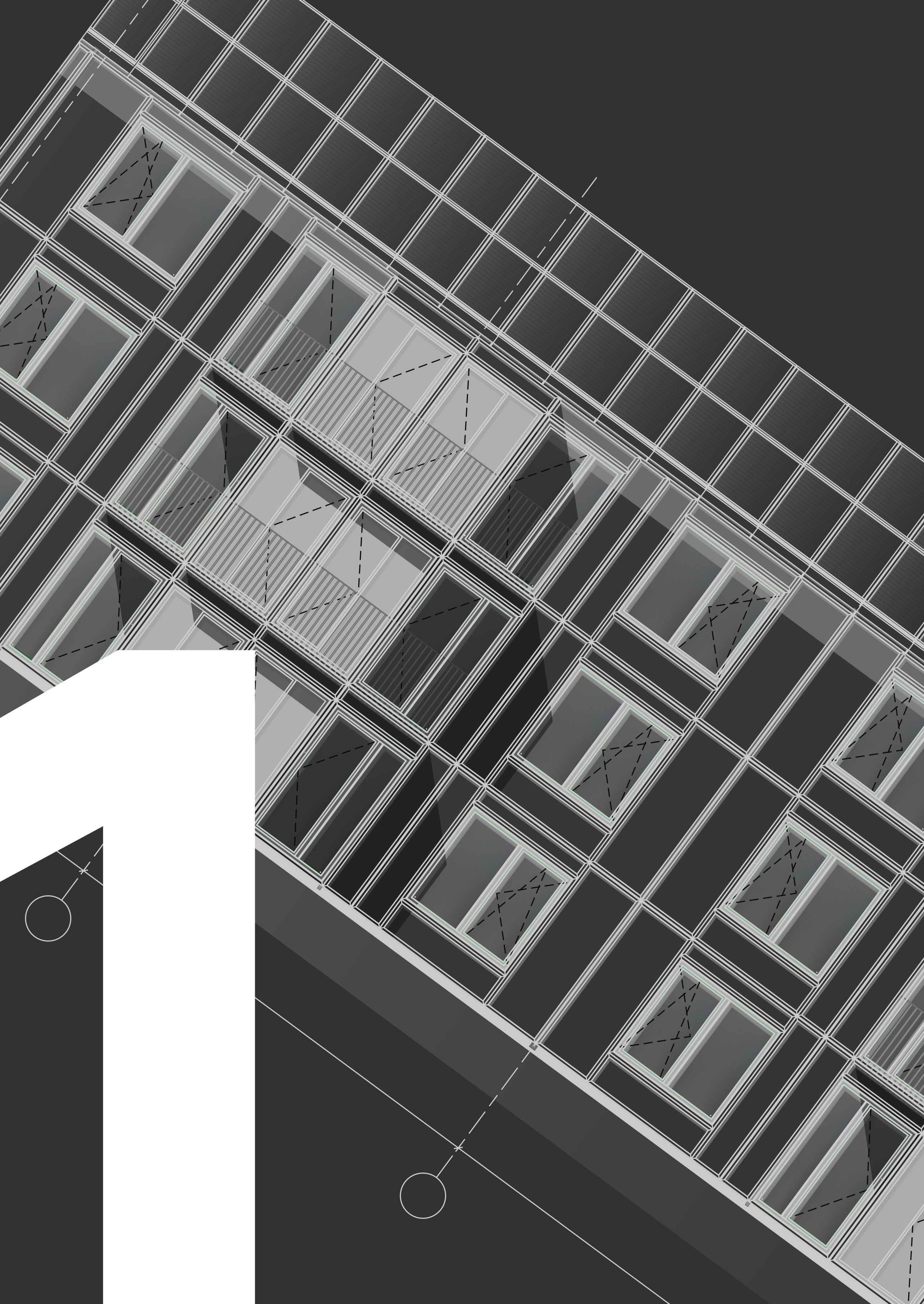
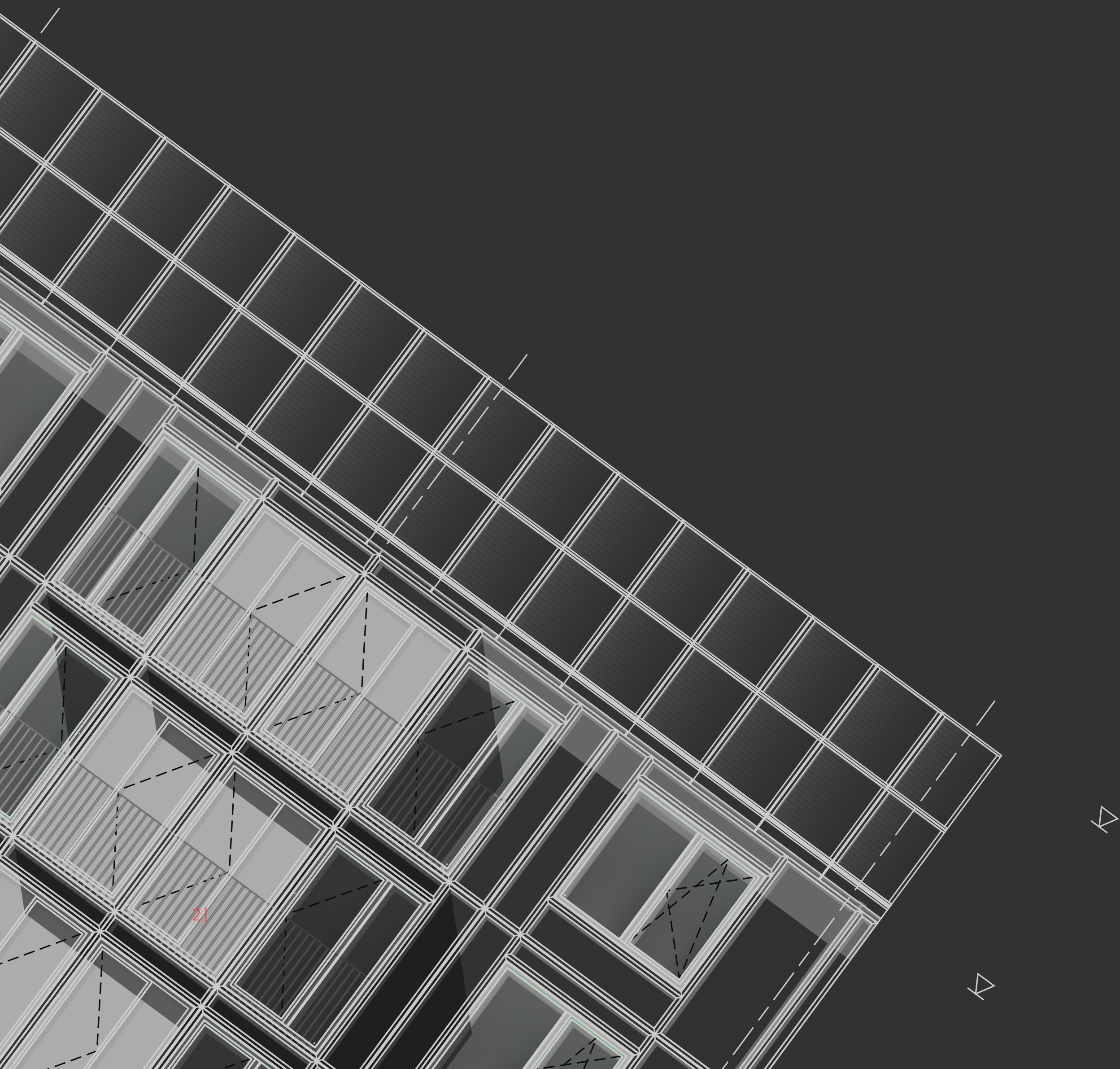
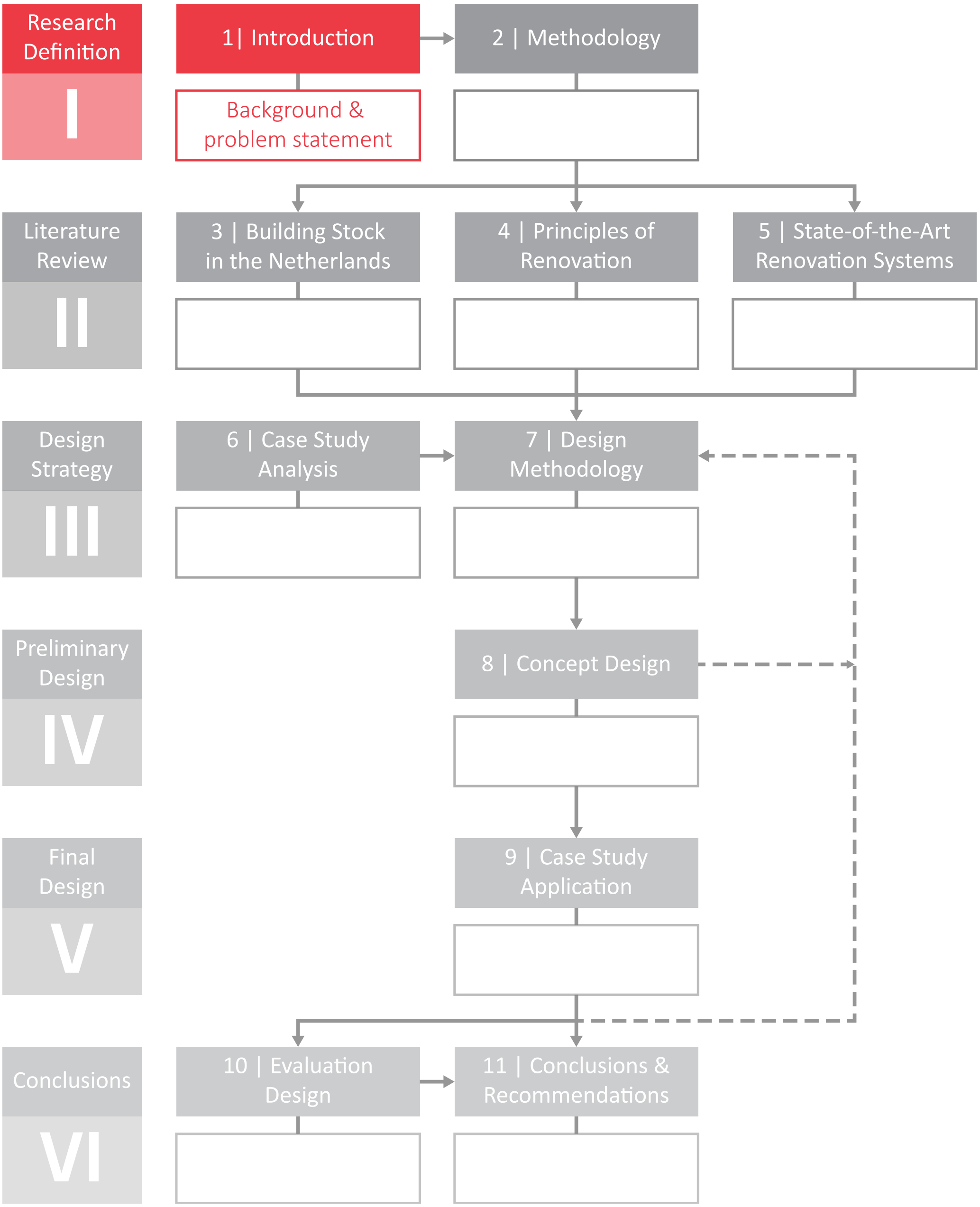


CHAPTER 1
INTRODUCTION

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1 Introduction

§ 1.1 Background

The rapid depletion of natural resources and the subsequent climate changes is one of the largest issues the European union currently faces. As we near the point of doing irreversible damage to the ecosystem the European Union has agreed upon inducting an energy policy that applies to every member state. For 2020 the greenhouse gasses should be reduced by at least 20%, the share of renewable energy should be increased to 20% and the improvement of energy efficiency by 20%. These goals were adopted as the 20-20-20 goals (European Union, 2010). The building sector is a major influencer on the possible achievement of these goals, as it comprises 40% of the total energy consumption in the European Union. Out of the building sector as a whole the household sector as a subsection has one of the highest potentials for energy reduction, as It comprises approximately 25% of the total energy consumed in the European Union.

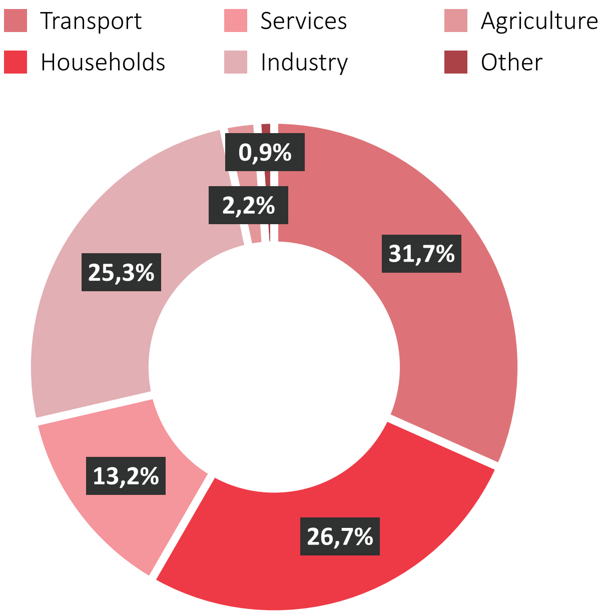


Fig. 1.1.1: *Final energy consumption European Union 2010 (Konstantinou, 2014).*

The recognition of the importance of this sector has led to the European Directive on the Energy Performance of Buildings (EPBD) to impose separate goals for every new building in the residential and service sector by 2020: The nearly zero-energy building (nZEB) (Hermelink, et al., 2013). A nearly zero-energy building is a building that during a year uses nearly as much energy as its produces. These new regulations and the energy reduction that accompanies it are the first step towards achieving the long-term goals of the European Union: The reduction of CO2 by 88 – 91% by 2050 (European Union, 2010).

Although these regulations assure new buildings are up to standards the majority of the existing building stock requires the same level of attention. In the Netherlands alone the total residential stock, as of 2012, consists of around seven million dwellings (Ministry of National Affairs and Kingdom Relations, 2013). It is projected that more than half of the building stock, that were built before the 1970's, have poor energy efficiency. The majority of this part of the building stock consist of post-war apartment blocks that utilised industrialised building methods focussing on quantity instead of quality. Through renovation of the older building stock to nZEB levels together with the regulations for new buildings the necessary CO^2 reduction can be achieved. It is projected that the European Union needs to increase their investments in the next decade up to €200 billion in order to produce a higher standard of energy-saving building components and equipment and subsequently increase the rate and depth of renovations to achieve these goals.

The building envelope is one of the main influencers of the energy consumption in buildings as it functions as the barrier between the exterior and the interior. The building envelope influences the energy consumption through heating, cooling and ventilation systems. In order to get these buildings to nZEB levels the energy loss needs to be resolved by improving the thermal insulation of the building envelope and by replacing the installations that reached the end of their service life with more energy efficient systems. Furthermore, the building envelope can also contribute to the energy production of the building, through the use of renewable energy sources.

In order to achieve the set goals, the focus should not only be on the quality of renovations, but also the quantity. It is projected that the current renovation rate of 1% of the existing building stock needs to be at least doubled in order to renovate 100% of the existing building stock in 40 years (BPIE, 2011). Initiatives, like "de stroomversnelling", a platform created by the Dutch ministry of housing which brings together different experts and stakeholders, aim to accelerate this process by exchanging knowledge. The aim is to renovate 4.5 million dwellings by 2050 (Stroomversnelling, 2015).

Several researches aim to accelerate the renovation rate by utilising semi-prefabricated or prefabricated systems. Semi-prefabricated systems use components manufactured in industrialised settings and are combined on-site to form a façade. Prefabricated systems manufacture completed façades in factory settings and the system as a whole is applied on-site. Both approaches have the benefits of reducing the construction time, costs, energy consumed and potential disturbance to occupants. In the Netherlands different semi-prefabricated and prefabricated approaches have been employed for the same reasons.

§ 1.2 Scientific Problem

Buildings are products that are expected to last a lifetime, but due to the complexities of buildings some components are in need of replacement sooner than others. For instance, the structure has a service life expectancy of around 100 years, while the façade has a life expectancy of around 30 years (Konstantinou, 2014). While all the components within the façade construction also have different service lives. With the added given that also the installations become outdated very fast. The service life of the complete facade is determined by the component that first reaches the end of its service life if that component cannot be individually removed, leading to all the other components being discarded before they reached the end of their potential. This issue is only partially answered by the building industry. For instance, the stroomversnelling project includes a contract between contractors and clients that ensures the contractor maintains the renovation during its life-cycle, which is 30 years (Stroomversnelling, 2015). After that a large part of the renovation needs to be overhauled or even completely redone, requiring a new investment and new contracts to maintain it.

Furthermore, there are uncertainties about future regulations and living standards. The building industry has the tendency to react to current regulations and not to possible future requirements, due to the higher investments costs. Leading to the possibilities that dwellings built now could be just as outdated in the future as the dwellings built in the past are now. The focus on present-day efficiency, instead of building for the future, leads to solutions that are unequipped to adjust to future regulations and living standards.

As stated earlier, high investments costs is one of the main deterrent for the building industry to renovate the older building stock. Newly built dwellings in general are more appealing to invest in due to the higher return rate (Konstantinou, 2014). As the renovation market is currently an inexperienced market it hasn't benefitted fully of the phenome of the "learning curve". The learning curve is the process of products becoming cheaper over time (BPIE, 2011). Initial investments for nZEB renovations are currently very high as it hasn't benefited yet of increasing competition between contractors and innovation of cheaper methods to construct, adding to the deterrent effect.

Lastly, the problem with current prefabricated systems used for renovation require to be customised for every project. While design principles can be reused the system has to be built from the ground up to adjust to different requirements. Requirements can differentiate per project on architecture, energy performance and functionality. Prefabricated systems should be better equiped to not only provide adequate quality, but should also focus on quantity and scalability to be able to effectively renovate the Dutch building stock within the required timescale.

§ 1.3 Goal Thesis

The scientific problem is distilled into the following research question for the thesis:

"In what way can a prefabricated building envelope system for energy reduction renovation of building envelopes of Dutch post-war apartment blocks be designed to be future proof by taking into account service life and changing standards?"

§ 1.4 Objectives

In order to achieve the goal of the thesis several objectives are formulated:

- Create an overview of the current situation of the Dutch building stock eligible for renovation. Focussing on the energy consumption, assessment of energy performance and building physical problems.
- Create an overview of the parameters and principles necessary for adequate renovation. Focussing on the current requirements as well as the future requirements.
- Assess current state-of-art prefabricated systems based on criteria formulated from the second objective to gain an understanding of implemented strategies.
- Formulate a design methodology consisting of criteria, tools and assessment method based on the literature.
- Utilise design methodology to formulate a design for a façade system that satisfies the formulated criteria.

- Implement the façade system on a case study and construct two separate scenarios with different timelines to evaluate the present day and future performance of the façade system.

§ 1.5 Scope of the Research

The scope of this research focusses on the design of a prefabricated building envelope system for post-war apartments of the Dutch building stock. Focussing on this typology and the variables that are present within this typology to design a system. Focussing on every possible typology present in the Dutch building stock would increase the number of possible variating elements to an unmanageable scale in the context of the duration of this research project.

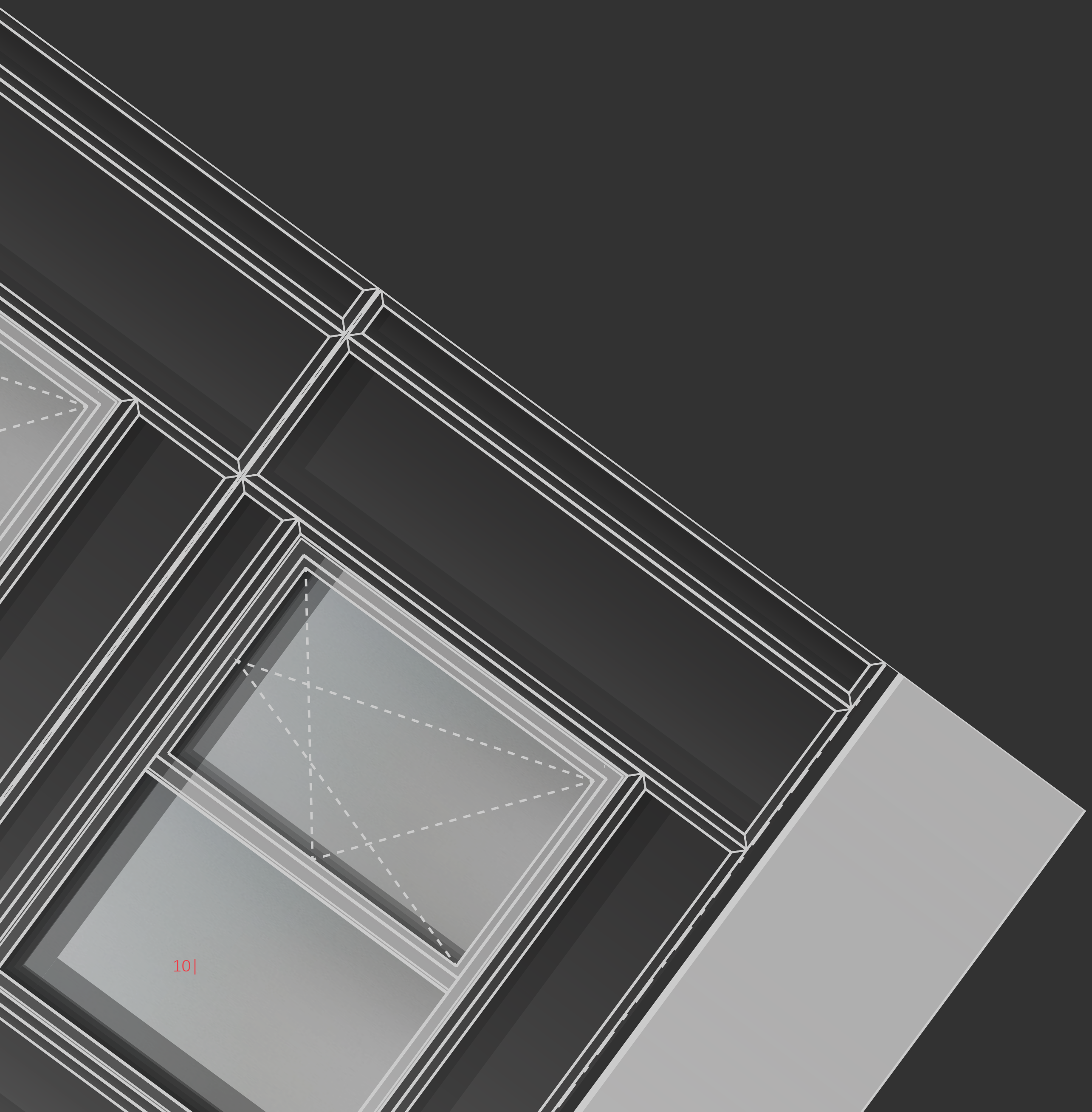
This thesis focusses on incorporating energy reductional methods in a building envelope design, while taking into account the service life of components within and be adjustable to future changing demands, due to living standards or new regulations. The final design will be assessed on these criteria.

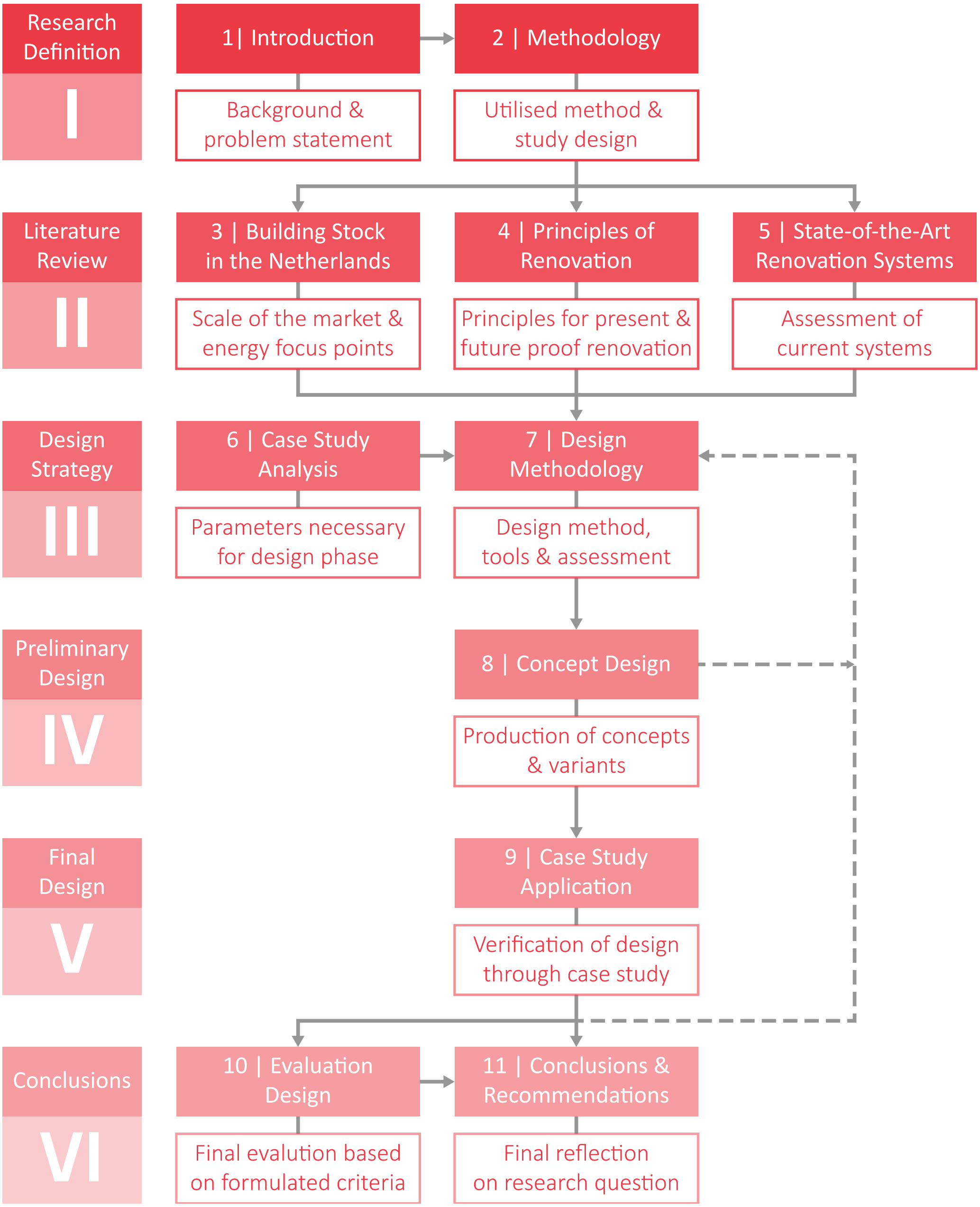
Although the design will take into account the life cycle of the system, it mainly focussess on the application on-site and the subsequent upgrading on-site. Although the manufacturing process and the recycling process after the building envelope system exceeded its service life are taken into account in the design process, it is not elaborated further.

The system will be designed for a single case study but will be designed in such a way that the system is scalable to different buildings of the same typology.


2

CHAPTER 2
METHODOLOGY

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Utilised method & study design
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Principles for present & future proof renovation
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Final evalution based on formulated criteria
Final reflection on research question

2 Methodology

This thesis consists of six parts of which parts two through five are dedicated to the research. The research consists of four main activities:

- Part II: Data collection and evaluation of literature and translate to design tools.
- Part III: Formulating requirements according to the literature and a case study analysis.
- Part IV: Utilise design tools to produce a design concept.
- Part V: Verify design by application on the case study and evaluate according to set requirements.

This research selects and evaluates literature on three fields of study: The context of the situation, the essential principles associated with renovation projects and the assessment of state-of-the-art projects focussed on solving the renovation problem. The literature is then utilised to for a detailed case study analysis of the parameters that need to be taken into account as well as the measures that are utilised for the renovation in 2ndSkin project.

The accumulated knowledge of the literature and the case study is then condensed to formulate a design methodology, consisting of a list of present-day and future requirements, an assessment method and abstract design tools.

Based on the design by research methodology several scenarios are constructed to gain a perspective of possible future changes on how the components of the façade system should function in the present, as well as the future. The design tools are utilised to produce a variety of design concepts on an abstract level, of which a final design concept is chosen for further elaboration. The design is then applicated on the case study and several scenarios are constructed which evaluates the design resilience to future changes.

The final design and the application of the design are evaluated accroding to the set criteria to formulate a final answer to the research question.

§ 2.1 Chapter 3: Building Stock in The Netherlands

Chapter 3 consists of a literature review on the current situation of the Dutch building stock to define the focus for the renovation process. By going from broad, assessing the scale of the renovation market, to deep, assessing the energy consumption. Furthermore, additional information about parameters that should be taken into account are addressed. This information leads to the focus for the renovation and parameters that have to be taken into account.

§ 2.2 Chapter 4: Principles of Renovation

Chapter 4 consists of a literature review on the principles associated with renovation. It evaluates the approaches and the specific measures available to reduce the energy consumption. Furthermore, the term 'future proof' and the methods to assess it are defined in more detail. Lastly, the chapter elaborates on possible strategies to engage the renovation issue as a whole, as well as project specific issues.

§ 2.3 Chapter 5: State-of-the-Art Renovation Systems

Chapter 5 consists of a literature review and evaluation of state-of-the-art projects that utilise prefabricated systems. The systems are evaluated based on a list of criteria in three fields of study: Architecture, construction and application. The projects are then subsequently compared to draw conclusions and recommendations for the design methodology.

§ 2.4 Chapter 6: Case Study Analysis

Chapter 6 consists of an analysis of the case study of the existing situation that will be utilised to further define the requirements for the design phase of this research. Typology, thermal performance and building physical problems will be evaluated into detail. Furthermore, the specific measures utilised by the 2ndSkin project to solve these issues will be utilised to be used as a reference for the design phase.

§ 2.5 Chapter 7: Design Methodology

In chapter 7 the accumulated knowledge from the literature review and the case study analysis is combined to formulate a list of criteria subdivided in three fields of study: Energy, Architecture and Future Proof. All the individual criteria are defined in detail to clearly state how the design for the building envelope system should function on every aspect. Following up on that, three sets of design tools are formulated in the shape of diagrams that are abstracted from the literature. Lastly, an assessment method is chosen functioning as a guiding tool in the design process.

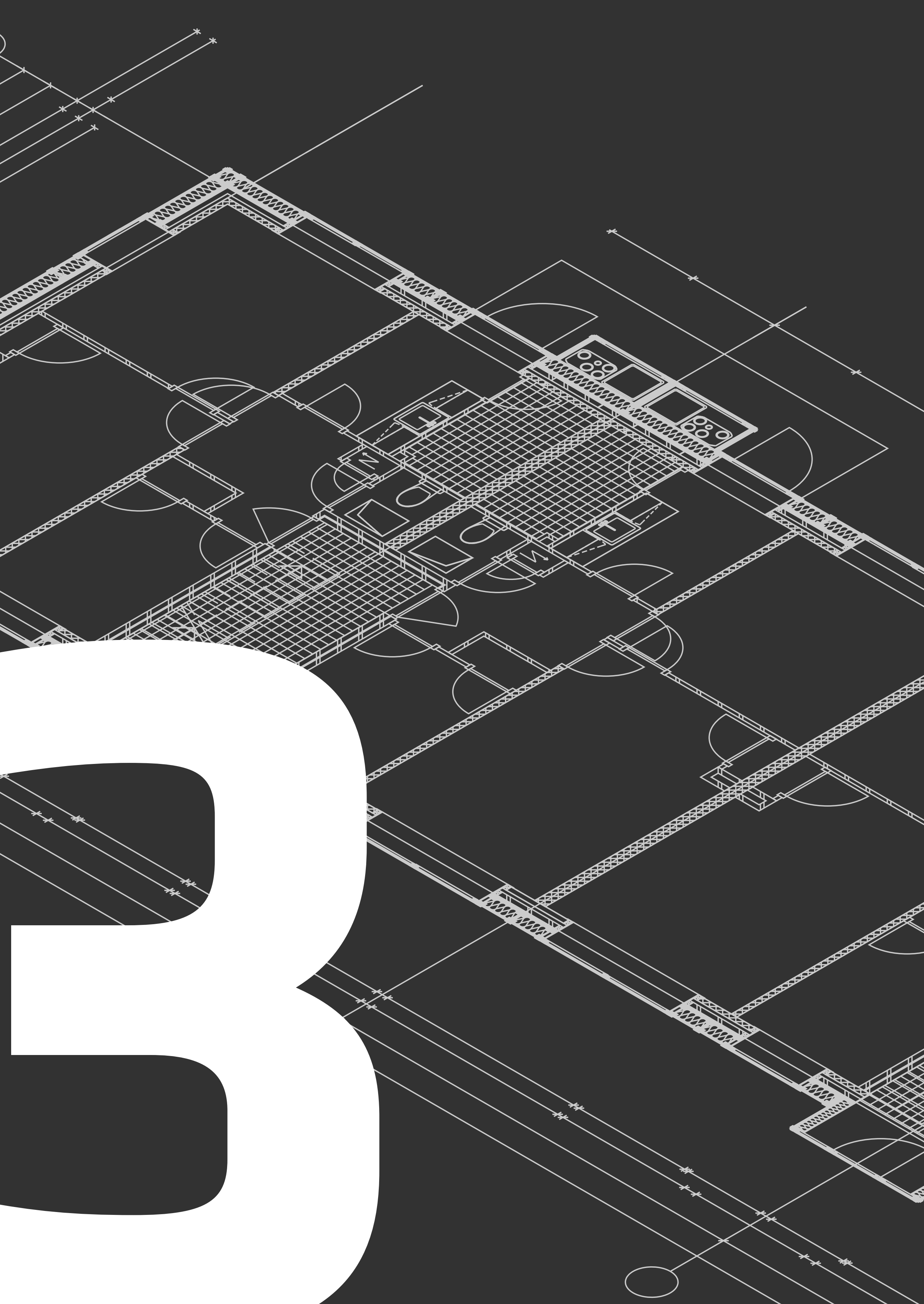
§ 2.6 Chapter 8: Concept Production

In chapter 8 the design tools are evaluated based on the criteria from chapter 7 and a final set of design tools is combined to produce several design concepts to investigate several possible solutions. The chosen concept is further elaborated on a component level in order to prepare the design for the case study application. The chapter follows an abstract to detailed path.

§ 2.7 Chapter 9: Case study Application

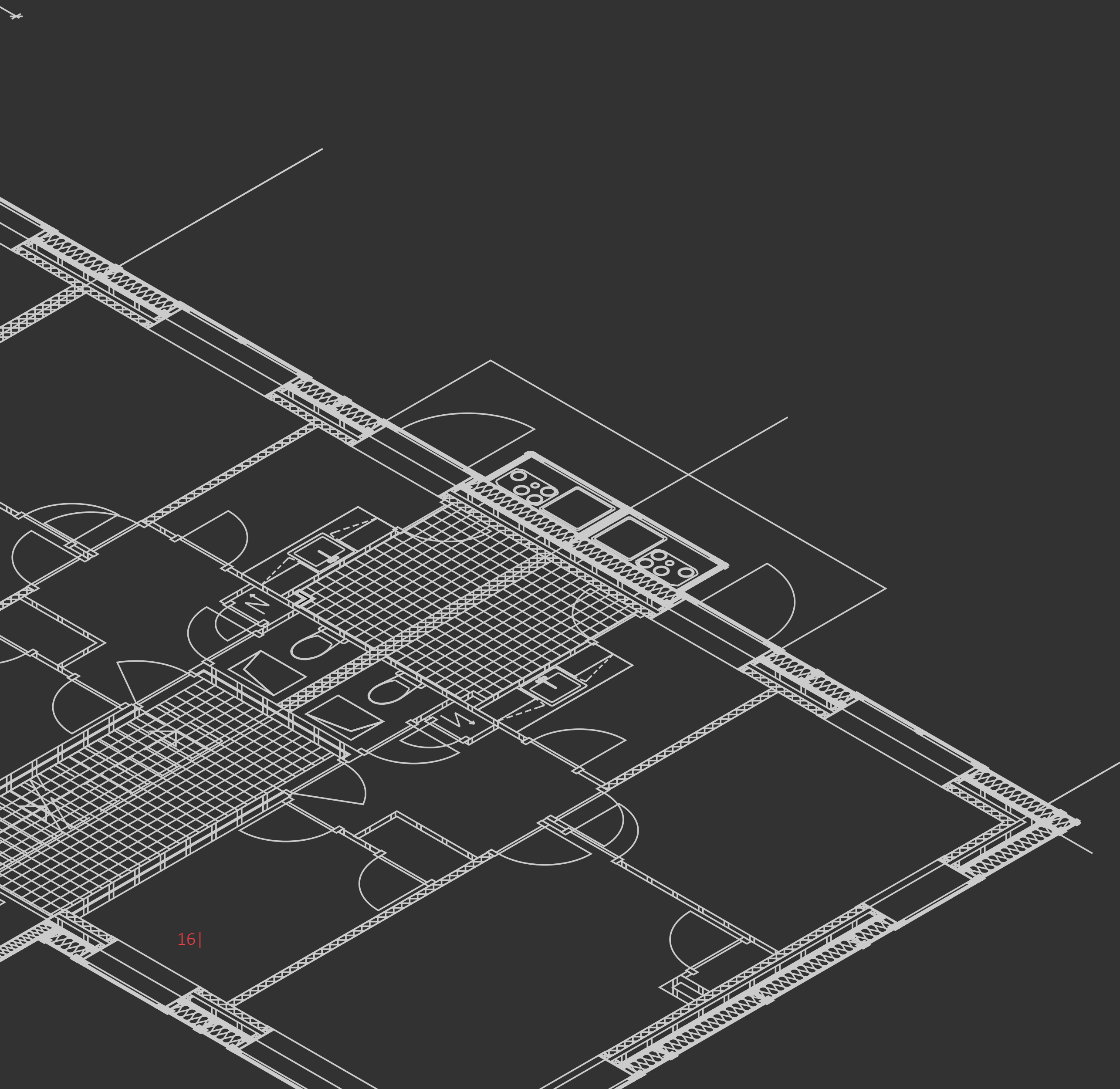
In chapter 9 the final design is applicated on the case study and further elaborated with sections, elevations, isometrics and details. Two separate scenarios are constructed based on the literature review and case study analysis. Both scenarios are compiled of a timeline with specific measures that are taken per timeslot. The measures are then translated to step-by-step actions that need to be performed to the building envelope system's design in order to evaluate if the intended resilience to these changes is achieved.

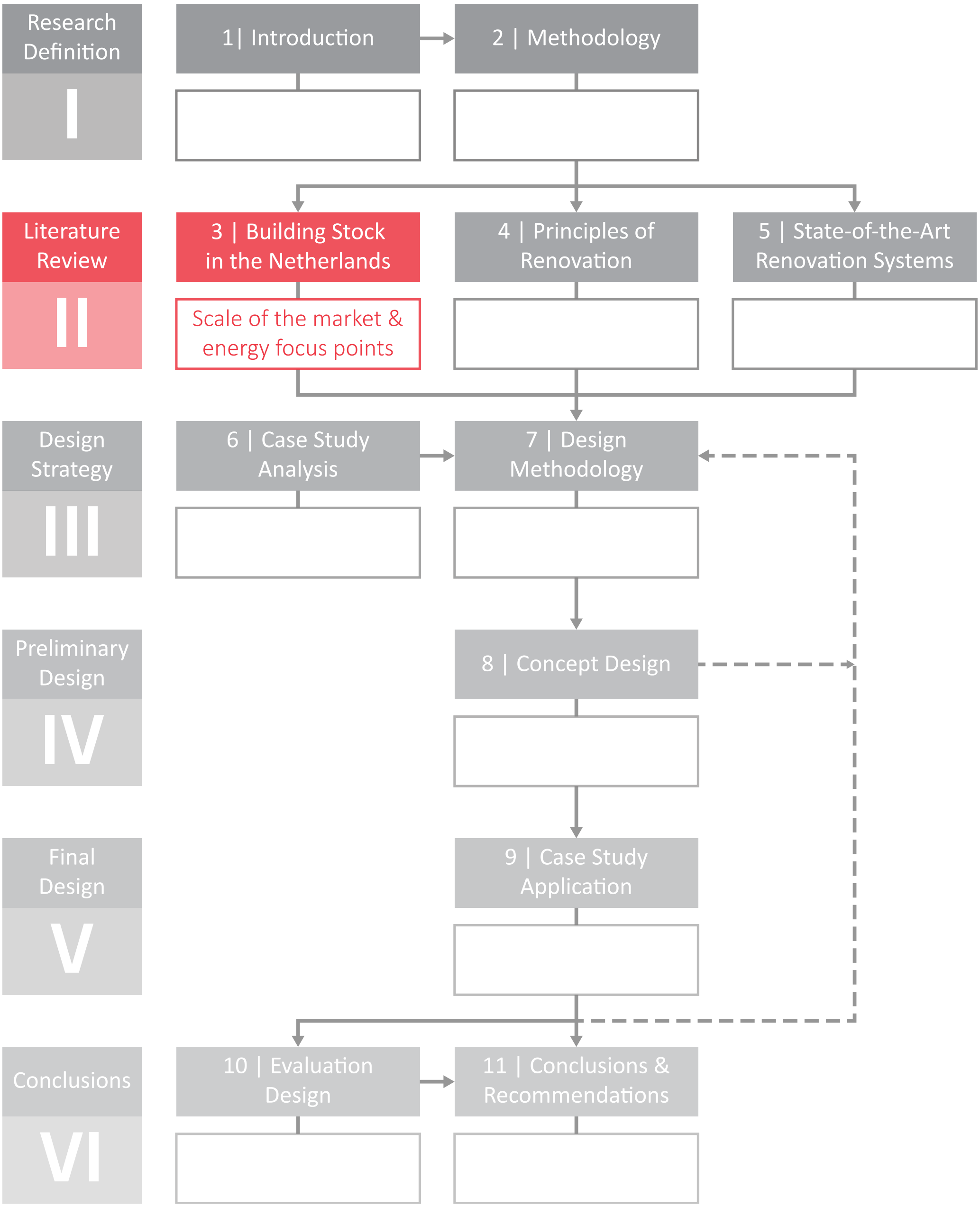
3



CHAPTER 3

BUILDING STOCK IN THE NETHERLANDS

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3 Building Stock in the Netherlands

In chapter 3 the current situation of the renovation market is elaborated further. The chapter follows a large scale to small scale structure in order to portray a wide, as well as detailed overview of the current context. Furthermore, it gives the terminology in which dwellings are measured based on their energy performance.

Paragraph 3.1 starts off with addressing the Dutch building stock in numbers in order to define the scale of the issue. In paragraph 3.2 focusses on the part of the stock that is eligible for renovation. Paragraph 3.3 follows up with argumentation of why renovation is preferred over demolition. Paragraph 3.4 delves deeper into the individual incentives to renovate. Paragraph 3.5 zooms in to the building level and describes the energy consumption distribution of individual dwellings. Paragraph 3.6 then focuses on energy labels, through which dwellings can be measured and compared.

§ 3.1 Building Stock

As of January 2012, the Dutch building stock encompasses exactly 7.266.295 dwellings that house around 17 million people. Since 1985 the building industry realised around two million dwellings (37%), at a pace of around 100.000 dwellings per year till 1995 until around 60.000 a year in 2011 (Ministry of National Affairs and Kingdom Relations, 2013). Although the building industry slowed down the pace of realising new dwellings there is still a considerable amount of stock added to the total every year. The prognosis is that another 1.2 million new household will be realised by 2040.

The composition of the Dutch building in terms of number of rooms has seen a slight increase in people living in dwellings with five or more rooms, and a slight decrease of people living in four rooms (Ministry of National Affairs and Kingdom Relations, 2013). The percentage of people living in one or two rooms and three rooms has been percentage wise relatively stable. Furthermore, the amount of people living in single and multifamily dwellings has been relatively stable since 1985.

The main transformation the building stock has gone through in ownership status is the transition of renters' market to a buyers' market, where the percentages have flipped to respectively 40% and 60%.

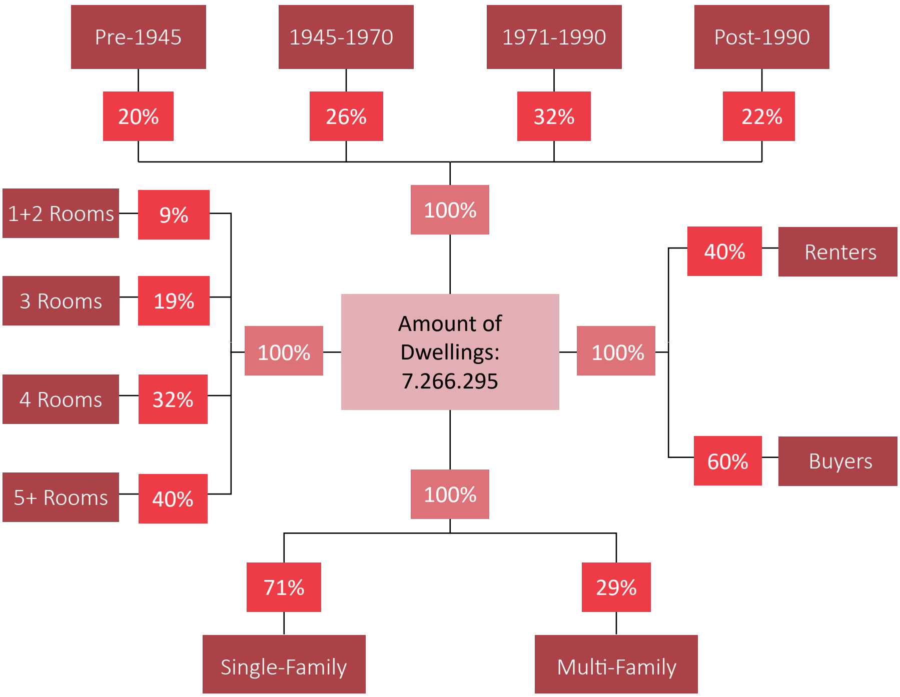


Fig. 3.1.1: *Dwellings divided in categories (Ministry of National Affairs and Kingdom Relations, 2013).*

§ 3.2 The Renovation Market

The largest growth in the building stock was after second world war until 1970 where the building stock had to accompany the steep growth of the population. As of 2012 these dwellings amounted to around 1/3 of the total building stock, to accompany a growth of around four million people (Itard & Meijer, 2008). In this period the implementation of prefabricated systems was introduced to accompany this growing demand. The majority of buildings were built using a new prefabricated system: system dwellings. An industrialised approach that focused on quantity instead of quality. This new approach cut down significantly on costs due to the decrease of construction time on-site.

Finally, about 20% of the total stock consists of pre-1945 built dwellings (Ministry of National Affairs and Kingdom Relations, 2013). These typologies of dwellings are still popular on the building market but are also ones that have the poorest energy performances, which we will elaborate further on in paragraph 3.5.

§ 3.3 Demolition or Refurbishment

Both these age bands of dwellings are candidates for either demolition or renovation. The building industry often promotes demolition and new construction, due to the preference to conserve a business-as-usual course, and other related profit related motives of involved parties, such as housing associations and the municipalities (Konstantinou, 2014). The main disadvantage of the approach is that it is costly, slow and unpopular. Demolition often includes the relocation of occupants, where they have little say in, and occupants often struggle to find adequate replacement dwellings.

Furthermore, there is the ecological standpoint for renovation. Transformation of existing dwellings is a more environmental efficient way of achieving the same energy goals, as most of the building mass and structure rarely needs replacing. As a result, new homes use four to eight times more resources than an equivalent refurbishment (Itard & Klunder, 2007).

§ 3.4 Incentives Renovation

The incentives for renovation of the older building stock are widespread. In the first place, as stated in the background, the rapid depletion of the natural resources and the subsequent climate changes is the main reason to renovate the older building stock. The European Union aims to reduce the CO2 levels by 88 – 91% by 2050 (European Union, 2010) to counter these processes. The building sector is one of the key players in achieving these goals, as it comprises 40% of total energy consumption in the European Union. Out of this building sector the household sector constitutes to approximately 25% of the total energy consumed. Energy is consumed in the building sector through manufacturing of building materials, transport of materials, construction of the building, operating the building and finally through demolition. The original building stock is well known for its inefficiency in all sections of the process, although that is a negative given there is also a large potential for improvement through renovation. In paragraph 4.6 we will further discuss the relationship in the total energy consumption between these sections of the building process.

When looking at the bigger context, adequate research of the impact of renovation of energy inefficient residential buildings to reduce energy consumption and tackle greenhouse gas emissions is avalaible and legislation to enforce it, but it is rarely the main motivation for the owner of manager of a property. Renovation is often initiated by the need of a technical or functional upgrade, such as resolving the building physical problems, along with financial and social motivation (Konstantinou, 2014). These motivations are often interconnected and can differ per individual project.

Financial motives can be deemed as one of the main influences on deciding to renovate or not. Investing in an energy efficiency renovation has a direct benefit on reduction of energy bills and easily accountable payback time. Furthermore, resolving technical damage and increasing the energy efficiency generally lead to higher property values. The downside is the initial investment that is required, which could have a deterrent effect. Keeping these initial investments as low as possible should lead to higher acceptance to renovate.

Social factors are also deemed necessary to include, renovation has the potential to regenerate socially problematic areas. In the bigger context renovation could lead to employment opportunities through the renovation market. In the residential sector, employment gains are typically higher than in other sectors (Konstantinou, 2014). The main barrier would be to prove the social benefits beforehand to stakeholders, which are harder to predict.

In order to achieve the goal of 2050 also the Netherlands is doing its part, through the project “stroomversnelling”. The stroomversnelling is platform instituted by the Dutch minister of housing in collaboration with stakeholders involved in renovation (Stroomversnelling, 2015). The stroomversnelling project’s goal is to accelerate the net zero energy dwelling projects and their first aim was reducing CO^2 emission by 20% in 2020, reducing it to the levels of 1997. The platform identified that the best way to reach these goals is through renovation of the older building stock, as the housing stock sector only grows with 1% per year. Focusing on just new built dwellings would not have the intended effect on the CO^2 emissions. Most project associated with the platform focus on zero energy dwellings.

In retrospect, the first incentive of this thesis is to reduce the energy consumption of the old building stock, as also stated by the European Union, and will always have the intended result: energy reduction. Secondary incentives, albeit financial, social or functional are context dependent and are harder to predict. The barrier of high initial investment costs should be considered, due to its large deterrent effect on stakeholders.

§ 3.5 Energy Consumption

The dwellings that are candidates for renovation are mostly built before 1981. Until the 1970s dwellings did not incorporate insulation at all. From 1960 until 1970 the first dwellings were realised with insulation, albeit relatively thin layers, as seen in figure 3.5.1. The turning point was the energy crisis of the 1970s, the high energy prices during this period led to the growing incentive to reduce the use of fossil fuels. In these years the first regulations regarding thermal resistance of facades were first introduced. The implementation of regulations is seen in the overall decrease in required energy through combustion of gas for heating per m^2 in figure 3.5.2.

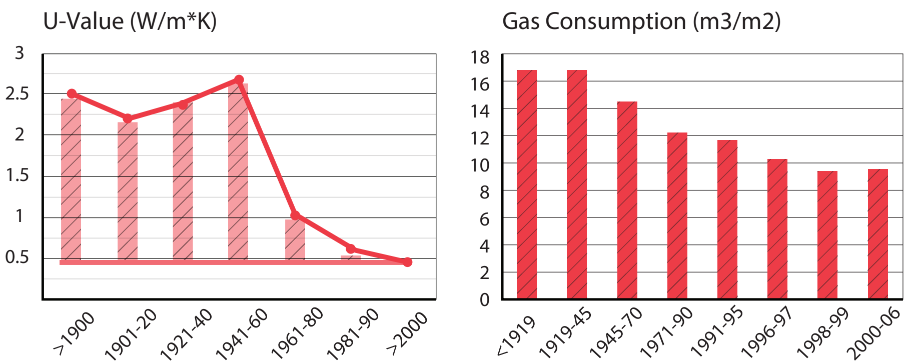


Fig. 3.5.1: *Average U-value façades in The Netherlands Through the years (BPIE, 2011).*

Fig. 3.5.2: *Average gas consumption per m² in the Netherlands for different typologies (Vollebregt, 2011).*

Apart from heating, other forms of energy consumption are required in dwellings, such as domestic hot water and electricity for cooking, lighting and other appliances. Still the major influencer is the space heating which accounts on average for 57% of the total energy consumption in dwellings (BPIE, 2011). Reduction of space heating is therefore the most important factor and can be significantly reduced through renovation of the building envelope. Although the overall gas use has declined through the decades the overall energy consumption has increased, this is due to the increased use of appliances and the increased living standards in The Netherlands and Europe. Improvements in energy efficiency per square meter and per appliance has been countered by the larger average sizes of dwellings.

The first incentive to target the dwellings built before 1981 is established. Although, as noted earlier, the dwellings built between 1961 and 1980 have a drastically higher thermal resistance then the dwellings built before that period, it is still two and half times higher than dwellings built after 2000.

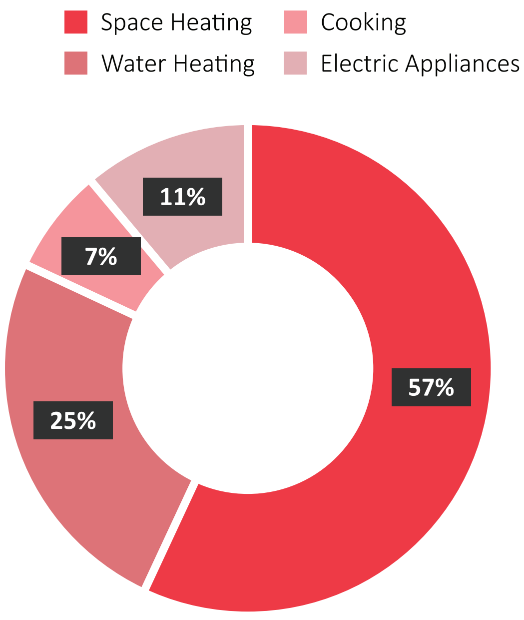


Fig. 3.5.3: *Distribution energy consumption (BPIE, 2011).*

§ 3.6 Energy Labels

In order to accurate measure and compare individual buildings is it required by the Energy Performance Building Directive (EPBD) for every building to have an energy performance certificate (EPC) (Konstantinou, 2014). The EPC indicates the energy performance of a building, determined either through calculated or actual annual energy consumption that are necessary for the building to run adequately.

The directive was implemented in 2002 is applicable to every member state of the European Union, although every country has its own minimum requirements for new buildings and renovations. The Netherlands already implemented a scale system before the directive that resembles the scale system of electrical appliances, rated from A to G. With A being the most energy efficient and G being the worst (BPIE, 2011). In the Netherlands the energy label is mandatory in order to sell or rent a dwelling and revalidation of the energy label is required after ten years.

The EPC is determined through calculation as described in the Dutch Building Code in article 5.2 (Ministry of National Affairs and Kingdom Relations, 2012). As of 2012 the building code uses NEN 7120 to calculate the EPC. It takes into account the building aspects, installations and standard occupancy behaviour. The EPC is expressed as an index, where the energy consumption of a building in 1990 is taken as the benchmark of 1.0. An EPC of 0.6 than indicates that the building consumes 40% less energy than the benchmark building. As of the first of January 2015, the minimum required EPC for new dwellings is determined at 0.4.

An EPC of 0.4 translates to a thermal resistance of the ground floor of 3.5 m^2*k/w, the façade 4,5 m^2*K/w and the roof of 6.0 m^2/k*W. It should be noted that due to the difference in façade surfaces between, for example, a detached dwelling and a row house the thermal resistance value should be adjusted accordingly. Correcting factors can be found in NEN 7120.

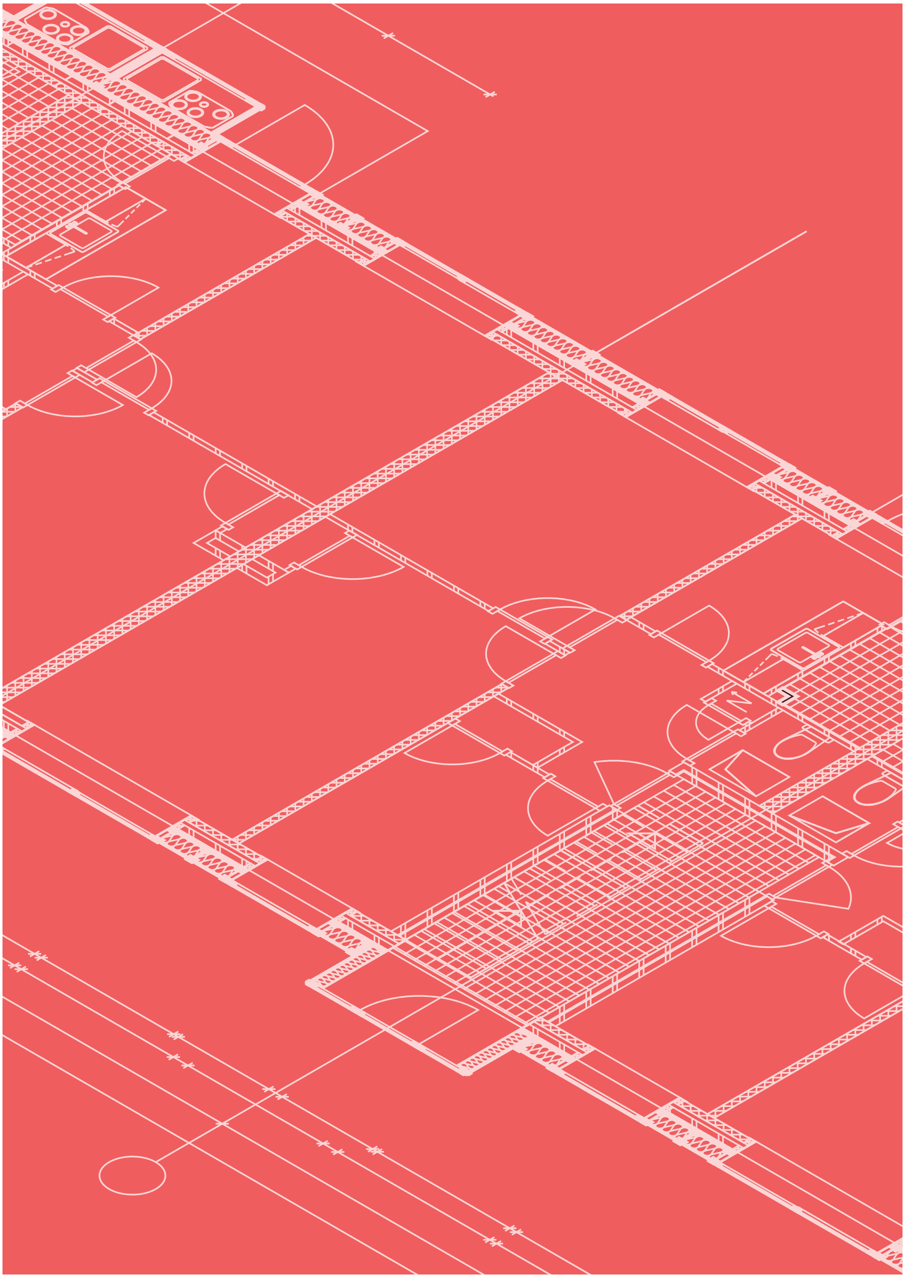
If we rank the dwellings built before 1981 on the grading scale of the energy labels, the majority would be labelled as D or lower. D translates to an EPC of 1.8 (Netherlands Enterprise Agency, 2018), which amount to 80% more energy consumed than the benchmark buildings. The energy savings potential is enormous for this sector.

§ 3.7 Conclusion

Based on chapter 3 the following conclusions can be drawn. The buildings with the most potential for large scale renovation are the dwellings built after world war II when prefabricated systems were first implemented. These dwellings have overall poor architectural quality and were built without energy reduction measures. Furthermore, large scale renovation can be performed on these dwellings due to comparable building techniques and dimensions.

The main incentive for renovation is achieve the goal of the European Union to reduce CO^2 levels by 88-91% by 2050. Secondary incentives, albeit financial, due to creating new jobs, or social, due to rejuvenation of problematic areas, are context dependent and are harder to predict. High investment costs should be considered when renovating building, due to its high deterrent effect on stakeholders.

In dwellings the main energy consumers are space heating at 57% and water heating at 25% and should be addressed in energy reduction renovations. In order to compare buildings and buildings before and after renovation energy labels can be utilised, such as EPC. EPC describes the annual energy consumption of a building and is expressed as an index, with an average building from 1990 serving as the benchmark at 1.0 EPC. The average EPC of the targeted buildings in this thesis is 1.8, for new buildings this set at 0.4, further decreasing in the future.



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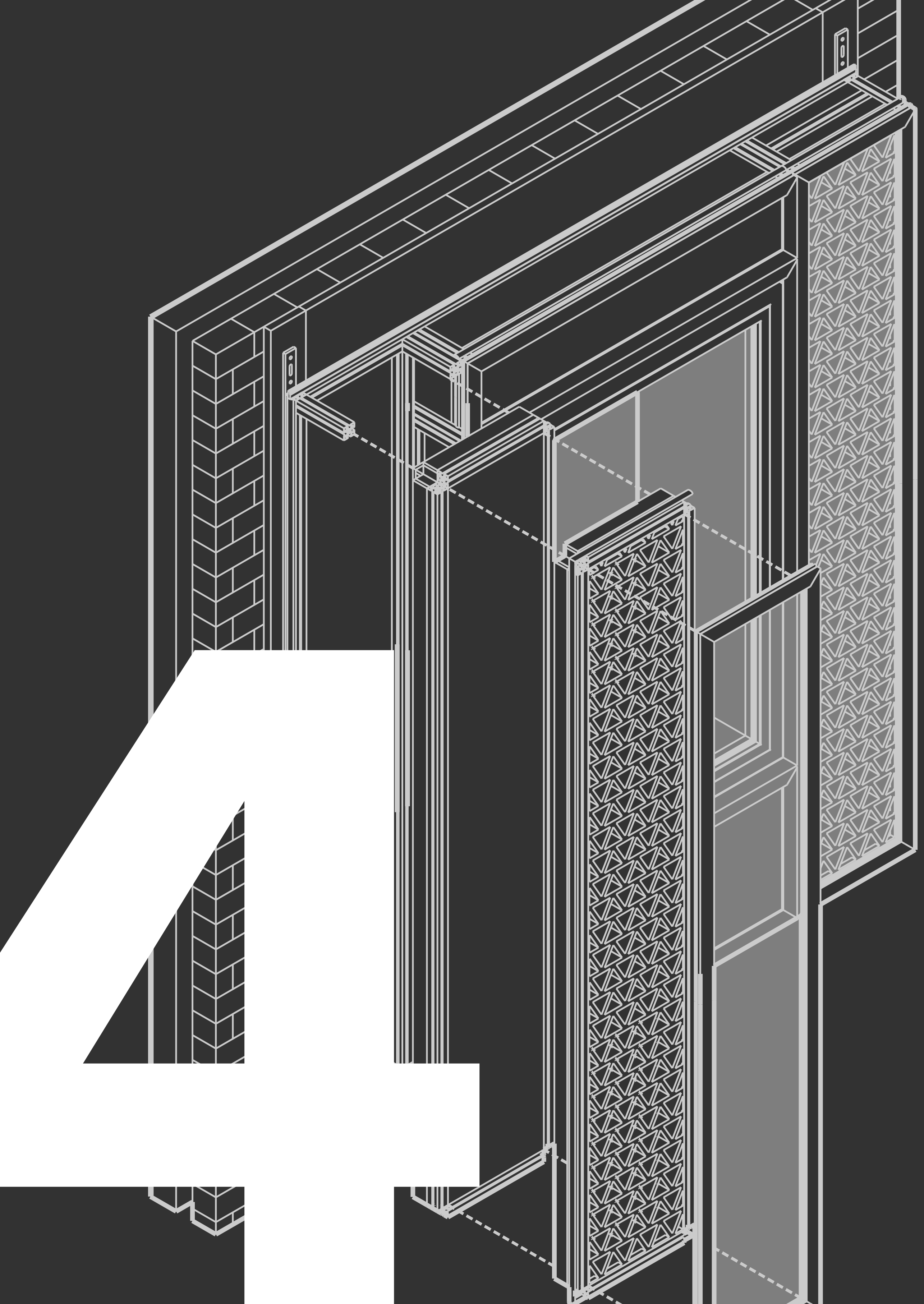
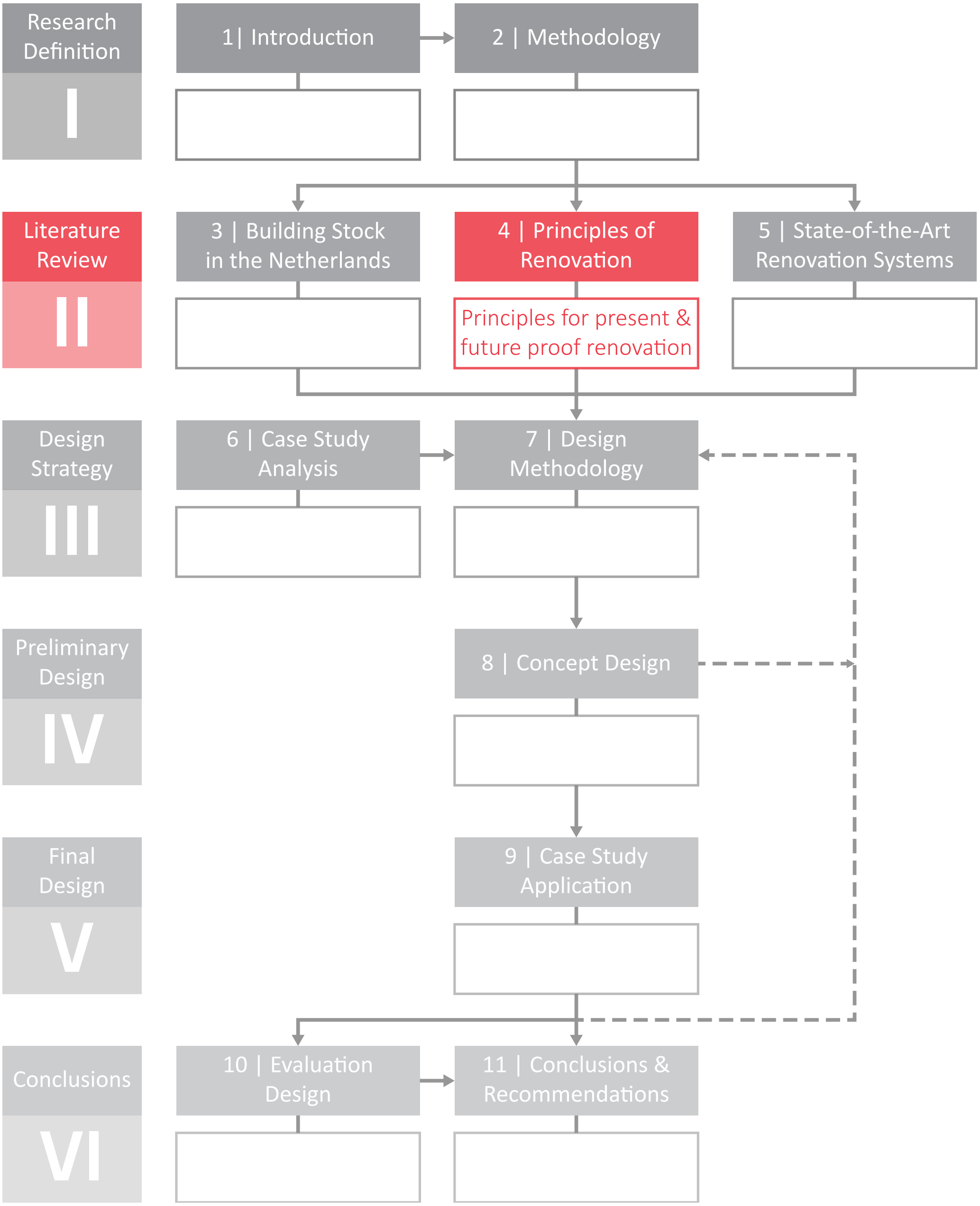


CHAPTER 4
PRINCIPLES OF RENOVATION


Research Definition
I
1| Introduction
2 | Methodology
Literature Review
II
3 | Building Stock in the Netherlands
4 | Principles of Renovation
Principles for present & future proof renovation
5 | State-of-the-Art Renovation Systems
Design Strategy
III
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VI
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4 Principles of Renovation

In chapter 3 the context and scale of the renovation issue was elaborated. In chapter 4 the available principles and tools in order to produce an efficient renovation will be elaborated further. Furthermore, the principles of achieving a future proof renovation are elaborated.

Paragraph 4.1 will elaborate in a broader sense the different approaches that can be utilised in order to achieve an energy reductional renovation. Paragraph 4.2 lists the passive and active measures that can be directly used in order to achieve the energy reduction, which are elaborated in more detail in paragraph 4.3 and 4.4. Paragraph 4.5 will discuss the principle of the circular economy and the tools that can be used in order to formulate a future proof design. In paragraph 4.6 the life cycle assessment is introduced and how it can be utilised to measure the effectiveness of the renovation through the years. Paragraph 4.7 elaborates on the different renovation levels in terms of energy reductional percentages, which is coupled in paragraph 4.8 to the ambitions of the European Union to a determine renovation plan through the years. Paragraph 4.9 will then discuss the strategies that can be utilised and which strategy is compatible with these ambitions.

§ 4.1 Energy Approach

The next step in reducing the energy consumption, while simultaneous increasing the living conditions, of the original building stock is defining an appropriate strategy and defining the steps to accomplish that goal. To achieve nearly-zero energy dwellings that use less fossil fuel energy sources, a wide variety of design techniques can be utilised. Techniques, such as appropriate component selection, in this thesis materials and systems, taking into account the local climate in the building renovation, utilise the positive effects of the sun and the air and protect against its negative effects. The combination of this effects ensures a holistic approach to the renovation process, commonly referred to as environmental or bioclimatic design (Konstantinou, 2014).

Bioclimatic design, as developed in 1960s by the Olgyay brothers (Konstantinou, 2014), is an approach to building design that encompasses a variety of criteria that are unique to every project. Criteria, such as location, surroundings, typology and orientation, and transform these criteria into a design brief. The goal for every project is to incorporate the advantages of the criteria, as well as protecting from the disadvantages. Advantages such as solar radiation, wind direction, availability of water and vegetations. And disadvantages, such overheating and heat loss. All these criteria should be formulated in such a way that the goal is to achieve sustainable buildings that retain from damaging the environment and promote building physical comfort.

§ 4.1.1 *Trias Energetica*

A concept that buildings upon bioclimatic design is the Trias Energetica. The Trias Energetica is the most commonly used strategy to ensure that taken sustainable measures are implemented efficiently. The concept was introduced by Lysen in 1996 (Ministry of National Affairs and Kingdom Relations, 2015) and further improved by Duijvestein. The Trias Energetica consists of three individual steps: Firstly, the energy demand should be minimized. Secondly, the remaining energy demand should be provided via renewable energy sources. Thirdly, if an energy demand still remains, and the use of fossil fuels is inevitable, the systems using fossil fuels should be as efficient as possible.

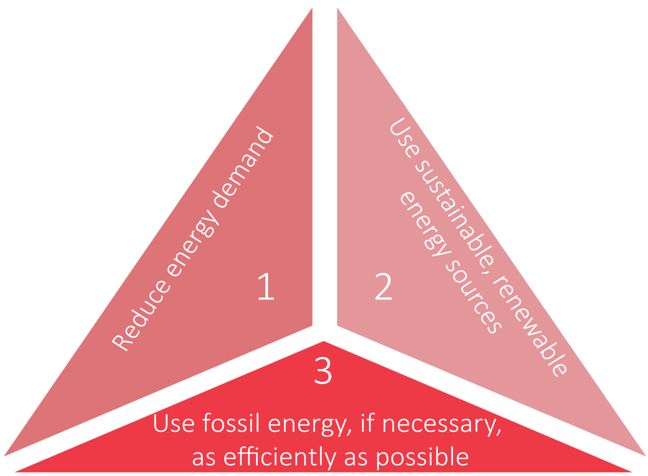


Fig. 4.1.1: *Trias Energetica (Konstantinou, 2014).*

§ 4.1.2 *New Stepped Approach*

Although the concept Trias Energetica is an abstraction of the process of sustainable building, as concrete measures have to be taken by the designer, there is widespread critique on the strategy. The critique on the approach is the lack of progress it produced in the Netherlands (Van den Dobbelsteen & Tillie, 2011). In particular, the impact of step two, the use of renewable energy, is minimal, as 96% of the Netherlands still relies on non-sustainable energy.

This is why Van den Dobbelsteen suggested to revamp the Trias Energetica and add a new step: The New Stepped Strategy. This strategy adds an intermediate step between step one and step two, respectively the minimisation of the energy demand and the use of renewable energy sources: The reusing of waste streams. The use of fossil fuels is removed from the equation.

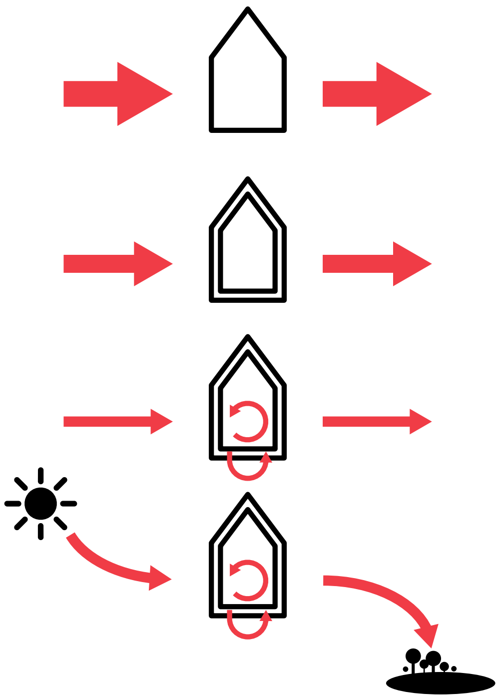


Fig. 4.1.2: *New Stepped Approach (Van den Dobbelsteen & Tillie, 2011).*

§ 4.2 Passive and Active Measures

Both approaches rely on two groups of measures in order to be successfully executed. The passive measures and the active measures. Passive measures rely on minimising energy demand and maximizing energy gain. Active measures rely on the production of energy and usage of energy through heating, cooling, ventilation and lighting and appliances. Figure 4.2.1 presents an overview of the different passive and active measures.

In the following paragraphs the individual passive and active measures are described further. Not every measure is relevant in the context of this thesis. For instance, measures that cannot be applied to the building envelope, measures that are site specific, measures that are not applicable to the Dutch climate, measures that require major adjustments to the building's structure or shape and measures that are very costly are all excluded.

§ 4.3 Passive Building Design Measures

Passive measures are measures that reduce the energy demand of a building by incorporating the local climate, the building layout and the material properties. Passive measures can be indexed based on three different levels of functionality: Heat protection, solar heat gain and heat rejection.

§ 4.3.1 *Heat protection*

A building façade should be adequately designed in order to prevent heat flow due to temperature differences, which is both beneficial during summer and winter. The main strategies to utilise in order to achieve a low thermal transmittance is by using insulation for the opaque parts of the façade, increase air tightness and utilising insulated windows for the open parts.

Insulation

An insulative material is a material with a high thermal resistive value that prevents heat flow between adjacent rooms with a temperature difference. Most insulation materials also have a positive effect on sound insulation. In general insulation material can be subdivided according to their raw material origin basis: organic, inorganic/mineral or oil-derived (Konstantinou, Ignjatović, & Zbašnik-Senegačnik, 2018). Furthermore, insulation materials manufactured through artificially means also exist, such as vacuum insulation panels.

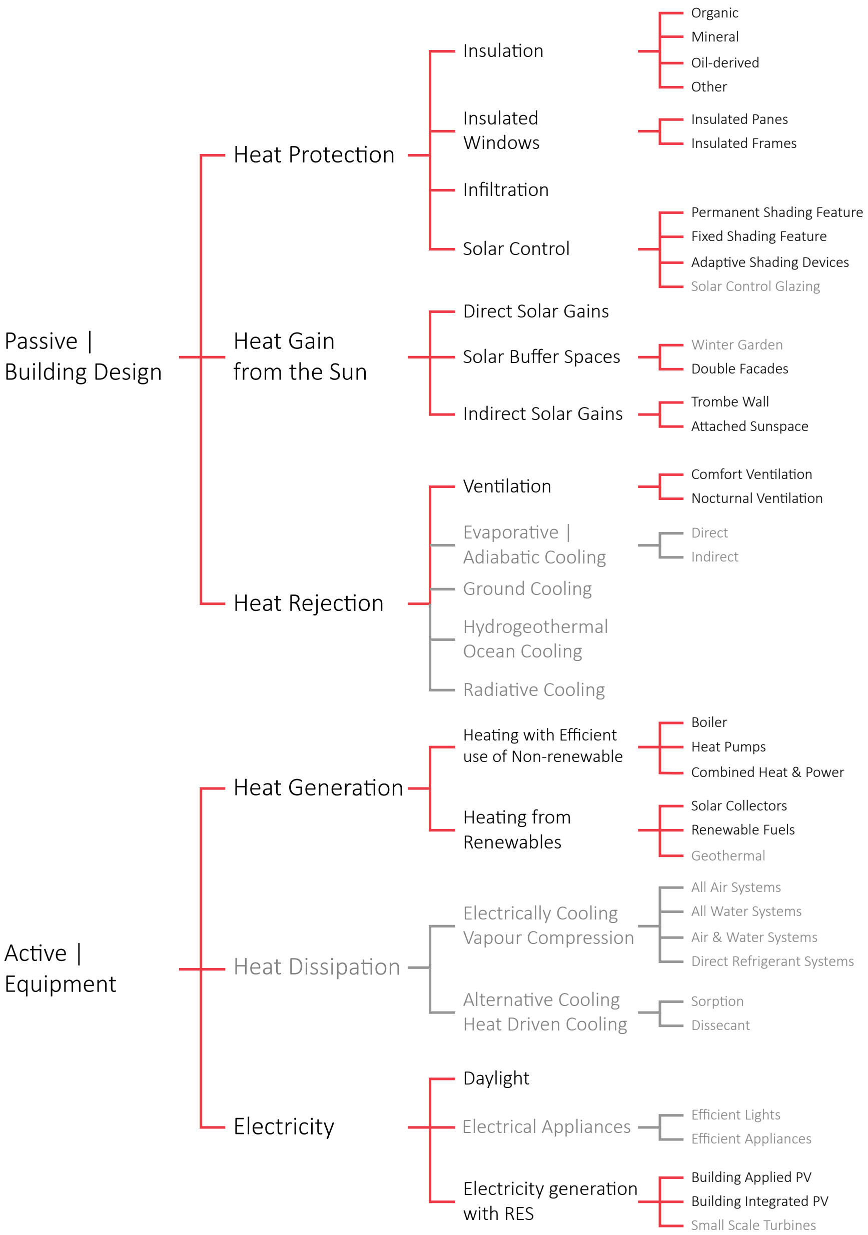


Fig. 4.2.1: *Overview of design principles of passive and active measures, in conjunction with Trias Energetica Steps, measures that are not applicable to a renovation project are greyed out (Konstantinou, Ignjatović, & Zbašnik-Senegačnik, 2018).*

Insulation material can also be subdivided based on form: Fibre, foamed and granulate insulation. The application is the dominant factor in selecting a suitable form of insulation. For instance, granulate insulation can be inserted in between structurally hollow places. Insulating panels or matting are cut to size and can be installed accurately that way. Foam insulation are suitable for external application due to their increased strength (Dubois, Remy, & De Bouw, 2016).

Insulated Windows

Windows fulfil are important components of the building envelope that in first instance supply necessary daylight and ventilation to the interior. Furthermore, they provide a view to the exterior. The downside is the poor thermal resistance that most window configurations possess.

The insulative value of a window can be increased in three ways that can be used in conjunction with each other: By increasing the amount of glass panes and subsequently the number of cavities the thermal insulation of the windows can be increased due to the increased volume of air. If the cavities are filled with a less conductive, slow-moving gas, such as krypton or argon, the thermal resistance can be increased further. Furthermore, by adding a low-emissivity coating the surface emissivity of the of the glass can reduced. These coatings consist of a microscopically thin layer of metal oxide or semiconductor film and are applied on the faces between the panes, facing the cavity.

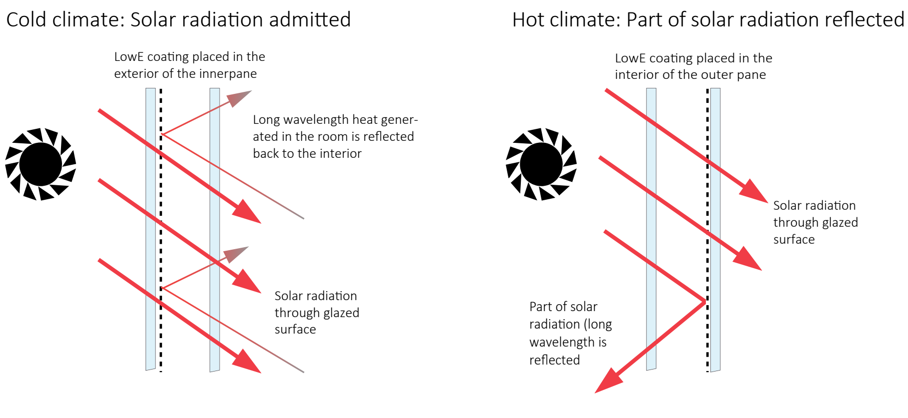


Fig. 4.3.1: *Diagram of coating placement (Konstantinou, et al., 2018).*

As important as the glazing is the window frame. Window frames come in a wide array of materials and combinations of materials. When choosing materials with high thermal conductivity it is important to incorporate thermal breaks to avoid thermal bridges. Most commonly window frames, consists of timber, aluminium, steel or plastic. The choice of the frame depends on the cost, the properties and the architectural expression.

Infiltration

Infiltration describes the movement of air through leaks, cracks or other adventitious openings in the building envelope. Air leakage is one of the leading causes of heating energy loss. Air leakage occurs at joints of the building envelope, such as door and windows, cracks, etc.

Adequate airtightness has to be considered during the production of the building envelope system as well as when the system is applicated. The type of leakage should dominate the decision for a suitable solution. Air barrier membranes and sealants, such as expanded foam, gun-applied sealants, tapes and filllers can be utilised to prevent uncontrolled air and water flow through the construction (Konstantinou, et al., 2018).

Solar Control

Solar radiation can have a positive effect during the winter, but during the summer it should be prevented from entering the interior due to overheating problems. Solar control is best applied on the exterior of the façade. Interior shading is not as effective as the heat already entered the interior, but does requires less maintenance then exterior shading.

Furthermore, a distinction between fixed and movable systems should be noted. Fixed systems require less maintenance, are more efficient if adequately designed, but offer no possibility of user control. This leads to varying performance throughout the day.

When choosing horizontal or vertical shading types is determent on the orientation of the relevant façade. Horizontal shading is effective in blocking sunlight on the southside, while maintaining a clear visual path to the exterior. A cantilever is a suitable option for seasonal shading, blocking the high angled sun during the summer, while allowing the low angled sun during the winter to penetrate the interior. On east and west façade vertical shading is more effective due to the lower angled sun.

§ 4.3.2 ***Heat Gain***

Passive solar heating is beneficial during the winter when energy for heating of the interior is needed to create a thermally comfortable indoor environment. Through the utilisation of transparent elements in the building envelope the solar energy can be collected and distributed to the interior without the use of mechanical equipment (Konstantinou, et al., 2018).

Direct Solar Gain

Sunlight is directly collected via glazed surfaces of the façade, especially on south facing surfaces. Glass is permeable for ultraviolet radiation emitted from the sun, but impermeable for long-wave heat radiation, emitted from materials. Heating a interior space with direct solar gains is dependent on the orientation, the position and size of the transparent areas, as well as the interior layout.

Solar Buffer Space

A solar buffer space is a space in between the interior and the exterior. The space is exclusively heated by solar irradiation. Transmission losses between the interior and exterior are hereby reduced due to the higher temperature in the buffer space, which leads to lower transmission losses.

A different way to create a buffer space is through the use of double façade constructions. Double facades consist of two separate facades placed in succession of each other to create a buffer space in between.

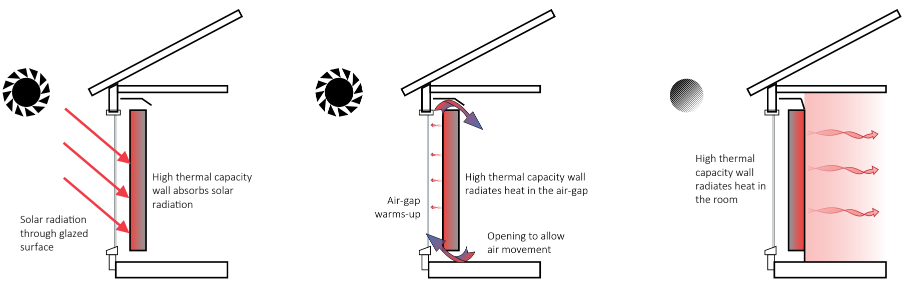


Fig. 4.3.2: *Principles of Trombe wall and attached sunspaces (Konstantinou, et al., 2018).*

Indirect Heat Gain
Indirect solar heat gain occurs when components with high thermal mass store heat. This can be done by placing a heat-absorbing element between the incident solar radiation and the interior that needs to be heated.

When the solar energy passes through the transparent layer and is absorbed by the heat-absorbing element it can be used to heat the interior several hours later when the temperature drops. The most commonly known technology that utilises this principle is the Trombe wall. Due to the fact that a Trombe wall needs to be directly connected to the interior space, it is difficult to apply to renovation projects where the existing building envelope is not removed and replaced with a new envelope.

§ 4.3.3 ***Heat Rejection***
Heat prevention strategies are an effective method of preventing heat from entering the interior of a building, which reduce cooling demands. Although the cooling demand is lowered heat prevention strategies alone are usually not enough to lower the interior temperatures to comfortable levels for occupants. It is therefore necessary to utilise passive strategies aimed at transporting heat generated or stored indoors to the exterior of the building.

Heat rejection strategies aim to remove indoor heat and release it into an exterior heat sink, such as air, water or ground. Passive strategies accomplish this without energy consumption although the system can potentially benefit from additional equipment, such as fans and pumps, which are called hybrid or low-exergy heat rejection systems.

The heat rejection strategies are categorised based on the heat sinks they utilised as the base for their cooling principle (Samuel, Nagendra, & Maiya, 2013). For renovation the most relevant technique is heat dissipation through ventilation.

Ventilation
The most widely used method for heat dissipation strategy. Two main categories of ventilation based on: Comfort ventilation or nocturnal ventilation (Konstantinou, et al., 2018). Comfort ventilation is utilised when the occupants finds it necessary, improving the occupants perceived comfort. Nocturnal ventilation is utilised during the night, removing heat to cool the building down for the next day. Furthermore, three ventilation strategies based on spatial orientation can be distinguished: Single-sided ventilation, cross ventilation and stack ventilation. Single-sided ventilation will be applicable to every situation, whereas cross ventilation and stack ventilation are dependent on the configuration of the building.

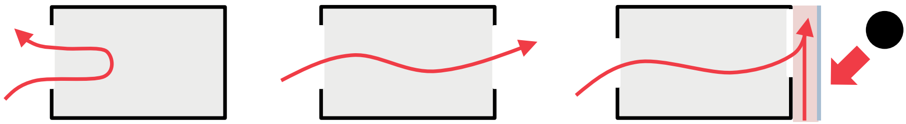


Fig. 4.3.3: *Ventilation strategies: single-sided, cross and stack ventilation ((Konstantinou, et al., 2018).*

§ 4.4 Active Measures

Passive measures alone do not ensure the complete elimination of the energy demand through all seasons, additional active measures need to be employed to achieve this goal. The active measures encompass all the technical building systems, which are the equipment utilised for heating, cooling, ventilation, hot water, lighting and the combination thereof.

§ 4.4.1 *Electricity*

As stated in paragraph 3.5 11% of the total energy consumption in dwellings can be attributed to appliances. Although this part is small in comparison to, for example, the space heating it should be considered in an energy reduction renovation, as it can contribute majorly to the energy performance of a building.

Daylight

Daylight can be used to significantly reduce the need for artificial lighting. For occupants, daylight is the preferred form of illumination in buildings, as it provides the best colour rendering for the human eye. Artificial lighting constitutes to around 10% of the total energy electricity consumption in dwellings. Replacing it with natural daylight as much as possible would positively reduce the energy demand of dwellings.

In renovation projects the chosen strategy determines the number of options available of increasing daylight penetration. For instance, when the existing building envelope is preserved the existing window dimensions dictate the window dimensions of the renovation.

§ 4.4.2 *Electricity Generation (RES)*

Electricity generation from renewable resources can further reduce the energy demand in buildings and can replace energy produced through fossil fuels. Renewable resources include solar radiation, wind and water movement. The most commonly renewable energy production technologies used on a building scale are photovoltaic (PV) panels and small-scale wind turbines.

The annual output of PV system is mostly determined by the orientation and angle of the panels surface. In the Netherlands the best possible configuration for the PV panels is south-facing at an angle of 30 to 35 degree (Israëls & Stofberg, 2017).

§ 4.5 Circular Economy

As important as energy reduction in existing buildings is, the life cycle of the renovation is important as well. An approach that address this matter is the circular economy. The Ellen MacArthur Foundation, frontrunner in promoting the concept, describes the circular economy as an industrial system that is restorative or regenerative by intention and design. The circular economy is based on the following principles (Ellen MacArthur Foundation, 2013).

- Design out waste. Waste should be eradicated by designing components to fit within a biological or technical materials cycle, designed for disassembly and refurbishment.

- Build resilience through diversity. Modularity, versality, and adaptivity are important assets that need to be prioritised in designs, in order to keep up with a world that is evolving at an accelerated rate. Diverse systems with bountiful connections and scales are more resilient than system built primarily for efficiency.

- Rely on energy from renewable sources. Same as with the Trias Energetica and the new stepped approach.

- Think in 'systems'. Describes the ability to understand how parts influence each other within a system, and the relationship of the system to its parts is crucial.

- Waste is food. Describes the ability to reintroduce products and materials back into the biosphere through non-toxic, restorative loops. Improvement are also possible on the technical side. Which is called upcycling.

Incorporating these principles into the design process will ensure the design will be more adapted to the future context, disregarding these principles will result in the design becoming outdated fast.

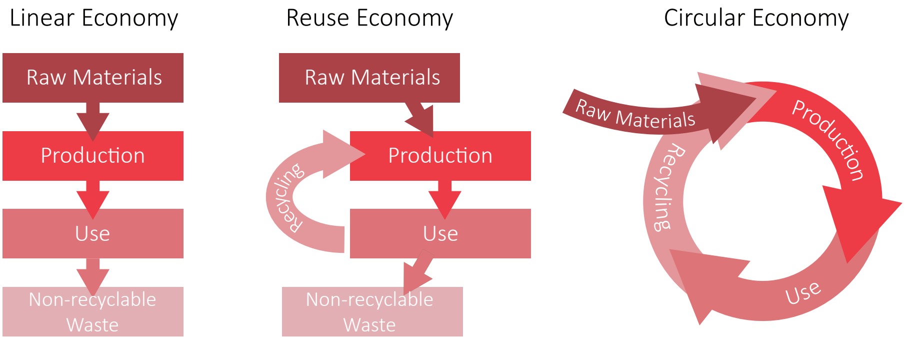


Fig. 4.5.1: *From linear to circular economy (Ellen MacArthur Foundation, 2013).*

§ 4.6 Life Cycle Assessment

As described in chapter 2 energy labels are required to sell or rent a dwelling. Nevertheless, energy certifications only refer to the operational energy and doesn't include other aspects related to the life cycle of a building. The life-cycle energy of a building consists of three energy types: the embodied energy, the operational energy and the demolition energy (Loussos , Konstantinou, Van den Dobbelsteen, & Bokel, 2015).

- Operational energy is the energy that is consumed to heat, cool, light and power the appliances in a building.

- Demolition energy is the energy that is consumed to demolish and dispose of the components of a building at the end of its life cycle.

- Embodied energy is the quantity of energy consumed to extract, process, produce and supply materials to the construction process. It is not only the energy to produce the building at the start of its life cycle, but also to maintain and renovate the building, called the recurring energy, is included in it.

A life cycle assessment is an analytical method used to comprehensively quantify and interpret these energy and material flows over the entirety of its life cycle, process and service. Different European standards, such as EN-15804 (2012), developed a systematic approach for the assessment of environmental performance of buildings based on a life cycle approach.

In order to accurately assess the life-cycle of a renovation first the system boundary has to be determined. The system boundary determines all the processes that are relevant and have to be taken into account for the object of assessment. For a renovation the boundary takes into account production and transportation of new building components, construction and waste management of the renovation process, and the end-of-life stage of replaced building components (Konstantinou, 2014).

The assessment of the environmental performance of buildings takes into account environmental information of construction products. Therefore, embodied energy is interrelated with the life cycle assessment. Information of the embodied energy of materials is most often provided by the products manufacture, or are found in the databases, such as the database of the Dutch Institute of Building Biology and Ecology (NIBE). Embodied energy is expressed globally in energy consumed in mega joule (MJ) and in global warming potential (GWP) in kilogram CO^2.

Although there are uncertainties regarding embodied energy values and the life-cycle assessments they can be used as benchmarks to determine the life-cycle performance of buildings. LCA should be integrated in the design process as the requirements of buildings, regarding energy and resources from building construction, operation and disposal, will further increase in the future.

§ 4.6.1 ***Embodied energy vs. Operational Energy***

When looking to the relation between embodied and operational energy, studies have shown that the relation between operating and total life-cycle energy is linear (Sartori & Hestnes, 2006) (figure 4.6.1). Hence, low energy consuming buildings are more energy efficient than conventional ones in terms of total life cycle energy, even though their embodied energy is higher. The importance of the embodied energy of the building's materials will grow, when nearly zero energy is needed to operate the building. For highly energy-efficient buildings, the embodied energy accounts for approximately 40% of the total energy consumed during a life cycle. The part of embodied and demolition energy consumed raises to 100% if the operational energy is zero (Loussos, et al., 2015).

Therefore, in the first case reducing the operational energy consumption should be the priority by using passive and active energy reduction measures, when low operational energy consumption is minimised the embodied energy should be addressed.

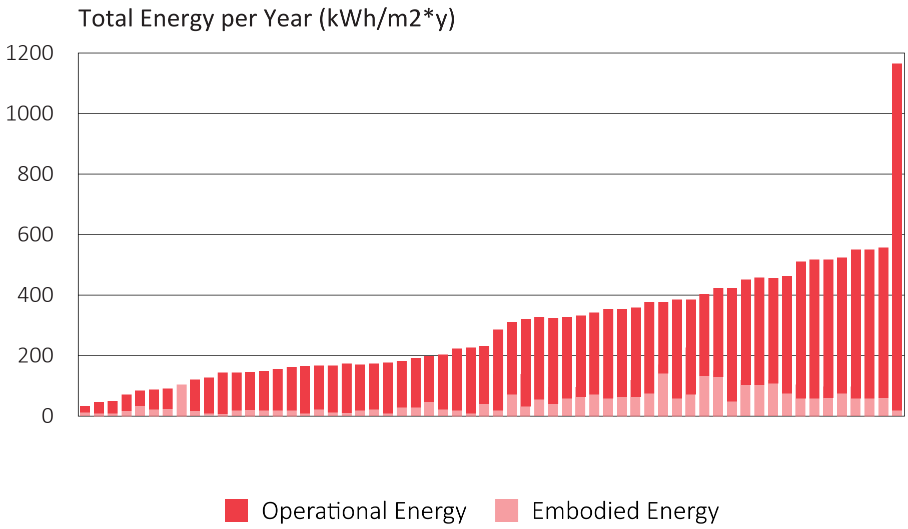


Fig. 4.6.1: *Operating energy versus total energy consumption (Sartori & Hestnes, 2006).*

§ 4.6.2 *Service Life*

Another important aspect of life cycle assessment is determining the service life of every component. Different components of the façade have different levels of durability and have different levels of required maintenance. The service life of a building or a component is described as the actual time during which the building or any of its components performs without unforeseen costs or disruption for maintenance and repair (Kayll, 2014). Figure 4.6.2 gives an overview of some materials and their different service lives in years.

In the table we can observe that there is a large variety in the service lives of different components within the façade, with a maximum difference of 39 years. Some components, such as the façade cladding can be replaced without the replacement of other components. Others, such as the sealings, could lead to the failure of the whole façade.

The ISO-15686 (Langston, 2011) on service life planning for buildings and constructed assets provides a basis of how to assess the durability of buildings. The estimated service life of any components is calculated as its theoretical life multiplied by a series of factors that influence the service life. These factors are: quality of components, design level, the work execution level, indoor environment, outdoor environment, usage conditions and maintenance level. It important to address all these factors in a design in order to maximise the service life of individual components.

Elements	Materials	Service life of the building's elements (years)		
		Minimal	Maximum	Average
Claddings	*Rendering*	20	81	50
	Paint	4	10	7
	Ceramic	15	57	36
	Stone	20	70	45
Windows, Doors and Protection Elements	*High Quality Wood*	10	69	40
	Aluminium	10	58	34
	PVC	10	49	30
Comices, Eaves, Door and window Frames	*Stone*	20	60	40
	Cement/Concrete	20	60	40
Joint's Seal		3	20	11
Fastening Elements/Doors and Window Fittings	*Galvanized Steel*	0	10	10

Fig. 4.6.2: ***Estimated service life for each façade element (Kayll, 2014).***

§ 4.7 Renovation Levels

Renovations on buildings are being done all over Europe and not every renovation achieves the same levels of energy reduction. This is due to the wide variety of parameters that can possible obstruct the ability of a building to be renovated. In this section we will categorise the different levels of renovations in order to distinguish the different options available.

The term “renovation” has been widespread used to describe a wide variety of improvements to an existing building. In this thesis the term renovation is used to specify that an energy performance upgrade is done on an existing building.

Qualitatively, a renovation done to the building façade, for example the wall and windows, will result in a lower energy reduction than a renovation that addresses the entire building envelope and its energy systems, such as HVAC and Lighting, as well as the utilisation of renewable technologies (BPIE, 2011). Therefore, it is beneficial to categorise the different levels of renovation.

The Building Performance Institute Europe ranks renovation levels according to energy consumption reduction, from minor to nearly zero energy building (nZEB) (BPIE, 2011).

At the most basic level, the energy performance of the building can be improved by the implementation of a single measure, such as replacing the boiler or the insulation of the roof space. The minor renovation level encompasses energy savings up to 30% through the application of one to three of these low-cost and easy to implement measures.

The most extensive renovation level involves a holistic approach, where all the components of an existing building, that are relevant to the energy use, are replaced or upgraded, as well as the use of renewable energy technologies for additional energy production. The goal of such a holistic approach is to reduce energy consumption and carbon emission levels to nearly zero, or in the case of an “energy positive” building to less than zero. An energy positive building produces more energy from renewable sources than it consumes over a full year (BPIE, 2011). When the reduction of the energy reaches the standard of a passive house, below 15 kWh/m^2 per year, the need for a traditional heating system is nullified. The passive house renovation is considered to be point at which the energy savings to investments costs are maximum, as is shown in table 4.7.1. The BPIE proposes to call these renovations with energy savings higher than 90% as nearly zero energy buildings (nZEB).

In between this minimum and maximum renovation levels are renovations with a number of replacements or upgrades. This group can be divided into "moderate" renovation, involving three to five improvements resulting in energy reductions in the range of 30% to 60%, and "deep" renovations, which utilises a holistic approach, using a wide array of measures working as a whole. Deep renovations reach an energy reduction in the range of 60% to 90%.

In retrospect, renovating every building to deep or nZEB levels can prove to be to costly for some buildings and stakeholders could be deterred to invest.

Description (Renovation Type)	Final Energy Saving (% Reduction)	Indicative Saving (for modelling purposes)	Average Total Project Cost (€/m^2)
Minor	0-30%	15%	60
Moderate	30-60%	45%	140
Deep	60-90%	75%	330
nZEB	90%+	95%	580

Fig. 4.7.1: *Renovation levels and their average costs per m^2 (BPIE, 2011).*

§ 4.8 Ambitions for Large Scale Renovation

In the last paragraph the different levels of renovation are elaborated, in this paragraph we will further discuss the ambitions of the Building Performance institute Europe. The BPIE is a non-profit organisation that was commissioned by the European Union to formulate scenarios in which the energy and CO^2 reduction goals of the European Union are achieved.

The BPIE developed a renovation model which allows scenarios to be examined in order to illustrate their impact on the energy use and CO^2 emissions. The variables used are the different percentages of buildings renovated each year and the different levels of renovation, as described in paragraph 4.7, these two variables are combined to formulate scenarios that result in individual prognoses up to 2050. It takes into account the reduction in cost for renovations through the years due to increased experience in renovation ("the learning curve") and growing competitiveness, as shown in figure 4.8.1 (BPIE, 2011). The two scenarios with the most impact on the CO^2 production will be elaborated further.

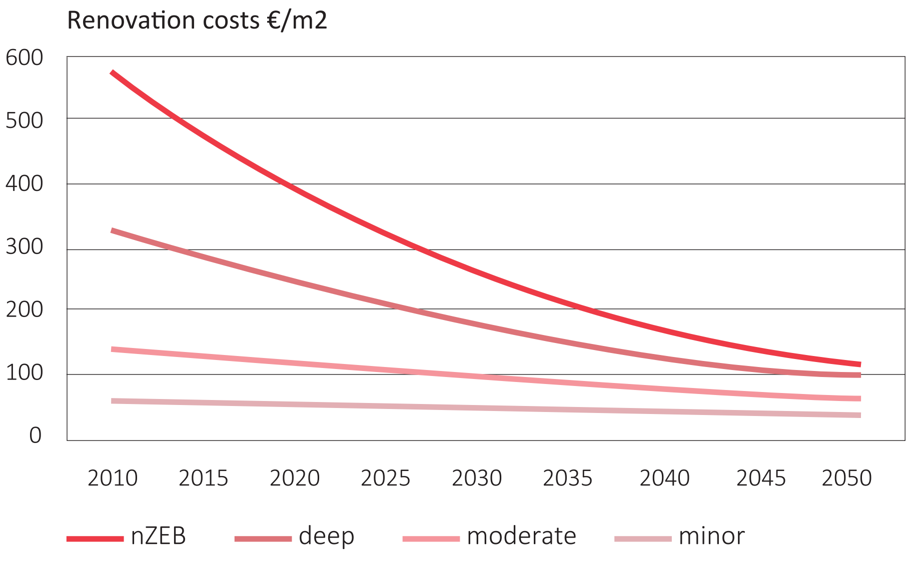
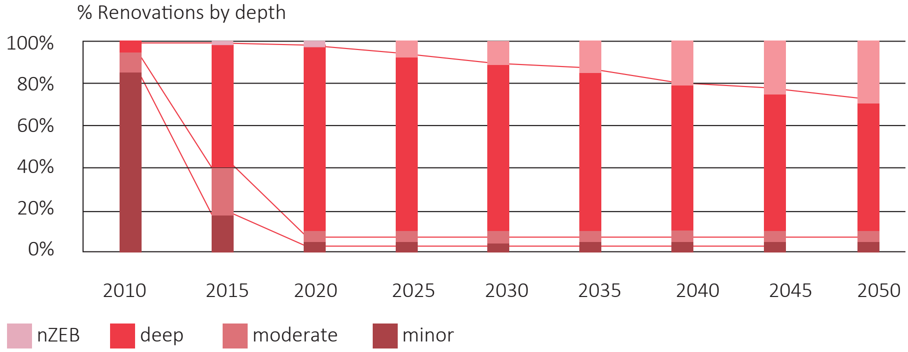


Fig. 4.8.1: *The learning curve (BPIE, 2011).*

In the deep renovation scenario (Fig. 4.8.2), deep renovations are the dominant renovation activity until 2050. nZEB renovations become more prominent from 2020 onwards to account for 30% of the total by 2050. Minor and moderate each account for 5% of the total.

The two-stage renovation scenario (Fig. 4.8.3) depicts a case where some properties are renovated twice with different measures. Properties that undergo minor or moderate renovation, get another upgrade 20 years later to deep and nZEB renovations.

The two scenarios and a third baseline scenario, portraying the effects if the renovation rate doesn't change at all, were compared and their effects on the CO^2 reduction untill 2050 are portrayed in 4.8.4. Based on the table a number of conclusions can be drawn.



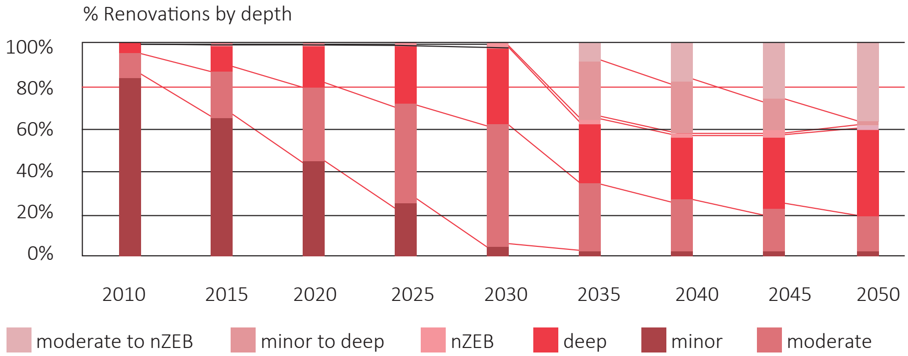


Fig 4.8.2: *(Top) Renovation Deep scenario (BPIE, 2011).*

Fig 4.8.3: *(Bottom) Renovation Two-stage scenario (BPIE, 2011).*

The deep scenario delivers the required energy and CO^2 savings as envisioned by the European Union. However, the steep increase in investments can have a deterrent effect on the motivation of the building industry to execute this scenario, as it is a step change compared to the current reality of renovation practices.

The two-stage renovation scenario achieves the best results concerning energy and CO^2 savings, while taking advantage of the learning curve. The step change is minimal, so the building industry will have a bigger incentive to follow this scenario then the deep scenario. Therefore, if renovations are designed to follow the two-stage scenario as described by the BPIE the potential to lower the investments cost could be even higher.

Scenario		0	3	4
Description	Unit	Baseline	Deep	Two-stage
Annual Energy Saving	*TWh/a*	365	2.795	2.896
2050 Saving as % of Today	*%*	9%	68%	71%
Investments Costs (Present Value)	*€ Billion*	164	937	584
Savings (Present Value)	*€ Billion*	187	1.318	1.058
Fast Decarbonisation				
Annual CO_2 saving in 2050	*$MtCO_2/a$*	742	932	939
2050 CO_2 saved (% of 2010)	*%*	71.7%	89.9%	90.7%
Slow Decarbonisation				
Annual CO_2 saving in 2050	*$MtCO_2/a$*	182	732	755
2050 CO_2 saved (% of 2010)	*%*	18%	71%	73%

Fig 4.8.4: *Overall results to 2050 (BPIE, 2011).*

§ 4.9 Renovation strategies

Every renovation project starts with defining a strategy. The building industry dealt with renovation issues using different strategies, that address a wide variety of functional and energy efficiency problems. These intervention strategies can be categorised in five main groups: Replace, add-in, wrapping, add-on and covering (Konstantinou, 2014). It should be noted that different hybrid strategies are also known to be used, where two or more strategies are used simultaneously. We will shortly review these strategies.

§ 4.9.1 *Replace*

Replacement of the original façade is one of the most common forms of refurbishment. The original façade is completely removed and a new better performing façade is applied. It is also possible to replace just the elements that are inadequate. The replacement of façades is applicable to a wide variety of buildings, such as building with façade panels or curtain walls.

§ 4.9.2 *Add-in*

When the building exterior of a building cannot be adjusted, due to for example monumental status, it is possible to the renovate the façade from the inside. Insulation can be added to the internal side of the external walls. This strategy is often accompanied with the replacement of the windows, as they are commonly outdated too. If the replacement of the windows is not allowed then secondary glazing can be added on the inside as an alternative.

§ 4.9.3 *Wrapping*

This strategy builds a second façade around the original façade. The second layer can consist of external insulation, covering up balconies through cladding or second facades. The main consideration, in order for this strategy to be implemented successfully, is to check if the construction of the building can carry the load of a secondary façade. This strategy is often accompanied with replacement of outdated building physical components and windows.

§ 4.9.4 *Add-on*

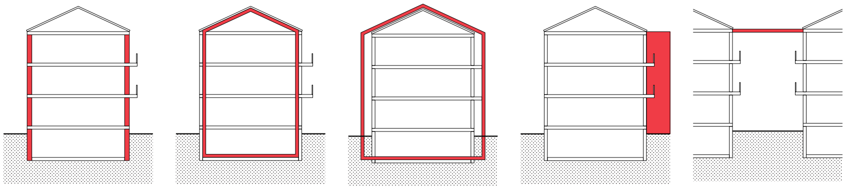
When a building requires a functional upgrade and extra space needs to be created the add-on strategy can be employed. The add-on strategy includes a wide variety of upgrades that can be used. From adding new balconies to a completely new building as an extension of the original. Most often this strategy comes with additional structure in front of the original building in order to support the new facades.

§ 4.9.5 *Covering*

This strategy can be employed when internal courtyards and atria in buildings need to be covered up. The covering of these spaces, commonly done with transparent parts, leads to an increase in heat gains and opens up extra functional space. This intervention leads to a whole reconsidering of the architectural concept due to its adjustments to the relation between the interior and exterior space. The most important criteria are the shape of the building and the availability of spaces that can be covered up.

§ 4.9.6 *Viable Strategy*

Based on the above description of the strategies and their subsequent benefits and limitations, and considering the main research question of this thesis, the most viable strategy would be the wrapping method. The wrapping strategy leaves the existing intact as much as possible, which would result in less disturbance of the occupants during the application process. Furthermore, the applicability of the strategy to many different typologies suits the goal of the thesis for the design to be mass applicated.



	Replace	Add-in	Wrap-it	Add-on	Cover-it
Description	Old façade elements- removed and replaced with new ones	Upgrade from the inside	'Wrapping' the building in a second layer	New structure is "added on" to the existing building	Cover parts or entire internal and external courtyards and atria
Intervention Variation	Replace the entire Façade Replace parts	Internal insula-tion Cavity insulation Box window	External insula-tion, Cladding of the balconies Second skin façade	Small interven-tion, such as adding new balconies New building as an extension Addi-tional floor	Cover parts or entire Heated or unheated space
Benefits	New components with better perfor-mance Eliminate the physical problems	Adequate for monumental status Increase the thermal resistance	Solve thermal bridges Increase the thermal resistance Dif-ferent cladding possibilities Little disturbance	Out-dated façade no longer exterior New façade with performance Increase space Functional benefits	Create thermal buffer Enhance natural ventilation with stack effect Out-dated façade no longer ex-terior Additional space
Limitations	Great impact on users Higher costs	Critical connec-tion thermal bridging need attention Big disturbance for users	Not applicable to monumental buildings Possible space limitation	Needs to be combined with other strategies for facades non-adjacent to new structure Structural lim-itation	Not applicable to all cases Depending on layout and func-tion of the building Overheating risk

Fig. 4.9.1: *Renovation strategies according to type of intervention in residential building renovation (Konstantinou, 2014).*

§ 4.10 Conclusion

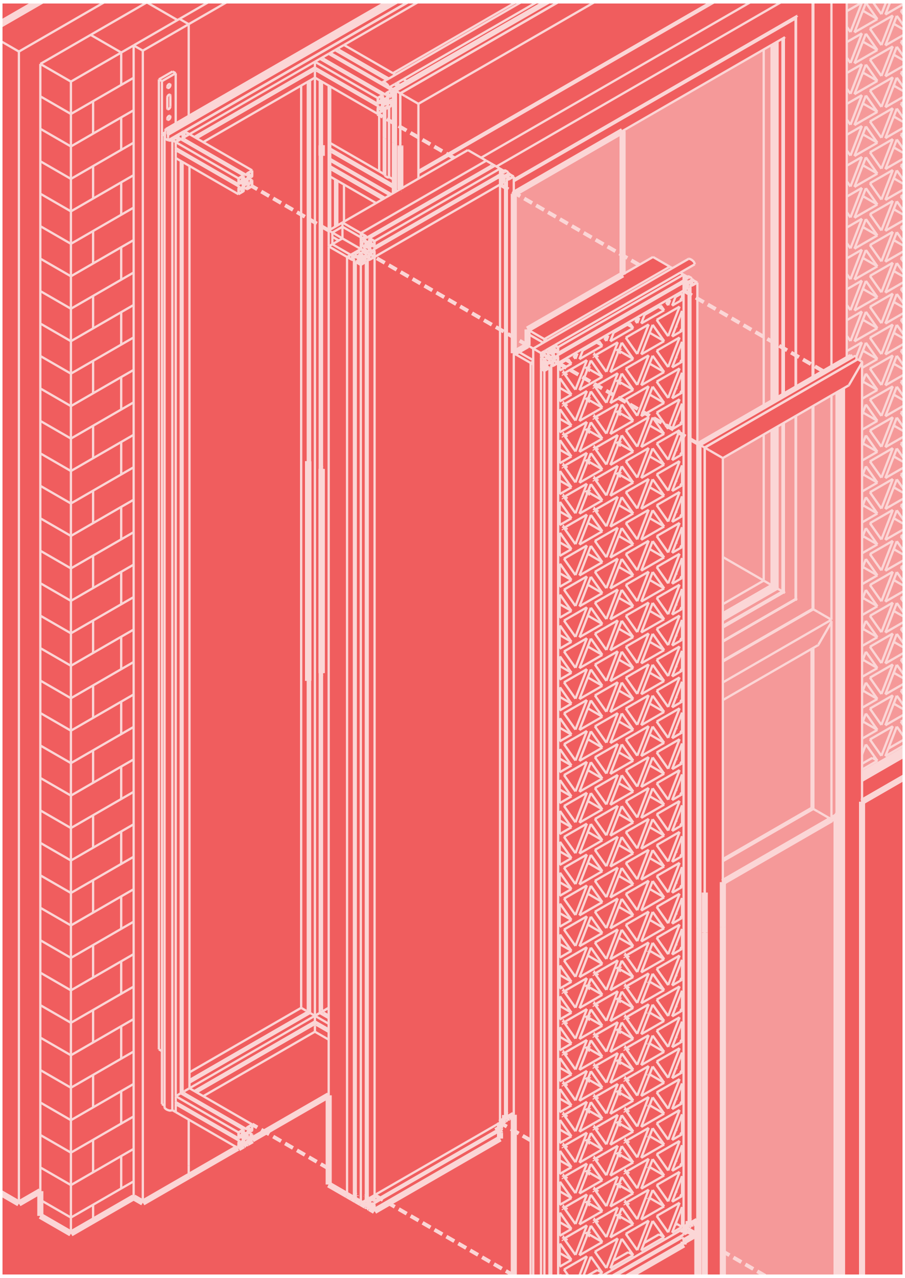
Chapter 4 described the tools and principles that are necessary for a successful energy renovation, as well as the principles that are useful to formulate a future proof renovation. In order to reduce energy two concept can be utilised. The Trias Energetica which consists of three steps: Reducing energy demand, provide remaining demand through renewable sources and provide, if necessary, the remaining energy demand via systems that use fossil fuels as efficient as possible. The New Stepped Approach adds an intermediate step, which is reusing waste streams, and banning fossil fuels from the equation. Either strategy relies on distinct active and passive measures that can be utilised to achieve it.

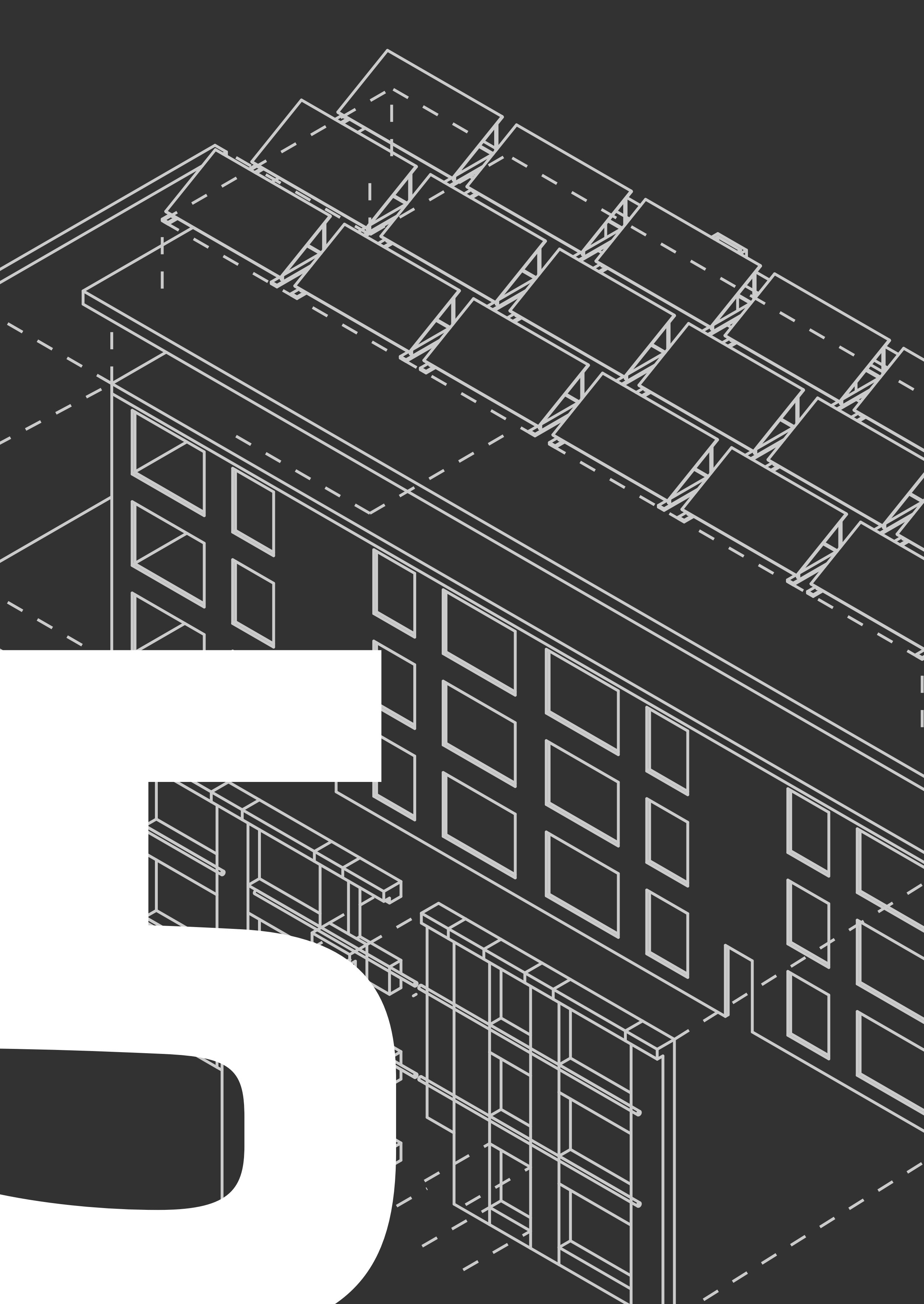
An approach to achieving future proof design is through the principles of the circular economy. The circular economy is an industrial system restorative and regenerative by intention and is based on the following principles: Design out waste, build resilience through diversity, rely on renewable resources, thinking in systems and using waste as food for a new cycle.

An approach to assessing the durability of a renovation is through the life cycle assessment. The life cycle energy of a building consists of three types of energy: the embodied energy, the energy that is consumed for the materials, the operational energy, the energy consumed for heating, cooling, light and appliances and finally the demolition energy, the energy that is consumed to demolish and dispose of the components. In general, the operational energy is the most dominant form of energy consumption and should be the prioritised when renovating.

Furthermore, the strategies were discussed to achieve the overarching CO^2 reduction goals of 2050. The Building Performance Institute Europe calculated that in order to achieve this goal a stepped approach has to utilised in order to keep investments costs as low as possible. By using the phenomenon of the “learning curve”, which describes that through increased competitiveness and growing experience renovation costs will decrease, a more financial sound way of achieving those goals can be established.

The chosen overarching strategy has to be combined with a viable project strategy that can execute it effectively in terms of quality and quantity. There are five main strategies to choose from: Replace, add-in, wrap-it, add-on and cover-it. In the scope of this thesis the most viable strategy would be the wrap-it approach. The wrap-it approach leaves the existing building envelope intact, resulting in less disturbance to occupants and can be easier scaled to different typologies.

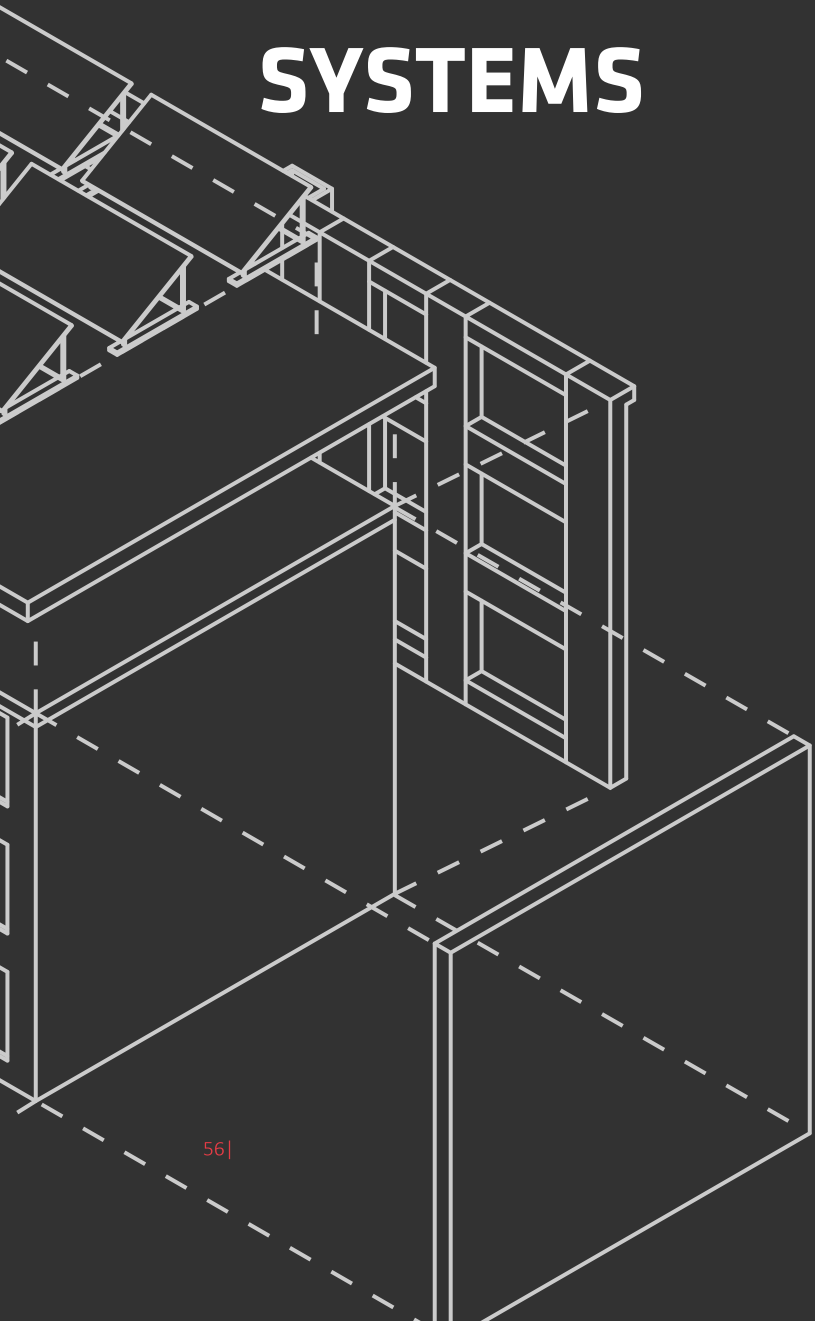


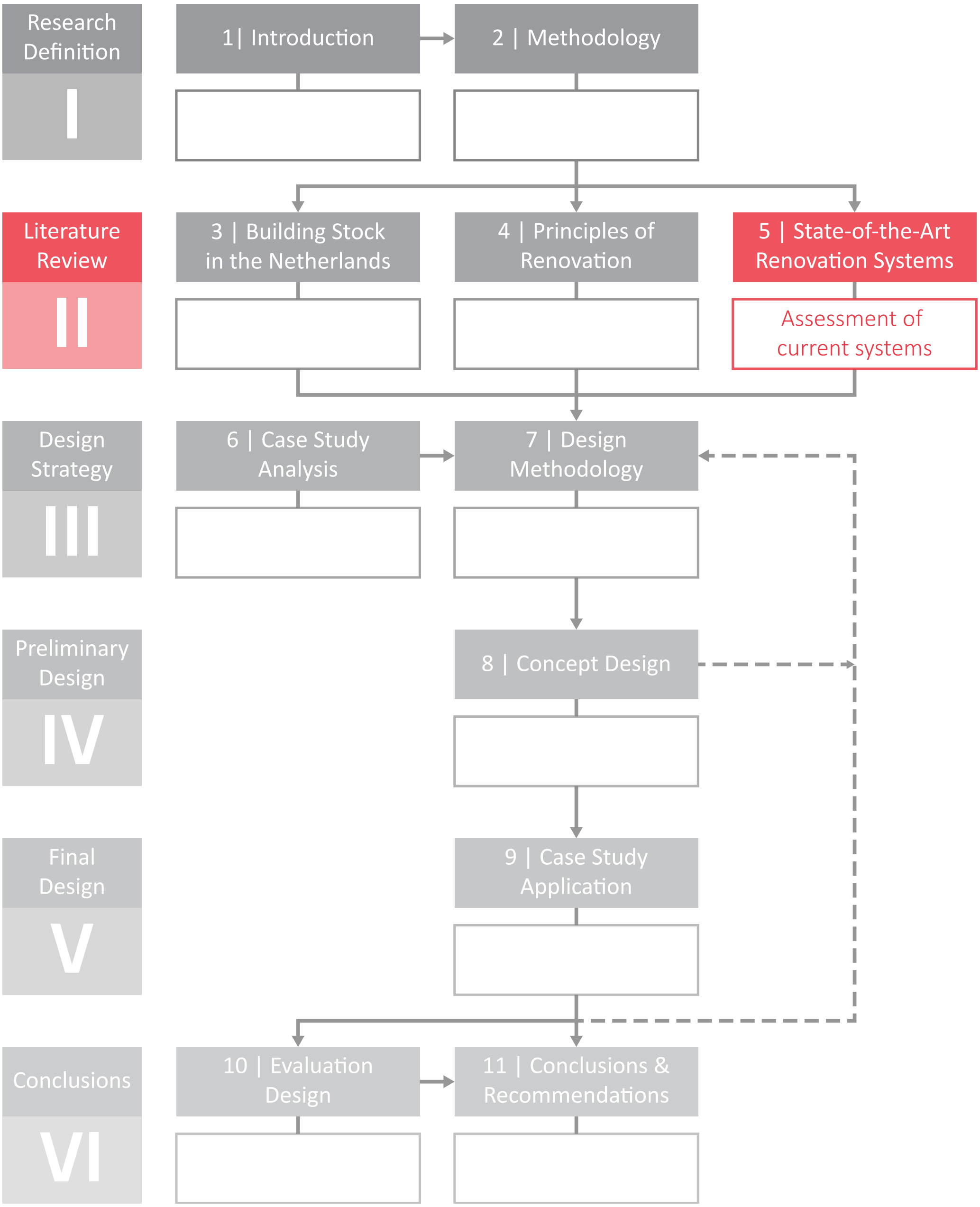


5

CHAPTER 5

STATE-OF-THE-ART RENOVATION SYSTEMS





Research Definition
I
1| Introduction
2 | Methodology
Literature Review
II
3 | Building Stock in the Netherlands
4 | Principles of Renovation
5 | State-of-the-Art Renovation Systems
Assessment of current systems
Design Strategy
III
6 | Case Study Analysis
7 | Design Methodology
Preliminary Design
IV
8 | Concept Design
Final Design
V
9 | Case Study Application
Conclusions
VI
10 | Evaluation Design
11 | Conclusions & Recommendations

5 State-of-the-Art Renovation Systems

The previous chapter gave an overview of relevant general principles and tools that form a basis for the renovation design task. Chapter 5 will further deepen that knowledge by analysing different state-of-the-art prefabricated façade renovations and their unique aspects.

Paragraph 5.1 consists of an analysis of the original 2ndSkin project in order to understand the project's key attributes. Based on this analysis and the knowledge acquired in the previous chapter, paragraph 5.2 will formulate the criteria required for the assessment of three different state-of-the-art renovation methods. Paragraph 5.3 the assessment of every individual criterium will be elaborated. In paragraph 5.4 the ENDIS method will be assessed, which is an example of a semi-prefabricated method. Paragraph 5.5 will be about the assessment of TES Energy Façade, which is a renovation method based on the usage of wooden constructions. Finally, paragraph 5.6 will assess MeeFS, a conceptual renovation method based on the use of different modules. Paragraph 5.7 will draw a comparison between the different methods followed by a discussion and conclusion.

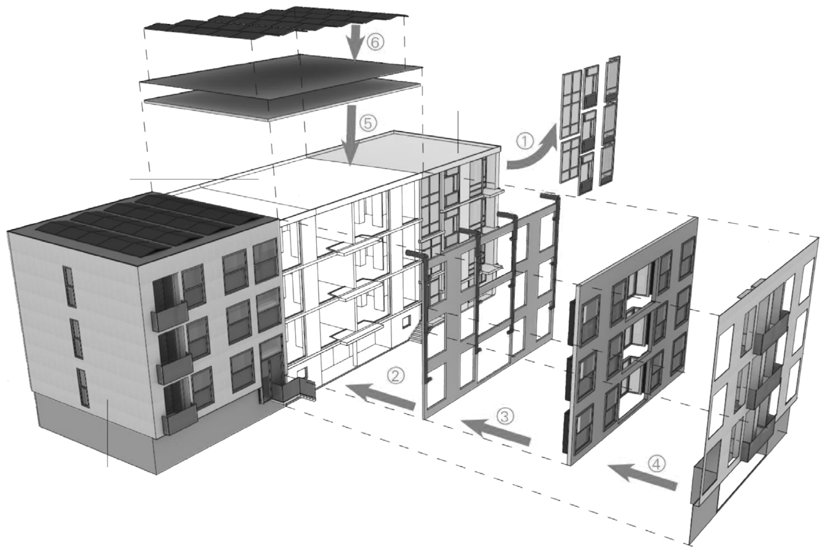


Fig. 5.1.1: *(Top) Variant utilised for the demonstrator project (TKI/Energo, 2016).*
Fig. 5.1.2: *(Bottom) Concept prefabricated variant 2ndSkin (TKI/Energo, 2016).*

§ 5.1 2ndSkin Project

The 2ndSkin project brings together different stakeholders of the building industry, with the aim of integrating different expertise and objectives into an innovative building renovation concept, that achieves zero energy use of a dwelling, while simultaneously offering upscaling possibilities (Konstantinou, Guerra Santin, Azcarate Aguerre, & Klein, 2017). The 2ndSkin project in the first place aims at renovating Dutch porch apartments. The intention is to renovate as much as possible on the exterior of the building. New installations for the heating, ventilation and hot water are also placed on the outside. The method is aimed at porch dwellings built before 1970, but can also be applied to different dwelling typologies. The aim is to first apply the method on a full-scale prototype. After the subsequent evaluation the aim is to apply the method on a residential block of around 20-40 dwellings in Rotterdam, in order to test the scalability of the method. In Rotterdam alone, there are 53.100 of this dwelling typology, nationally there are 520.000. On a large scale this plan of action should accelerate the transition of the city of Rotterdam to an energy neutral city.

Innovative Features

The innovative character of the method is that the renovation including the installations is performed from the outside using a modular façade system. The façade panels are lightweight and can be applied to the existing façade without adjustments to the façade or foundation and the interior remains untouched during the renovation process. The installation is placed as a separate unit against the exterior of the façade, so no floorspace is sacrificed in the interior. By separating the installations, a wide array of possibilities can be applied in terms of energy supply and ventilation.

The 5 pillars of the 2ndSkin Project

Customisation and Unity. On one hand the method allows for customisation in tune with the individual wishes focused on the installations, on the other hand unity can be created through façade finishes and architecture. There can be chosen from a wide array of installation packages and facades finishes. The façade will be produced from sustainable materials, preferably bio based, in line with the concept of the circular economy.

Disturbance for occupants. Occupants can remain in their homes from the start of the renovation until the end, which minimises disturbance and costs.

Flexible maintenance. Maintenance to the renovation can be performed without the occupants being home, this also applies to the chosen installations.

Small maintenance, such as the replacement of the filters of the ventilation system, are also not an issue.

High quality and minimised construction time. Due to the industrialised production of the modular building components high quality and a quick application process can be assured. Furthermore, the system can be applied by smaller contractor companies.

Installation. The energy installation in combination with the façade renovation should assure an energy efficient building. Different levels of renovation are dependent on the choice of systems. The available systems are:

- All electric: a heating pump provides the required energy.
- Bivalence: a heating pump in combination with a condensing boiler provides the energy.
- Just a condensing boiler.

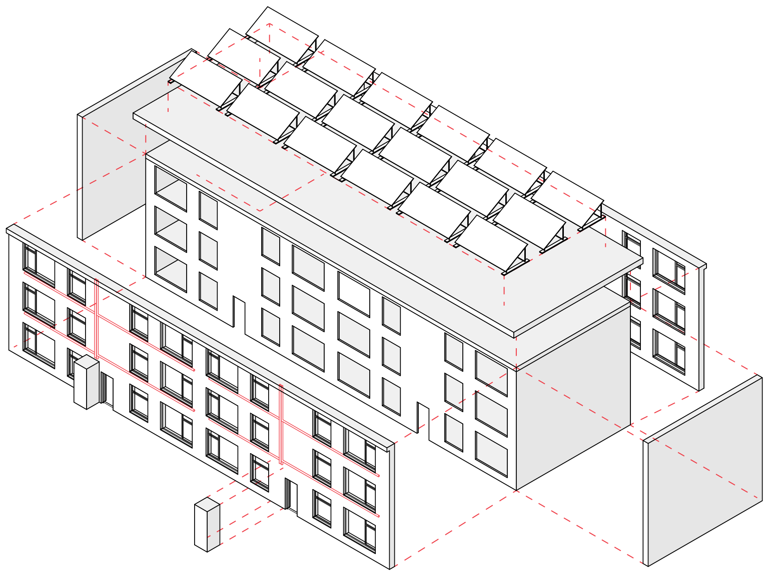


Fig. 5.1.3: *Concept 2ndSkin Approach (Own illustration).*

The choice depends on the ambitions of the contractor and the available funds. The choice can be made to adopt a nearly zero energy approach and at a later stage install better technology when it's become cheaper and more advanced due to the learning curve. This can be implemented without doing intens adjustments. In all cases solar panels are installed on the roof.

§ 5.2 Criteria Formulation & Assessment

In order to analyse the projects from paragraph 5.3 and onwards, first a method of assessment needs to be formulated. For all these systems we will analyse their distinctive features, isolate and abstract them. By doing so we can dissect how a system works and compare the individual elements of every system. The criteria are based upon the literature review from chapter 3 and 4 and the 2ndSkin project. The criteria are divided in four categories: Façade composition, architecture, construction and application. We will discuss the categories and criteria further.

The façade composition category will be assessed through description and pointing out the advantages and disadvantages. The categories architecture, construction, application and long-term funcionality will be assessed through a grading scale from one to five. We will further discuss what the minimum and maximum encompasses per criteria.

§ 5.2.1 *Façade Composition*

The façade composition gives an overbiew of the distinct features used by a renovation system in order to distinguish what makes the system unique in comparison with other systems. The following criteria are distinguished:

Innovative Features

The innovative features describe all the features that make the system efficient for renovation of dwellings. It encompasses the individual components, as well as how the system works as a whole.

Renovation Strategy

The typology of strategy used as described in section 5.1. By categorising the renovation strategies a comparison can be made with the conclusion drawn in paragraph 4.9.6.

Module Size

Describes the module size of the system and why a specific size is chosen. The module size has an effect on a variety of properties, such as the ease of application, construction time, but also the transport and additional tools required to install it.

Connections

Describes the different connections that are needed to accurately apply the system for renovation. It encompasses the connection between the system and the façade, the connection between panels, as well as additional building components that need to be connected to the system.

§ 5.2.2 ***Appearance***

Customisation

The amount of customisation options that are available to the system. Customisation of different systems, such as the cladding, windows, etc. Renovation of façades should not only address building physical problems, but also restoring or upgrading the architectural concept. Design freedom is often limited in prefabricated systems and could potentially have a deterrent effect on stakeholders.

●○○○○ No customisation options are available or are very limited.

●●●●● A wide variety of customisation options are possible in installations, systems, claddings, windows, etc.

§ 5.2.3 ***Construction***

Level of Prefabrication

Level of amount of labour that can be done off-site in order to reduce the amount of labour on-site. Retrofitting buildings completely on-site leads to longer construction times (Hadzimuratovic & Swedmark, 2016). The ability of a system to be mass produced and assembled in factory conditions leads to higher quality components and lower costs.

●○○○○ The system construction and application happens mostly on-site.

●●●●● The system has to be only applicated on-site, no construction labour, additional interior labour and installation of additional components have to performed on-site.

Integration

Describes the possible integration of installation into the façade. The 2ndSkin project utilised a separate unit to house the installations. Integration in the façade unit could possibly further minimise application time on-site.

●○○○○ No integration of systems in the façade system.

●●●●● Every installation is integrated in the façade system.

Sustainable Materials
Describes the incorporation or the ability of the system to incorporate sustainable materials in order to accompany the concept of the circular economy. The incorporated materials and components should be degradable or recyclable to conform to this criterion.

●○○○○	The doesn't include the possibility to include sustainable materials.
●●●●●	All components consist of sustainable materials.

§ 5.2.4 *Application*

Structural Adjustments
Describes the required adjustments needed to the façade, structure or foundation in order for the system to applied efficiently. Large adjustments lead to longer construction time, which results in higher costs.

●○○○○	Adjustments have to be made to the foundation, façade and structure of the buildings.
●●●●●	No adjustments are needed.

Adaptability
Describes the adaptability of the system to multiple typologies. Indicates the amount of adjustments are necessary off-site or on-site in order for the system to be used on a different typology. Also, the adaptability to different window sizes, construction types and external features, such as balconies and entrances, are included in this criterion.

●○○○○	System cannot adapt to different typologies and parameters.
●●●●●	System can easily adapt to different typologies and parameters.

Disturbance
Describes the necessity for additional work on-site in order for the system to be adequately installed. It also includes the additional work needed inside the dwelling. This type of work is considered to be disadvantageous for the tenants. Certain type of work is however inevitable, and the amount of disturbance that is excessive is mostly subjective. Although the goal is to keep the disturbance at a minimum level, such as evading the necessity of tenants to move out during the renovation process. Furthermore, practice shows when the amount of additional measures rises on-site, costs due to additional labour also rises (Konstantinou, Guerra Santin, Azcarate Aguerre, & Klein, 2017).

●○○○○ Occupants have to be relocated during the process of renovation.

●●●●● Occupants can remain in their homes and experience no disturbance during the process of renovation.

Construction Time

Describes the average necessary time needed for a refurbishment method to be applicated on-site. Although it is difficult to compare different solutions to each other through these means due to the wide variety of parameters that influence the construction time, such as the development stage of the renovation method, surface size of the renovated façade and so forth, it should give some indication of the effectiveness of the relevant renovation method.

●○○○○ The duration of the application process is in the region of months to a year.

●●●●● The duration of the application process is in the region of days to one week.

§ 5.2.5 ***Long-Term Functionality***

Upgradability

Describes the ability of the system to be adapted to new requirements due to regulations or due to changing needs of the occupants. It analyses the amount of effort, cost and time is required to adapt the system, if it is possible at all. Upgradability encompasses the ability of the system to adjust the addition of installation and energy production systems, but also the ability to replace components, such as façade finishing, due to different life cycles of the components or to benefit from the learning curve.

●○○○○ The system leaves no space for upgrading components.

●●●●● The system allows for the upgradation of large variety of components, such as the cladding, windows, installations, etc. The upgrading can be performed with ease.

Maintenance

Describes the ability of the system to be repaired without replacement and the ability to perform maintenance on the system. A system should facilitate repair and maintenance to ensure time and costs are minimised.

●○○○○ Maintenance takes considerable labour and is difficult to perform.

●●●●● The system is adapted to maintenance of different components and is easy to perform.

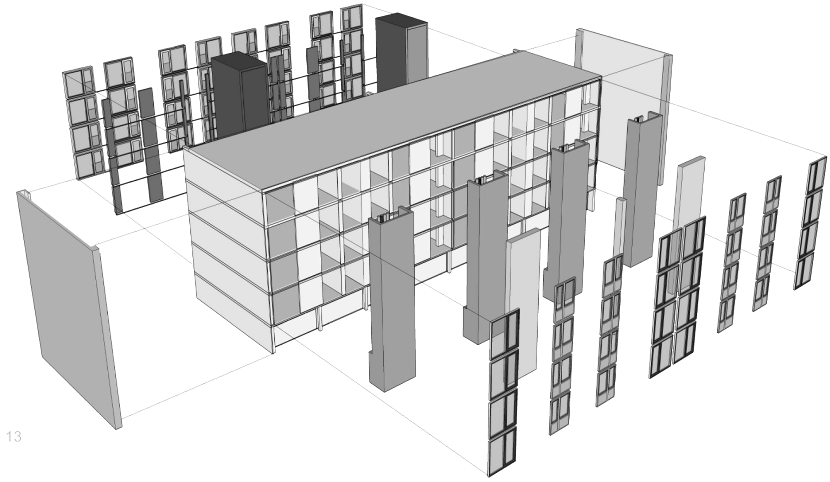


Fig. 5.3.1: *(Top) Impression of renovated apartment block (ENDIS, 2018).*
Fig. 5.3.2: *(Bottom) The components of the ENDIS approach (ENDIS,2018).*

§ 5.3 Energy Neutral Sustainable in Steel (ENDIS)

Energy neutral sustainable in steel (ENDIS) is a renovation solution which focuses on steel components. The system is manufactured in factory conditions as much as possible to minimise construction time and minimize costs due to failures. The system is fully modular and focuses on post-war porch dwellings (ENDIS, 2018). Part of the ENDIS approach is to use tool that customers can utilise to state their ambitions and objectives for a particular building, this way customers can influence the process, which lead to higher acceptance afterwards.

The ENDIS system uses a semi-prefabricated approach, integrating piping, ducts and installation in a separate vertical shaft on the exterior of the building to ensure vertical transport. Although all the components can be manufactured in an industrialised setting, the whole system has to be put together on-site, which leads to longer construction times and higher disturbance to occupants. The vertical shaft also requires a separate construction to bear the concrete shaft.

The system uses collective heat generation with district heating as the energy source. By keeping the heat generation collective additional costs due to maintenance can be avoided. Ventilation is also centralised for the same reasons through a central supply and drainage installed in the shaft. The maintenance necessary can be performed in the shaft and occupants do not need to be present when maintenance is performed.

The prefabricated façade system is applied in front of the existing floor line and due to the exterior application thermal bridges are resolved. The set frames will be reused in the renovation, but the windows will be replaced. The shaft needs a separate construction made out of steel to support it.

ENDIS envisions to incorporate flexibility in their project, so that the renovation can be upgraded when required, but recognises the issue that in the future new regulations and new living requirements might change, rendering the intended flexibility reversed. Furthermore, ENDIS also intends to do a case study to further investigate the possibilities of an element façade instead of a components façade. By utilising an element façade building time and labour on-site can be minimised, although transportation and use of additional tools, such as cranes, could complicate the renovation process.

§ 5.3.1 ***Assessment Façade Composition***

Innovative Features

The ENDIS façade system is innovative in the way the installations are integrated. By separating the installations in a vertical shaft, the system ensures easy accessibility when maintenance is required.

Renovation Strategy

The ENDIS system can be used for a wide variety of strategies, the most used method is the wrap-it strategy.

Module Size

The semi-prefabricated system uses components instead of modules, research is being conducted into using an element façade as an alternative.

Connections

The system will be connected at the floor lines, clear description of the chosen connections hasn't been described yet.

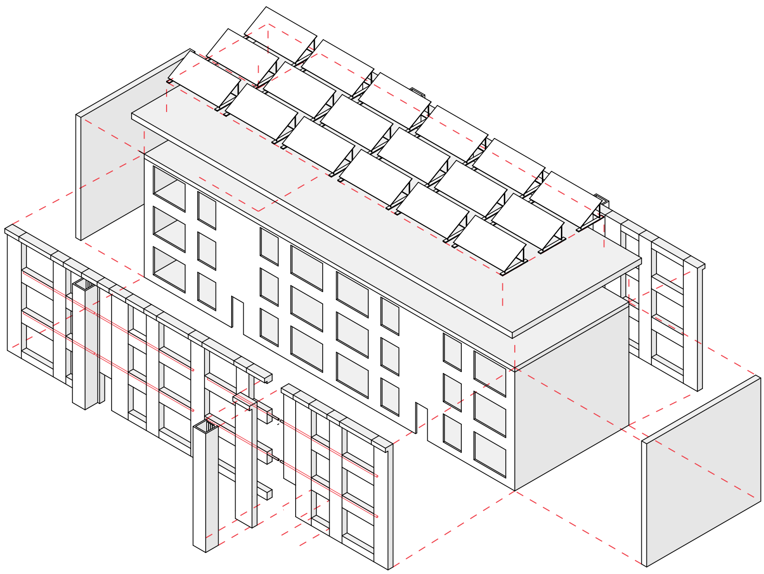


Fig. 5.3.3: *Concept ENDIS approach (Own illustration).*

§ 5.3.2 ENDIS Assessment

Architecture, Construction, Application and Long-Term Functionality

Aspect	Grade	Elaboration
Customisation	●●●●●	*Due to the approach every project can be customised in all aspects.*
Level of Prefabrication	●●●○○	*Semi-prefabricated. All components are manufactured in a factory, but have to be assembled on-site.*
Integration	●●○○○	*Installations are combined with the thermal renovation, but are separated.*
Sustainable Materials	●●●○○	*ENDIS uses steel as its main selling points, although it's highly recyclable the embodied energy is high.*
Structural Adjustments	●●○○○	*No structural adjustments are needed to the original building. The shaft needs a separate support structure.*
Adaptability	●○○○○	*The approach involves a customised approach per project. The system doesn't adapt to parameters.*
Disturbance	●●●○○	*Although occupants can stay in their homes, a relatively high amount of on-site labour must be performed.*
Construction Time	●●●○○	*Approximately seven weeks on average are necessary to wrap a existing building.*
Upgradability	●○○○○	*Upgradability is not integrated in the design of the system.*
Maintenance	●●●●○	*Maintenance can be easily performed on the intallations without occupants present.*

Fig. 5.3.4: *Table ENDIS assessment (Own illustration).*

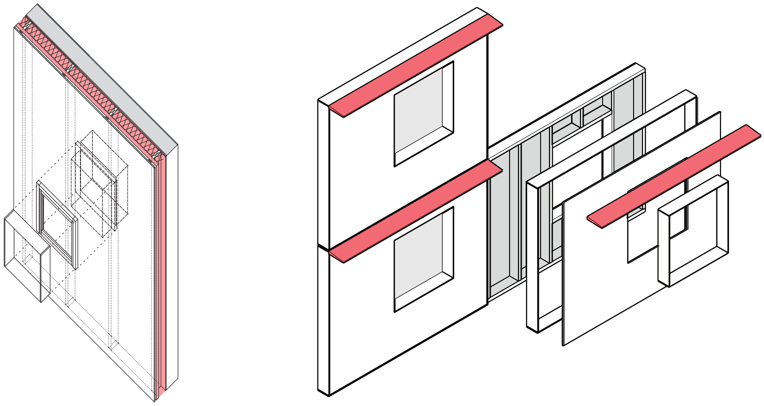


Fig. 5.4.1: *(Top) Risor College renovated with TES Energy Facade (Cronhjort, 2009).*
Fig. 5.4.2: *(Middle) The timber structure forming the basis of TES (Cronhjort, 2009).*
Fig. 5.4.3: *(Bottom) Exploded view of the necessary components (Cronhjort, 2009).*

§ 5.4 TES Energy Façade

Timber-based element systems for improving energy efficiency of building envelopes (TES Energy Façade) is a research project aimed at creating a prototype design of a wood-based prefabricated façade element system for improving the energy efficiency of the building envelope (Cronhjort, Nuikka, Hirsi, & Lylykangas, 2009). The system targets the building stock built after the 1950s. The project is a joint research project with partner universities from Germany, Norway and Finland and it aims at creating a basis that could be utilised throughout Europe.

TES Energy Façade combines a self-supporting or suspended structure with an infill of insulation and the ability to incorporate a wide variety of cladding materials. The system utilises large-sized timber frames elements and is adjustable to multiple typologies. The system offers opportunities to be utilised in constructions with load-bearing walls as well as skeleton frames. In the first case the system can be applied in front of the original façade, in the second case the system replaces the original façade completely.

The TES Element Façade is more a design approach than a fixed system. It offers the opportunity to adjust to different types of building geometries and required functionality accordingly. It offers the option to produce ordinary high insulating wall segments up to complete space extension modules. The level of prefabrication is furthermore determined by the configuration of the load-bearing elements of the existing situation of a project. For example, it is possible to prefabricate only the structure and applicate insulation, air- and watertight layers and cladding afterwards, but it is also possible to prefabricate modules with all functionalities a facade requires, such as cladding, integrated windows, solar control devices, HVAC services and solar collectors.

§ 5.4.1 *Assessment Façade Composition*

Innovative Features

TES Energy façade gives the user a method to design a prefabricated façade suitable to the requirements of every individual project. By giving the client basic details the process of renovation is accelerated. Ventilation ducts and tubing can be integrated in the façade if it’s necessary.

Renovation Strategy

Although TES energy façade gives options to use a variety of renovation strategies, the wrap-it strategy ensures the least disturbance to occupants.

Module Size
Module size can be up to four stories high, the width of the modules is adjustable but preferably split per window. Module size should be adjusted to ensure transport is possible to the building site.

Connections
The system is attached to the floor lines with screws. Furthermore, it usually uses a adaptation layer consisting of lathes and insulation to ensure the existing facade' surfaces is evened out.

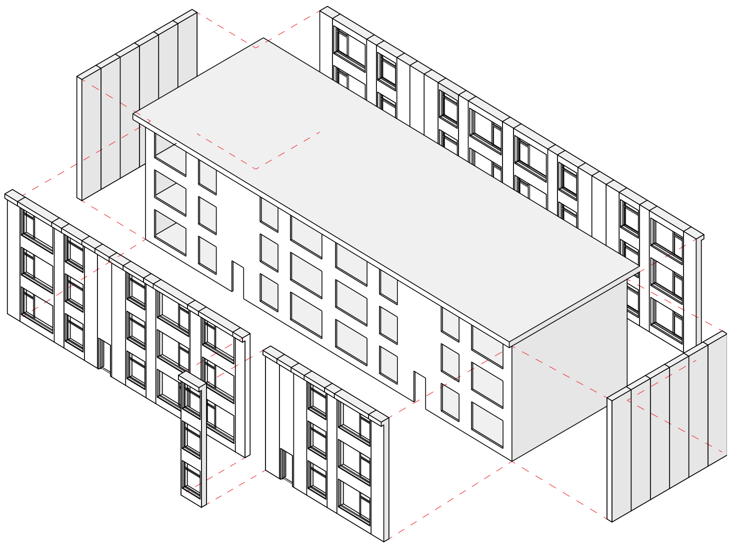


Fig. 5.4.4: *Concept TES Energy Facade (Own illustration).*

§ 5.4.2 TES Energy Facade Assessment

Architecture, Construction, Application and Long-Term Functionality

Aspect	Grade	Elaboration
Customisation	●●●●○	*The TES Energy Facade can be customised on every aspect, the basic wooden construction is the only constant.*
Level of Prefabrication	●●●●○	*The elements can be four stories high, other sizes are also possible.*
Integration	●●●●○	*Installations can be integrated into the panel, with piping and ducts tucked into the insulation layer of the panel.*
Sustainable Materials	●●●○○	*The construction is made out of wood, which is a material with low embodied energy, the other materials are adjustable.*
Structural Adjustments	●●●●●	*No adjustments have to be made to the structure.*
Adaptability	●●●○○	*The system comes with standard details that can be used for a large variety of typologies, the details have to be adjusted accordingly.*
Disturbance	●●●●○	*Disturbance is relatively minimised, with occupants remaining at their homes. Cranes need to be used to place the modules.*
Construction Time	●○○○○	*Construction period was approximately one and a half years which is, even when considering the scale of the projects, very slow.*
Upgradability	●○○○○	*The panel doesn't integrate upgradability in it's system.*
Maintenance	●●○○○	*Maintenance is difficult to the installation due to the closed-off nature of the system.*

Fig. 5.4.5: *Table TES Energy Facade assessment (Own illustration).*

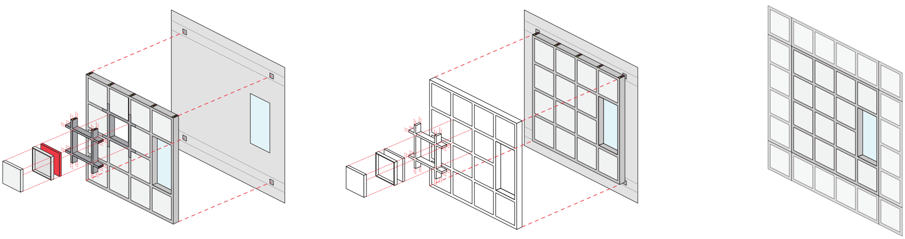


Fig. 5.5.1: *(Top) Render of proposed renovation of a case study in Mérida, Spain(Rozanska,2016).*
Fig. 5.5.2: *(Middle) Photos of system applicated in Mérida, Spain (Rozanska, 2016).*
Fig. 5.5.3: *(Bottom) Main concept of MeeFS (Rozanska, 2016).*

§ 5.5 Multifunctional Energy Efficient Façade System (MEEFS)

MeeFS is a European funded project by MeeFS Retrofitting aiming to develop, evaluate and demonstrate an innovative energy efficient multifunctional façade system focused on the residential building sector. The result envisioned by MeeFS Retrofitting is a highly flexible and modular system. Flexible in the sense that it can adapt to multiple typologies and architectonic configurations. And modular in the sense that it combines different technical solutions (MeeFS Retrofitting, sd).

The renovation sector faces a wide variety of challenges which MeeFS Retroffitting tries to tackle. The system offers thermal insulation, a wide variety of different aesthetical options and applicability to different typologies and façade orientations.

The concept idea of MeeFS is based on efficiency and an integrated multifunctional system (Rozanska, 2015). The system combines energy efficient panels and technological modules, where installations are integrated, as well as composite façade structure materials. All elements are combined to form a completed façade for building envelope renovation.

The energy efficient panels and modules integrated in the façade will include technology for reducing the energy consumption or for supplying energy by means of RES. Two energy efficient modules are in development: a module for passive solar protection and energy absorption and a module for solar energy collection and ventilation.

The façade will be produced with composite materials, fibre reinforced polymers, for improved lightness. This is to ensure the easy application. With the aid of life cycle analyses recyclability considerations are being taken into account for all the components of the façade.

The industrialised construction system is designed to be non-intrusive for occupants in order to minimise disturbance. The system allows for personalised configurations for each façade typology, orientation and local climatic conditions, using standardised panels and technological modules. The system aims to be cost effective during its service life, with low maintenance needed, easy assembly and disassembly.

The system will be applied in a case study in Spain with a continental climate. The building will be monitored before and after the renovation to evaluate the performance of the applicated solution.

§ 5.5.1 ***Assessment Façade Composition***

Innovative Features

MeeFS façade system is innovative in the way that it splits the system in separate modules. The base structural system is always the same but the infill can be adjusted according to the project's requirements.

Renovation Strategy

MeeFS uses a wrap-it approach, in order for the disturbance for occupants to be minimised.

Module Size

The module size is adjustable to the project's requirements, but typically is square shaped and accordingly shaped to the buildings size. The inserted sub-modules are intended to have a fixed size.

Connections

MeeFS utilised a horizontal steel support bracket mounted at floor level from which the completed modules with sub-modules are suspended.

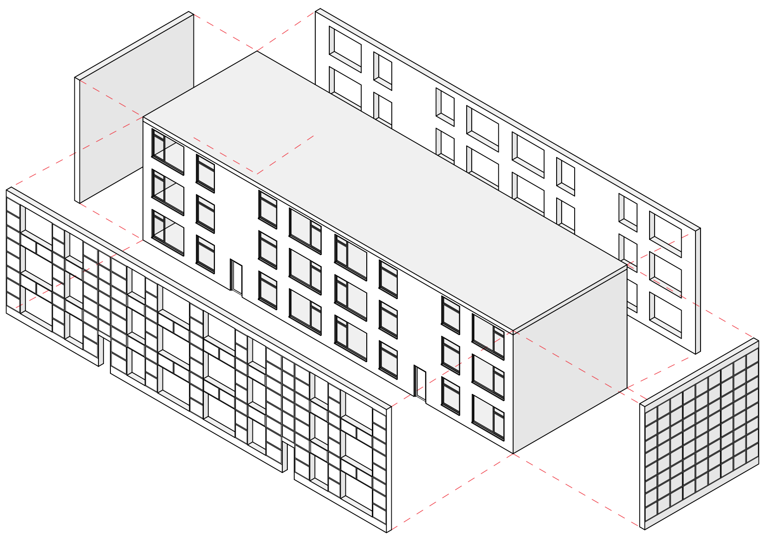


Fig. 5.5.4: *Concept MeeFS approach (Own illustration).*

§ 5.5.2

MeeFS Assessment
Architecture, Construction, Application and Long-Term Functionality

Aspect	Grade	Elaboration
Customisation	●●●●○	*Every project can choose between a range of technical modules, facade panels, etc. The base system stays the same.*
Level of Prefabrication	●●○○○	*The sub-modules can be installed in the main frame off-site or applicated on-site.*
Integration	●●●●○	*MeeFS gives the opportunity to choose from a wide variety of technical modules.*
Sustainable Materials	●●○○○	*MeeFS uses complex modules, and the materials haven't been selected yet. There are plans for using FRP for the structure.*
Structural Adjustments	●●●●●	*No structural adjustment have to made.*
Adaptability	●●●○○	*The system is adaptable to multiple typologies, but the sub-modules are intended to be fixed in sizing.*
Disturbance	●●●●●	*The occupants can remain at home and necessary construction apparatus is minimal.*
Construction Time	●●○○○	*The installation of the prototype on a part of the facade took 12 weeks. When mass produced this installation time should decrease.*
Upgradability	●●●○○	*The system shows potential to incorporate upgradability, but the intention to do so is not elaborated.*
Maintenance	●●○○○	*The complexity of the system is high, making the maintenance process relatively labour intensive.*

Fig. 5.5.5: *Table MeeFS assessment (Own illustration).*

§ 5.6 Comparison Assessed Systems

As shown in the assessment of the different projects that adaptability and upgradability is difficult to integrate in the systems. From figure 5.6.1 it can be concluded that on average the systems perform low on these aspects. ENDIS does elaborate on the issue and recognises that integrating these aspects is difficult and requires more extensive research. The future performance of these systems is therefore mostly unknown. The assessment led to the recognition of the following attention points:

A project-to-project approach is utilised. Renovation projects can reuse design principles and solutions, but every renovation has to be customised to different requirements. The renovation rates could rise if systems were more adapted to renovating large amounts of dwellings.

Renovation projects tend to aim for a final solution. Therefore, the systems focus on the current regulations and living standards, not incorporating how these could change in the future. The systems leave limited options to change or upgrade the renovation if the mentioned parameters change.

Systems are designed as closed constructions. They are designed to form a final product where maintenance of components within the system is difficult to perform. Therefore, the different service lives of the individual components of the building envelope are disregarded, leading to the possibility of the façade to fail as a whole, leaving a lot of components to be discarded before they have reached their potential service life.

Comparison Assessments

Aspect	Grade Endis	Grade TES	Grade MeeFS	Average
Customisation	●●●●●	●●●●○	●●●●○	●●●●◐
Level of Prefabrication	●●●○○	●●●●○	●●○○○	●●●○○
Integration	●●○○○	●●●●○	●●●●○	●●●◐○
Sustainable Materials	●●●○○	●●●○○	●●○○○	●●◐○○
Structural Adjustments	●●○○○	●●●●●	●●●●●	●●●●○
Adaptability	●○○○○	●●●○○	●●●○○	●●◐○○
Disturbance	●●●○○	●●●●○	●●●●●	●●●●○
Construction Time	●●●○○	●○○○○	●●○○○	●●○○○
Upgradability	●○○○○	●○○○○	●●●○○	●○○○○
Maintenance	●●●●○	●●○○○	●●○○○	●●○○○

Fig. 5.6.1: *Table Comparison different systems (Own illustration).*

§ 5.7 Conclusion

In chapter 5 state-of-the-art prefabricated renovation systems had their functional aspects isolated, analysed and compared to determine their effectiveness in performing energy reduction renovations. The 2ndSkin project was the first project to be analysed. The 2ndSkin utilises five principles, the pillars of the approach, that not only focusses on energy reduction, but also the process before, during and after the renovation, which are deemed of equal importance. The five pillars are: To give the option for customisation, but also the option for unity. Customisation through installation choice, but unity through façade finishing. To minimise the disturbance to the occupants during the process, occupants are able to remain in their homes during the process. Flexible maintenance is ensured, without the need for occupants to be at home. High quality and minimised construction time due to prefabricated modular building components. And finally, the option to be combined with multiple installation packages.

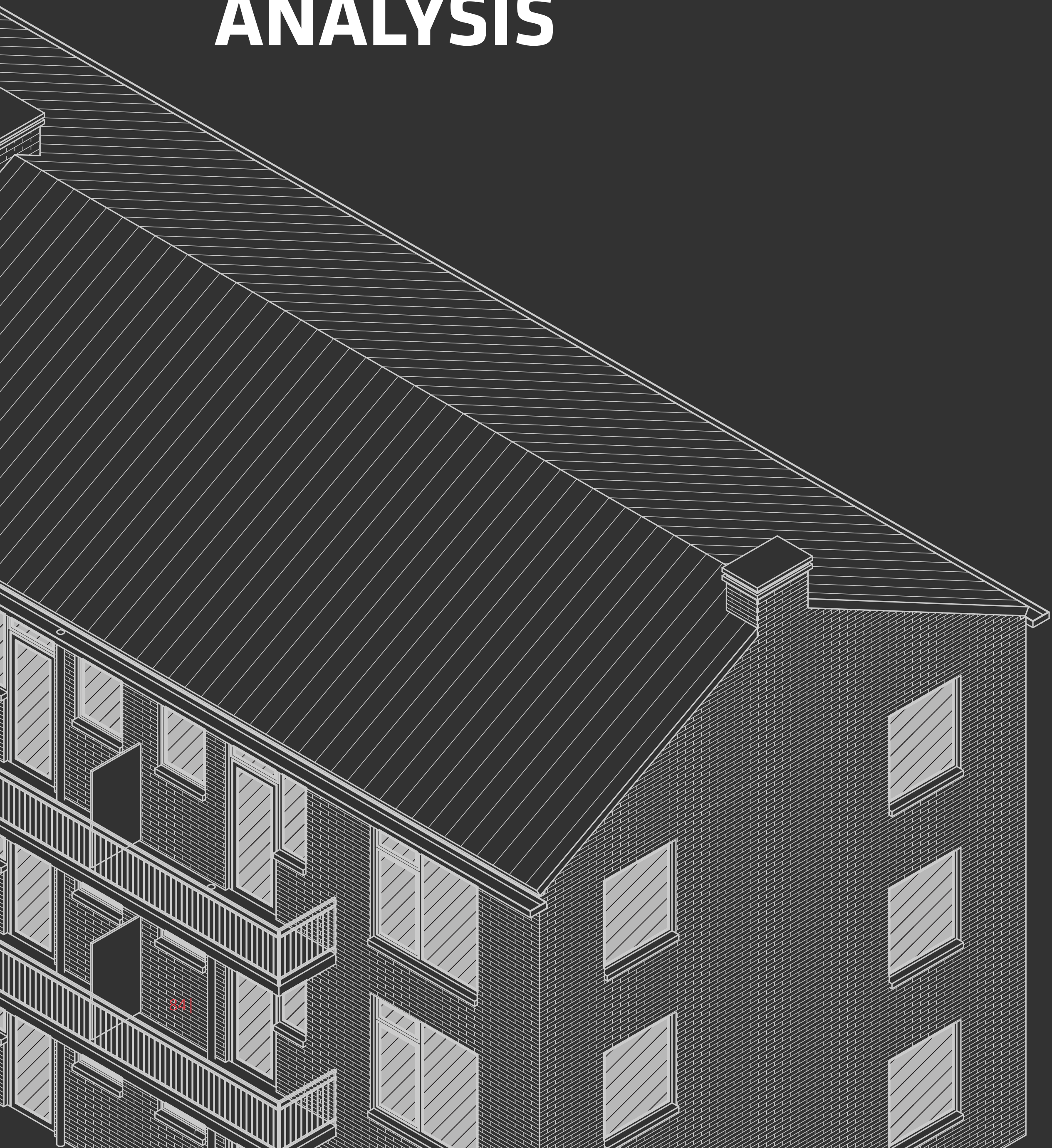
Based on the first analysis and literature from the previous chapters, a list of criteria and a method of assessing was formulated in order to analyse three other projects in four fields of study: architecture, construction, applicability and long-term functionality. Furthermore, the criteria list functions as a requirement list for the design phase of this thesis. The three assessed projects were: ENDIS, TES Energy Façade and MeeFS. ENDIS utilises an approach which uses a customised approach per individual project. TES Energy Façade utilises standard detailing based on wooden components to formulate a renovation proposal. And finally, MeeFS uses a base structure where different technological modules with different functional purposes can be placed inside in order to form a completed façade.

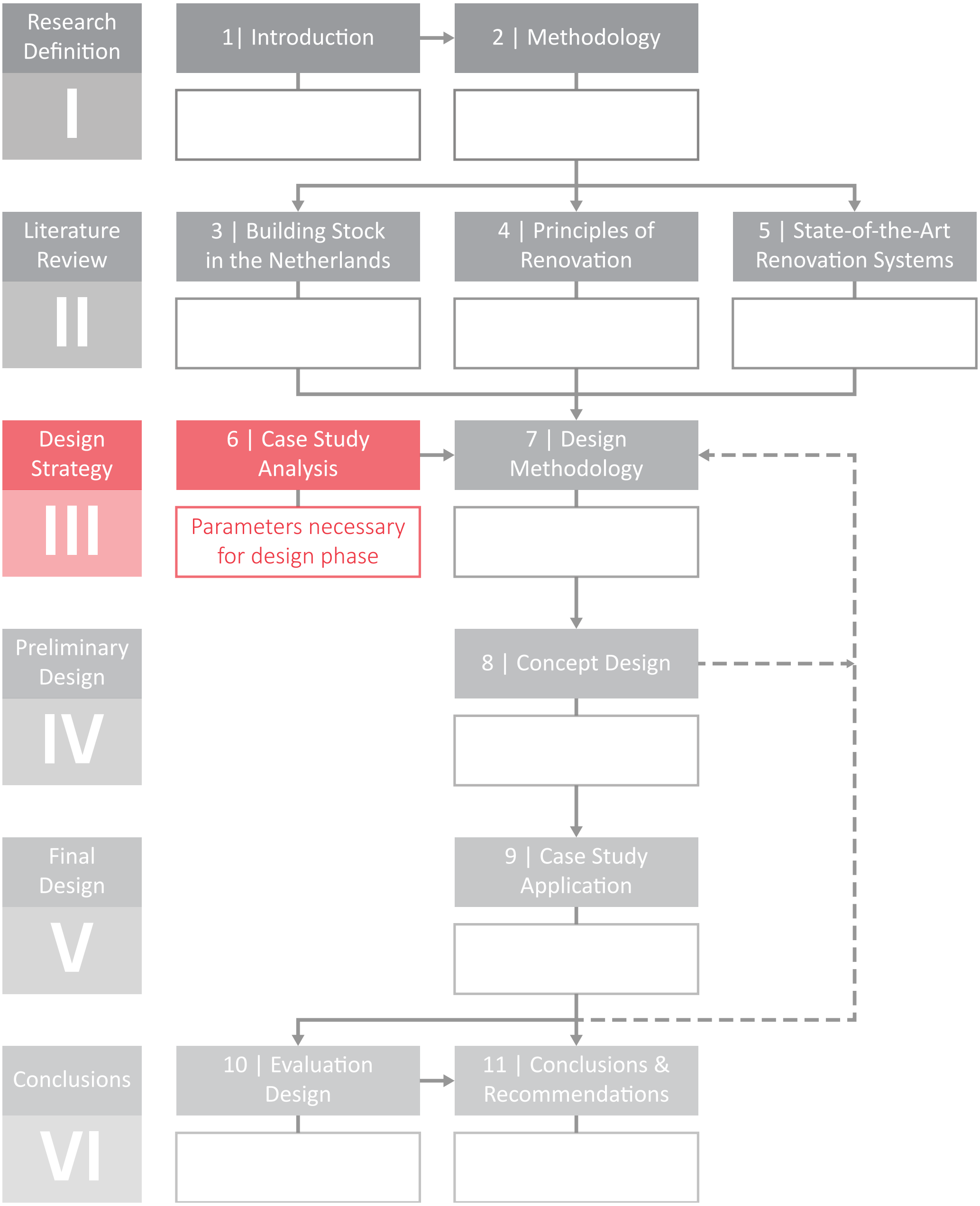
Based on the comparison the main issues that are present in these systems are the project-to-project approach, which is not adapted to renovating on a large scale. The systems' lack of adaptability to future changes. And finally, the systems are designed as closed constructions, where maintenance and replacement on internal building components is difficult to perform.

6

CHAPTER 6

CASE STUDY ANALYSIS




Research Definition
I
1| Introduction
2 | Methodology
Literature Review
II
3 | Building Stock in the Netherlands
4 | Principles of Renovation
5 | State-of-the-Art Renovation Systems
Design Strategy
III
6 | Case Study Analysis
Parameters necessary for design phase
7 | Design Methodology
Preliminary Design
IV
8 | Concept Design
Final Design
V
9 | Case Study Application
Conclusions
VI
10 | Evaluation Design
11 | Conclusions & Recommendations

6 Case Study Analysis

In chapter 6 a chosen case study will be analysed and the issues and potentials discussed. These findings will be combined with findings from the literature review of chapters 3, 4 and 5 to formulate a design methodology for the design task.

In paragraph 6.1 the choice for the case study and its context will be elaborated further. Paragraph 6.2 will focus on the apartment block's typology to clarify its position in the Dutch housing market. Paragraph 6.3 will focus on the construction method utilised in order to understand the specific reasoning behind the detailing of the case study. Paragraph 6.4 will elaborate further on the case study's measurements to gain an understanding of the scale of elements. This followed up in paragraph 6.5 with measurements on the thermal resistance of the case study. In paragraph 6.6 the different parameters that need to be addressed in the design are listed and discussed. All these parameters require unique solutions that need to be incorporated in the design phase. Paragraph 6.7 will delve deeper into the energy efficiency problems present in the existing design. Finally, in paragraph 6.8 the approach and measures utilised by the 2ndSkin project to renovate the case study is analysed in more detail.

§ 6.1 Context

The case study chosen for this thesis is an apartment block at the Soendalaan in Vlaardingen. The apartment block is situated in a neighbourhood with similar apartment blocks. 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 building was chosen due to its availability of the original drawings and the fact that the design of this thesis can be compared with the 2ndSkin project, were the circumstances in terms of context are equal.

The apartment block consists of three stories with an attic that was intended to remain vacant. It consists of four apartments per floor that are orientated south to north. There are two semi-public entrances located on the south side of the block, where one entrance connects six apartments. The porch entrance is located within the constraints of the building, but connected to the exterior. All apartments are exactly the same size at 53.7 m^2 per apartment, consisting of a living room, two bedrooms, a kitchen and a bathroom with an additional separate toilet.

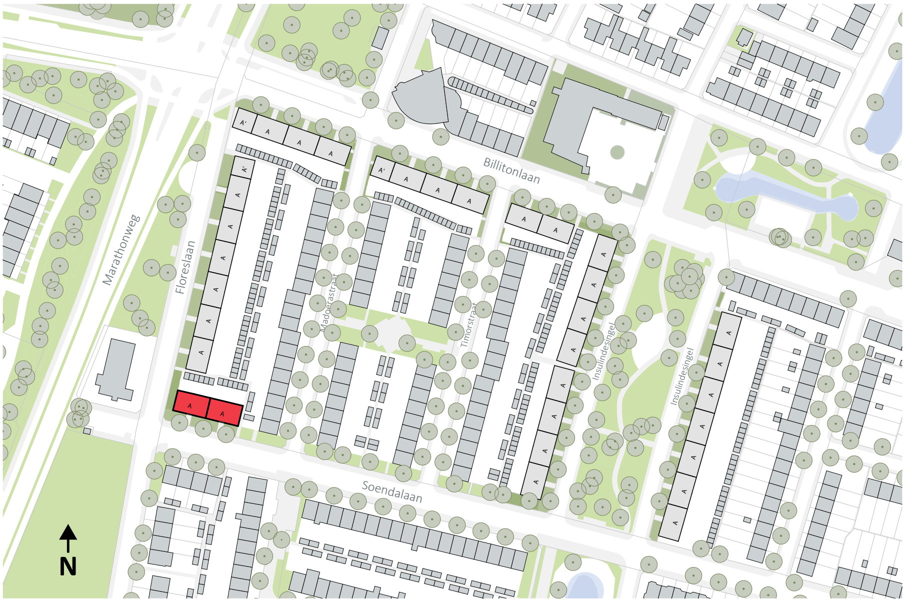


Fig. 6.1.1: *The urban context of the case study in Vlaardingen, the Netherlands (Boess, et al., 2017).*

§ 6.2 Typology

During the post-war period, between 1945 and 1975, around 2.6 million apartments were fabricated in a high tempo in order to satisfy the growing demand for dwellings during the reconstruction period of the Netherlands. During this period 2.6 million dwellings were built, 25 percent of which are so-called industrialised buildings. The apartment block at the Soendalaan is part of that 25 percent. The industrialised building methods strived to minimise the labour time on-site significantly, which led to the development of a wide array of building techniques, known as 'systems'. The key factor of the effectiveness of these building techniques was repetition, which led to a steep increase in the built rate of new apartments. This same repetition can be utilised for the renovation of these dwellings to increase the rate of renovations.

Fig. 6.2.1: *On-site photos of the case study (Boess, et al., 2017).*

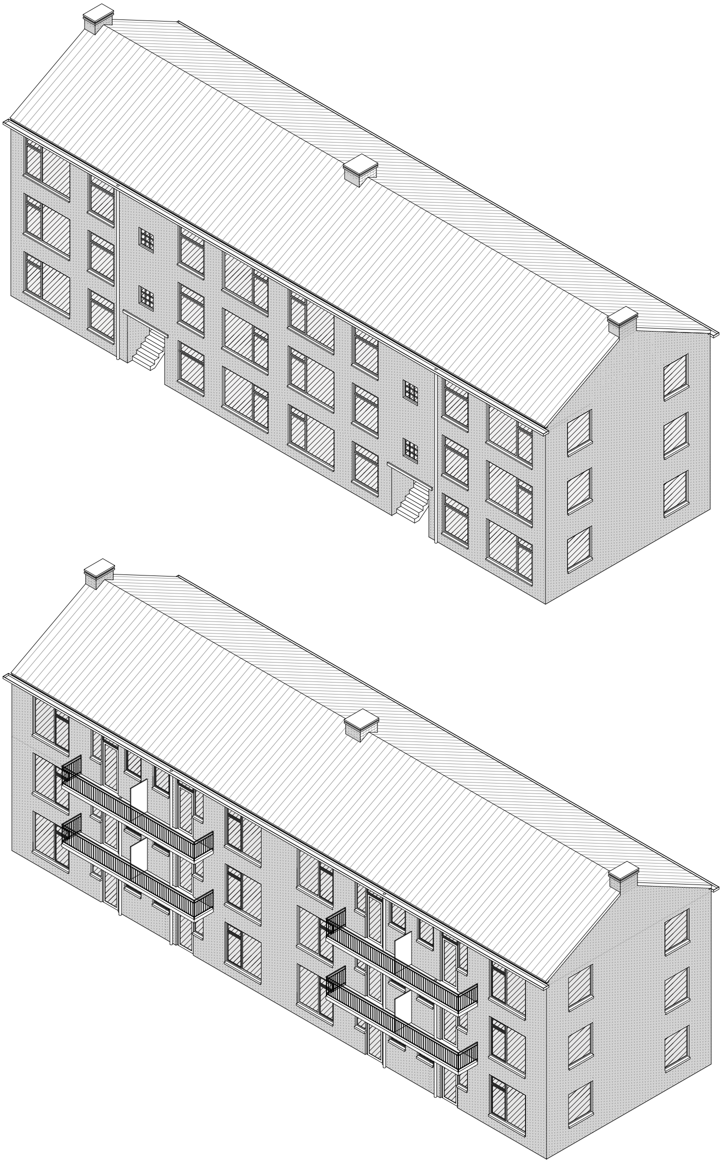


Fig. 6.2.2: *Isometric View South & East (Above) and North & West (Below) (Own Illustration).*

§ 6.3 Construction Method

The construction method used for the apartment block of the case study is the simplex method, which is an uncommon method and is ranked 25th of most used system construction methods. The simplex method in the larger scale of system construction methods is fairly underrepresented, the main advantage is that most methods, due to the focus on quantity instead of quality, have similar dimensions (Bouwhulp Groep, 2013). This way the renovation solution designed for this particular case study doesn't have to be adjusted much to be able to be applicated to other system typologies.

The simplex method uses prefabricated story high concrete elements. The concrete elements form the interior of a cavity wall. The elements are transported to the site and placed using a crane, the brick exterior of the cavity wall is built manually and on-site. The concrete elements form the structural layer of the dwellings (Bouwhulp Groep, 2013). This method of construction could be characterised as semi-prefabricated. Although the simplex method is not fully prefabricated, it still uses utilises repetition to simplify the construction process. The apartment block is four apartments wide, where the first apartment is mirrored to form the second apartment and the repeated to form the third and fourth apartment.

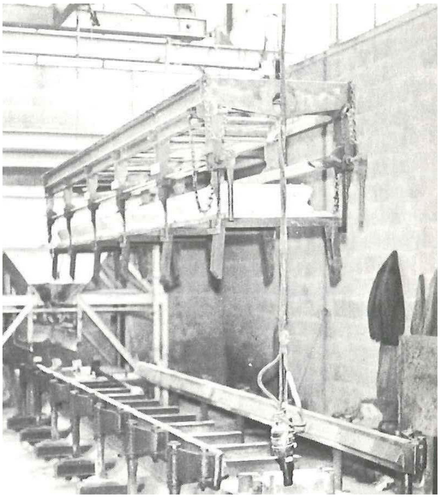


Fig. 6.3.1: *Production of the concrete wall panel (Simplex, n.d.).*

Fig. 6.3.2: *Mounting of the wall panels, a crane is used to uphold the weight (Simplex, n.d.).*

§ 6.4 General Measurements

The rectangular shaped block has a width to depth ratio of 3:1. The grid divides the width in four equal parts while the depth stays undivided, every part house one apartment. As described earlier, the apartments are of equal size and L-shaped, sacrificing some space on the south side of the apartments to house a semi-public porch entrance. In table 6.4.1 the most important dimensions of the apartment block are listed.

General Measurements	
Length	28.800 mm
Width	9000 mm
Height	11.000 mm
Height Floor	2600 mm
Grid 1-2	7220 mm
Roof Angle	28°
Windows	
1	W: 2515 x H: 1875 mm
2	W: 1430 x H: 1875 mm
3	W: 1325 x H: 1495 mm
4	W: 1978 x H: 1875 mm
5	W: 548 x H: 1359 mm
6	W: 940 x H: 2450 mm
7	W: 884 x H: 1100 mm

Fig. 6.4.1: *Table portraying the most important measurements (Own Illustration).*

§ 6.5 Thermal Resistance Value

The case study's energy performance is in line with the average energy performance for a building in that particular time period, before the inclusion of insulation was required by law. The facades consist of 10 cm of brick façade, 7 cm of cavity and 10 cm of concrete structural panel. The windows have been replaced in the past and consists of double glazing and wooden frame, however they still are a major source of heat loss due to the window-to-wall ratio of approximately 40%. The roof consists of 7 cm of woodwool cement slab, which has minimal insulative value. The ground floor slab solely consists of 15 cm concrete, with 35 cm of crawl space. The crawl space insulates slightly, but the concrete foundation connected to the concrete slab of the ground floor form a thermal bridge directly to the exterior soil, leading to heat losses.

Component	Thermal Conductivity	Thermal Resistance
Facades	2.56- 2.86 W/m*K	0.35- 0.39 m^2/K*W
Roof	1.28- 3.03 W/m*K	0.33- 0.78 m^2/K*W
Ground Floor	1.89- 2.70 W/m*K	0.37- 0.53 m^2/K*W

Fig. 6.5.1: ***The calculated thermal conductivity and thermal resistance of the different building components (Kuijpers-Van Gaalen, Zeegers, Erdtsieck, & Van der Linden, 2011).***

§ 6.6 Parameters

Apart from the measurements of the apartment block the different unique elements of the façade need to be considered. These elements complicate the application of a second renovation façade and require unique solutions in order for the renovation to function properly. The elements can all be found in apartment blocks of the same typology, but vary in size, amount, placement, etcetera. In order to design a suitable solution every unique element needs to be isolated and analysed to gain insight of their influence on the final design.

Windows

In the apartment block there are two archetypes of windows distinguishable: The double glazed, wooden frame windows and the single glazed, concrete frame windows used for the entrance. The double glazed, wooden frame windows are in fair condition, but are not up to nZEB level standards. The concrete window is used exclusively for the entrances and functions solely as a light source for the dimly lighted entrance. The wooden frames windows come in eight unique sizes, excluding the doors, with all the individual apartments having al the sizes, with the exception of the corner apartments that have two additional same-sized windows as supplementary light sources, bringing the total of uniquely sized windows to nine. The wide variety of window sizes complicate the use of a standardized system for renovation. Furthermore, the removal of the windows is fairly easy due to the incomplexity of the detailing. The windows can be removed from the outside and given the condition of the set blocks is fair, a new improved window could be installed in its place.

Gutters

The external gutters run across the north and south side of the apartment block, with two drain pipes extending from the ground floor to the roof and four on the north façade, two of which extending from the ground floor to the roof and two connecting the ground floor to the balconies on the second floor. When utilising a wrap-it approach it is impossible to not remove the gutter and the drain pipes during the renovation process. The gutter is also essential in the roof to wall connection of the renovation, when replacing the gutter and the drain pipes.

Balcony

On the north façade all the apartments of the first and second floor are outfitted with a balcony. One balcony slap is connected to two apartments. Maintaining the balconies is of importance due to the fact that removing them would be in conflict with the Dutch building regulations (BRIS, 2018), which prescribes that every dwelling, except student dwellings and retirement homes, have to be outfitted with a personal exterior space, such as a garden or balcony. Removing the balconies would lead to a degradation of the current living standards and comfort, which is undesirable.

Entrance

The traditional porch entrances form the semi-public entrance to all the apartments on the south façade of the block. One entrance is connected to six apartments. The main issue with current entrance is the low thermal resistance of the walls inside of the porch entrance that are directly connected to the exterior air. Renovation along the inside would dramatically increase the number of square meters that need to be renovated.

Roof

One of the critical details for the renovation is the connection of the roof and the wall. The roof consists of a wooden substructure and ceramic roof tiles. In order to renovate from the exterior of the apartment block at least the roof tiles need to be removed, which fortunately can be done relatively easily as there are loosely placed on the wooden substructure. Furthermore, the roof needs to be checked for its structural capacity to ensure additional materials can be placed on top.

Chimney

Another point of interest are the multiple chimneys that are present on the roof. The chimneys are mostly used for the kitchens and functions as exhausts. The chimneys are located on the edges of the roof and two in the centre of the roof that are combined. One chimney is connected to three apartments directly underneath. The chimneys protrude from the roof and could form an obstacle during the renovation. Their functional purpose, as air exhausts, should be retained or replaced with an alternative pathway.

Fig. 6.6.1: *Analysis of the different design parameters. From top to bottom: Different window sizes, the uninsulated entrances, the balconies and the chimneys & rain pipes (own illustration).*

§ 6.7 Building Physical Problems

Building physical problems are obtained through a multitude of causes in a multitude of buildings sections. These problems can be divided in energy efficiency problems and physical problems. The case study harbours both categories of these problems to a certain degree. These problems arose due to aging, inappropriate detailing or detailing that was appropriate for its time period, but has become outdated. All of these problems should be addressed in a possible solution in order to obtain a successful renovation.

In terms of energy efficiency problems, the main issues at work are the lack of sufficient insulation, which is non-existent, and the thermal bridges located at the connection of the balconies to the interior floors and at the connection between the landing of the exterior and the interior floor. These cold bridges have the same cause, the floors are uninterrupted concrete slabs running from interior to exterior where heat can easily flow due to the low thermal resistance of the concrete.

Furthermore, there are possible problems related to air leakage and air tightness of the openings. Although these are not directly distinguishable in the details, they could have occurred during the building process due to construction errors or could be insufficient for contemporary standards. The renovation should ensure that an airtight building envelope that complies to current standards is achieved in order to reduce heat loss.

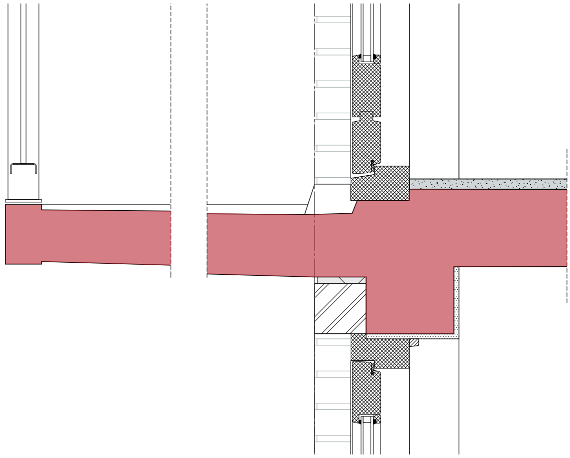


Fig. 6.7.1: *Thermal bridge present in existing situation. Heat is transported from the interior to the exterior through the concrete balconey directly connected to the interior floor slab (Boess, et al., 2017).*

§ 6.8 2ndSkin Solution

In this paragraph the 2ndSkin project is analysed on the methods the project's utilised to solve the energy efficiency and physical problems. The original project's intention was to use a prefabricated façade system with a separate box attached on the north side of the apartment block in which the installations are situated. In the demonstrator project, that was realised, the prefabricated façade system was replaced with an exterior insulation finishing system (EIFS), due to the simplicity of the method and the tight schedule of the project. Due to the fact that the new façade system designed for this thesis is also prefabricated the decision was made to analyse the prefabricated variant of the 2ndSkin project with bamboo cladding, as is described in the 2017 report (Boess, et al., 2017), coupled with the installation box used in the demonstrator project. It should be noted that the prefabricated variant was intended to be used with a decentralised mechanical ventilation system instead of decentralised used in the demonstrator.

§ 6.8.1 *Façade System*

The main system used for the improvement of the thermal insulation value is a structural insulation panel system (SIPS). The lightweight sandwich panel consists of a wooden shell with a core of EPS and four integrated wooden stiffeners. The system thickness used in the 2ndSkin project is 221 mm thick and achieves a thermal insulation value of 6.5 $m^2/W*K$. The ventilation pipes are placed in an additional panel consisting of wooden planks and EPS of 80 mm thickness. The SIPS is a vapour open

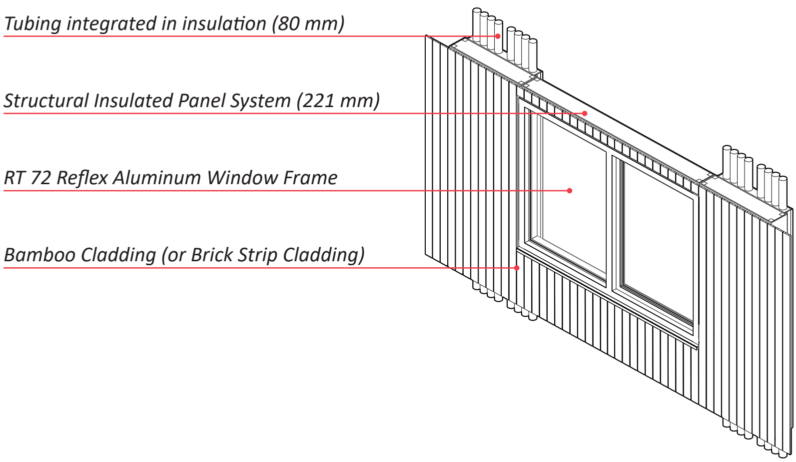


Fig. 6.8.1: *Isometric view of prefabricated variant of the 2ndSkin project, intended to be combined with centralised mechanical ventilation (own illustration)*

construction, meaning the vapour is allowed to enter the system, on the exterior a water barrier is placed. The cladding and supporting structure are then attached to the system.

The window consists of double layered glass with a plastic frame and can be placed directly placed against the SIPS. An interior lining consisting of wooden planks is used to cover and protect the SIPS and the ventilation panel system.

A substructure consisting of wooden columns connected to the existing façade with steel brackets evens out the existing facade and functions as the attachment point for the prefabricated modules. On the sides of the prefabricated modules battens are placed which function as horizontal connecting elements between the modules and the substructure. The panels are fixed with screws. Additional battens are placed on the top and bottom of the panels to vertically connect panels.

§ 6.8.2 *Building Installations*

The buildings installations package consists of one heat pump per three apartments, a heat exchanger per apartment and a boiler per apartment. Six installations boxes are grouped together per six apartments and another six are grouped for the other six apartments. The installation boxes consist of 100 mm thick insulated walls. In this paragraph the individual components are described further.

Heat Pump with boilers and booster

The used heat pump in the demonstrator is an Itho WPU 55, which is succeeded nowadays by the WPU 5G (Itho Daalderop, 2018), situated on the ground floor. A ground source heat pump which extracts energy from the ground to heat or cool water is used. The heat pump is attached to a reservoir boiler to store the heated or cooled water, where it can be further heated to be used for the showers or the kitchen. The used boiler is an Itho Boiler with a capacity of 150 litres. An all-electric variant was chosen due to its popularity with policy makers and stakeholders in the Netherlands, as it reduces the need for natural gas, which can be substituted by the solar panels located on the roof (Boess, et al., 2017).

On the first floor another boiler is placed of 150 litres with a booster heat pump also by Itho Daalderop. The booster is used as intermediary elements to ensure the heated water of the heat pump is pumped to the above lying apartments. On the second floor the space is solely occupied by a boiler of 150 litres.

Heat Exchanger

Every apartment has an individual heat exchanger for ventilation. The heat exchanger is coupled to a mechanical ventilation system used both for the supply and removal of air. The used heat exchanger is an Itho HRU 300. Air is sucked in from the exterior and is heat is exchanged inside the system. The heated or cooled air, dependent on the required temperature in the interior, is then supplied to the two bedrooms and the living room. The outlet air is transported from 'wet' rooms, the kitchen and bathroom, back to the heat exchanger and transported via the ventilation pipes in the walls to an exhaust located on the roof of the installation box.

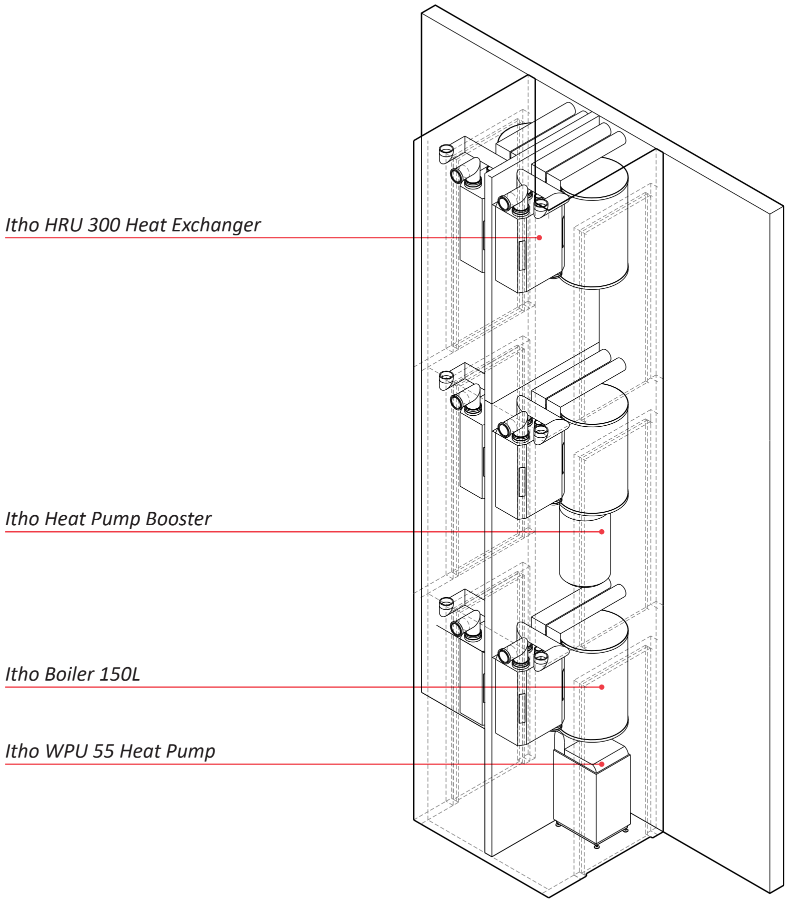


Fig. 6.8.2: *Isometric view of the installation box located on the north facade, two installation boxes provide heat, warm water and ventilation for all twelve apartments (Own Illustration).*

§ 6.8.3 *Service Life*

When observing the data in terms of service life of the different materials utilised in the 2ndSkin demonstrator variant and the prefabricated variant some conclusions can be drawn. The service life of the EIFS used in the demonstrator project is relatively short with 30 years, with signs of degradation after 15 years (Boess, et al., 2017). Naturally, the EIFS offer energy reduction for a limited time-period, and is difficult to remove as it is glued to the existing facade. The prefabricated variant has materials with a wide variety of service lives, with the EPS insulation and the bamboo cladding being the deciding factor for the service life of the entire façade. The bamboo cladding could be removed with relative ease, but the EPS cannot be removed from inside the SIPS without compromising the system, resulting in the combined failure of the whole system. It is therefore beneficial to utilise materials with equal service lives to optimise the use of those materials (Boess, et al., 2017).

The building installations have a guaranteed minimum life expectancy of 15 years (Itho Daalderop, 2018), but with adequate maintenance the service life can be lengthened to 20 to 25 years.

Component	Lifetime (Years)
EIFS	30
Timber Post	80 - 100
Stainless Steel U-Profile	> 100
Timber Post + Wooden Stiffeners	80 - 100
Chipboard P5	80 - 100
EPS	30
Fiber Cement	> 50
Brick Strips	> 100
Foam Glass	60 - 100
Untreated Wood (Bamboo Slats)	30
PVC	> 100
Itho WPU 55	15-25
Itho HRU 300	15-25

Tab. 6.8.1: *Service life expectancy for considered and utilised materials and building installations (Boess, et al., 2017).*

§ 6.9 Conclusion

In chapter 6 the case study was analysed in more detail in order to formulate an applicable design strategy in chapter 7. The industrialised building method utilised for the construction of the apartment block situated at the Soendalaan uses standardised components and are therefore highly repetitive. The repetitive nature of the buildings is beneficial for the application of prefabricated systems, as the number of uniquely sized modules can be decreased. Furthermore, the building's structural layer of 100 mm concrete is capable of supporting additional weight. The general parameters that require the most attention when applying a renovation are the multitude of different window sizes. Seven uniquely sized windows can be distinguished in the building. In terms of building physical problems, the thermal resistance is poor, as no insulation is applied anywhere in the building and there are several thermal bridges leading to a higher energy consumption. The most severe thermal bridge, the balconies, requires an adequate solution.

The second part of the chapter delved deeper into the 2ndSkin project's approach to solving the energy efficiency problems, where a distinction was made between the intended prefabricated variant and the exterior insulation finishing system (EIFS) variant applicated on the case study. The prefabricated variant utilised a structural insulation panel system and integrated tubing for the full decentralised mechanical ventilation system. The EIFS variant utilised a decentralised heat exchanger per apartment and a centralised heat pump in combination with a boiler per apartment. Two heat pumps, six heat exchanger and six boilers where placed in an exterior installation box to provide for six apartments. The utilised building installations package in demonstrator will be utilised and integrated in the design for the new façade systems to achieve the required energy consumption reduction.

Finally, the expected life expectancy of the components used in the renovation systems was listed to gain insight when potentially an overhaul of the renovation is required to be performed in the future. The material or component with the lowest service life, if It cannot be individually separated from the other components, is the decisive factor for when the whole system's functioning is nullified. Therefore, service lives have to be synchronised or components have to be designed to be easily separated from each other to avoid unnecessary premature demolition of the complete façade.

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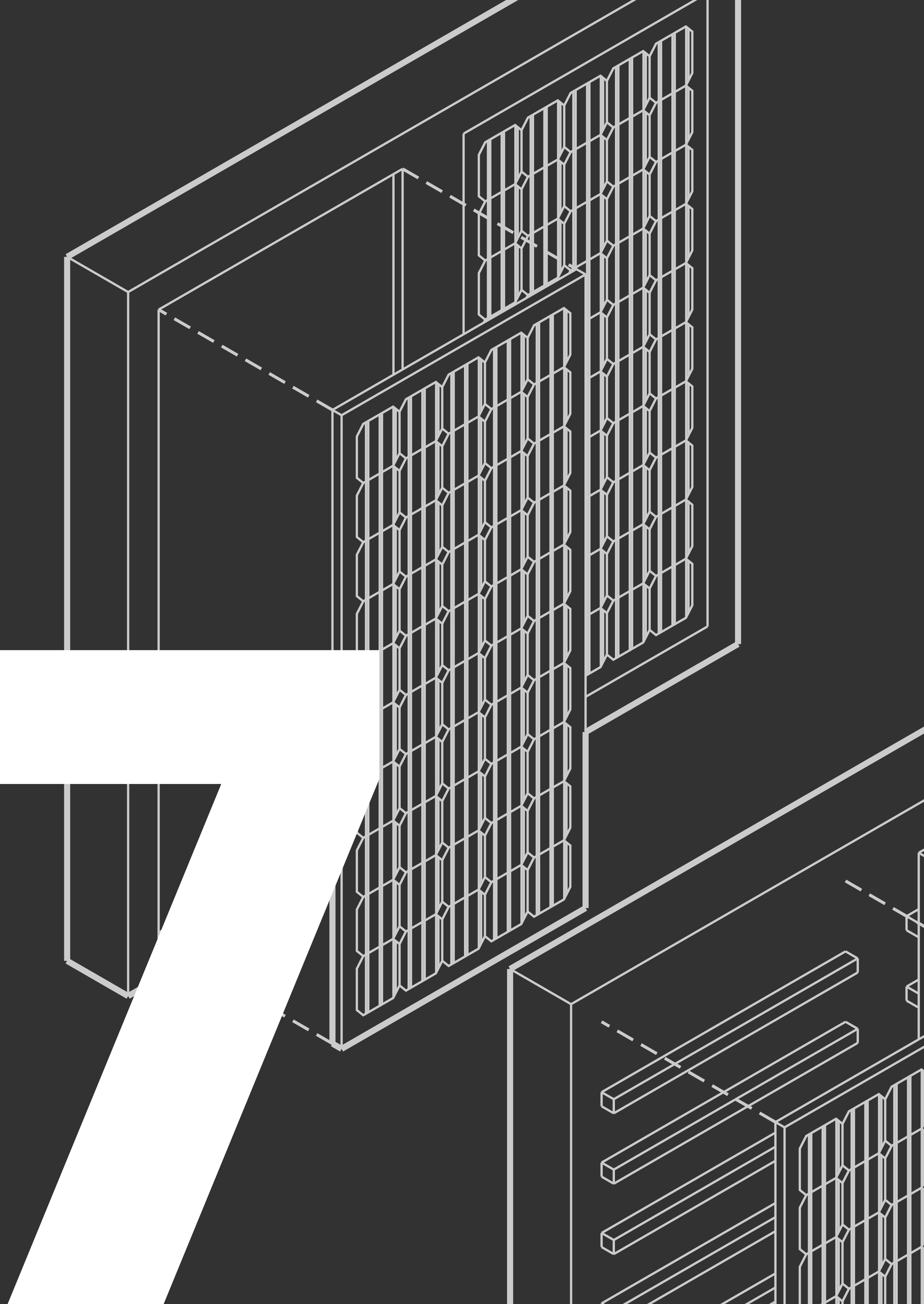
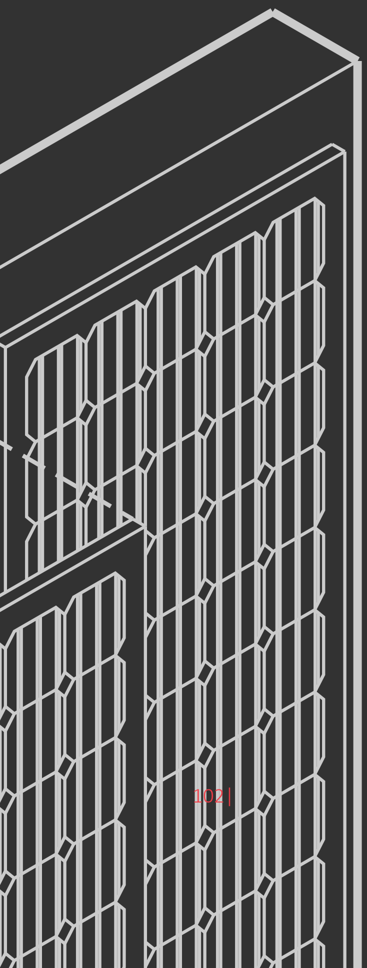


CHAPTER 7
DESIGN METHODOLOGY



7 Design Methodology

Based on the literature study and the assessments of the reference projects a design methodology has to be formulated that acts as the guiding theme for the design. The design methodology consists of requirements, principles, challenges and tools that can be consulted in order to accurately formulate an appropriate concept.

Paragraph 7.1 elaborates the required functionality the design has to fulfil to be successful as a façade. In paragraph 7.2 the different fields of study and relevant criteria for the final design are discussed. Paragraph 7.3 discusses the strategy that is utilised to produce design concepts that comply to the requirements. Paragraph 7.4 portrays a set of design tools that can be utilised in order to aid the design process. Finally, in paragraph 7.5 the method for assessing the concepts is elaborated further.

§ 7.1 Required Functionality as a Façade

Before describing the required qualities necessary for the design to comply to the research goal of this thesis, the design must also comply to the different requirements necessary to function as a façade. The façade defines the architectural appearance of the building, provides views from the inside and outside, absorbs push and pull forces from wind loads, carries its own weight and possible other components.

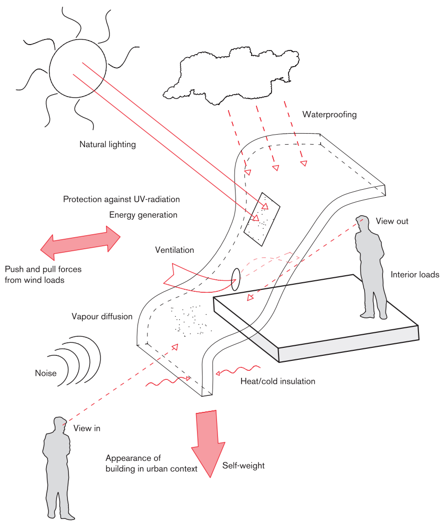


Fig. 7.1.1: *Required functionality facade (Knaack, Klein, Bilow, & Auer, 2007).*

Furthermore, the façade should allow sunlight to penetrate the interior, as well protect from it when it becomes disadvantageous. It also resists penetration of water and handle humidity from within and without. The façade provides insulation to not only heat, but also cold and noise and can potentially facilitate energy generation (Knaack, Klein, Bilow, & Auer, 2007).

Although these requirements seem general they form an overarching list of requirements on top of the personally determined list of required criteria which have to be complied to during all phases of the design process and beyond: the conceptual phase, while designing the principles of construction, during detailing and finally during the construction phase.

It is desirable to design a façade that complies to all these complex requirements, while being as simple as possible. The façade should be an adaptive envelope that is in functioning similar to the human skin, fulfilling multiple functions of the body.

§ 7.2 Fields of Study

The aim of this graduation thesis is to design a prefabricated façade system for energy reduction renovation that is future proof by considering the changing standards and service life. Aside from this, the renovation should be architectural sound in order to gain widespread acceptance. Therefore, three subject fields can be distinguished: energy, future proof and architecture. Within these three subject fields are specific criteria that have their own personal required quality, which will be the benchmark for assessing the final design. Not every quality will be achieved as described below, achieving quality in one criterion could have a deterrent effect on a different criterion. The opposite is also imaginable, where improvement of one criterion leads to the improvement of an another.

The main goal is to achieve a future proof facade, which will be elaborated further in paragraph 7.2.3, therefore this field of study will be the main researched area. Nevertheless, the façade has to be effective as a renovation and as a façade in order to be competitive in the renovation market. These fields of study should not be neglected and function as important secondary assessment criteria. Figure 7.2.1 shows an overview of the requirements.

These three subject fields form the basis of the decision process regarding the design. All decisions relevant for the design should address one of the three subject fields or multiple subject fields. To further make the design task explicit, the fields are further subdivided into required qualities and required building physical properties.

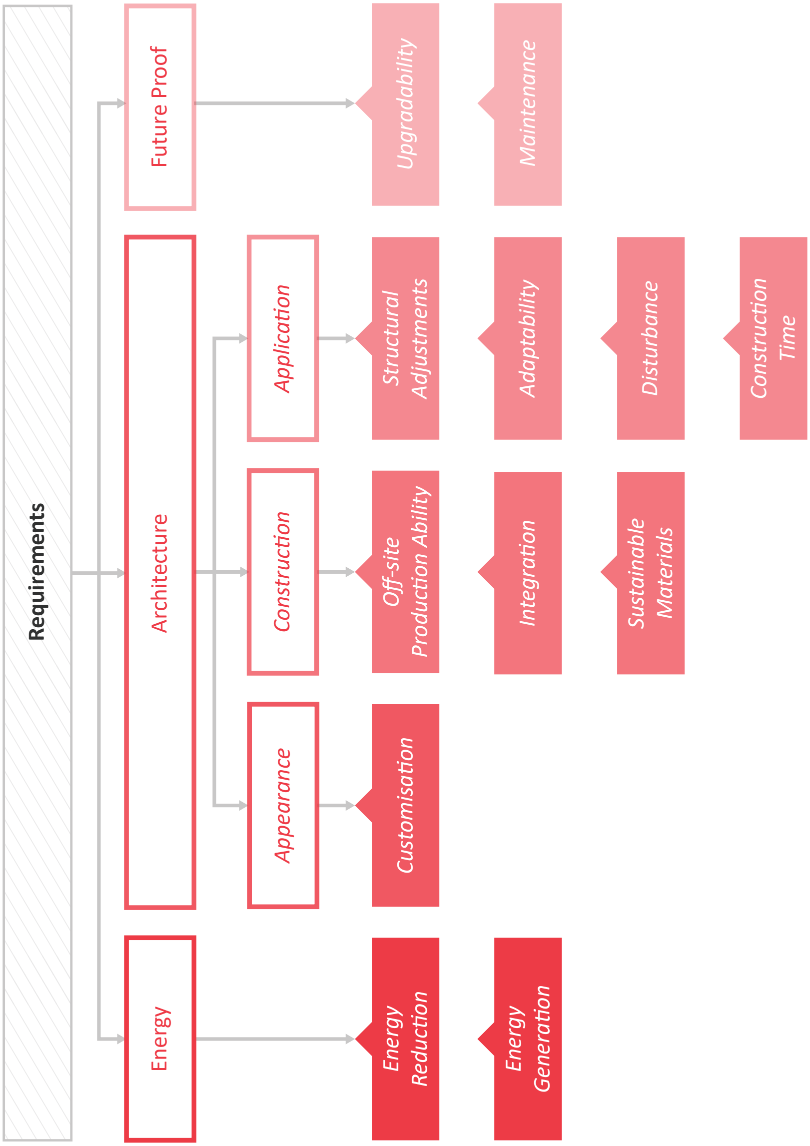


Fig. 7.2.1: *Requirements divided in fields of study and criteria (Own illustration).*

§ 7.2.1 ***Energy***

This subject field involves all the energy reductional and productional measures needed to ensure the façade becomes more energy efficient. The aim is to take the stepped approach as was suggested by the BPIE in order to reduce initial investment costs and utilise the learning curve. Four levels of energy reduction measures will be used: shallow, medium, deep and nZEB levels of renovation, all three levels are expressed in an energy reduction percentage. The façade system is required to be able to incorporate all three levels and be able to be updated to a higher level of renovation when required.

Energy production

Concluded from the literature and the analysis, the main energy production method would be through the use of use of photovoltaic panels. The same layout for the photovoltaic panels will be used as in the pilot project of 2ndSkin.

Energy reduction

The energy reductive measures of the 2ndSkin project will be used as described in paragraph 6.8, consisting of an exterior insulation layers, replacement of the windows by new window frames with double glass. For the building installations an all-electric ground source heat pump is utilised on the ground floor and a booster for the heat pump on the first floor per three apartments, as well as additional boilers for every individual apartment. Furthermore, every apartment will be outfitted with a heat exchanger for ventilation with necessary tubing.

Finally, further energy reduction measures will be mainly based on including the passive measures described in paragraph 4.4 and paragraph 4.5.

§ 7.2.2 ***Architecture***

The field of study architecture encompasses three sub-fields consisting of appearance, construction and application. The appearance will mostly be affected through the cladding and is the main criteria determining the aesthetic quality. Construction includes all the criteria that affect the production of the façade system and application includes the criteria that affect the overall construction process on-site.

In architectural terms the renovation should appeal to occupants in order to gain acceptance for the renovation in the first place. The goal of the façade system is not to portray a singular architectural vision, but allow for the inclusion of a wide variety of architectural concepts.

§ 7.2.2.1 ***Appearance***

Customisation

The design should be able to permit the inclusion of a large variety of different components, materials and finishes according to the project's unique requirements, while simultaneously sustain a base system that can be reused for every project. The base system should not be built from scratch for every new project in terms of detailing.

In terms of specific customisation options, the system should include a wide variety of demountable type of façade finishing and exclude renderings, as renderings would prohibit the system from being demountable.

§ 7.2.2.2 **Construction**

Off-site Production Ability

In order to simplify the application of the renovation on-site the façade system should aim to be fully produced in a factory setting. Furthermore, the complexity of the system should be minimised in order to ensure a smoother production process.

Integration

Integration of installations in the facade module is preferred over exterior additions, as long as it does not compromise the ability of the system to be upgraded or maintained. However, if the chosen package of installations cannot be integrated in the façade module, for example due to sizing, it should be possible for the system to function also with exterior installations.

Sustainable Materials

As was concluded from the literature, when the operational energy of a building is minimised through renovation, the embodied energy becomes significant. Materials selected for the renovation of the façade should be low in embodied energy or be eligible for an environmentally friendly disposal method, either by recycling or effective downgrading. Furthermore, the amount of material necessary to construct the system should be minimised.

§ 7.2.2.3 ***Application***

Structural Adjustments

Adjustments to the existing structure of the building envelope should be minimised at all costs to avoid increased disturbance to occupants and construction costs. Further additional work to foundations and necessary substructures should only be performed if absolutely necessary in order to ensure the structural integrity of the energy reduction renovation.

Adaptability
Although the system will be designed for a case study the system's ability to adapt to different typologies is deemed important. The system should also be able to conform to the different parameters that can change within the same typology, such as window sizes, entrance sizes, roof pitches, etc. Adaptability excludes the points mentioned under upgradability and maintenance.

Disturbance
Disturbance to occupants should be minimised at all times through minimising the labour on-site and ensuring a swift and adequate application process of the energy renovation. Occupants should be able to remain in their dwellings during the renovation process. The façade system should allow for temporary compromising construction activities to the daily lives of occupants to be performed as fast as possible.

Construction Time
The construction time on-site should be minimised in order for the façade system to be a viable alternative for existing methods. The benchmark for the construction time is the current 2ndSkin project utilising prefabricated modules, which should be in the order of magnitude of several weeks (Boess, et al., 2017). When the design of the façade system has comparable steps towards the finalised energy reduction renovation, then it can be assumed the construction time is similar.

§ 7.2.3 ***Future Proof***

Future proof in this thesis encompasses the qualities that ensure the long-term functionality of the façade system. Adapting to changing standards, albeit functional or technological advancements, are the main aim of this field of study. The goal is not to predict future advancements, but design a façade system that can adapt easily to changes, and allows for these changes to happen.

Although that is the general description of the term future proof in this thesis, it is necessary to further personalise the term in order to be able to assess it in the design stage. Future proof is described in two criteria in this thesis upgradability and maintenance, where upgradability encompasses all the changes to the façade where there are clear physical changes to the façade and the maintenance encompasses all the changes that are necessary to return the façade to its original intended state. Future proof also encompasses the whole life cycle of the façade, from construction to demolition.

Upgradability
The system should allow for upgradation when the system as a whole becomes obsolete or individual components within the system become obsolete, either due to changing occupant desires or changing regulations. Also, more superficial upgrades such as replacing façade finishes should be facilitated accordingly. Naturally speaking, the ease of upgrading should also accompany the ease of demounting the system. This criterion assesses the effort, cost and time that is necessary to perform such upgrades.

Although upgradability for as many components as possible is desirable, but some components require a higher level of upgradability than others due to their intended function. In figure 7.2.1 an overview of the different functionalities and how they could potentially change, the time period generally required for that change and the affected context.

Function	Context	Reason for Change	Period of Change
Thermal Insulation	Whole Facade	Technology Regulations Awareness	Short Term Short Term Middle Term
Sound insulation	Whole Facade	Technology Regulations Environment	Short Term Short Term Long Term
Water & Air Tightness	Whole Facade	Technology Regulations	Short Term Short Term
Appearance	Whole Facade	Fashion	Middle Term
Daylight	Individual Part	User Use	Short Term Long Term
Energy Gaining & Storage	Individual Part	Technology Regulations Awareness	Short Term Short Term Middle Term
Ventilation	Individual Part	Technology User Use	Short Term Short Term Long Term
Heating/Cooling	Individual Part	Technology User Use	Short Term Short Term Long Term

Fig. 7.2.2: *Possible changes to functionalities, short term indicates a time period of 1-3 years, middle term 3-10 years and long term 10+ years (Own illustration).*

Maintenance
The system should allow for maintenance to all the individual components of the system. All types of maintenance are included, this includes repair due to damage, as well as preventive maintenance. When performing the maintenance, it should be relatively easy to access the relevant components. In table 7.2.2 the different components and their approximate rate of maintenance are elaborated further.

Component	Maintenance Rate	Reason(s)
Cladding	High	First layer of defence, damage due to water, wind, etc.
Water Barriers	Low	Protected by cladding
Insulation	Low	Protected by water barriers, potentially vapour damage.
Windows	Medium	General sturdy components, incidental damage due to impact possible.
Shading	High	Dependent on static or movable system. Movable systems are in general vulnerable.
Building Installations	High	High in maintenance, replacing of parts is common.
Piping	Low	Generally protected and manufactured of long-lasting material.

Fig. 7.2.3: *Possible rate of maintenance required per individual component (Own illustration).*

§ 7.3 Design Strategy

In order to design a façade system for renovation that satifies the thesis goal a design strategy has to be formulated that achieves the required qualities, as described earlier, and incorporates the found knowledge described in the literature review. Furthermore, included in the design strategy should be design process. In the following paragraphs the different steps of the process and the relevant strategy for that step will be discussed in further detail. The multiple steps will be executed in part four of this thesis.

§ 7.3.1 *Identifying Potential Component Changes*

The first step is to identify how the components of façade system could potentially change over time. The components, including the installations, will subjected to the reasons of change described in paragraph 7.2.3 in order to construct the possible long-term scenarios. These component changes formulate the present and future functional program for the façade system.

§ 7.3.2 *Concept Production*

The second step of the design process should be about the production of several concepts that potentially have the required qualities for further development and can support the potential changing components. In order to effectively incorporate the literature review in the design process the use of design tools will be incorporated. The design tools, which will be discussed further in paragraph 7.4, can be combined to form a guiding theme for the concepts. In order to choose the relevant design tools for combination they have to be first assessed on the qualities described in paragraph 7.2. While the design tools form the foundation for the production of a concept, they have to be elevated to a lower level of abstraction in order to fully grasp their potential, but not be too pronounced to disallow further development.

§ 7.3.3 *Concept Development*

The third step develops the concept to a point where it can be applicated to the case study in order to be developed further. It consists of developing the system and the individual components in detail. Further deviation in design options for multiple components will be explored and assessed in this section in order to come to a solution that best fits the research goal of the thesis. The assessment of the options will be based on the described qualities, as well as on their effectiveness to fulfill the individual required functionality.

§ 7.3.4 *Application Case Study*

The final concept will be applied to the case study and combined with the strategy the 2ndSkin project utilised in the demonstrator project. In order to solve energy efficiency issues that cannot be solved by the building envelope system designed for this thesis. The application will be assessed and the design will be adjusted to issues that arise during this step. The final detail drawings will be included in this section. Finally, fictional scenarios will be formulated and the building envelope system will be adjusted according to the steps required in the scenarios to portray the systems' resilience.

§ 7.4 Design Tools

The design tools are isolated abstract representations of tools that can be combined to formulate a concept. Every design tool is a representation from sections of the literature that all have their unique functionalities, together they form a summary of the literature and a way to utilise the literature in the design process. Every design tool affects the design in one field of study or more on a multitude of criteria, either positive or negative. The design tools are helpful in quickly combining the right aspects into a multitude of concepts. These concepts still have to be taken from their initial abstract level to a more detailed level in order to assess if the design tools are combinable.

The design tools can be divided into three categories: Typology tools, energy tools and buildability tools. The typology tools are used to get the right functionalities into the design concept and formulate an overall guiding theme and typology. The energy tools are utilised to get the necessary energy reductive and productive measures into the design concept. Finally, the buildability tools are used to form a method for the construction and application of the design concept.

All the design tools are categorised into groups of 1 to 4 design tools. The design tools within a group are opposites or variations of each other and affect the same criteria. Most design tools within the same group are interchangeable and are not combinable, for example when choosing a connection typology, which can be either wet connections or dry connections. While in other groups the design tools are combinable, for example when choosing for insulation improvement, adding insulation as well as upgrading the windows leads to the desired effect. It will become apparent in the description of the design tools and in figure 7.4.46 which tools are interchangeable and which are combinable. Furthermore, it is also imaginable that the combination of two design tools could form a new design tool, for clarity purposes these combinations are left out of the matrices. In the following sections the individual design tools per category will be discussed further.

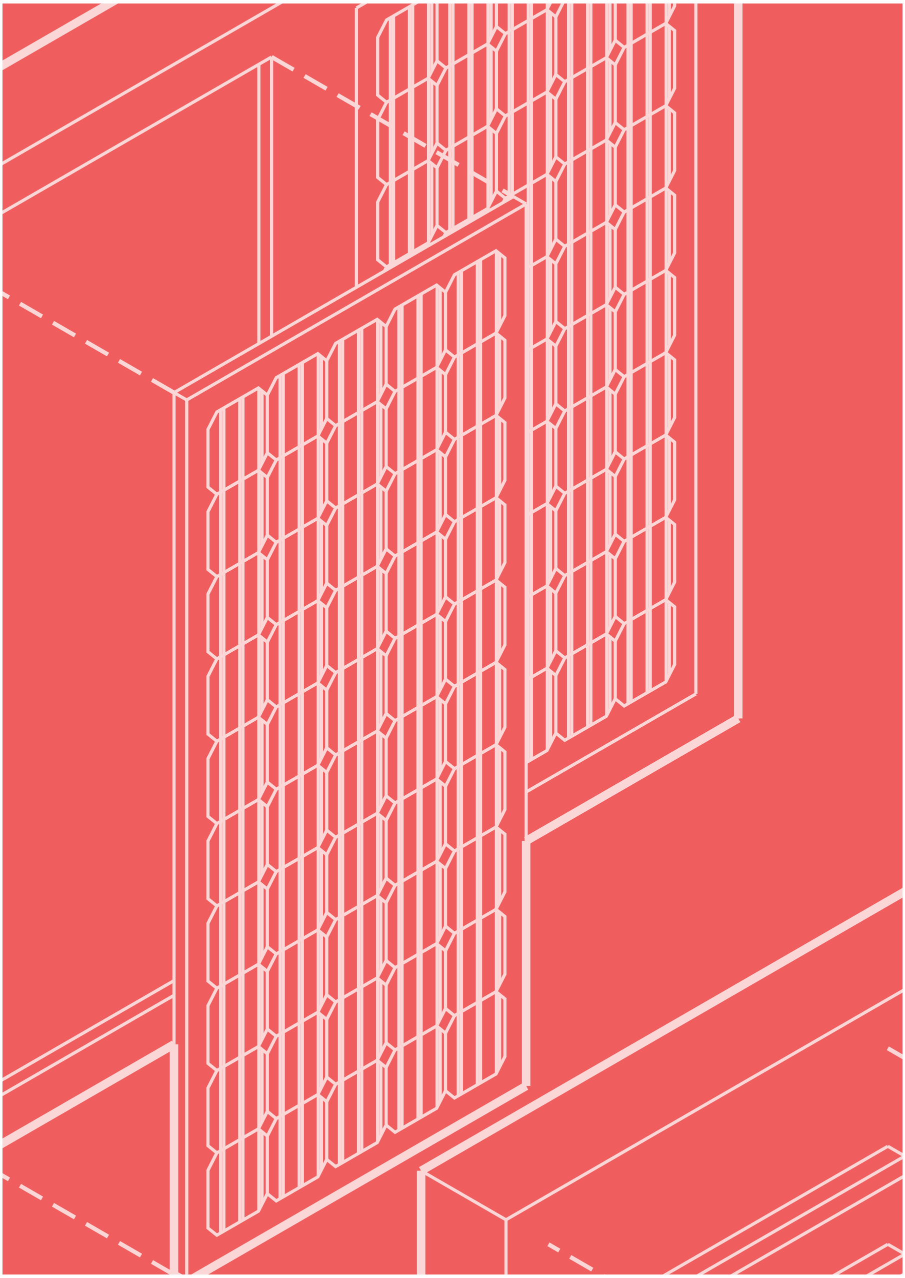


Fig. 7.4.1 *Principle System*

A principle system uses a general approach with principles for every project, such as ENDIS, which formulates customised details for every individual project. A principle system is in theory adjustable to every building and typology, the downside is that the system has a lengthier design process, as no preparation before the start of a project in terms of materials and components can be established.

Fig. 7.4.2 *Adjustable System*

An adjustable system uses a set of general components and standard details that are adjustable to every project, such as utilised by TES Energy Facade. In theory this approach can be adjusted to every typology, as long as the standard details can be applied successfully. Some degree of raw materials can be stored before the start of the project, but these materials have to be processed to the right measurements.

Fig. 7.4.3 *Fixed System*

A fixed system uses standard components, materials and fixed sizing in order to fabricate a façade, such as MeeFS, which utilises a supporting structure and modules which are prefabricated. This system is adjustable to a project, as long as the standard components fit the project's measurements. This ensures necessary components can be stored before a project starts, decreasing the preparation time required, but this also decreases the scalability of the approach.

Fig. 7.4.4 *Horizontal Orientation or Vertical Orientation*

Fig. 7.4.5 The module orientation will affect the visual appearance, the assembling procedure and the integration of installations. Vertical shafts are more difficult to integrate in horizontal modules and vice versa. The choice for horizontal or vertical orientated is determined by the static system, load-bearing capacity and structure of the existing wall. Massive walls can adapt to both orientation, while the adaptation to skeleton or plate walls is dependent of load-bearing capacity and available fixing points.

Fig. 7.4.6 *Small Size*

Smaller sized panels are easier to transport and easier to apply on-site. Furthermore, mounting the panels can be achieved with smaller construction apparatus. The disadvantageous side is the sheer number of panels that need to be placed.

Fig. 7.4.7 *Large Size*

Larger sized panels need more specialised transport in order to be effectively be transported on-site. On-site the panels need construction cranes to be placed accurately. The construction time on-site is decreased due to the lesser number of panels and connections between panels.

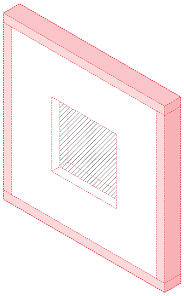


Fig. 7.4.1:
Principle System

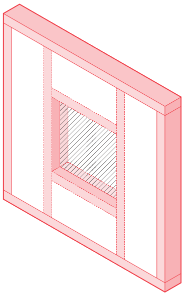


Fig. 7.4.2:
Base System

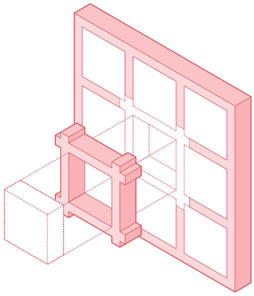


Fig. 7.4.3:
Fixed System

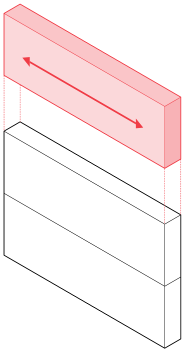


Fig. 7.4.4:
Horizontal Orientated

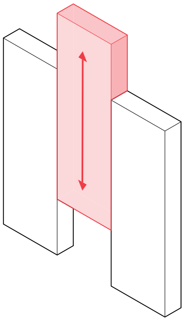


Fig. 7.4.5:
Vertical Orientated

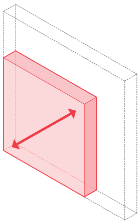


Fig. 7.4.6:
Small Modules

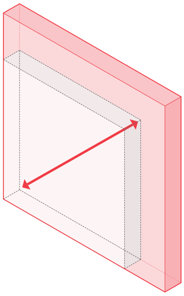


Fig. 7.4.7:
Large Modules

Fig. 7.4.8 *Closed System*

A closed system is a system where the individual functional components of the façade cannot be taken apart. A closed system is more difficult to perform maintenance on, however the system as whole is more protected.

Fig. 7.4.9 *Layered System*

A layered system is a system where the functional components are distinctively placed in successive layers. A layered system has the benefit of being easier to dismantle and perform maintenance on the first layers, however this become increasingly more difficult with successive layers.

Fig. 7.4.10 *Modular System*

A modular system divides the functional components into modules that together form a facade. A modular system would make maintenance and replacement easier, at the cost of the increasing number of connections necessary.

Fig. 7.4.11 *Component Façade*

A component façade is a typology of façade where completed parts with different designated functionalities are connected together on-site to form a completely functioning façade. Transport of smaller parts is relatively easy, but construction time on-site is lengthened.

Fig. 7.4.12 *Element Façade*

An element façade is a typology of façade where completed modules with all necessary functionalities are connected to each other in order to form a completed façade. The advantage is that element façades don't require much installations time on-site, but transport needs to be carefully planned.

Fig. 7.4.13 *Wet Connections*

Wet connections are connections that are permanently fixed due to chemical components. In general, wet connections are stronger than dry connections, but cannot be taken apart at the end of the facade's lifespan, leaving no other option than demolition (Maes, 2015).

Fig. 7.4.14 *Dry Connections*

Dry connections are connections that are free from permanent fixing. Panels that are connected with dry connections can be taken apart at all times, which ensures fast disassembly and possible reuse of separated components. Disadvantageous is that dry connections are more ductile and less strong as wet connections (Maes, 2015).

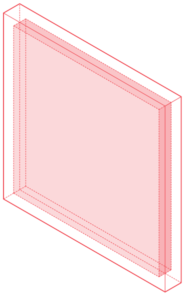


Fig. 7.4.8:
Closed System

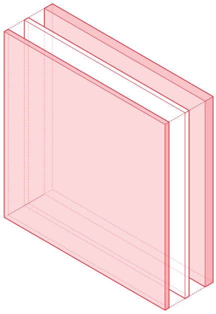


Fig. 7.4.9:
Layered System

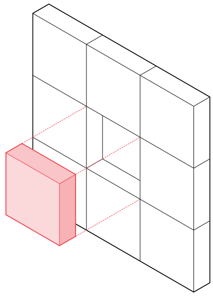


Fig. 7.4.10:
Modular System

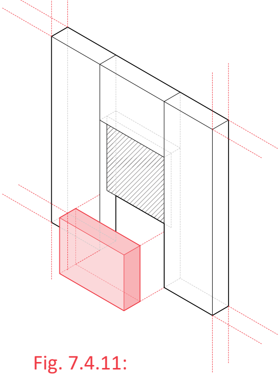


Fig. 7.4.11:
Component Facade

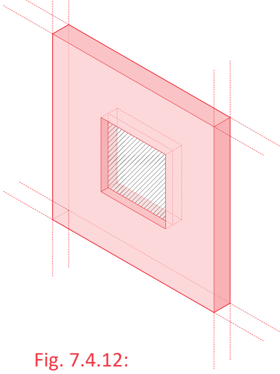


Fig. 7.4.12:
Element Facade

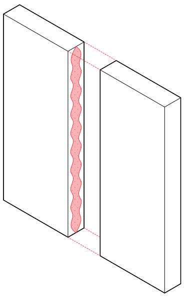


Fig. 7.4.13:
Wet Connections

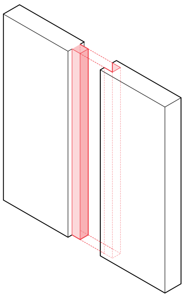


Fig. 7.4.14:
Dry Connections

Fig. 7.4.15 *Integrated Installations*

Integrating installations inside the facade would significantly increase the complexity of the system. Repair and maintenance would be more complicated, due to restricted access. However, integrating the systems would also decrease the number of components that need to be installed on-site.

Fig. 7.4.16 *Separate Installations*

Separating the installations from the façade system would ensure the complexity of the facade is lowered. Repair and maintenance can be performed more easily due to the accessibility to the installations. However, it would increase the number of components that need to be installed on-site and the required space.

Fig. 7.4.17 *Horizontal Shading*

Horizontal shading is an effective way of solar control on the south façade, where the angle of the sun is at its highest. As the shading is stationary, user control is limited.

Fig. 7.4.18 *Vertical Shading*

Vertical shading is an effective way of solar control on the west and east façades, where the angle of the sun is generally lower. As with horizontal shading, the light intensity is not adjustable, and the view is blocked slightly.

Fig. 7.4.19 *Adaptable Shading*

Adaptable shading, albeit horizontal or vertical, has the benefit over stationary shading by given the user full control over the light intensity. The downsides are the larger maintenance costs.

Fig. 7.4.20 *Cantilever Shading*

Cantilever shading is effective for seasonal shading, where it blocks the high angled summer sun, while allowing the low angled winter sun to be able to freely penetrate the interior. The cantilever does subject the existing construction with relatively high extra weight.

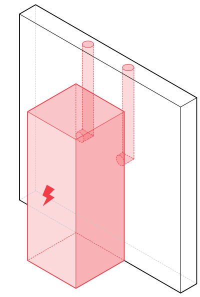


Fig. 7.4.15:
Separated Installations

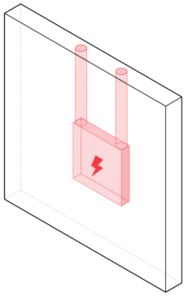


Fig. 7.4.16:
Integrated Installations

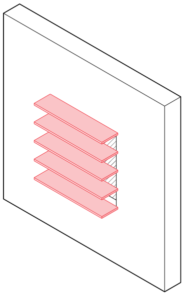


Fig. 7.4.17:
Horizontal Shading

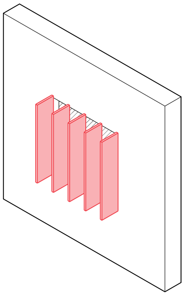


Fig. 7.4.18:
Vertical Shading

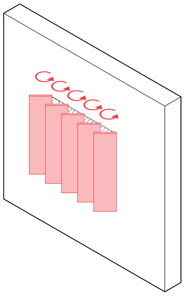


Fig. 7.4.19:
Adaptable Shading

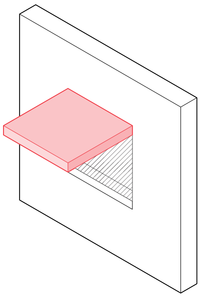


Fig. 7.4.20:
Cantilever Shading

Fig. 7.4.21 *Apply Insulation*

The application of additional insulation is the main tool in lowering the energy demand, the application is the determining factor in choosing a suitable insulation form and material.

Fig. 7.4.22 *Replace Windows*

The replacement of windows can reduce the energy demand further. Window setting blocks can be reused for the placement of the new window, if in fair condition. The airtightness of the new window should be ensured in order to achieve maximum energy reduction.

Fig. 7.4.23 *Trombe Wall*

The Trombe wall is a method of indirect solar gain. An element absorbs heat during the day and releases that energy during the night. The Trombe wall needs to be directly connected to the interior, which increases the disturbance to the occupants during the renovation process.

Fig. 7.4.24 *Box Window*

Box window is a form of double façade that is constrained to one window. The second pane of glass acts as a buffer space where the air is heat is preheated for ventilation.

Fig. 7.4.25 *Attached Sunspace*

The attached sunspace is a larger form of double façade generally engulfing the entire south façade, is uses the same principles as the box window, while also enhancing the living space. The downside is the relatively high floor space required for it.

Fig. 7.4.26 *Building Applied Photovoltaic*

Applying photovoltaic can reduce the energy demand further and replace fossil fuels. Applying them on a surface requires a substructure to support it, and the panels can be replaced easier this way.

Fig. 7.4.27 *Building Integrated Photovoltaic*

Integrating photovoltaics in the module structure ensures the PV is better protected, and minimises the required maintenance. The downside is the space necessary in the building envelope system, which has to be accounted for in the design. This in turn leads to increased complexity.

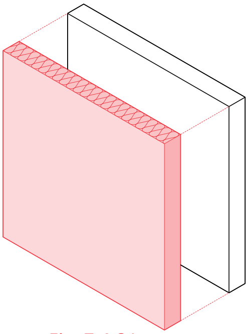


Fig. 7.4.21:
Apply Insulation

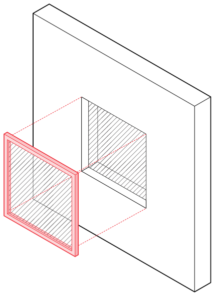


Fig. 7.4.22:
Replace Windows

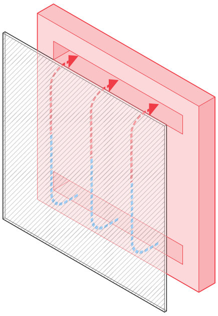


Fig. 7.4.23:
Trombe Wall

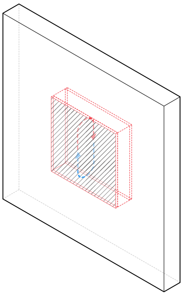


Fig. 7.4.24:
Box Window

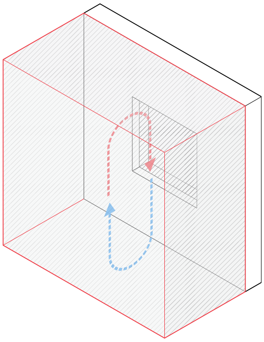


Fig. 7.4.25:
Attached Sunspace

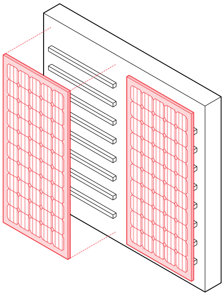


Fig. 7.4.26:
Building Applied PV

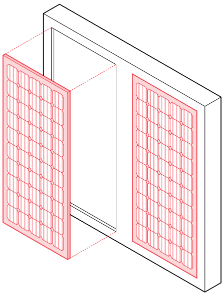


Fig. 7.4.27:
Building Integrated PV

Fig. 7.4.28 *Composite Insulation System*

Composite insulation panels consist of insulation covered with reinforced priming material and a finishing plaster, and are manually brought up and permanently fixed to the existing façade. Downside of this system is the inability of the system to be demounted afterwards.

Fig. 7.4.29 *Semi-prefabricated Facade System*

A semi-prefabricated system generally uses a prefabricated substructure which is filled with insulation. Cladding can be integrated in the prefabricated system or manually applied. The system uses smaller components which are easier to transport. The downside is the increased labour on-site.

Fig. 7.4.30 *Prefabricated Module System*

Prefabricated modules are assembled in a fabrication hall for optimal quality. The full modules are mounted on a substructure attached to the existing façade. Prefabricated systems require the least amount of labour on-site, but require careful planning.

Fig. 7.4.31 *Exterior Flush-mounted*

The advantageous side of mounting windows on the exterior is that they are easy to manufacture and assemble. Disadvantageous is that integrating shading is difficult.

Fig. 7.4.32 *Centre-in-reveal*

Mounting the windows in the centre of the reveal ensures that the window is integrated in the insulation level. Disadvantageous is the increased effort required for manufacturing and installation.

Fig. 7.4.33 *Interior Flush-mounted*

Interior flush-mounted windows have the most optimised position for a heat dissipation device, and allow for integration of shading. Disadvantageous is the need for insulation of the reveal which decreases the glazed area.

Fig. 7.4.34 *Fixed Module System*

Fixed modules offer quick assembly and excellent sealing and waterproofing (Geier, 2010). Disadvantageous is that access to the intermediate space is closed off and the overall repairability of the system is decreased.

Fig. 7.4.35 *Single Fixed Modules*

Single fixed modules offer the intermountability and allow for access to the intermediate space. Disadvantageous is the fact that assembly, sealing and waterproofing require more careful planning.

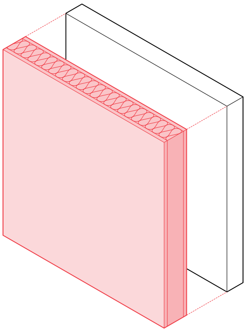


Fig. 7.4.28:
Composite Insulation System

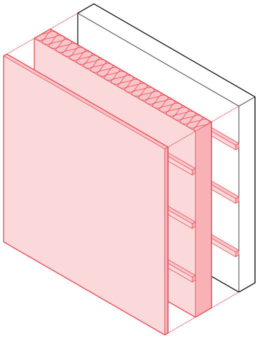


Fig. 7.4.29:
Semi-prefabricated System

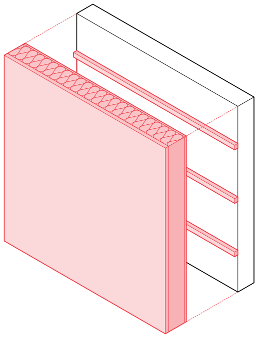


Fig. 7.4.30:
Prefabricated System

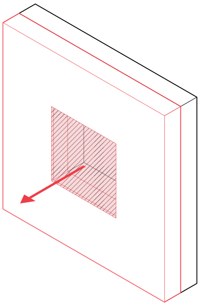


Fig. 7.4.31:
Exterior Flush-mounted

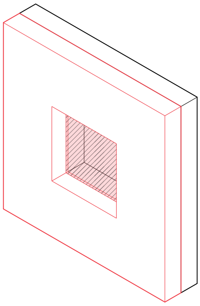


Fig. 7.4.32:
Centre-in-reveal

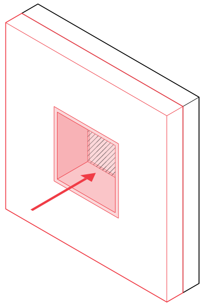


Fig. 7.4.33:
Interior Flush-mounted

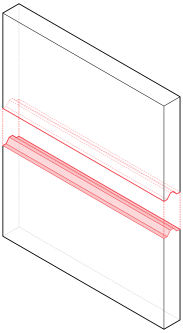


Fig. 7.4.34:
Fixed Module System

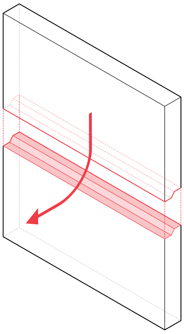


Fig. 7.4.35:
Single Fixed Modules

Fig. 7.4.36 *Standing Construction*

Self-supporting panels are structurally decoupled of the existing structure, which is advantageous if the existing structure is incapable of supporting the extra weight. Self-supporting panels are therefore useable for a larger range of typologies. However, the self-supporting panels need to be outfitted with an independent supporting structure and subsequently foundation, which could increase the use of necessary materials, time and costs.

Fig. 7.4.37 *Single Fixing*

When fixing an area covering self-supporting module, acting as a plate, to the top of the building and to the foundation the module functions as a single-span construction. Single-span constructions require thick modules in order to provide buckling stability (Geier, 2010).

Fig. 7.4.38 *Segmented Fixing*

When fixing an area covering module to several points all over the façade the module functions as a continuous beam construction, which requires lower thickness modules to provide buckling stability.

Fig. 7.4.39 *New Foundation*

A new foundation is necessary when the existing foundation is not capable of carrying additional load. Adding a new foundation has the advantage that it can applied to multiple typologies, while the disadvantage is the amount of additional labour required on-site.

Fig. 7.4.40 *Load Application Plinth*

Loading the standing construction onto the existing foundation via the plinth is possible if the existing foundation is able to carry additional weight. It decreases the amount of labour required on-site, but it might not be applicable to every building.

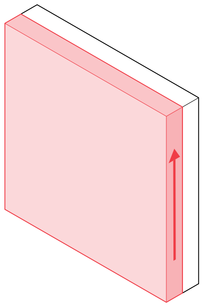


Fig. 7.4.36:
Standing Construction

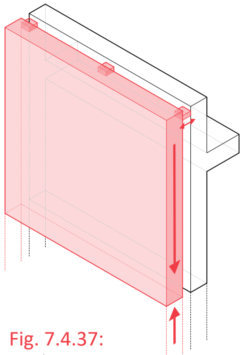


Fig. 7.4.37:
Single Fixing

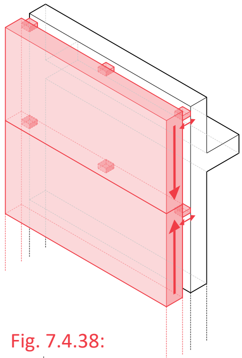


Fig. 7.4.38:
Segmented Fixing

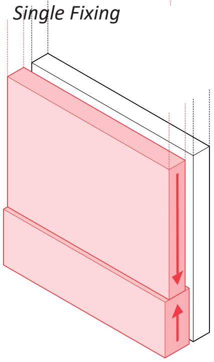


Fig. 7.4.39:
New Foundation

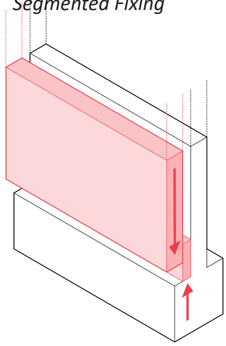


Fig. 7.4.40:
Load Application Plinth

Fig. 7.4.41 *Suspended Construction*

Supported panels are structurally coupled to the existing structure. The existing structure should be subjected to analysis to ensure if it is capable of supporting the added weight. Because of this, not every structure will be capable of supporting extra weight, limiting the scalability of such systems. However, in contrary to self-supporting systems no extra support structure is necessary in the new system, ensuring a minimisation of necessary materials, time and costs (Geier, 2010).

Fig. 7.4.42 *Suspended from Eave*

Suspending the modules from the eave of the existing façade has the beneficial effect that no additional substructure is needed and a minimisation of fixing points. Downside is that the modules have to be a full building height, which would require special preparation when transporting the modules.

Fig. 7.4.43 *Substructure Loaded*

Using a substructure to suspend the modules from has the additional beneficial effect of evening out the uneven existing façade, which would reduce application time of the modules on-site. Nevertheless, mounting the substructure needs preparation on-site and therefore need either scaffolding or mobile cranes.

Fig. 7.4.44 *Existing Foundation*

Suspended modules can, when lightweight, be loaded on the existing foundation if it can carry the additional load. It decreases the amount of labour on-site, but buildings have to be checked extensively if they can carry the additional load.

Fig. 7.4.45 *Reinforced Foundation*

If the existing foundation is incapable of carrying additional load it should be reinforced. Reinforcing the foundation can be daunting task and requires additional preparation. The weight of the suspended modules can be transferred through a substructure to the strengthened foundation.

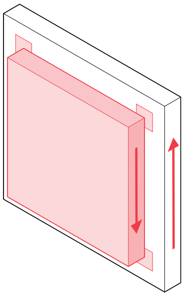


Fig. 7.4.41:
Suspended Construction

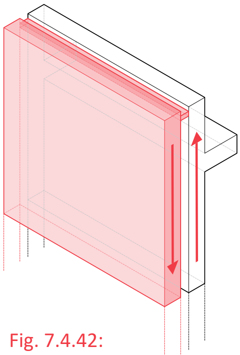


Fig. 7.4.42:
Suspended from Eave

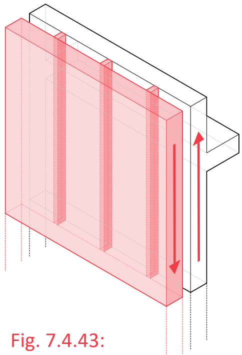


Fig. 7.4.43:
Substructure Loaded

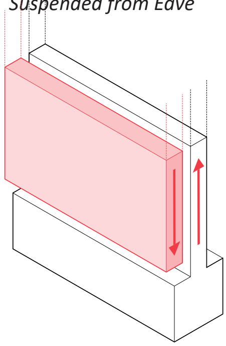


Fig. 7.4.44:
Existing Foundation

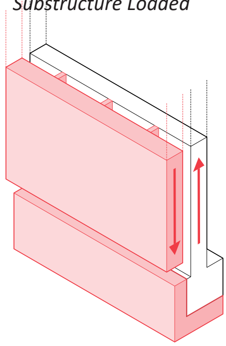


Fig. 7.4.45:
Reinforced Foundation

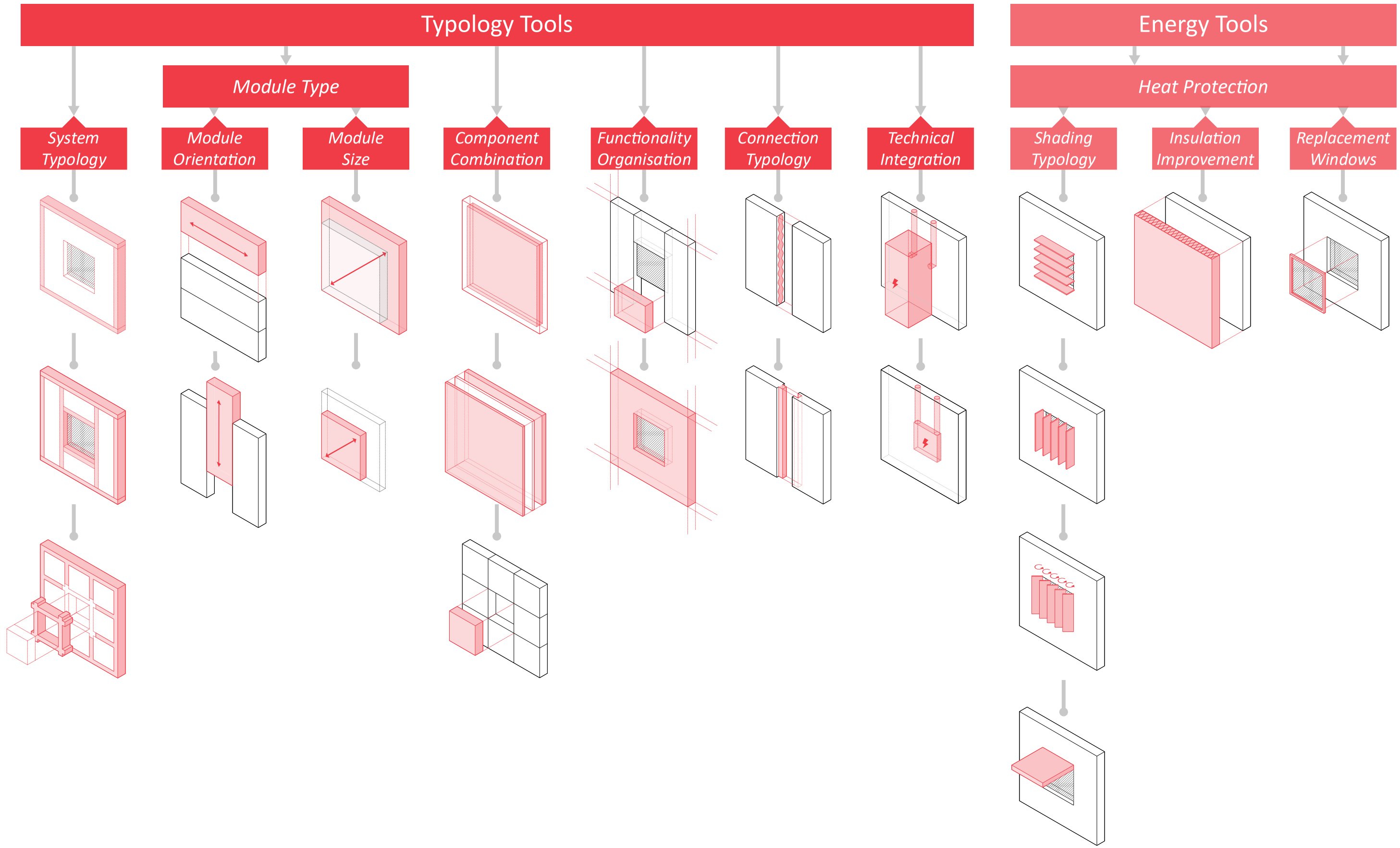
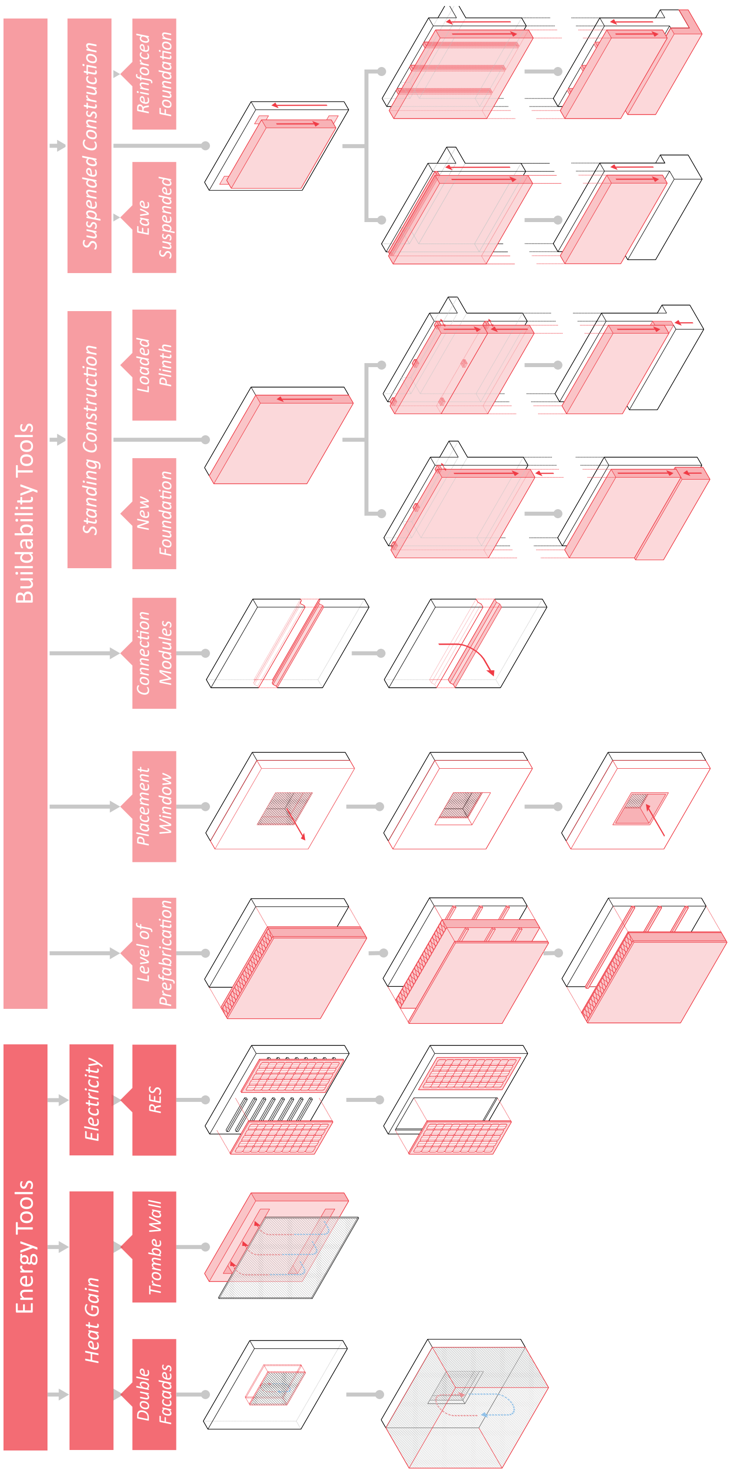


Fig. 7.4.46: *Summary of elaborated design tools, subdivided in their relevant categories (own illustration).*


Buildability Tools
Suspended Construction
Reinforced Foundation
Eave Suspended
Standing Construction
Loaded Plinth
New Foundation
Connection Modules
Placement Window
Level of Prefabrication
Energy Tools
Electricity
RES
Heat Gain
Trombe Wall
Double Facades

§ 7.5 Design Assessment

In order to choose between different concepts in the design phase it is necessary to formulate an assessment method. The assessment method is a multi-criteria decision method which includes all three fields of study and the relevant formulated criteria. Although the criteria are all described in an independent manner and defined to avoid overlapping it is imaginable that improvement in one criterion can lead to the improvement or diminishment of one or more other criteria. Furthermore, judging of the criteria is dependent on the decisionmaker's expertise on the subject and independence in order to make the right assessment. The capacity to process and asses a large number of criteria at once can become problematic, that is why a clear and defined structure is needed to increase the reliability of the multi-criteria decision method. There are two defined methods of assessing a criterion: Ordinal methods and cardinal methods.

§ 7.5.1 *Ordinal Methods*

According to ordinal methods, which can also be termed as a qualitative method, the criteria are ranked from 'worst' to 'best', according to the decision maker's expertise and intuition on the criteria relevant subjects (Department for Communities and Local Government, 2009). Advantageous to this method is that criteria can be judged without being accurately described, as long as a clear distinction between options is listed, they can be ranked.

The criteria can also be ranked in the right order, to mark their importance for the design process. Due to only qualitative properties to be judged, this method is relatively simple and reliable. However, the final results can however not be described in a score, so no definitive conclusions can be based on the methods, a final judgment call is necessary from the decisionmaker.

§ 7.5.2 *Cardinal Methods*

According to cardinal methods, which can be termed as a quantitative method, the effectiveness per option for every criterion must be qualified. This way every option is judged independently, mostly according to a grading scale (Department for Communities and Local Government, 2009). All the criteria are assessed according to the same scale in order to have a fair comparison. Furthermore, the criteria can be ranked according to scale factors. The importance of the criteria has to be judged again by the decision maker.

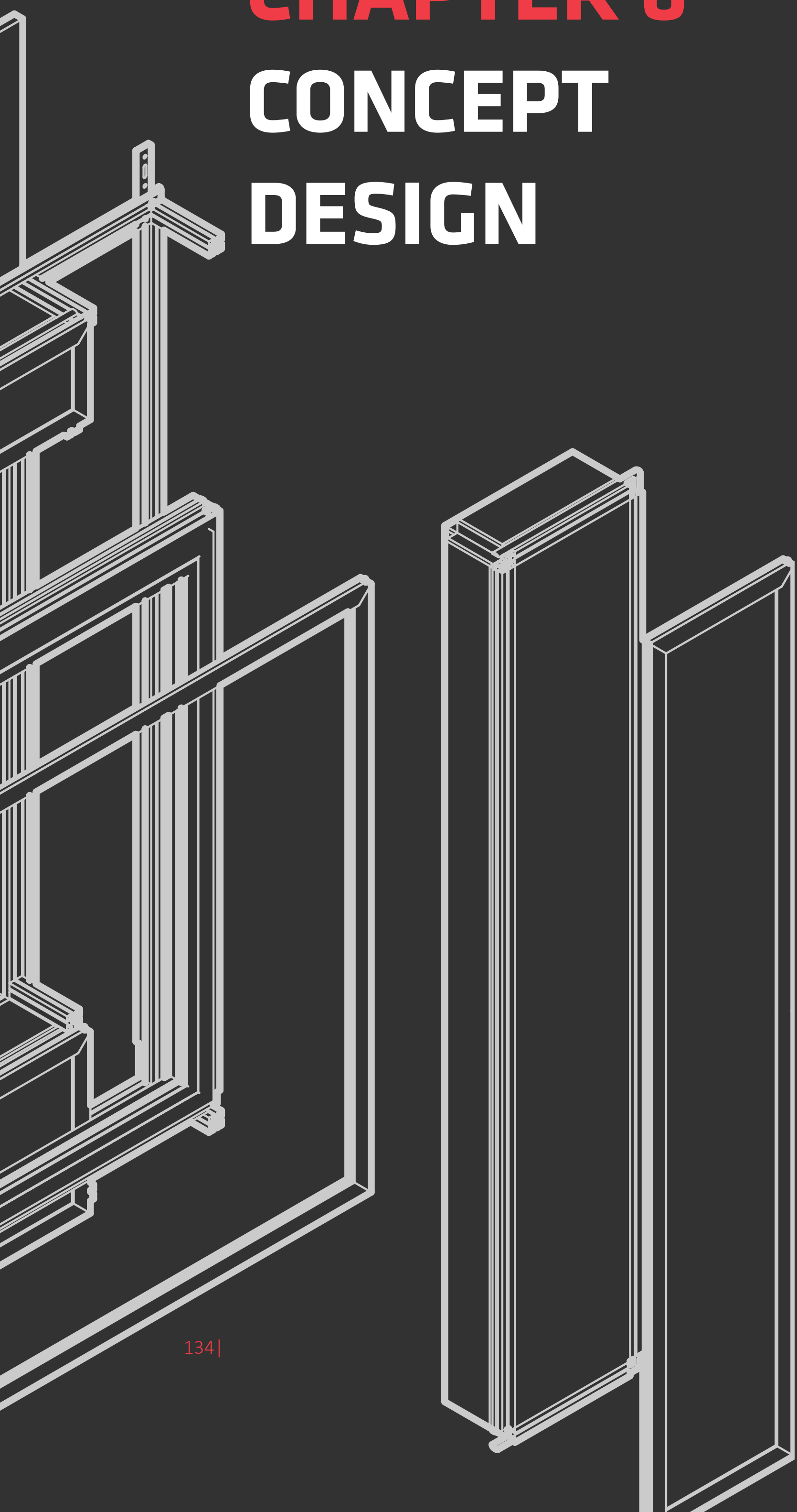
Furthermore, this method is highly reliable on the expertise of the decision maker and has to clearly define his interpretation of the grading scale in order effectively judge every criterion. The advantageous side of this method of the ordinal method is that a score can be calculated that gives a clear judgment. What needs to be assured is that the criteria are independent from each other, otherwise the could potentially give a skewed score.

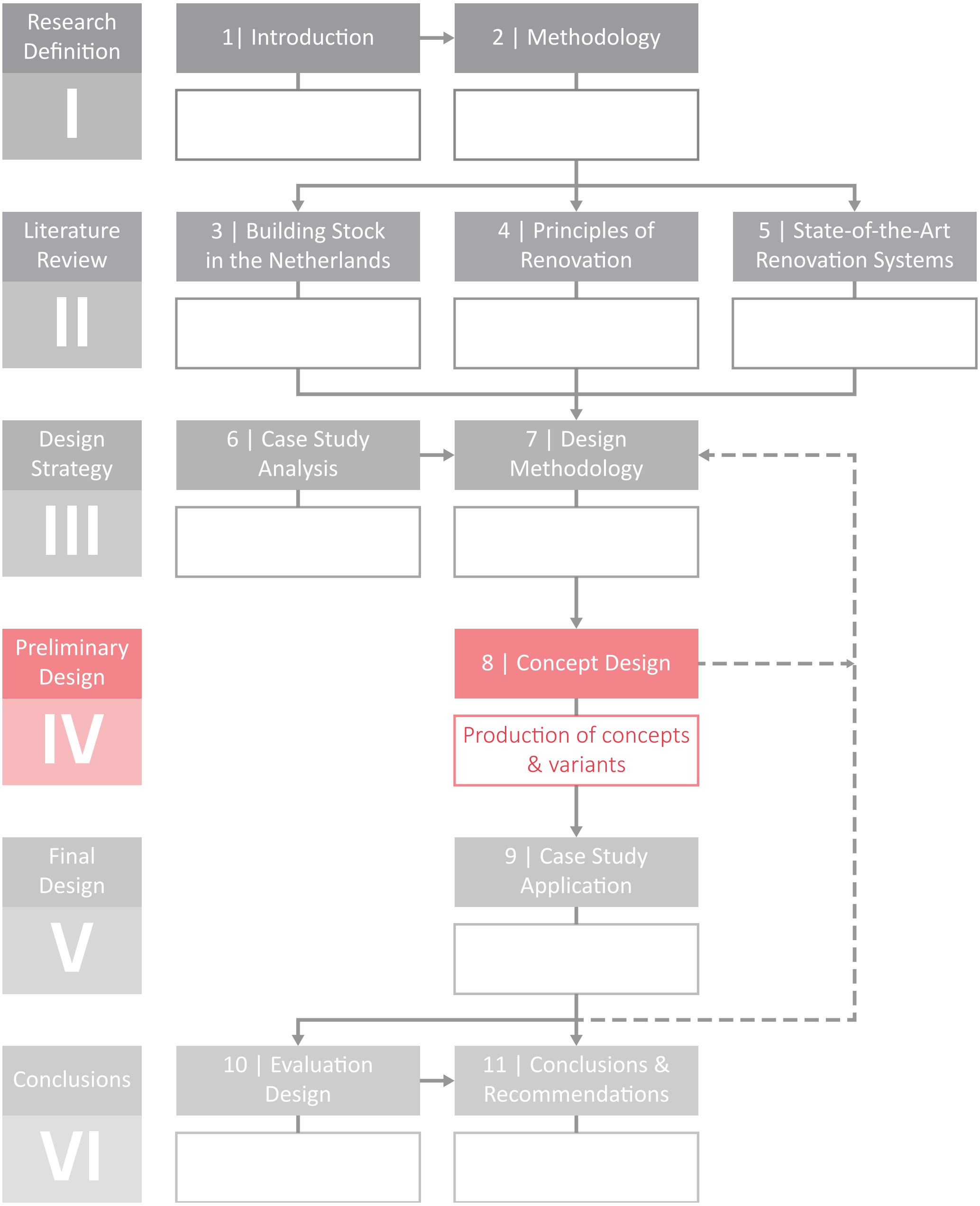
§ 7.5.3 *Method Choice*

The chosen option is to use the cardinal method utilising a simple scale of either negative, neutral or positive. As most criteria cannot be judged to an exact score. This scale leaves room for personal interpretation for the designer to come to a final decision and use the assessment as a guiding tool instead of a definitive decision tool.

8

CHAPTER 8
CONCEPT DESIGN




Research Definition
I
1| Introduction
2 | Methodology
Literature Review
II
3 | Building Stock in the Netherlands
4 | Principles of Renovation
5 | State-of-the-Art Renovation Systems
Design Strategy
III
6 | Case Study Analysis
7 | Design Methodology
Preliminary Design
IV
8 | Concept Design
Production of concepts & variants
Final Design
V
9 | Case Study Application
Conclusions
VI
10 | Evaluation Design
11 | Conclusions & Recommendations

8 Concept Design

In chapter 8 the knowledge received from the literature review and the case study analysis will be combined with the requirements and methodology described in chapter 7 to come up with the first design prototype.

Paragraph 8.1 will elaborate on the scenarios the components potentially could be subjected to and have to be taken into account in the final design. Paragraph 8.2 consists of an assessment of the design tools to determine which tools are utilised for the design process. In paragraph 8.3 concepts are produced that potentially could satisfy the list of requirements. From these concepts a final concept is chosen which is elaborated further to determine the final functionality of the façade system. Finally, in paragraph 8.4 every relevant component of the design is further developed to a level of detail adequate for next step in the design process: the application of the design on the case study.

§ 8.1 Component Scenario

In order to determine the future functional program of the building envelope system, scenarios have to be constructed in order to determine the future functionality and qualifications of the component. The basic functional components are taken from the 2ndSkin project, which includes the building installations. The different components are linked to the reasons for flexibility/upgradability and the reasons for maintenance described in paragraph 7.2.3 to determine how the component is going to change and what type of maintenance work is required. The changes that are described in figure 8.4.1 should be incorporated in the concept design in order to determine on which aspects upgradability and flexibility is required.

The table's intention is to determine scenarios that could possibly occur in the future. Naturally, some scenarios will occur at a higher rate than others and some not at all. For instance, the scenario 'technological upgrade' is a very relevant scenario, especially in the relatively new renovation market. Building installations become outdated fast due to the fast-growing technology, they can for instance become smaller or require additional components, either integrated into the façade or placed on the exterior. Integrating components in the facade could in the future be more preferred over exterior installations due to the space requirement. Moreover, if the service life of a component also come to an end, a technical upgrade will be preferred over replacing it with a technical redundant component, such as the piping, which could be replaced with new piping in a different shape or size. For other components this scenario is less relevant, such as for the insulation or the water barrier. Although technological advancements are being made for these components every year, older components can still function as long as their service life has not been exceeded. Replacing them with a technologically superior component would be unnecessary and costly. For instance, replacing conventional insulation with vacuum insulation could lead to reduction of necessary space required for the thermal insulation, but as the space required was already calculated into the design it would seem unnecessary to upgrade it before the end of its service life.

Stricter regulations could potentially affect the thermal and sound insulation. Most older building are excluded from updated regulations, but that will lead to new large-scale renovation in the future. That's why gradually upgrading would be more preferred. For instance, adding additional layers of insulation could be relevant in the future, as well as replacing an existing window with better types of glazing or additional glazing layers.

Enhanced awareness of climatic responsible behaviour can be either society or user controlled and dependent on trends and personal convictions. Users can be tempted to upgrade certain components before the end of their service life due to the environmental benefits or economical benefits. These scenarios often lead to small scale upgrades such as solar panels or adding and/or replacing components of building installations.

Upgrades due to changing in trends are hardly done in practice, due to the amount of costs and work related to the changing of an entire façade, even though they can lead to steep real estate worth increases. Upgrades due to fashion mostly relate to the aesthetical elements of the façade, which are the windows and the cladding. Occupants would far likely be induced to replace the windows or cladding if clear damage to the functionality or aesthetic quality is done.

As described in paragraph 4.6.2 the service life is determined by multiplying the theoretical service life with a number of factors: the quality of components, the design level, the work execution level, indoor environment, outdoor environment, usage conditions and maintenance level. Due to the large number of factors the minimal and maximum service life of components can vary extremely. Prefabrication leads to the maximum level of work execution, but the other factors can vary heavily. It can be suspected that the components that are directly in contact to the outdoor environment degrade the fastest, such as the cladding and the windows. Due to the high usage, building installations will degrade fast too. Deterioration can also either functional or aesthetical. For the façade it is mostly aesthetical, due to the relevant one-dimensional functioning: protection against the weather. For the window there could also be functional problems, such as the window not opening well anymore or possible thermal leaks.

Replacing due to damage is also most relevant for the cladding and the windows due to their functioning as first protecting layer. Furthermore, it might be possible that the insulation layer gets damaged due to vapour condensing in the insulating layer, leading to fungi growth (Konstantinou, 2014). This can be mostly prevented with an adequate level of design.

Upgrades due to a different use can possibly occur, but is highly unlikely to occur in the foreseeable future, as the Dutch land use plan in general prohibits changing the functional purpose of plots. It is however possible that the interior of the dwellings undergoes a functional change, for instance by adding or removing walls to gain bigger or smaller rooms. If this would to happen the building envelope system's functionality should change accordingly, by adding additional elements, such as ventilation units and/or solar control, or removing elements.

Upgrades due to changing of a user is a likely scenario. Users might want to do solely superficial upgrades, such as replacing the solar control elements.

Components	Functionality	Reason For Upgradability/ Flexibility
Cladding	Appearance	Fashion Damage Exceeded Service Life
Water Barriers	Water & Airtightness	Technoloy Upgrade Stricter Regulations Damage Exceeded Service Life
Insulation	Thermal Insulation Sound Insulation	Technology Upgrade Stricter Regulations Enhanced Awareness Environmental Change Damage Exceeded Service Life
Windows	Appearance Thermal Insulation Sound Insulation Daylight	Fashion Technology Upgrade Stricter Regulations Enhanced Awareness Different User Different Use Damage Exceeded Service Life
Shading	Appearance Daylight	Fashion Different User Different Use Damage Exceeded Service Life
Building Installations	Heating/Cooling Ventilation	Technology Upgrade Different User Different Use Damage Exceeded Service Life
Piping	Heating/Cooling Ventilation	Technology Upgrade Different User Different Use Damage Exceeded Service Life

Fig. 8.1.1: *Potential component changes according to different scenarios (own illustration).*

New Component		
New Cladding, potentially different substructure.		
Different form of water barrier, either thinner or thicker.		
Thinner insulation in different form.	Same insulation with added layer.	
Thinner or thicker frame, potentially manufactured from a different material.	Demountable window that allows for replacement of individual glazing layers.	Bigger windows
Shading out of different material or shape.	Different functioning shading, from static to movable or vice versa.	Adding additional shading elements
More efficient installation requring less space/	Aditional components integrated in the facade.	Additional components mounted on the exterior of the facade.
Different size or material piping.	Additional pipes.	Removing pipes.

§ 8.2 Guiding Theme

In order to formulate the concepts by combining suitable design tools, they first have to be assessed. The main tools utilised for the concept production phase are the typology tools. The concepts have to be able to integrate the energy tools. Finally, the buildability tools determine the method of construction. The assessment compares the options within the same category to each other, not to different categories. Not every criterion, as described in paragraph 7.2, is relevant for every category of tools. If the criterion is irrelevant than the cell is left blank for all options. This is to ensure a fair comparison can be made. Furthermore, if a clear favourite cannot be chosen the multiple options could be explored further in the concept production stage, as the assessment functions as an advisory tool, not a decisive tool. The given accumulated score also functions as an advisory tool. The criteria described under the main category 'future proof' are the most influential criteria for the final choice. Finally, if a clear assessment cannot be made, due to the abstract nature of the design tools, the assessment of an option should be linked to the examples given in the literature review and the analyses in chapter 5.

§ 8.2.1 *Typology Tools*

The typology tools are grouped into seven categories. In some categories a clear distinctive best option can be recognised. In other categories a combination of two options could be more suitable. We will discuss the results per group and determine which options are the most suitable for the concept production phase. No evaluation was made for the energy production and energy reduction criteria, as no clear evaluation could be made without additional information. Together with some other criteria these fields were left blank.

System Typology

From the three possible options the fixed system scores the best except on two criteria points customisation and adaptability, in which the principle system scores the best. Due to the fixed sizing it could be problematic to adapt the solution to different case studies or even different sized panels. Trying to have a more adaptive system would result in more adaptivity and customisation option, which would be preferable. The downsides would be that certain qualities such as off-site production ability, and upgradability could potentially suffer from it.

Module Orientation

The choice for the right module orientation is highly dependable to the existing structure and options. For most criteria the vertical orientation scores better due to the better integration of vertical channels, which better fits the building installation package of the 2ndSKin project prefabricated variant. Furthermore, vertical panels can be replaced easier than horizontal panels. Horizontal panels are stacked on top of each other and if the connections do not permit the removal of a middle panel, without removing a panel above, maintenance could prove to be troublesome to perform.

Module Size
In terms of module size there is trade-off in several criteria. Smaller modules generally score better on adaptability, disturbance, upgradability and maintenance. This can be constituted to the fact that smaller modules can be fitted more easily to different buildings, require less heavy transport and are easily replaced. This comes at the cost of lower integration possibilities, due to the sizes of building installations, and construction time, due to the number of components. Furthermore, larger panels offer more opportunities to be self-supporting, which could relieve the existing structure of additional loads.

Component Combination
From the component combination options, the modular variant scores best on almost all criteria. The closed system option scores negative on almost all criteria, although due to the finished nature of the option it could be relatively easy applicated on-site. The layered tool functions as an option between the two, scoring neutral on most criteria. The modular variant scores lower on disturbance and construction time due to the number of components that need to be addressed. This could be countered by finishing a panel with the modules off-site and transport the finished module to the worksite. As stated in paragraph 7.4, the downside is that every module has to function as a completed façade, adding to the complexity of the option.

Functionality Organisation
Between the option of using a component or element façade the element facade clearly scores better on the criteria described under architecture, but lower on upgradability and maintenance. Due to the completed nature of the element façade, making adjustments to the modules is in general more difficult. However, it scores better in areas such as off-site production ability, disturbance and construction time, due to lower number of components. The component façade scores better on upgradability and maintenance due to the easy interchangeability of components.

Connection Typology
For the connection typology there is only one clear option, which is the option for dry connections. Wet connections score low on every criterion other than adaptability, where it scores neutral. Dry connection does require additional planning in order to ensure water and airtight connections, as well as strong connections, on which wet connections typically score better.

Technical Integration
The options for separated or integrated installations create very contradicting results. Integrated installations offer benefits in terms of off-site production ability, adaptability, disturbance and construction time, due to the fact that the installations don't have to be separately installed on-site. Separated installations offer more options for upgradability and maintenance due to the fact that they can be easily accessed. For the design phase both options need to be incorporated in the design phase to offer maximum flexibility in choice.

§ 8.2.2 *Energy Tools*

The energy tools can be linked effectively to examples from the literature. The criteria energy production and reduction mostly focus on distinguishing active and passive measures and the potential for some options to include both.

Shading Typology
Horizontal and vertical shading both score positive on all criteria. They can be easily incorporated in every design and have no clear disadvantages. The adaptable shading also scores great on all criteria, but suffers for additional maintenance needed and is more vulnerable to damage. The additional mechanical systems needed for the shading to be operated effectively is also a point of interest. Cantilever shading could potentially be utilised to include solar panels, but scores negative on all other criteria except maintenance. Cantilever shading also adds additional weight to the existing structure and it is difficult to produce off-site.

Insulation Improvements
Both insulation improvement measures need to be incorporated in the design. The goal of the evaluation of these options were not to choose between them, but to evaluate their weaknesses. Adding insulation has no significant downsides, other than the maintenance, which can be difficult to perform as the insulation needs to be protected by water and vapour barriers to function properly. Replacing windows scores negative on most criteria. Customisation to the windows is difficult, the size is dependable on the window frame of the existing building, changing those dimensions requires extensive labour. Furthermore, the disturbance to the interior is rela-

tively high due to the temporary removal of the existing windows, which also leads to increased construction time. Upgradability is also difficult to perform due to the same reasons. Clear planning and adequate design should be incorporated in the concept in order to nullify these negative points in the final design.

Double Facades

The box window offers no clear disadvantages, it could be incorporated if it is functionally required. The attached sunspace scores negative on all criteria deemed important for this thesis. It cannot be integrated or produced off-site, requires more material, time, labour and space. The functional benefits to usable floor space could be incorporated in some specific renovation project, but in the goal and scale of this thesis it is disregarded.

Heat Gain Mass

For the Trombe wall the same conclusions can be drawn. The application requires extensive labour, costs, material and time and is disregarded in this thesis as a viable option.

RES

Both building applied PV's and building integrated PV's offer some distinct advantages and disadvantages. The building applied PV's can be easily maintained and replaced, but have to be applied after application of the building envelope system, leading to higher disturbance and higher construction times. The building integrated PV's can be applied to the building envelope system off-site, but are more difficult to upgrade. The exact space required for the PV's has to be incorporated into the building envelope's design. Therefore, when the PV's are required to be replaced, the new panels have to have the exact same dimensions. However, building integrated PV's could potentially benefit the architectural aesthetic of the building envelope.

§ 8.2.3 *Buildability Tools*

As described earlier, the buildability tools are utilised for the elaboration of the concept to ensure the system can be constructed and applicated in the most effective way. The buildability tools are not combinable and therefore require a clear choice. For the last four categories a choice has to be made between using a standing or a supported structure, then within the chosen group another choice is required in two different categories.

Level of Prefabrication

The composite insulation system clearly scores negative on all but one criterion: adaptability. The semi-prefabricated scores positive on most criteria, except for disturbance and construction time, due to the increased number of components that need to be applicated on-site. The clear-cut winner is the prefabricated system that does not offer any disadvantages on the chosen criteria. It should be noted that in the 2ndSkin demonstrator project a composite insulation system was used, which can be mainly contributed to the fact that a composite insulation system doesn't require extensive planning and costs. A prefabricated system requires extensive research and design process before it can be commercially and effectively applicated.

Placement Window

The choice for the placement of the window is a choice between the exterior flush-mounted option and the centre-in-reveal option. The interior flush-mounted requires additional insulated flashing that needs to be applicated on-site, adding to the disturbance and construction time, which is a clear downside. The exterior flush-mounted scores positive on all criteria except customisation and integration. The exterior flush-mounted option can be applied easily and can be produced and integrated in the façade system off-site. Furthermore, it can be replaced and upgraded more easily. However, due to the positioning, it is more difficult to integrate shading and customisation options are limited. The centre in reveal options is an option that offers the opportunity for more customisation and integration of shading devices at the cost of increased complexity.

Connection Modules

The fixed module system offers water and airtight connections, but that is also it disadvantage. Replacing individual panels for upgrading or maintenance becomes more difficult. The single fixed modules offer the possibility to replace individual panels, but at the cost of adaptability and the construction time, due to the fact that it needs a support structure either by the existing construction or by a substructure.

Standing Construction – Foundation

For the standing construction the choice for a loaded plinth or a new foundation is highly dependable on what the existing structure can support in additional weight. Using the existing foundation obviously reduces the disturbance and the construction time, but also puts a limit on the new façade system's weight, reducing the possibilities for future upgrades. Furthermore, the option could potentially not be applicable to every project. A new foundation scores positive on these criteria for the costs of increasing labour on-site.

Standing Construction – Module Support Type

An area covering module ensures a minimisation of connection points on the existing façade, but due to the need for a thicker module there is also a higher need for material, which in turn leads to higher embodied energy. A module connected segmentally requires less material. Furthermore, due to the lower number of connections required, the area covering module can be installed faster.

Suspended Construction – Foundation

For the suspended construction the choice for using an existing foundation or a reinforced foundation is, similar to the foundation assessment for the standing construction, dependable on the weight of the system and the weight the existing foundation can support. The clear favourable chooses is to use the existing foundation, due to the better grading on every criterion in the category architecture except adaptability. On the criteria upgradability and maintenance, the existing foundation scores lower than the reinforced foundation, due to the fact that upgrading the façade could increase the weight. Additional weight that the existing foundation could potentially not bear.

Suspended Construction – Module Support Type

Using a substructure has the benefit that the structure could be used to even the surface of the existing façade, but due to the additional labour that is required on-site this leads to longer construction processes with more disturbance to the occupants. This method however scores higher on upgradability and maintenance than suspending the module from the eave, as the substructure could remain even when individual modules have to be replaced for maintenance or for upgrading. Furthermore, it is more adaptable to different buildings, as long as they can support the load of the substructure and the modules. Suspending from the eave could potentially not be applicable if the surface is too uneven, leading to a lower grading in adaptability.

§ 8.2.4 ***Chosen Design Tools***

Based on the analysis of the usability and of the design tools and the requirements for the design the following design tools are selected to be utilised for the concept production phase. In this section the choices for each typology tool are elaborated further.

Typology Tools

For the system typology the choice was made to combine the design tools base system and the fixed system. The fixed system lacks in adjustable sizing of modules, therefore the constraint that every module should be the same size is relaxed.
The main factor for choosing the module orientation and size is the scenario of future replaceability. For that reason, the choice is made to utilise horizontal and smaller modules, which are more manageable than their respective counterparts. For the connection type the dry connections ensures this replaceability is possible.

For the component combination the layered system and the modular system are combined to produce possible design options. The modular system has the disadvantage that individual layers of the modules are inseparable, which could limit the upgradability of these layers. If the modules are layered this problem is solved, but the complexity is enhanced, which has to be accounted for.

The element façade and the component façade tools are combined to formulate a façade system that can be applicated as an element façade, but offers the flexibility of the components facade by being able to replace individual components.

The integrated installations are preferred over separated installations. The general prediction is that the installations will generable become more manageable in size and application. Therefore, integrating the installations in the façade would be more flexible towards future requirements. The option for separated installations should be given as an option, as currently some building installations are too large to be integrated into the facade.

Energy Tools

Based on current state-of-the-art projects and trends the applying insulation on the exterior and the replacement of windows should be integrated in the system over more complex tools such as the Trombe wall, box window and the attached sunspace. The latter tools have poor flexibility to different contexts and requirements and are only applicable to very specific cases, which diminishes the flexibility and scalability of the system.

All types of solar shading, except cantilever shading, should be integrated in the façade system. These types of shading are common choices for solar control in any type of building and foreshadowed to stay relevant in the future. Cantilever shading is excluded, as it does not provide convincing benefits over the mentioned other shading typologies.

Photovoltaic panels should be easily applicable in the façade system's design during the construction as well as in a later stage. By taking into account the potential replacement of cladding with photovoltaic panels, extended labour time necessary during the replacement can be avoided.

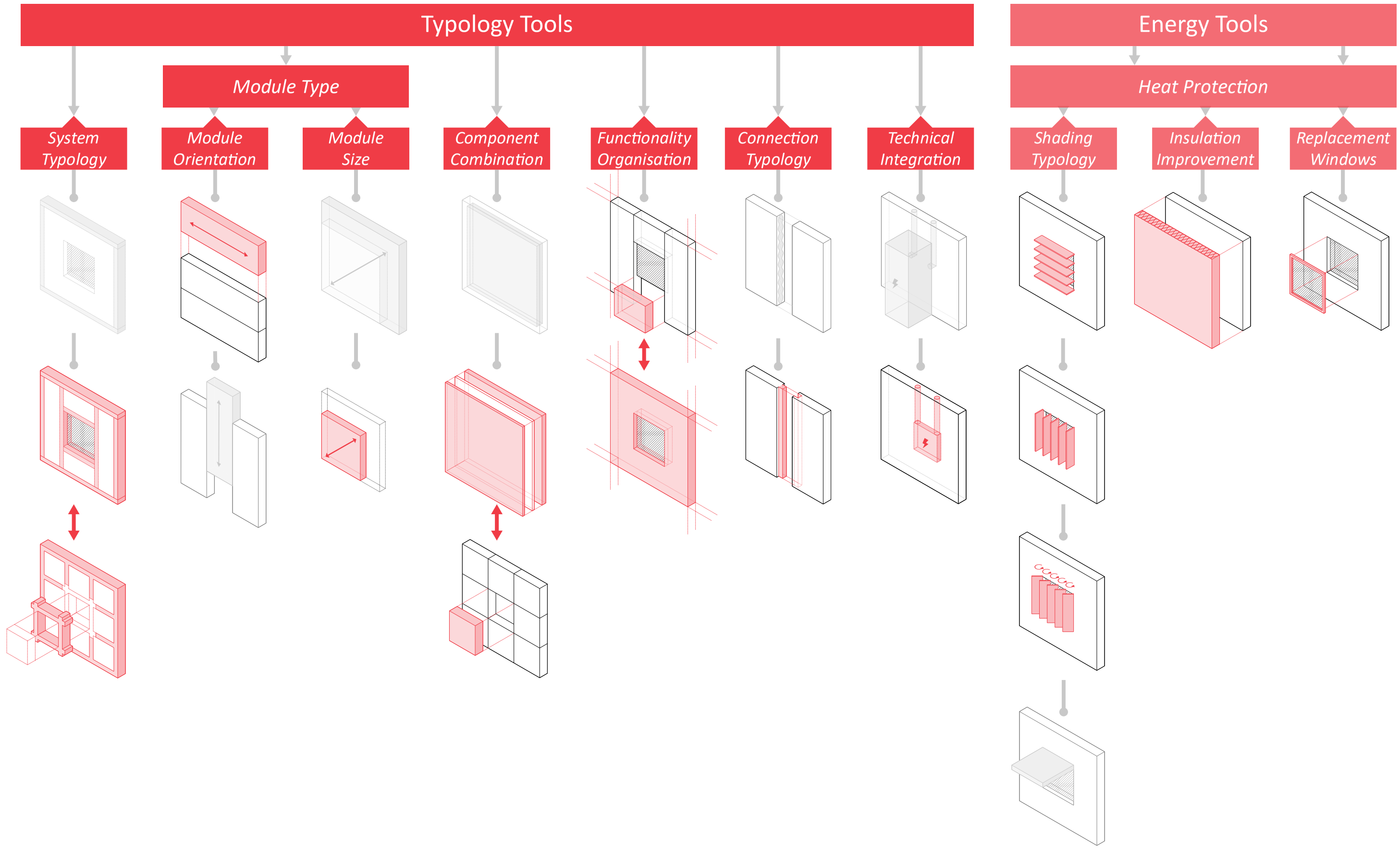
Buildability Tools
The prefabricated system offers the flexibility required and the reduced construction time that the façade system's design necessary for the system to be competitive with existing methods.

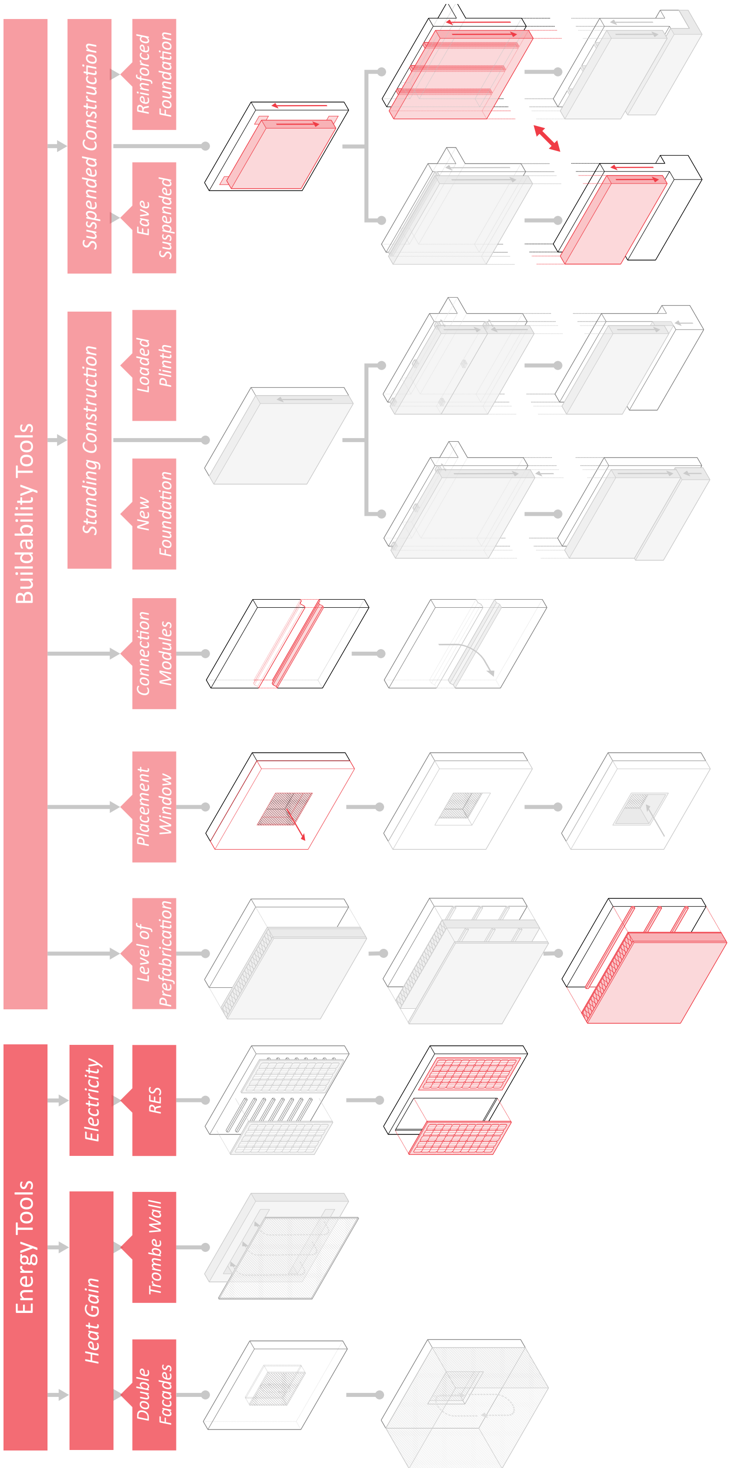
The exterior flush-mounted options offer the required flexibility and are easily applicated. The interior flush-mounted option requires too much additional work on-site that should be avoided. The beneficial points of the centre-in-reveal option such as integration of sun shading isn't convincing enough to prefer the option. Solar control can for instance also be integrated in the window frame itself, which is also possible with an exterior flush-mounted configuration.

A fixed module system is preferred over single fixed modules due to the connection between façade modules being relatively easier to achieve. The single fixed modules require extra precautionary labour to achieve water tightness on-site, which is disadvantageous and leads to increased labour time on-site.

A suspended construction in combination with a substructure and loaded on the existing foundation is preferred over a standing construction. A standing construction requires additional structural elements and subsequently heavier façade modules which requires additional construction apparatus. The additional work necessary to the existing façade further rules out this option. Furthermore, the substructure can be utilised as elements to even out the existing façade, which is often a problem with older facades.

Fig. 8.2.1: *Summary of chosen design tools (own illustration)*

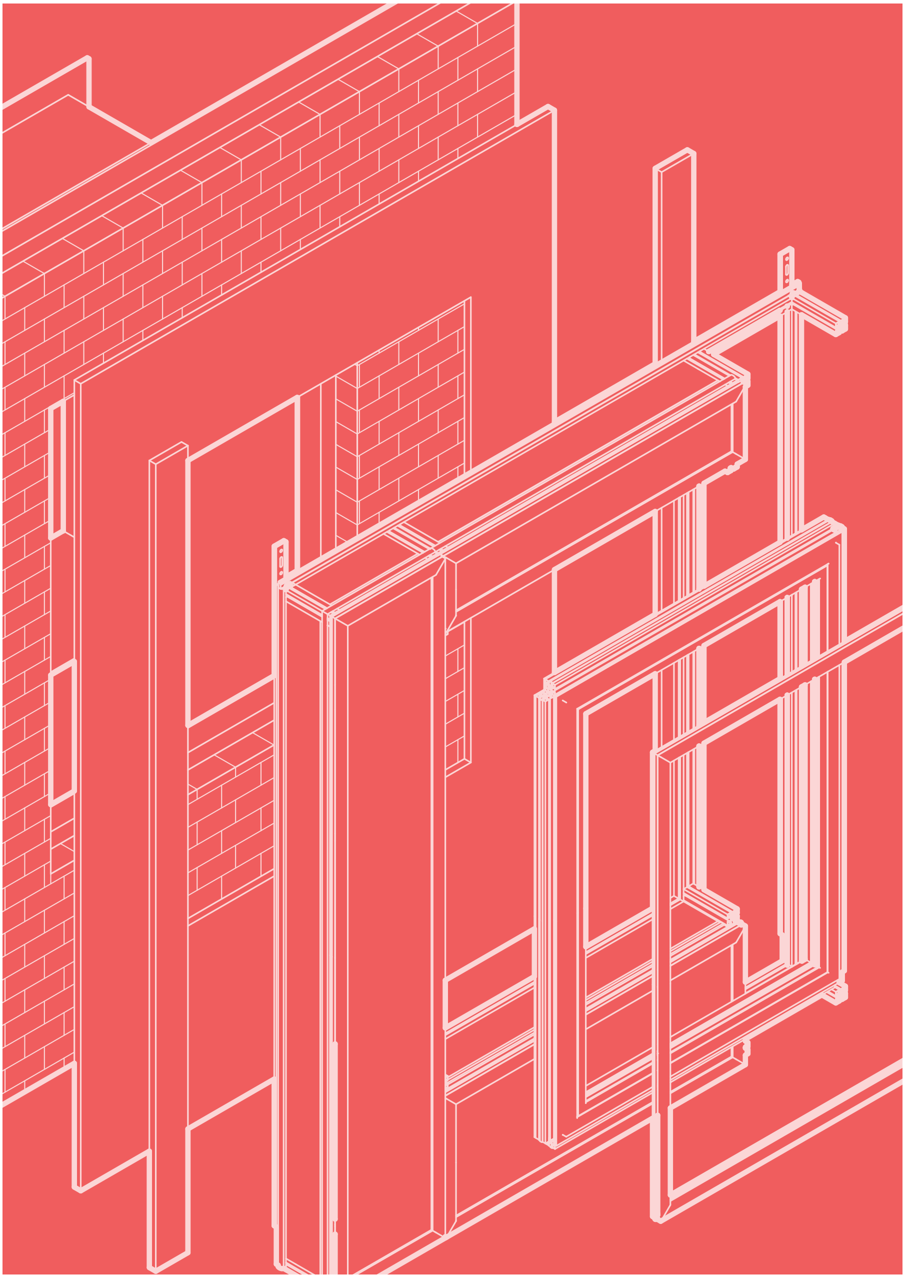



Buildability Tools
Suspended Construction
Reinforced Foundation
Eave Suspended
Standing Construction
Loaded Plinth
New Foundation
Connection Modules
Window Placement
Level of Prefabrication
Energy Tools
Electricity
RES
Heat Gain
Trombe Wall
Double Facades

§ 8.3 Concept Production

The next step is to utilise the design tools to produce a variety of concept typologies and variations of those typologies. The goal of this step is to produce a wide variety of possible concepts and evaluate them with the aid of the evaluation matrix, as well as describing the advantages, disadvantages and potentials. The design concepts are then compared and one chosen concept is developed further in paragraph 8.4. Due to the higher level of elaboration for these concepts than the design tools the evaluation matrix will have a more dominant decisive role. Results of the assessment can be found in the apendix.

For every concept a variety of infill strategies are possible: Standardised sizing, meaning using as much as possible modules of the same dimensions, or adjustable sizing, which adjusts the modules to the dimensioning of the required components. Furthermore, unlayered modules can be utilised, where all the functional layers are implemented in a closed module, or layered modules, where every function is separated in successive layers. Every concept, unless if it is deemed impossible, will have every variation assessed in order to grade how the changes affect the functioning of the system.



§ 8.3.1 *Vertical Frame*

The concept consists of vertical posts where in between infill modules are placed. The posts act as supports for the infill modules. The vertical orientation ensures a restricted width of the modules, but an unrestricted height.

Advantages

- The post can function as structural elements.
- The system is relatively simple, minimising the number of connections.
- Vertical piping can be easily integrated.

Disadvantages

- The posts and modules cannot be prefabricated and completed as one system. the different components have to be combined on-site, which lengthens the construction process.
- The post has to be adjusted to width of the different parameters, such as the windows, limiting the standardisation of the system.
- Integration of horizontal piping could proof to be problematic.
- The ability of the system to house thicker modules is limited.

Potentials

- The vertical posts could be used as levelling elements for the uneven existing surface.
- The vertical posts could be utilised for vertical piping, as well as function as the horizontal connection point for modules.

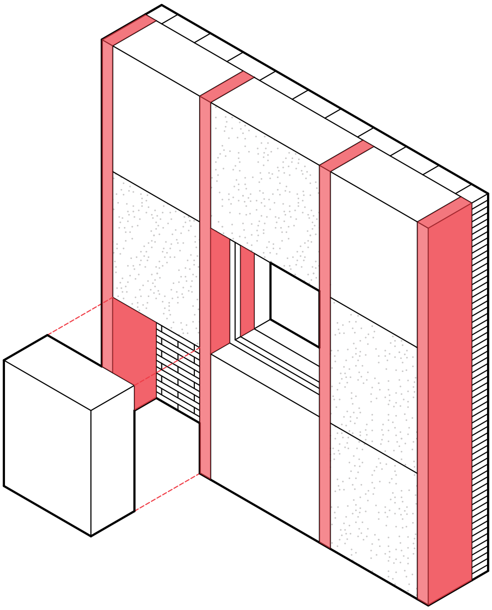


Fig. 8.3.1.1:
Standardised Size | Unlayerd

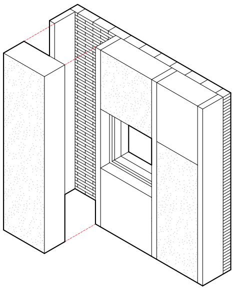


Fig. 8.3.1.2:
Adjustable Size | Unlayered

§ 8.3.2 ***Horizontal Frame***

The concept consists of horizontal beams that are structurally connected to the existing constructions. The beams act as supports for the infill modules. The horizontal orientations ensure a restricted height, but unrestricted width of the modules.

Advantages

- The system is relatively simple, not requiring a lot of connections to be made.
- Horizontal piping can be easily integrated.

Disadvantages

- The system cannot be self-supporting, which might deem it to be unsuitable for other building or typologies that do not have the required structural capacity.
- Combined windows with different heights require unique solutions, diminishing the standardisation of the system.
- The beams and modules cannot be prefabricated as one system. The different components have to be combined on-site, which lengthens the construction process.
- Integration of vertical piping can proof to be problematic.
- The ability of the system to house thicker modules is limited.
- Incorporation of components that have a large height is limited with this system.

Potentials

- Modules of different width could be used to form an interesting façade layout.
- The horizontal beams could incorporate holes for the vertical tubing, as long as they don’t compromise the structural integrity of the beams.
- The beams could be utilised as solar control.

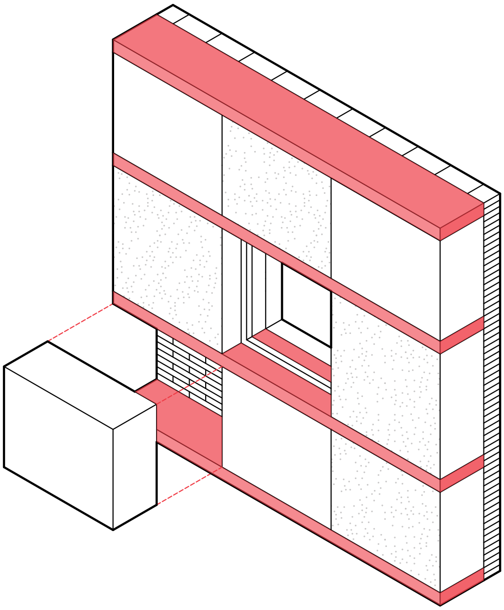


Fig. 8.3.2.1:

Standardised Size | Unlayerd

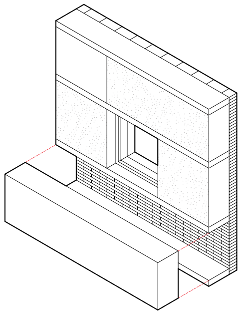


Fig. 8.3.2.2:

Adjustable Size | Unlayered

§ 8.3.3 ***Drawer***

The concept consists of a frame with dividers that can house the different infill modules. The box frame is structurally connected to the dividers to function as one structural unit. The inserted modules are supported by the frame.

Advantages

- The frame with dividers forms a strong structural unit and can be self-supporting, relieving the existing structure of additional loads.
- As the modules do not have to be outfitted with extra structural frames a minimisation of material can be achieved.
- On-site removal or replacement of individual modules does not compromise the structural integrity of the whole module.
- The whole system including the modules can be prefabricated off-site and applicated on-site, or in separate components.

Disadvantages

- Due to the frame being one unit it is difficult to replace modules with different sized modules.
- Water and airtightness are difficult to achieve due to the large number of connections.
- A relatively large amount of structural material is needed, adding to the weight.
- Integrating of piping is difficult due to the dividers.
- Upgrading the frame to accompany thicker modules is difficult to achieve.

Potentials

- The frame could be outfitted with a lid to ensure the water and airtightness.
- The dividers could be demountable to rearrange the dividers to house different sized modules or to be rearranged for a different building.
- The modules could cover up the frame to ensure the water and airtightness.
- The frame could house different holes for the piping.
- Possibly the frame could be segmented and stacked in order to house thicker modules.

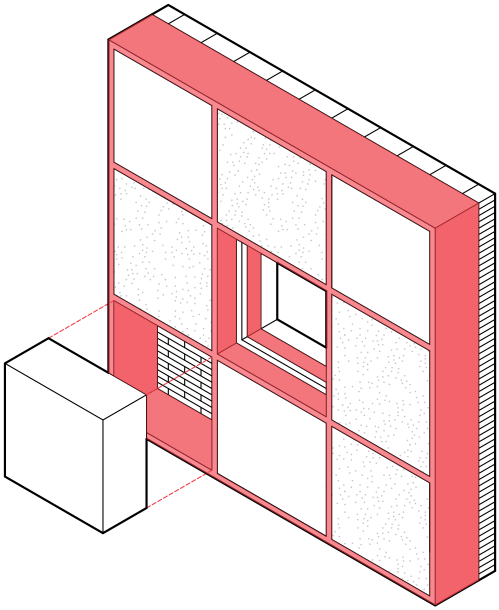


Fig. 8.3.3.1:
Standardised Size | Unlayered

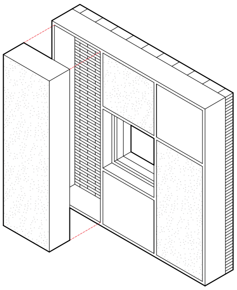


Fig. 8.3.3.2:
Adjustable Size | Unlayered

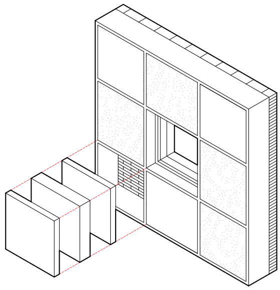


Fig. 8.3.3.3:
Standardised Size | Layered

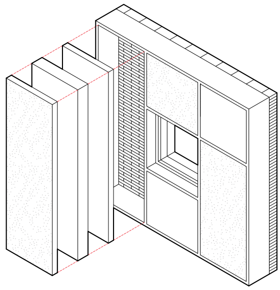


Fig. 8.3.3.4:
Adjustable Size | Layered

§ 8.3.4 *Surrounding Frame*

The concept is a variation of the drawer concept, it utilises a surrounding frame with no internal dividers. All modules have enclosing frames that are organised inside the surrounding frame. The completed frame with modules functions as one structural unit.

Advantages

- The completed frame could function as a self-supporting unit.
- The system offers more freedom then the drawer concept. Modules could be replaced with different sized modules with relative ease.
- The modules are outfitted with enclosing frames adding to their structural strength.
- Individual modules can be slid out of the surrounding frame and maintained or removed without compromising other modules.
- The whole system including the modules can be prefabricated off-site and ap-plicated on-site, or in separate components.

Disadvantages

- As lower situated modules also support the modules above, it might be nec-essary to temporarily remove the above module when replacing the lower situated modules.
- The frames of the individual modules need additional material for the frame, which increases the embodied energy.
- Water and airtightness are difficult to achieve due to the large number of connections.
- Although integrating piping within the module is easier to achieve with the flexible layout the concept provides, intermodular connections are still diffi-cult.
- Upgrading the frame to accompany thicker modules is difficult to achieve.

Potentials

- A lid could be used to ensure air and water tightness.
- The modules could cover the frame to ensure water and airtightness.
- Strategically places holes in the outer frame could be placed for the ventila-tion pipes.

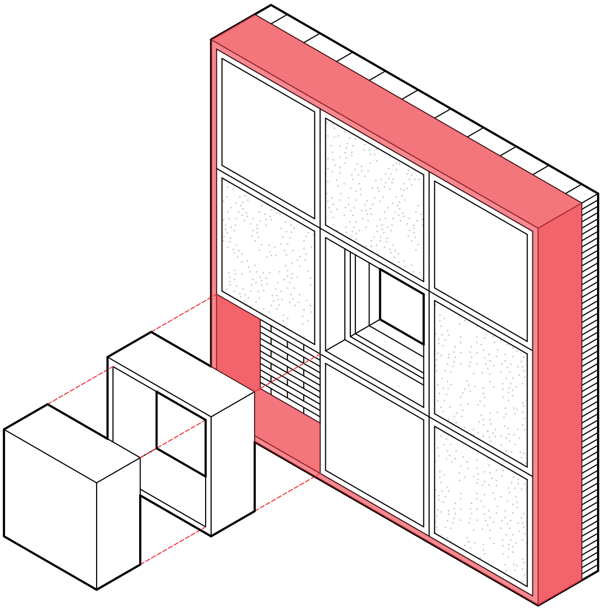


Fig. 8.3.4.1:
Standardised Size | Unlayered

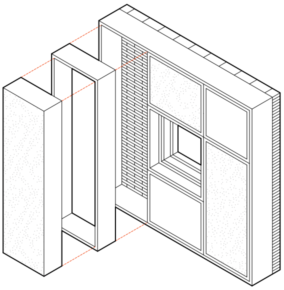


Fig. 8.3.4.2:
Adjustable Size | Unlayered

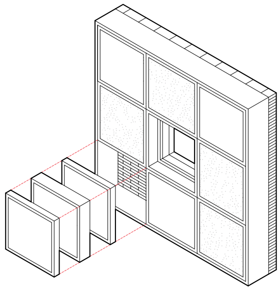


Fig. 8.3.4.3:
Standardised Size | Layered

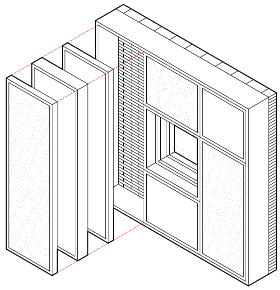


Fig. 8.3.4.4:
Adjustable Size | Layered

§ 8.3.5 *Self-supporting Modules*

The modules function as individual self-supporting units. The individual modules are prefabricated, organised and applicated on-site.

Advantages

- No additional frame is required for this solution.
- The modules are self-supporting, relieving the existing structure from additional loads.
- The small modules can be easily transported.

Disadvantages

- A large number of modules have to be combined on-site, lengthening the construction process.
- Due to the large number of connections water and airtightness is difficult to achieve.
- Due to the differently sized windows standardisation of the modules is difficult to achieve.

Potentials

- Thicker frame for the modules could be utilised in order to incorporate piping.
- Interlocking the frames also horizontally could ensure the modules maintain their structural integrity even when a single module is removed.
- The modules could be stacked in a similar system as a brick facade and function as a self-supporting facade.

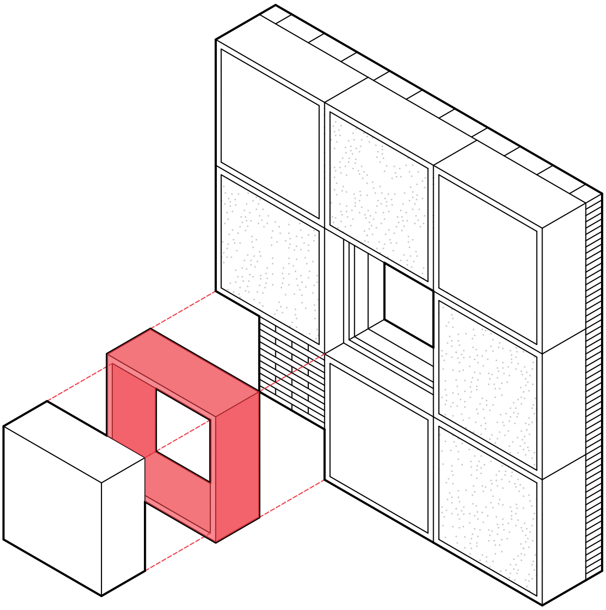


Fig. 8.3.5.1:
Standardised Size | Unlayered

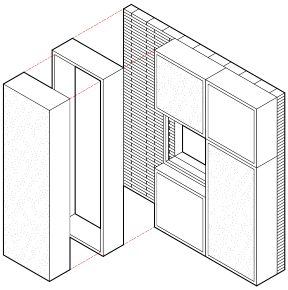


Fig. 8.3.5.2:
Principle System

§ 8.3.6 *Slot System*

The system centralises all upgradable components in a singular slot. The system is a closed system and together with the module can be prefabricated as one system, transported and applicated, or as separate components.

Advantages

- As the system is closed, a water and airtight system can be ensured.
- The number of connections is minimised, reducing the complexity.
- The module can be replaced without temporary disabling the system's functioning.
- Maintenance and repair can be centralised.
- The system and module can be completed off-site.

Disadvantages

- The system is upgradable only via the module, limiting the customisation options of other functions.
- The closed system is difficult to dismantle without producing waste.
- The module dimensioning is restricted to the slot's dimensions.
- Upgrading the system to house thicker modules is limited.

Potentials

- The pultruding module could be utilised as architectural element.
- Demountability of the closed system could be ensured by using dry connections.
- A slot could be left empty if required without compromising the functionality of the system as a whole.

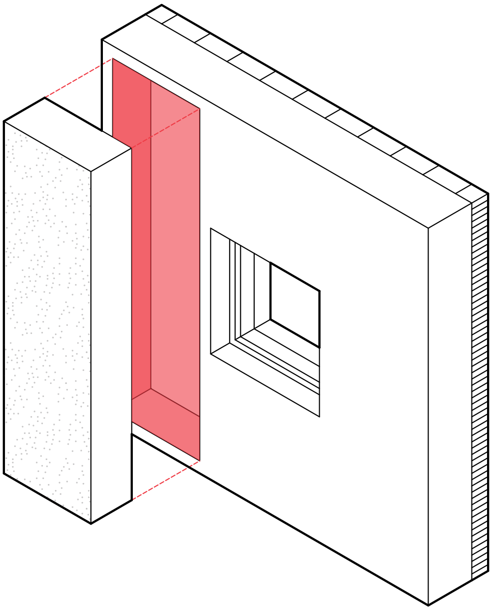


Fig. 8.3.6.1:
Standardised Size | Unlayered

§ 8.3.7 ***Add-on System***

The system is similar to the slot system, but the module is placed on the exterior of the panel. Similar to the slot system the add-in system is a closed system and together with the module prefabricated off-site. Both are then transported and connected on-site.

Advantages

- As the system is closed, a water and airtight system can be ensured.
- The number of connections is minimised, reducing the complexity.
- The module can be replaced without temporary disabling the system's functioning.
- Maintenance and repair can be centralised.
- The module is dimensionally unrestricted.

Disadvantages

- The system is just upgradable via the module, limiting customisation options.
- The closed system would be difficult to dismantle.
- The module has to be customised to every parameter, standardisation is therefore restricted.
- Reusing the module on different buildings is very restricted due to different measurements.
- Piping can be integrated, but are difficult to adjust to new building installations.
- Heavier building systems located in the module requires its own support structure.

Potentials

- The pultruding module could be utilised as architectural element.
- Demountability of the closed system could be ensured by using dry connections.
- The add-on modules could house additional structural framing to house heavier components, such as the heat pump.

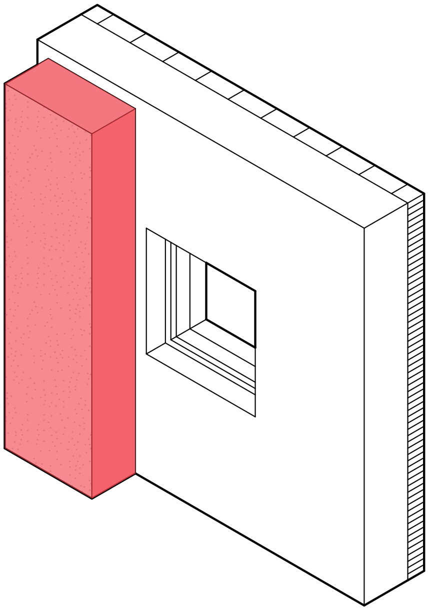


Fig. 8.3.7.1:

Standardised Size | Unlayered

§ 8.3.8 ***Open Frame System***

The open frame is a variation of the drawer concept, utilising beams and columns that are connected to form a structural bases into where the modules are slid in. The frame and the modules can be prefabricated and assembled to form complete modules or assembled on-site.

Advantages

- The open structure allows for integration of vertical and horizontal piping.
- Individual beams or columns could be placed or removed to house different sized modules.
- The beams and columns could be rearranged easier than the drawer frame, for instance to adjust to the different window sizes.
- Less material is needed than for the drawer concept.

Disadvantages

- Due to the arrangement there is an air gap between modules, which could lead to water and airtightness problems.
- Fixing the modules to the frames would require a multitude of connections.
- The complexity of the system increases.
- The beams and columns need to be indivually connected to each other in order to function as a structural whole.

Potentials

- The beams and columns could be utilised to even the surface of the existing facade.
- The structure could be locally expanded to house thicker modules.
- The frame could be dissassembled into individual parts to be resused, opening up the opportunity to use materials with higher structural strength, such as steel, that have higher embodied energy.
- The whole system could be self-supporting.

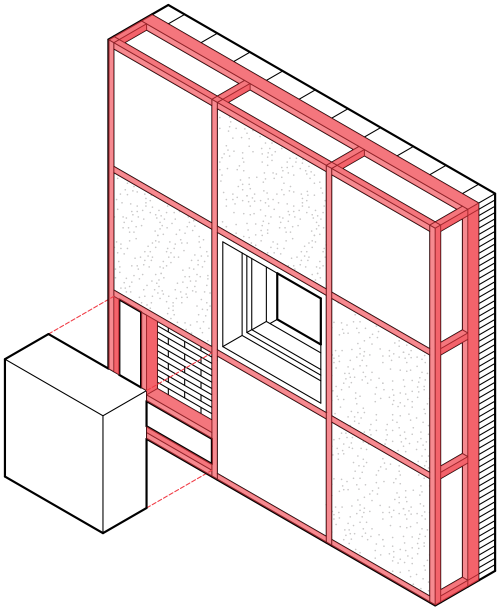


Fig. 8.3.8.1:
Standardised Size | Unlayered

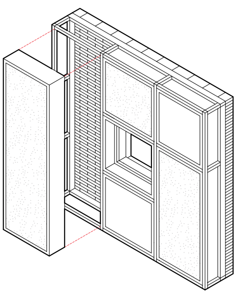


Fig. 8.3.8.2:
Adjustable Size | Unlayered

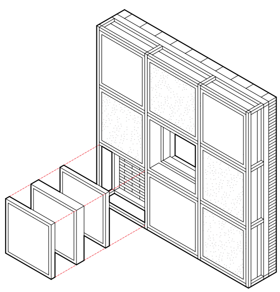


Fig. 8.3.8.3:
Standardised Size | Layered

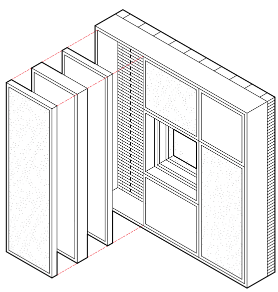


Fig. 8.3.8.4:
Adjustable Size | Layered

§ 8.3.9 ***Pin System***

The pin system uses a substructure which is applicated to the existing structure. The modules are placed in between the pins to form a completed system.

Advantages

- The pins can be insulated easier than the frames.
- Water and airtightness can be ensured relatively easy.
- The substructure minimises the necessary material required for the support structure.
- The modules can be freely placed within the grid of pins.
- Piping can be integrated relatively easy, both horizontal as vertical pipes are possible.
- Smaller sized modules can be replaced with larger sized modules.
- Connection points are relatively minimal.

Disadvantages

- The system cannot be self-supporting.
- The pins need to be structurally strong to support the modules, which can prove to be problematic for heavy installations.
- The system cannot be completed prefabricated. The system and the modules have to be connected on-site, which lengthens the construction process.
- The pins have to be outfitted with thermal breaks in order to avoid thermal bridges.

Potentials

- The pins could be lengthened relatively easy with extension poles in order to house thicker modules.
- The pins could be used to attach solar control onto.
- Different length pins could be used to house components of different thicknesses within the same panel.

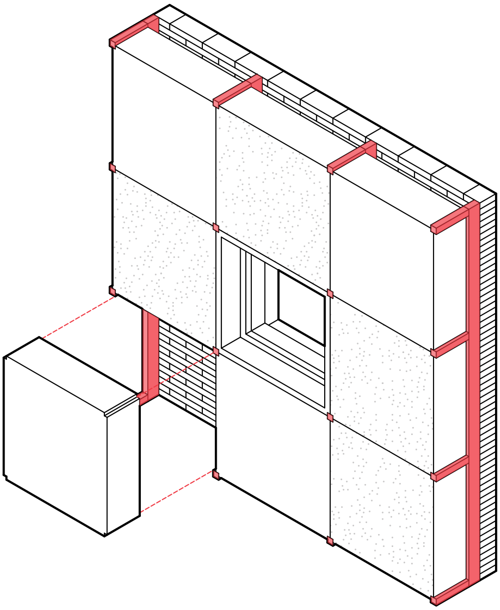


Fig. 8.3.9.1:
Standardised Size | Unlayered

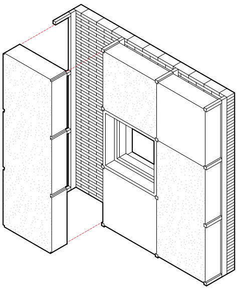


Fig. 8.3.9.2:
Adjustable Size | Unlayered

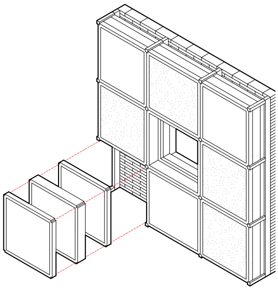


Fig. 8.3.9.3:
Standardised Size | Layered

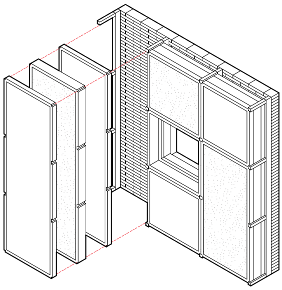


Fig. 8.3.9.4:
Adjustable Size | Layered

§ 8.3.10 ***Closed Modules***

The closed modules system utilises vertical cases with lids to form a closed unit. The modules are placed inside the cases. Multiple cases are placed adjacent to each other to form a complete façade.

Advantages

- The system can utilise a self-supporting frame.
- The lids ensure adequate water and airtightness.
- The system can be prefabricated as a whole and applicated on-site.
- The cases can be adjusted to different window configurations.
- The modules could be replaced with taller modules.

Disadvantages

- Adjusting to different width of the parameters, such as windows, would increase the number of unique panels and therefore the standardisation of the system.
- Integration of horizontal piping is difficult.
- The ability to house thicker is limited due to the frame.
- Integrating heavier installations could prove to be difficult.
- Replacing the modules with wider modules is impossible.

Potentials

- The lids could be openable in order to perform maintenance on the components inside.
- The vertical modules could be either coupled into facade panels or individually assembled on-site.

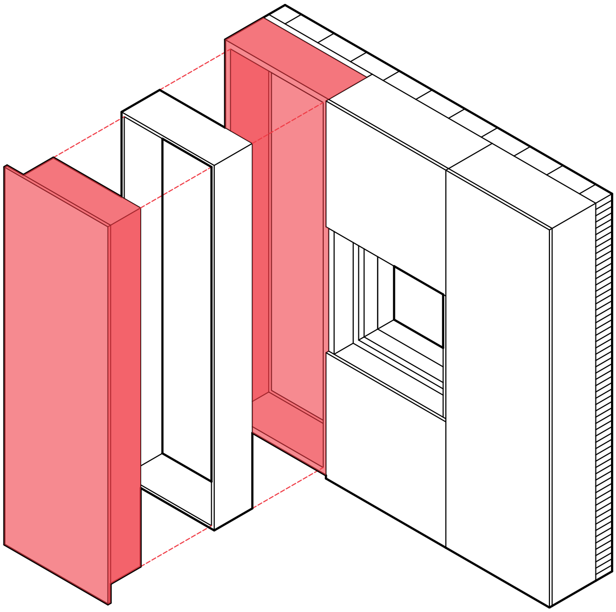


Fig. 8.3.10.1:
Adjustable Size | Unlayered

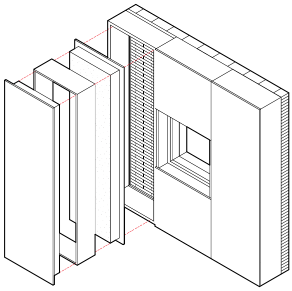


Fig. 8.3.10.2:
Adjustable Size | Layered

§ 8.3.11 *Chosen Concepts*

Based on the analysis, the system concept that proves to be the most promising is the open frame system. It offers the freedom required for the integration of building installations that require connections with other modules within the panel. It also offers more connection points for additional elements such as sun shading, as well as more structural performance than the pin system to include heavier components, such as the heat pump. Furthermore, the system can incorporate longer beams to include thicker modules, which is beneficial for the upgradability.

The choice is made to use adjustable sized modules instead of standardised sized modules. The number of different sized windows severely limit the usage of a standardised grid, as it would require a large number of unique panels. Furthermore, standardised modules also increase the number of modules required, leading to a longer production process. The integration of the larger components, such as the heat pump, was the final deciding factor, as it can not be integrated in small modules.

Finally, the choice was made to use layered modules instead of unlayered ones. This choice was solely based on the criteria upgradability and maintenance. Separating the functions ensures that replacing the modules, either due to damage, exceeding of a component's service life or for a functional upgrade, does not require to remove the complete module, which ultimately leads to wasting a lot of material.

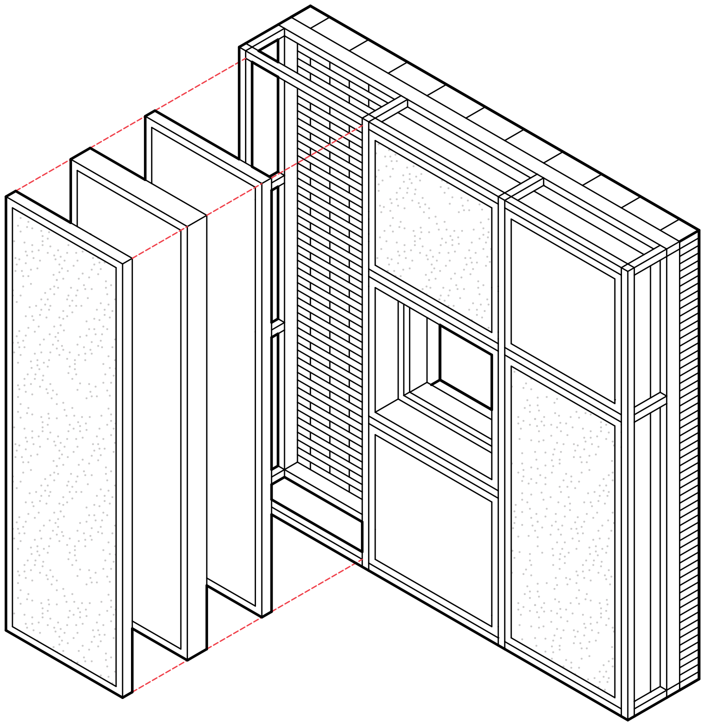


Fig. 8.3.11.1: *Chosen concept for further development: Open frame | Adjustable Size | Layered (own illustration).*

§ 8.4 Components

The concept consists of a multitude of components that together formulate the final design of the modules. In order to further materialise the concept, an area was chosen to design the panel for, which is located on the first floor of the south façade. The components that require attention are the frame, the frame connections, the module boxes, the protection layer, the cladding, the connections, the window and the adaptation layer, which will be discussed in their respective sections.

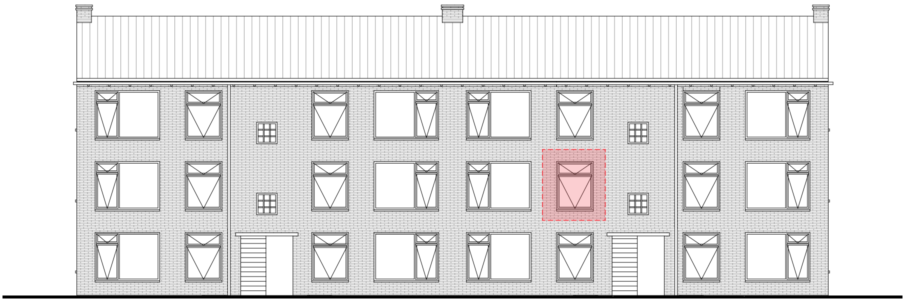


Fig. 8.4.1: *Location module on the south facade (own illustration).*

§ 8.4.1 *Frame*

The main element of the façade system is the frame construction in which the boxes are hung to form a façade. As described earlier the frame should be adjustable to different box sizes as well as thicknesses, while keeping an open structure in order to possibly connect adjacent boxes. Secondly, the frame should be rearrangeable by changing dimensions of the individual design areas, as well as being able to add or remove elements in order to respectively create additional design areas or to combine areas. Finally, the frame fulfils a structural purpose carrying the load of the modules and other components.

The design for the frame splits the frame in two groups: the main frame attached to the existing façade, and the framing around the modules that are placed into the main frame. By separating the frame, the modules can be slid into the frame and occupy the entire design area of the frame.

Every module has its own support structure consisting of four beams. By separating the design areas, the replacement of a single module does not affect structural integrity of adjacent modules.

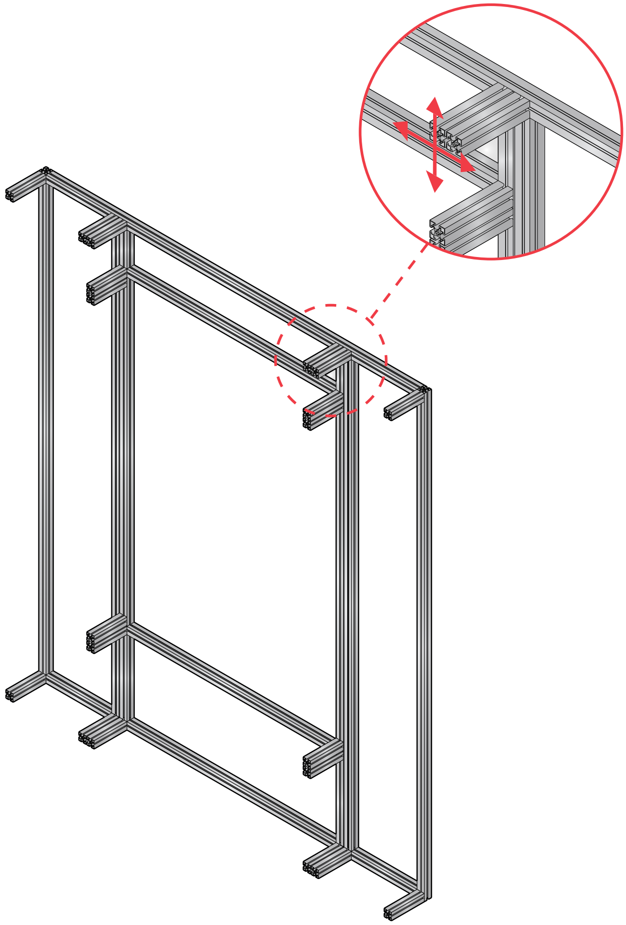


Fig. 8.4.2: *Frame consisting of aluminium T-slot Profiles, the T-slots can be flexibly connected to each other to construct different module and box sizes (own illustration).*

T-slot Extrusion Profiles

The component that most suits the requirements are T-slot extrusion profiles. T-slot profiles offer modularity and can be easily assembled and reassembled according to the functional and dimensional requirements. T-slots have high strength-to-weight ratios and can be easily machined and recycled. T-slot profiles come in a wide variety of geometries and sizes offering different levels of strength. The main parameters for choosing an adequate profile are the cross-section surface and the moment of inertia, as well as functional characteristics such as area for attachment of other façade components. Lastly, utilising the same extrusion profile as much as possible further adds to the reusability of the profiles, as well as simplifying the production process.

T-slot profile generally come in size increments of 15 mm. Based on the listed parameters the choice was made to further investigate 45 x 45 mm T-slot profiles that are generally utilised for applications in the same order of scale as facades (80/20 Incorporated, 2018), and offer surface area for attachment of façade components in the same order of scale as the 2ndSkin project described in chapter 6. Furthermore, profiles with rounded exterior edges are also excluded from further investigation, as they can potentially bring about unwanted air gaps in the construction.

The largest load possible is on the cantilevered beams attached to the main frame, every design area is supported by four cantilevered beams that are connected when a module is inserted. The critical design areas are the thicker modules with the heat pump and heat exchanger, increasing the weight and cantilevered length. For this scenario, as well as a frame without installations, preliminary structural calculations were made which can be found in figure 8.4.3.

Based on the calculations the lightest variant of the profiles is sufficient for panels without additional building installations, while leaving structural capacity to potentially install thicker panels. The heaviest variant is not sufficient for the panels with building installations. Adding a support on the outside of the frame and making the panels self-supporting would solve this issue and make the lightest variant an option for both scenarios. While this solution would also require a separate foundation, it is preferred over using larger profiles and subjecting the existing structure to larger loads, which could potentially damage the existing structure over time.

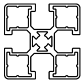
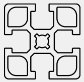
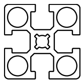
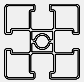
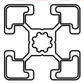
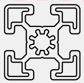
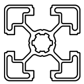
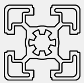
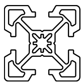
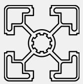
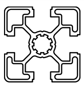
Profile			Ix, Iy	E	Weight	Cantilevered (Small Thickness)		Cantilevered (Large Thickness)		Additional Support (Large Thickness)	
						Deflection	Yield Stress	Deflection	Yield Stress	Deflection	Yield Stress
Minitec	45X45UL		9.95 cm^4	70.0 GPa	1.45 kg/m	0.07 mm	4.88 N/mm^2	9.76 mm	75.9 N/mm^2	0.65 mm	30.3 N/mm^2
Minitec	45X45F		14.2 cm^4	70.0 GPa	2.01 kg/m	0.05 mm	3.50 N/mm^2	6.95 mm	54.0 N/mm^2	0.46 mm	21.5 N/mm^2
Minitec	45X45		15.9 cm^4	70.0 GPa	2.21 kg/m	0.04 mm	3.14 N/mm^2	6.21 mm	48.3 N/mm^2	0.41 mm	19.2 N/mm^2
Minitec	45X45SST		6.47 cm^4	200 GPa	2.71 kg/m	0.04 mm	7.89 N/mm^2	5.41 mm	120 N/mm^2	0.36 mm	47.6 N/mm^2
80/20	45-4545L		9.20 cm^4	70.3 GPa	1.39 kg/m	0.07 mm	5.27 N/mm^2	10.5 mm	82.0 N/mm^2	0.70 mm	32.8 N/mm^2
80/20	45-4545		13.9 cm^4	70.3 GPa	2.04 kg/m	0.05 mm	3.56 N/mm^2	7.02 mm	54.9 N/mm^2	0.47 mm	21.9 N/mm^2
Coomach	45X45L-0		11.5 cm^4	68.3 GPa	1.60 kg/m	0.06 mm	4.25 N/mm^2	8.69 mm	65.9 N/mm^2	0.58 mm	26.3 N/mm^2
Coomach	45X45Z		14.0 cm^4	68.3 GPa	2.00 kg/m	0.05 mm	3.55 N/mm^2	7.20 mm	54.7 N/mm^2	0.48 mm	21.8 N/mm^2
Vention	45X45		15.4 cm^4	68.3 GPa	2.06 kg/m	0.05 mm	3.23 N/mm^2	6.56 mm	49.8 N/mm^2	0.44 mm	19.8 N/mm^2
McMaster-Carr	45X45WH		10.8 cm^4	68.0 GPa	1.52 kg/m	0.07 mm	4.52 N/mm^2	9.29 mm	70.2 N/mm^2	0.61 mm	28.1 N/mm^2
Rexroth Bosh Group	45X45LITE		10.9 cm^4	68.3 GPa	1.54 kg/m	0.07 mm	4.45 N/mm^2	9.10 mm	69.1 N/mm^2	0.60 mm	27.6 N/mm^2

Fig. 8.4.3: *Structural calculations for three different loadcases which the frame of the facade modules is subjected to. The red numbers indicate that the deflection exceeds its limit state (own illustration).*

§ 8.4.2 *Connections*

The frame consists of a multitude of connections with different structural requirements. Every connection can be subjected to direct force, cantilevered or torsional force. The different connection typologies all have their own profile of unique characteristics that fulfil different functional and structural requirements. Although the methods of connection aluminium profiles are endless, specific connectors have been developed over time to offer convenience, flexibility and structural strength. These connections can be categorised in two groups: external or internal connections.

External connections

External connections are connected to the outside of the T-slot to strengthen connection points, and are easily implemented in most application. Most external connections are reconfigurable and can be placed anywhere along the length of the profile. Due to the external positioning, the connections are easy to implement and offer the ability to connect more than two profiles (F and L Industrial Solutions, Inc., 2018).

Internal connections

In general, internal connections create stronger bonds than external connections due to the fact that they are machined into the profile. Internal connections are easy to assemble, require fewer parts and fewer material than external connections (F and L Industrial Solutions, Inc., 2018). Furthermore, the connections can be hidden in the slot of the profile, ensuring the design area is not affected.

Due to the fact that the design area is completely occupied by the boxes inserted into the frame, the choice was made to focus on the internal connections. In figure 8.4.5 the characteristics of the different internal connectors are described further.

According to the table, it can be concluded that double anchor is the strongest connection for 90-degree angles although it requires connections on either side of a profile, it is therefore the best solution for the connections of the main frame, that are required to carry the most loads. Furthermore, it offers the flexibility to reposition individual profiles in order to change the areas for the boxes and the windows. A downside is that there is some machining required by drilling holes in one of the profiles.

In order to standardise the connections as much as possible, the most logical choice is then to choose the single anchor connection for the connection of the boxes to the main frame. The single anchor requires the same machining to the profile as the double anchor, which simplifies the production process. The single anchor offers less structural strength than the double anchor, but every box is connected to the frame with eight double anchors to counteract this loss. Furthermore, due to the positioning and connection of the boxes to the main frame, the double anchor is ideal for the connection as it can be accessed in the slot of the profiles of the box, ensuring easy mounting and demounting.

For the lengthening of the profiles of the main frames, in order to accompany thicker boxes, the butt fastener is the best option. It again requires the same machining tools for drilling of the holes and forms a strong connection between two profiles. The flexibility is not required for these connections, as the connection will be flush mounted.

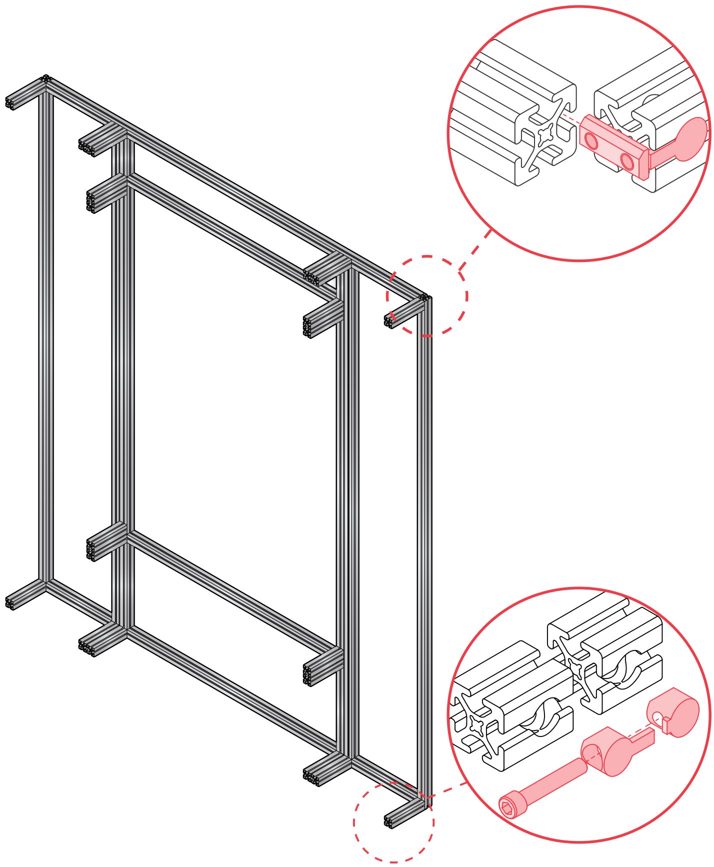
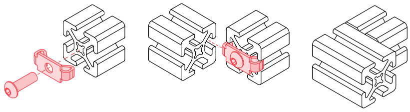
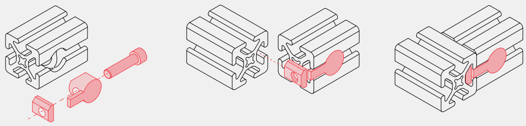
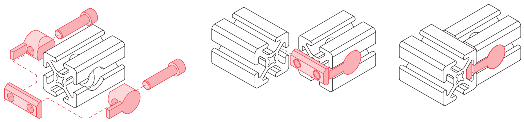
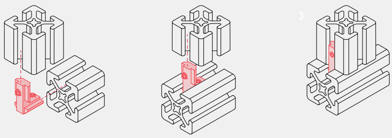
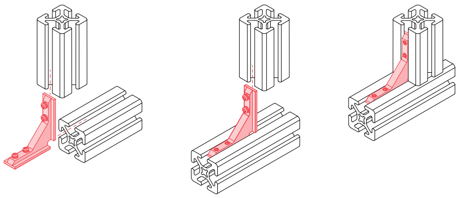
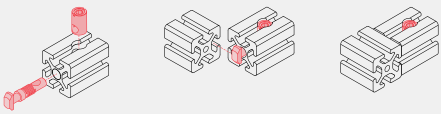
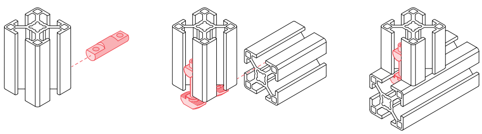
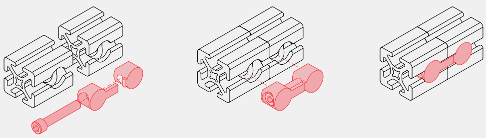


Fig. 8.4.4: *The double anchor connection is utilised to connect the main frame vertical and horizontal elements, the butt fastener can be utilised to lenghten profiles to accompany thicker boxes (own illustration)*

Fig. 8.4.5: *Different available connection methods for T-slot profiles (F and L Industrial Solutions, Inc., 2018)*

Part	Assembly Method	No Machining Required	Hardware Included
Standard End Fastener			✓
Single Anchor			✓
Double Anchor			✓
Hidden Corner		✓	✓
Inside Corner		✓	✓
Central Connector			✓
Bolt Connector Assembly			✓
Butt Fastener			✓

Flush	>2-Way Hub	Infinite Positiong	Visibility	Flexibility	Strength
✓	✓		●●●●●	●○○○○	●●●●○
✓		✓	●●●●●	●●●●●	●●●●○
✓		✓	●●●●●	●●●●○	●●●●●
✓		✓	●●●●●	●●○○○	●○○○○
		✓	●●●●○	●●○○○	●●○○○
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§ 8.4.3 *Module Boxes*

The individual boxes that are inserted into the main frame have a number of requirements according to the concept's guiding theme. Main objectives for the box design is that it can be mounted and demounted without excessive labour. Furthermore, the module box building system should be designed to be adjustable to different sizes and completely fill the design area created by the frame configuration to minimise potential air gaps. And lastly, the individual elements of the box should be removable without discarding the complete box, either to be reused in different boxes or to be recycled.

With the following parameters the box was designed and the chosen variant utilises L-shaped corner elements and straight planks to form a box. The surrounding T-slot profiles are mounted on the corner elements and the planks are connected via smaller steel L-shaped profiles. The required functional component can be installed in the box volume and finished with a lid to form a complete module. The box is then connected via the T-slots of the box to the T-slots of the main frame with single anchor profiles in every corner.

This variant ensures all individual elements can be reused as well as offering an easy way to construct boxes of different sizes. The lid can be removed with relative ease in order to perform maintenance on the component inside. Furthermore, the connections can be reached from the exterior and unfastened to remove the entire box.

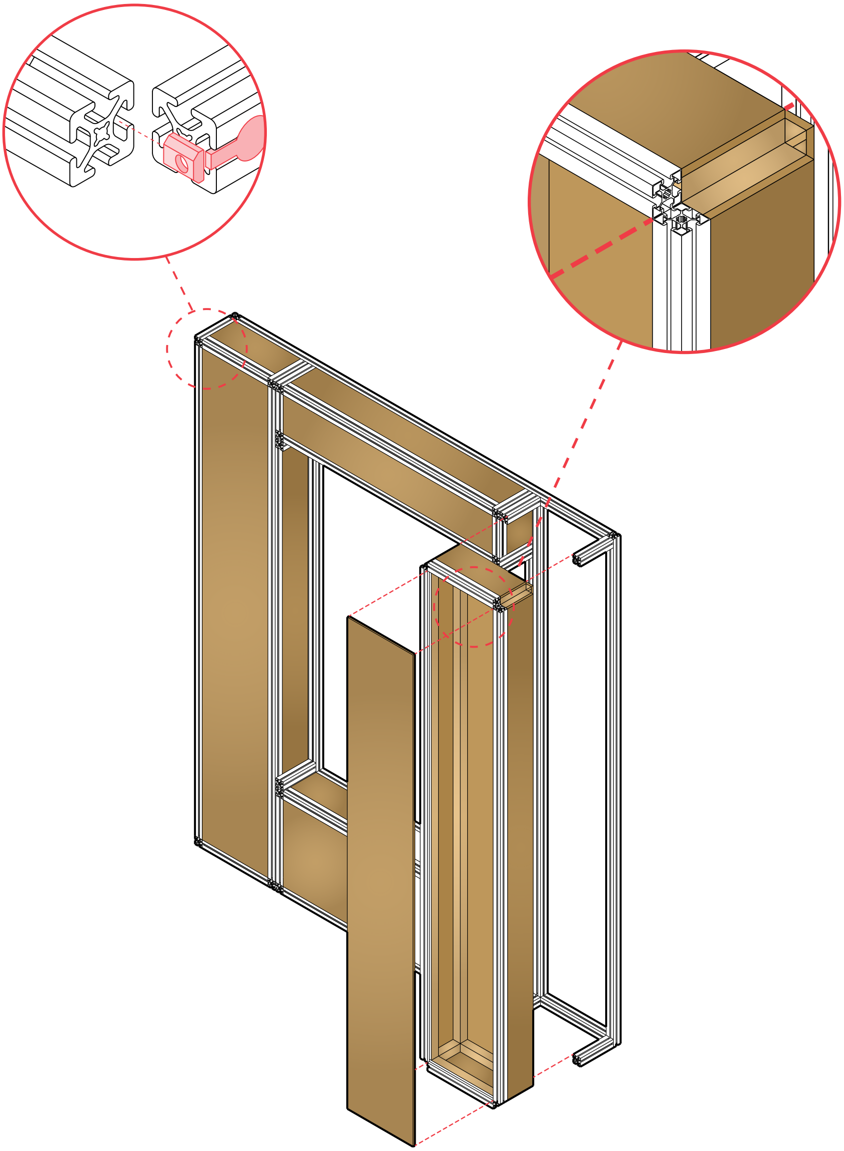


Fig. 8.4.6: *The box consists of four surrounding panels connected via L-profiles, the T-slot profiles of the secondary frame are mounted on the L-profiles (own illustration).*

§ 8.4.4 ***Protection Layer***

Due to the open structure of the frame and the stacking of the modules it is difficult to individually waterproof the boxes, for that reason the choice was made to create an additional water barrier functional layer on the exterior of the façade. The main problem then arises how the boxes can be individually accessed in case of maintenance or replacement. The choice was made to make individual water barriers for all underlying modules within the same sub-frame area. With a sub-frame area designating the space where a module can be placed. Furthermore, the water barrier should be solid of nature so it can be removed as one element, as well be remounted without excessive necessary labour.

With these parameters in mind the following design direction was chosen: A clamp construction around every sub-frame area with a finishing watertight panel. The clamp is a variation of the curtain wall clamp and is attached to the underlying T-slot frame. In figure 8.4.7 a multitude of design options are displayed, variations were made in the connection type to the underlying T-slot as well as the connection type between two adjacent clamps.

The chosen connection type is the fifth option that utilises a top clamp and bottom clamp that together form the completed clamp, based on a profile designed by Janssen Steel Systems (2018) and similar systems. The clamp utilises an insulated stud which is inserted into the slot of the extrusion profiles and fastened with a screw with a centring disk. The insulated stud can be placed anywhere along the slot of the profile. The option ensures the clamp can be mounted, demounted and remounted with relative ease. A solid top and bottom half of the clamp further ensures increased manoeuvrability over a rubber bottom half that can potentially bent when reapplying.

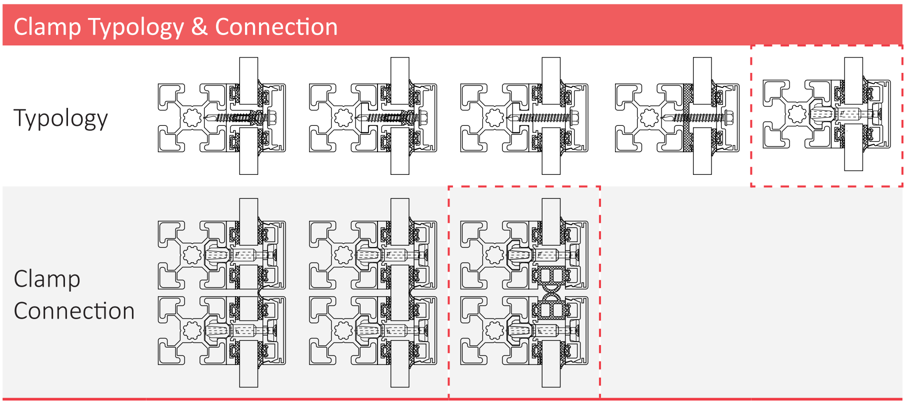


Fig. 8.4.7: *Typology options for the clamp and connection typologies to ensure airtightness between adjacent clamps (own illustration).*

For the connection point between two adjacent clamps the choice was made to use a rubber connection piece that forms an airtight connection by compression with the connection piece of the adjacent clamp. The rubber connection piece ensures that the clamp profiles can be removed individually without the removal of adjacent clamp profiles.

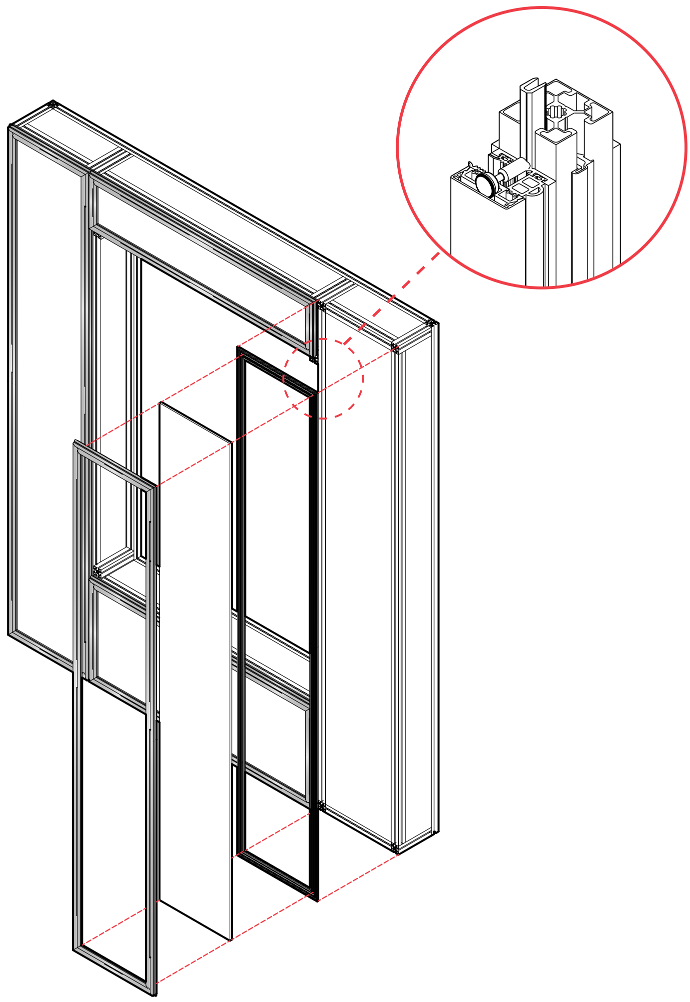


Fig. 8.4.8: *Connection of the clamp to the secondary frame of the boxes (own illustration).*

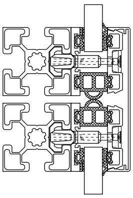
§ 8.4.5 ***Finishing Layer***

The appearance of the façade, and possibly functioning of the exterior layer, can be altered through the finishing caps of the clamp profiles as well as the cladding panels that are inserted into the clamp profiles. In this paragraph the possible customisation options are discussed further.

The cap of the clamping profile can be altered in a multitude of different ways, in figure 8.4.9 the different options are listed. Different materials can be utilised to achieve different aesthetic looks, as well as the cap shape can be altered to emphasise either horizontality, verticality or a more balanced aesthetic. Furthermore, the shape of the cap can be utilised to function as static solar control for windows. The replacement of the cap to introduce a new aesthetic look can be achieved relatively easily in the future, for example due to a change of fashion or due to a damage, by snapping off the frame cap and replacing it with a new cap different in shape and/or material.

The second way of changing the appearance of the façade is through panels inserted in the clamp profiles. Different materials can be utilised, as well as different functional components. An ordinary façade panel could potentially be replaced with a solar panel. Panels can be replaced relatively easy by unscrewing the clamp profile, replacing the panel and remounting the structure.

Customisation Options



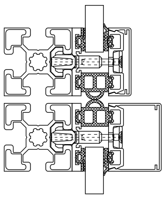


Fig. 8.4.9: *Examples for customisation of the aesthetical appearance of the facade (own illustration).*

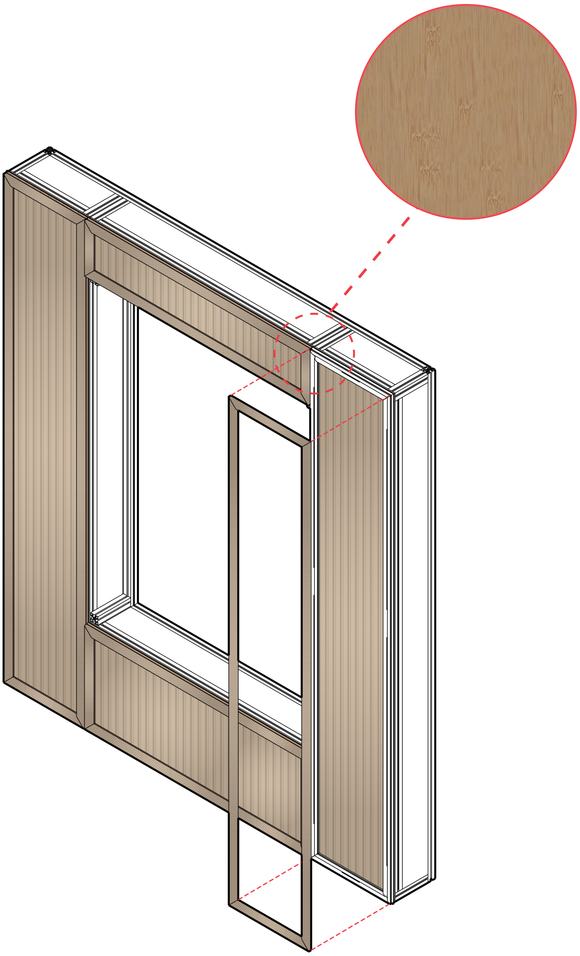


Fig. 8.4.10: *The cladding panel is mounted in the clamp profile and the clamp profiles is concealed with a finishing cap (own illustration).*

§ 8.4.6 ***Window***

The window configuration utilises the same strategy as the modules boxes by surrounding the window with four T-slot profiles which are slid into the main frame, as well as a clamping profile to ensure the water tightness. The elements to be designed are the connection of the window frame to the box frame, and the connection of the window to the interior. Furthermore, the window should be customisable to comply to the functional, as well as the aesthetical requirements of a project.

The different typological options are displayed in figure 8.4.11, an aluminium RT72 Reflex window by Kawneer was used for the design options (Kawneer, 2018), as was used in the prefabricated variant of the 2ndSkin project. It should be noted that different window types should be able to be incorporated in the module. The chosen option utilised for the design is not the clear best option, but a variant that could be utilised.

The option chosen for the case study application is an exterior flush-mounted window that is mounted on the T-slot frame via a corner profile, that is used to connect

RT72 Reflex Options

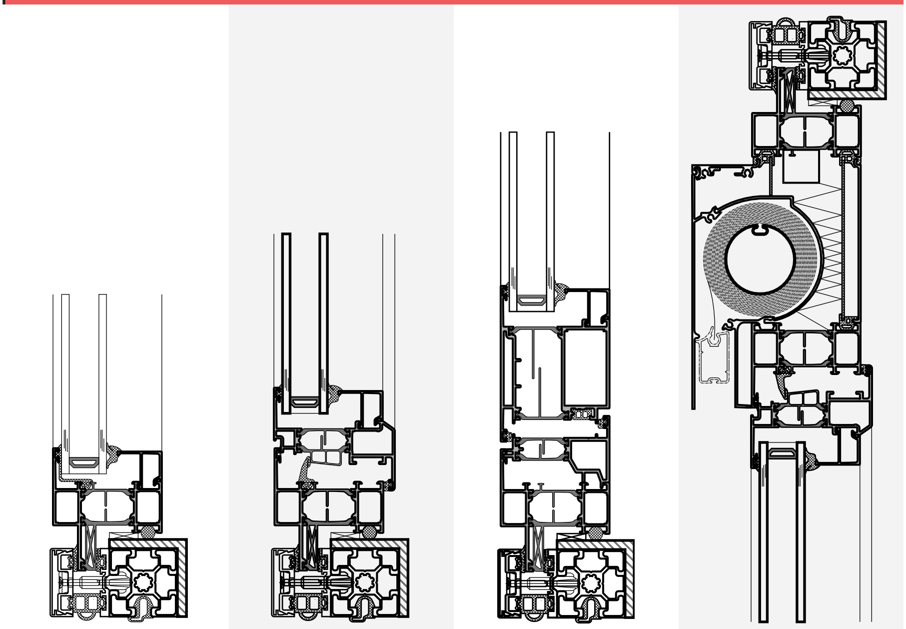


Fig. 8.4.11: *Variants of the RT72 Reflex modular Aluminium window frame (own illustration).*

the four T-slot profiles. The outer frame of the window is altered to be inserted into the clamp profile to create a watertight connection. Water that enters the window frame can be transported to the exterior via the outer frame. The complete construction can be prefabricated leaving only the internal lining to be applicated on-site. In order to applicate the internal lining the existing window and sill are to be removed. The generated gap between the lining and the existing structure is overcome with a setting block to support the lining.

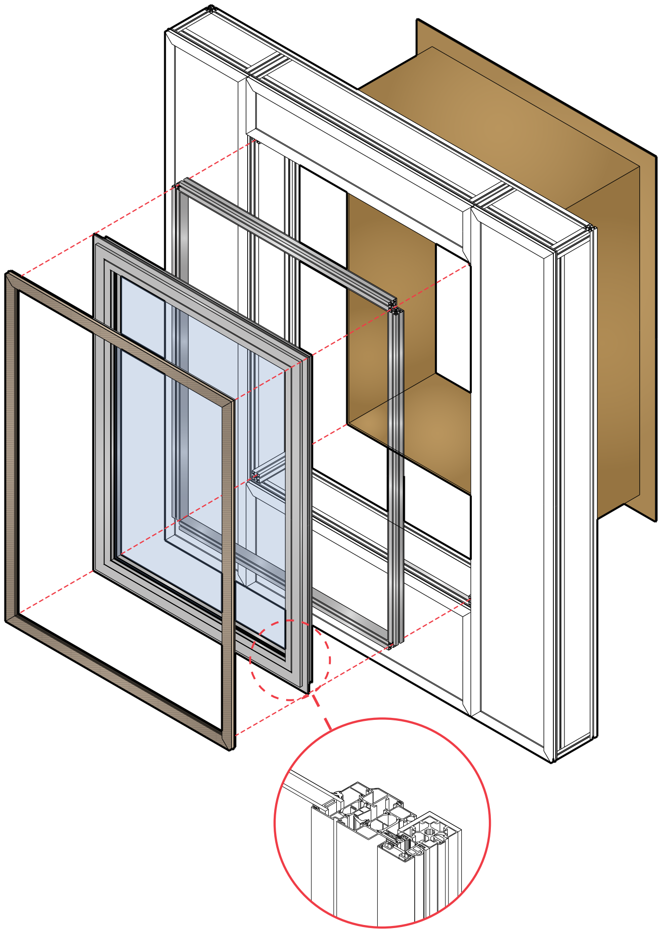


Fig. 8.4.12: *The window frame is mounted on the clamp profile and subsequently mounted in the main frame, the window is connected to the interior with an interior lining (own illustration).*

§ 8.4.7 *Module Connections*

Due to the interchangeability of the individual components of the façade system not only the module-to-module connection is important, but also the module box-to-box connection. As the boxes have to be relatively easy to mount and demount, some space between the boxes has to be maintained, while also ensuring an airtight fit when the boxes are in place. For both the module and the box, rubber elements are utilised to ensure airtight connections. In figure 8.4.13 the different connection typologies are displayed.

Box-to-box connections.

For the box-to-box connections it is important for the gap to be as small as possible to ensure unwanted movement of the boxes is minimised. A small gap can be ensured due to the prefabrication in a controlled environment. The chosen element consists of small rubber pieces inserted into the slots of adjacent boxes that are mirrored to ensure the gap can be relatively small. The air pocket inside the rubber connections ensures the rubber can be compressed easily when boxes require replacement.

Module-to-module connection

For the module-to-module two separate connections have to be made, one on the interior side and one on the exterior side, serving two different purposes. The connection on the interior is utilised for precisely placing the module horizontally and vertically. The connection piece fits into the slot of the above and adjacent modules and move several millimetres up and down and left to right until the correct position is reached. The allowance for this movement is necessary to absorb potential deviations in sizing of panels. If this deviation is not absorbed in the first connection it could potentially build up to a critical misalignment in adjacent panels. The chosen

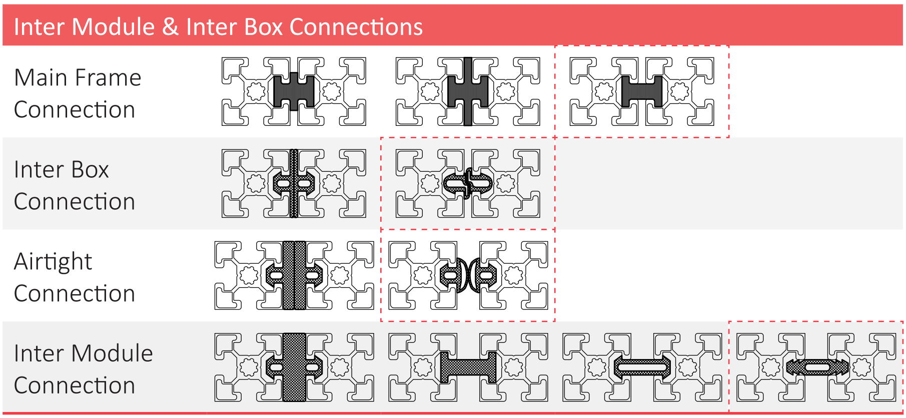


Fig. 8.4.13: *Different connection typology to ensure airtightness between adjacent boxes or modules (own illustration).*

connection has multiple teeth on both side of the connection that can be slid further in or out while retaining an airtight connection.

The connection on the exterior serves solely to create an airtight connection that prevents the penetration of water. The connection on this side consists of a rubber element on both sides of the panel, either horizontal or vertical, that are placed inside the relevant slots. These elements are pressed together during the mounting of the modules to create an airtight connection.

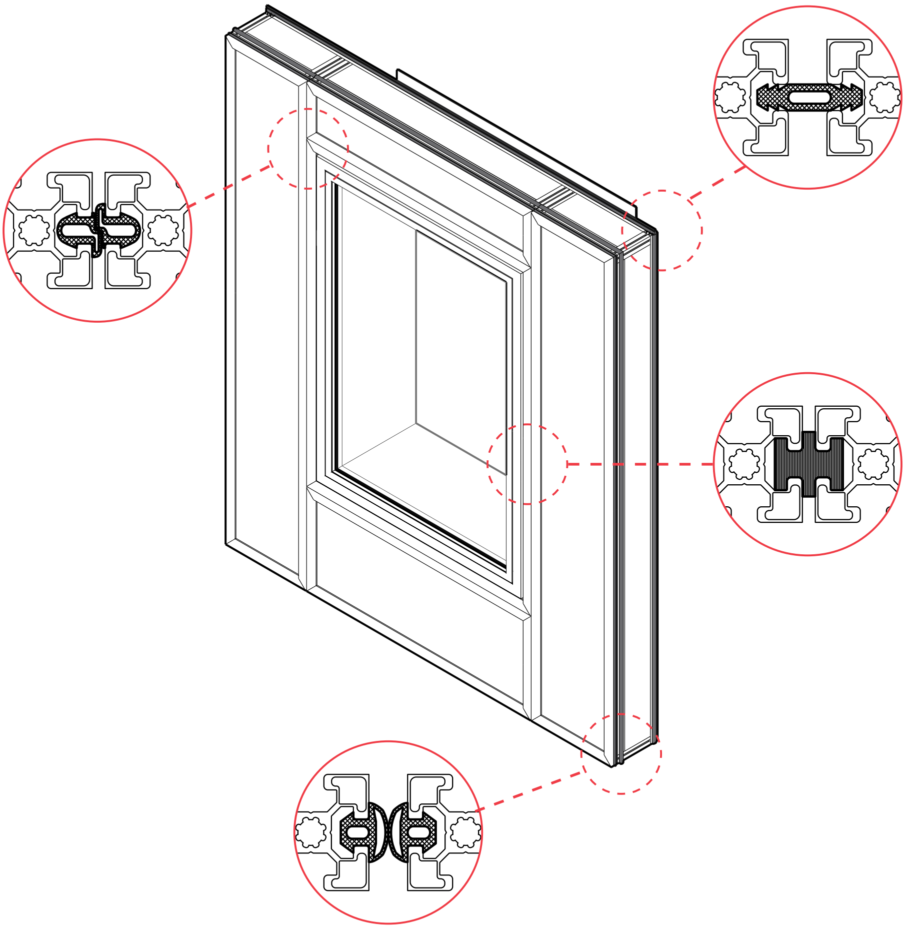


Fig. 8.4.14: *Together with the rubber connection in the clamp another two layers of rubber connectors are placed in succession to ensure an air and watertight connection (own illustration).*

§ 8.4.8 ***Adaptation Layer***

The brick outer layer of the existing structure could potential present irregularities, which can be more or less pronounced in certain areas. These irregularities can potentially offer problems when applicating the façade system which is perfectly straight. In order to counteract the negative effect of unwanted air gaps, which decreases the thermal performance of the building envelope, an adaptation layer is necessary to ensure the contact between the existing structure and the new façade system is perfect (Dubois, et al., 2016). Furthermore, the adaptation layer functions as a levelling element for the building envelope system's modules. The use of a substructure attached to the existing structure ensures the levelling process can be performed at a faster rate. The parameters for designing the substructure is dependent on the possible attachments points on the existing wall, the possible attachment point on the building envelope system and the load application possible.

The parameters offer a few possible options. Firstly, the choice can be made between vertical or horizontal laths. The choice was made to use vertical laths over horizontal laths, due to the more even load distribution on the existing walls. Vertical laths can directly transport the weight to the foundation.

Secondly, the void In between the vertical laths has to be filled up. This can be either done by installing insulation that can be compressed, or blowing in loose insulation after the application of the building envelope system's module. The best option is using a compressive insulation that remains in place when removing individual boxes. The thickness of the adaptation layer is dependable on the unevenness of the existing façade, but a minimum thickness of 30 mm is required (Cronhjort, et al., 2009).

The remaining element to be designed is the connection between the main frame of the façade system and the levelling laths of the existing structure. The final design utilises an steel flat element that is slid in the slots of the vertical T-slots to ensure the space between the levelling lathe and the module is minimised. The connecting element has a vertical slot for vertical adjustment of the façade module. The steel flat is connected to the module and the evening lathes via screws.

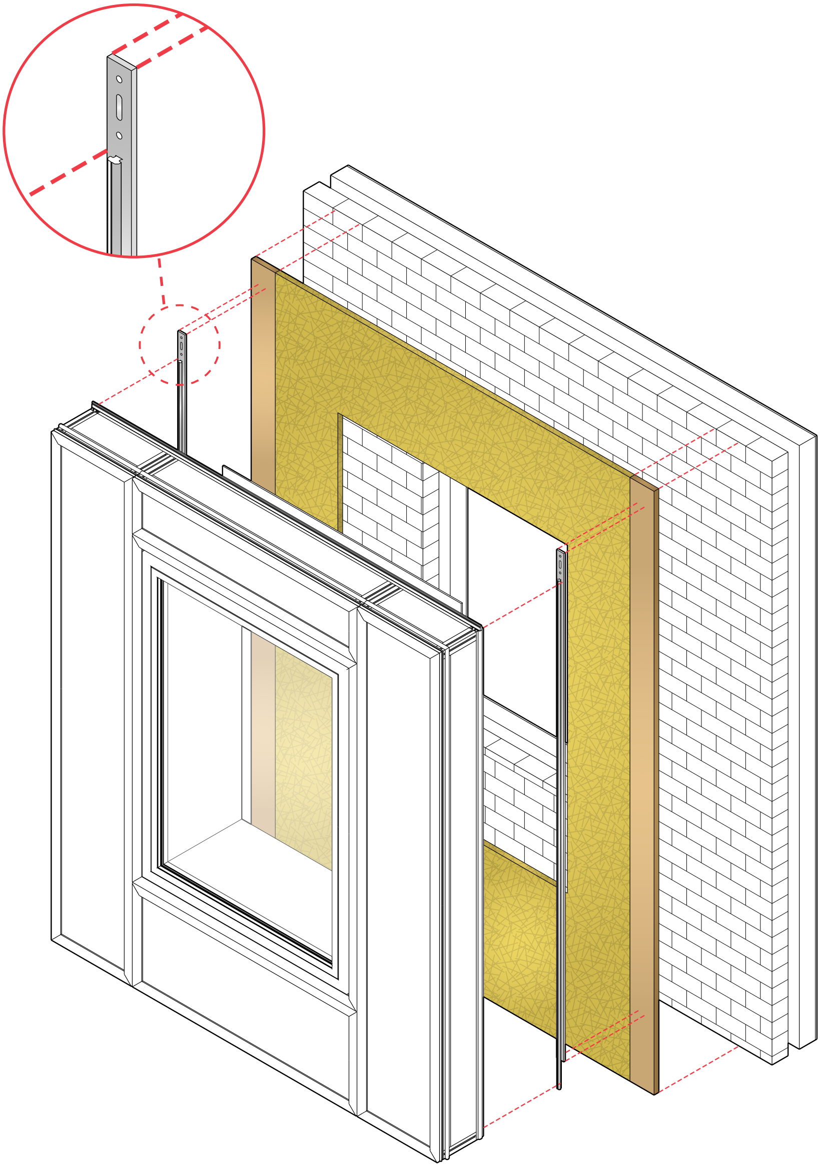


Fig. 8.4.15: *In between vertical laths compressible insulation is placed to level the uneven surface of the existing facade, the module is connected via steel flats to the vertical laths (own illustration).*

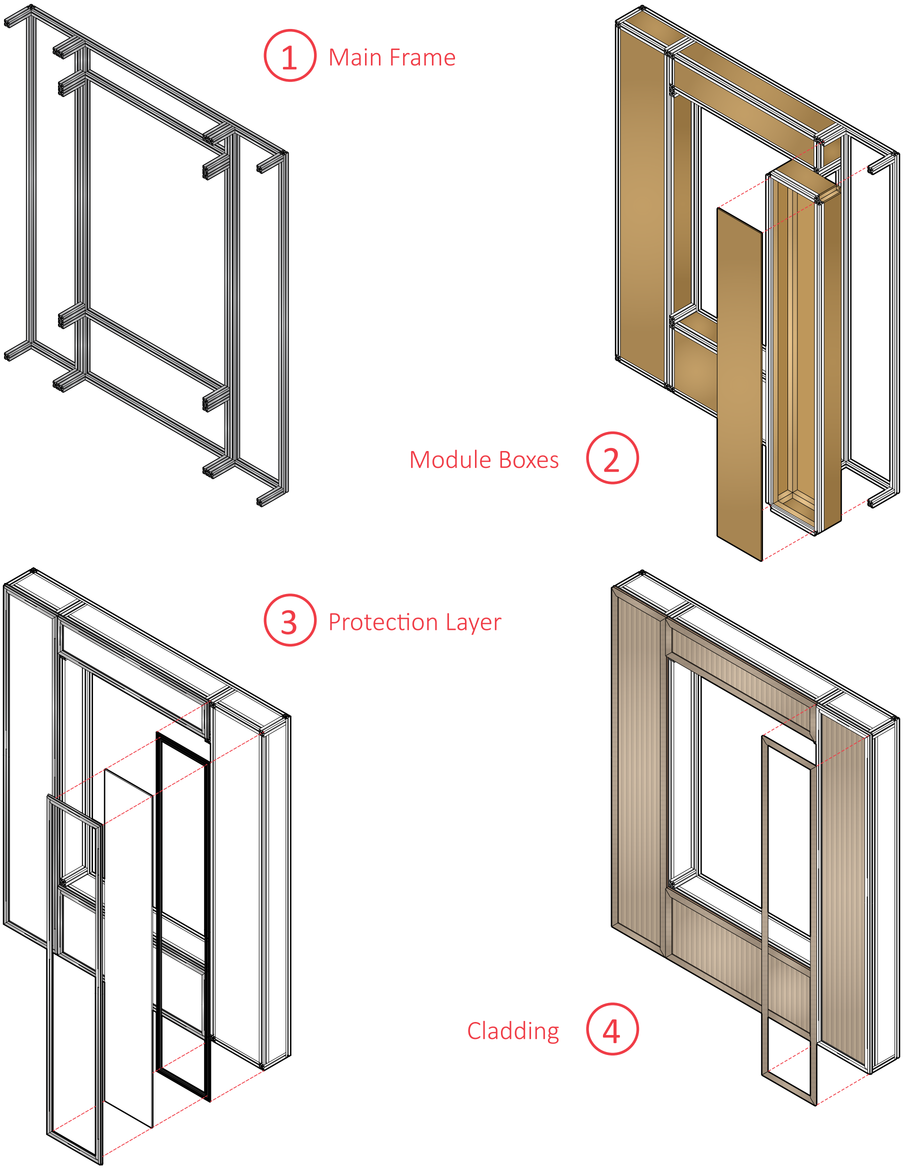
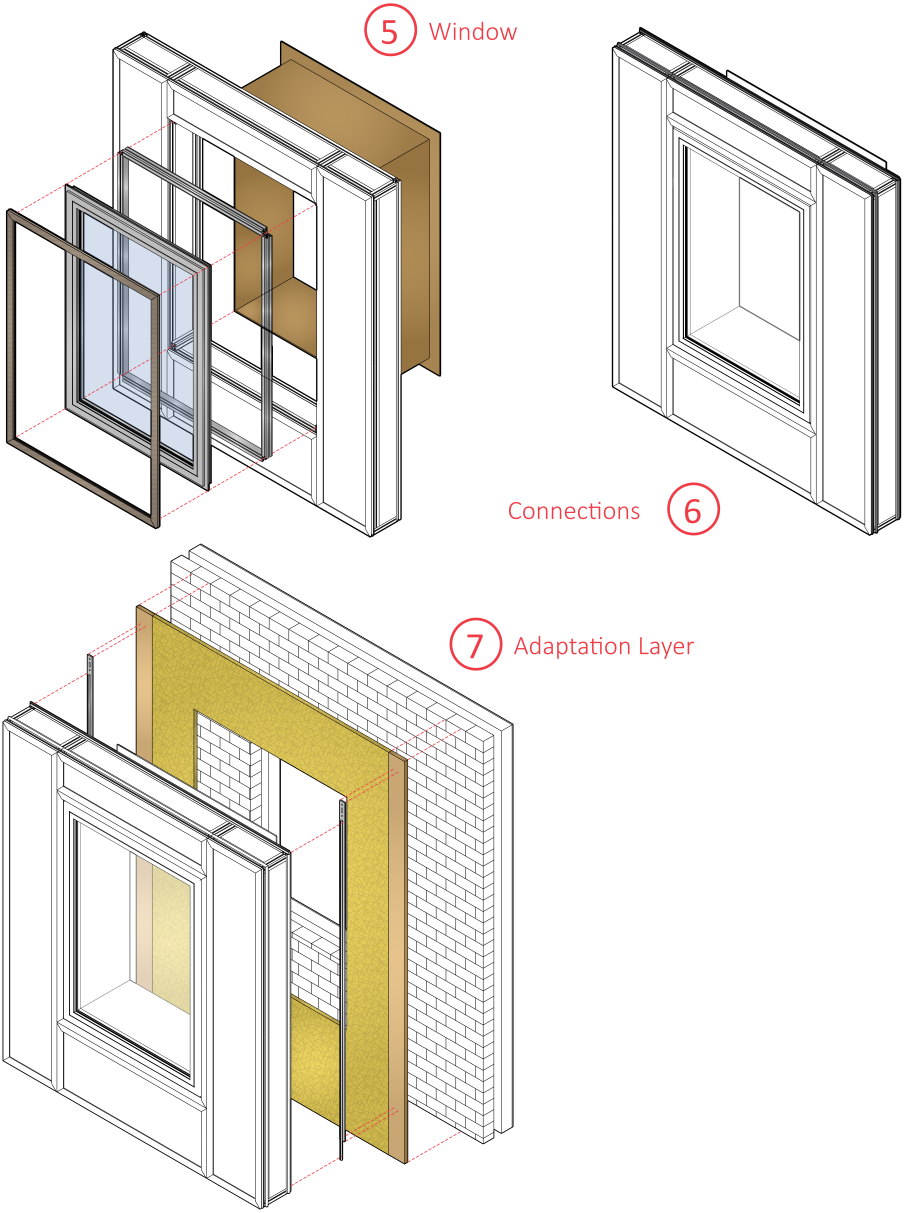


Fig. 8.4.16: *Summary of design steps (own illustration).*


5 Window
Connections 6
7 Adaptation Layer

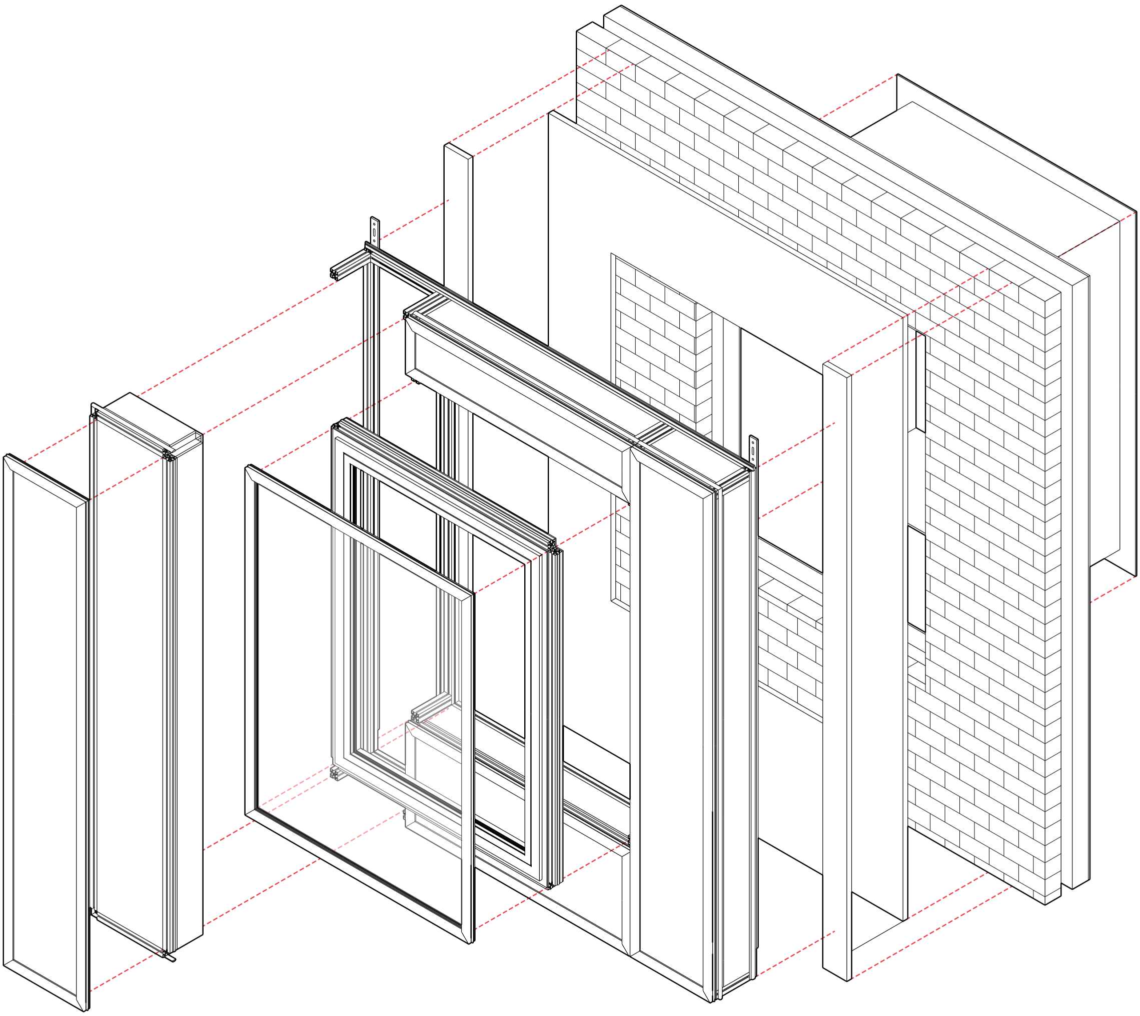


Fig. 8.4.17: *Exploded View assembly (own illustration).*

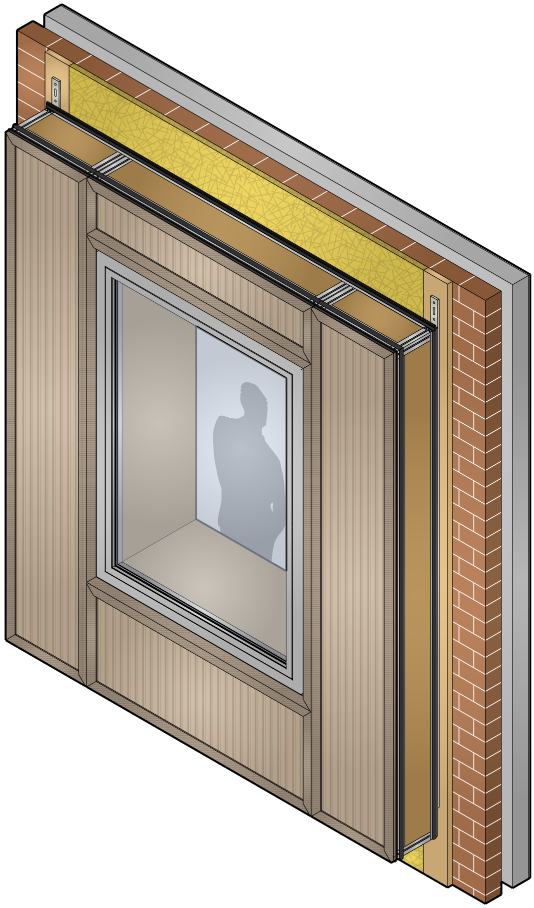


Fig. 8.4.18: *Isometric View completed assembly (own illustration).*

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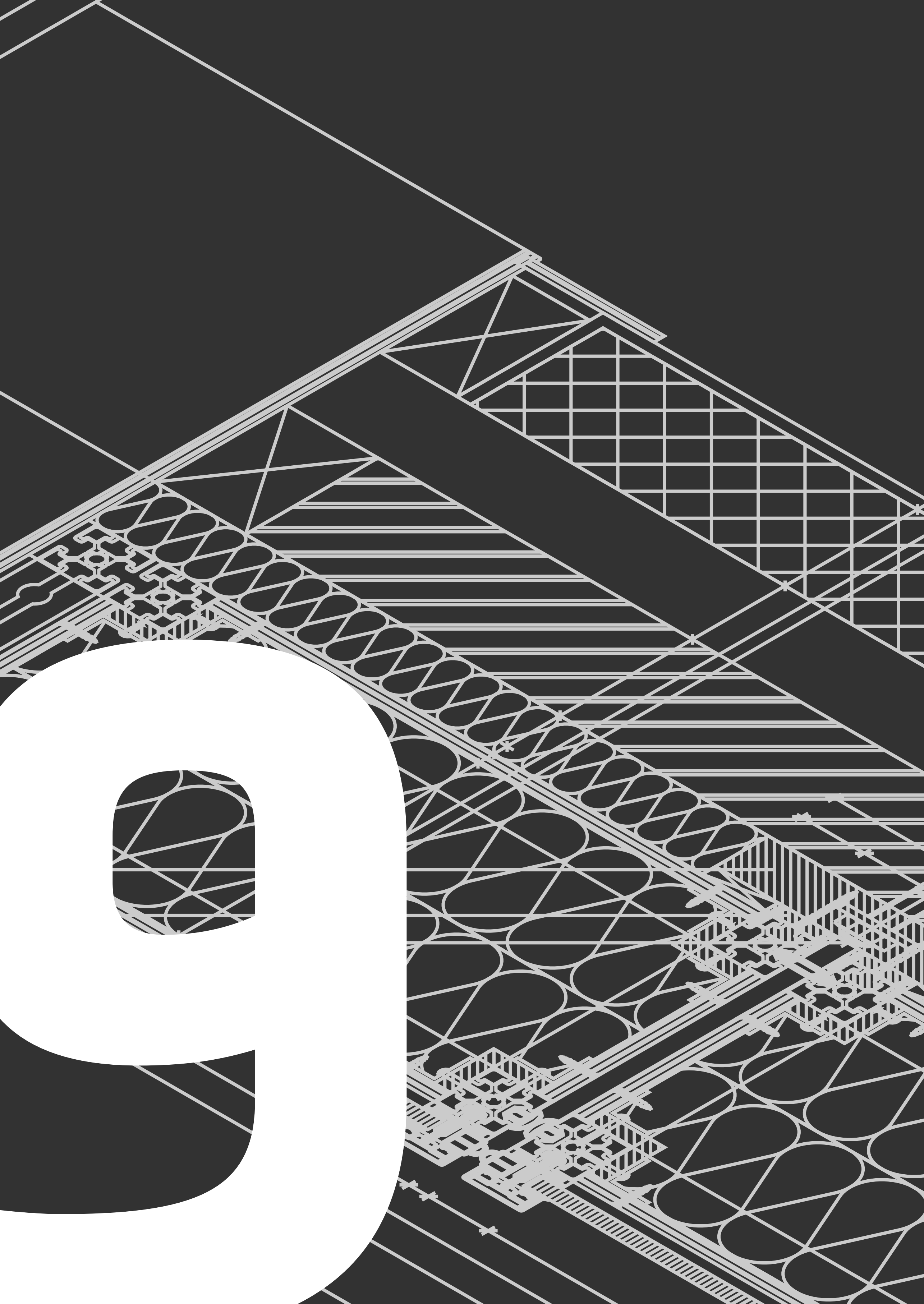
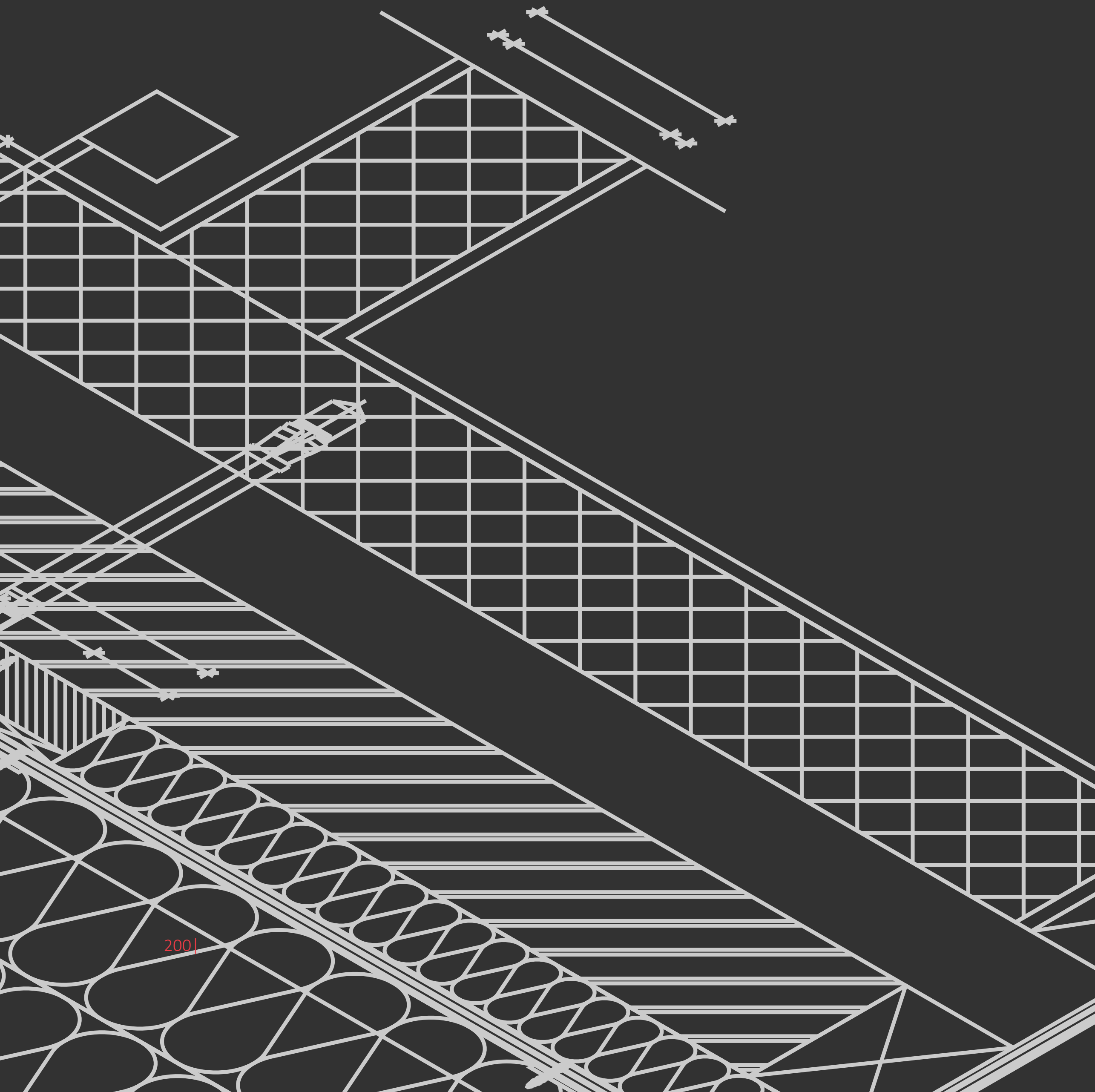
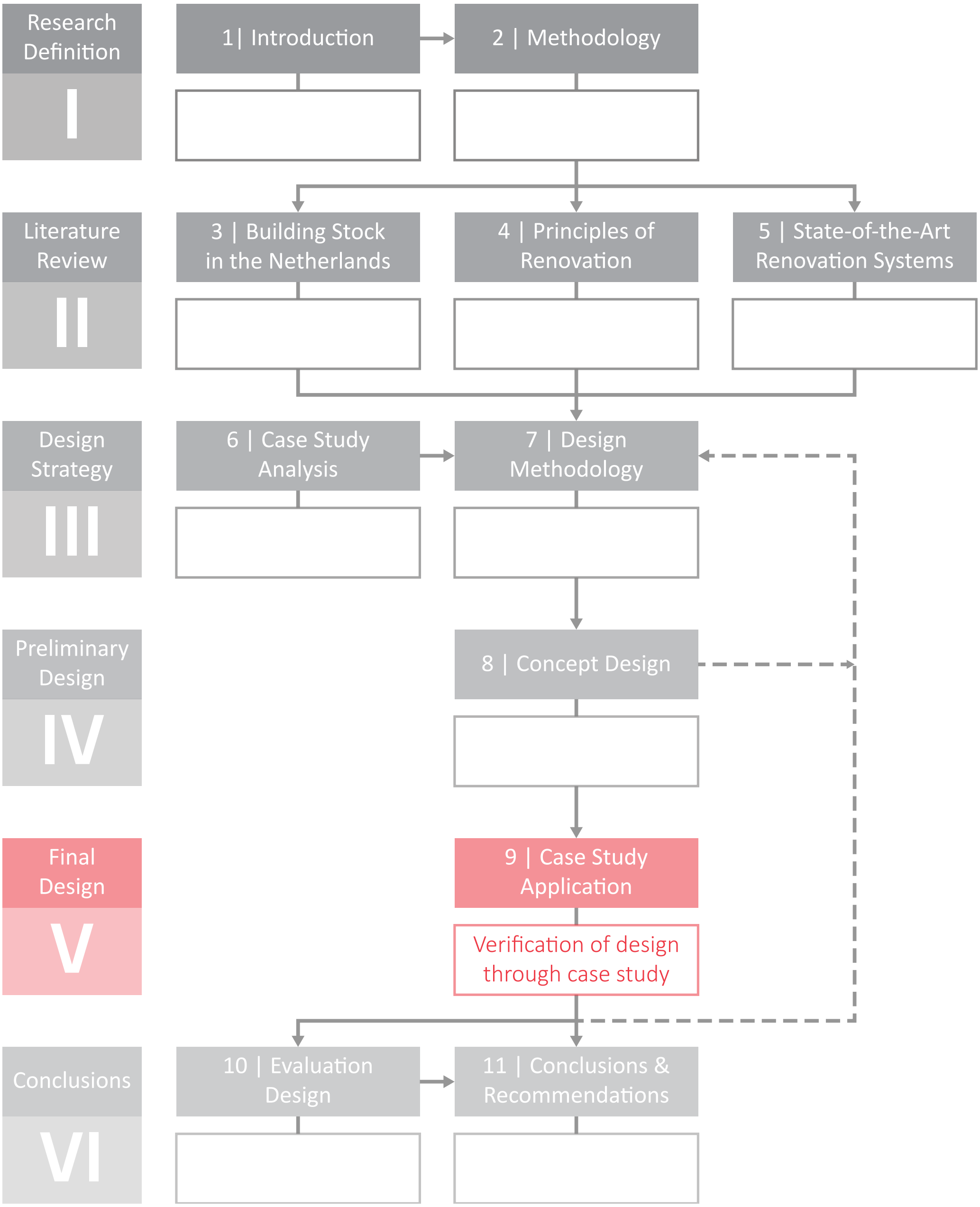


V

CHAPTER 9
CASE STUDY APPLICATION




Research Definition
I
1| Introduction
2 | Methodology
Literature Review
II
3 | Building Stock in the Netherlands
4 | Principles of Renovation
5 | State-of-the-Art Renovation Systems
Design Strategy
III
6 | Case Study Analysis
7 | Design Methodology
Preliminary Design
IV
8 | Concept Design
Final Design
V
9 | Case Study Application
Verification of design through case study
Conclusions
VI
10 | Evaluation Design
11 | Conclusions & Recommendations

9 Case Study Application

The concept design conceived in the chapter 8 will be further elaborated in chapter 9. The design exercise consists of adapting the concept design to the case study and its parameters, described in chapter 6, to a detailed level.

Paragraph 9.1 describes the overall strategy and package of measures applicated on the case study. Based on the strategy and measures a proposal is made for the grid in which the façade modules and box modules are placed. In paragraph 9.2 the final drawings for the set of measures are elaborated further. Paragraph 9.3 will present two separate scenarios which will be subjected to a number of changes according to a timeline to evaluate the final design's resilience to future changes. Paragraph 9.4 and paragraph 9.5 will elaborate the individual steps of both scenarios in further detail. Finally, in paragraph 9.5 different customisation options in terms in of aesthetic quality are presented.

§ 9.1 Strategy

The package of measures for application on the case study analysis closely resembles the measures utilised in the 2ndSkin demonstrator project in order assess the effectiveness of the new façade system.

The different measures will be implemented and adjusted accordingly to the new façade system's design. In the cellar the insulation will be implicated in the same manner as the 2ndSkin project. The balcony's will be cut off and a new self-supporting balcony will be placed. Two balcony constructions are placed per six apartments. Both measures are intricate to the energy reduction strategy for the apartment block, but go beyond the scope of this thesis, so will not be elaborated further.

The entrance will be closed off to thermally insulate the entrance area. Furthermore, the entrance requires to be pultruded from the existing structure in order to offer sufficient landing area for the existing stairs.

The installation boxes are placed in the same location as the 2ndSkin project on the north façade, on the division line between two apartments, but are rotated in order be placed parallel to the façade. Two installations boxes are placed in one façade module, bringing the total number of installations boxes to four. Maintenance on the installation boxes can be performed via the balconies, which run in front of the installation boxes. The boxes can be reached by opening the utility door integrated in

§ 9.1.1 *Grid*

The first step in the application process is the determination of the grid of the façade system's modules as well as the grid of the module boxes. The grid of the modules is based on achieving small modules sizes, to minimise the amount and size of the necessary construction apparatus, as well as minimising the amount of uniquely sized panels, to simplify the production process. The chosen main grid and secondary grid are based on the current project's requirement, as well as possible requirements for the future. If different functional requirements are set for the future, the grid could potentially chance. The building envelope system is designed in a way that multiple grids are possible. In figure 9.1.1 the main grid and secondary grid are portrayed, the numbering portrays an unique module size and the letters indicate a variant of the uniquely sized module in terms of secondary grid.

The façade system's complete modules all have a height of one storey and vary in width from 2100 to 4000 mm. The relatively small width ensures the complete modules can be transported with standard trucks. The same module sizes are used per floor and are mirrored on the centre line of the building in order to minimise the amount of uniquely sized panels. In order to connect the corners between perpendicular façade faces the modules on the north and south façade are elongated beyond the edges of the existing building.

The grid of the module boxes is based on the creating a wide variety of design area sizes that can house functionalities with different spatial requirements. For instance, smaller sized boxes could be replaced with boxes with decentralised heat exchanger units, while larger sized boxes could be replaced with boxes with centralised heat pumps. All different sized boxes are repeated multiple times in the grid, to ensure the amount of uniquely sized boxes stays at a manageable level.

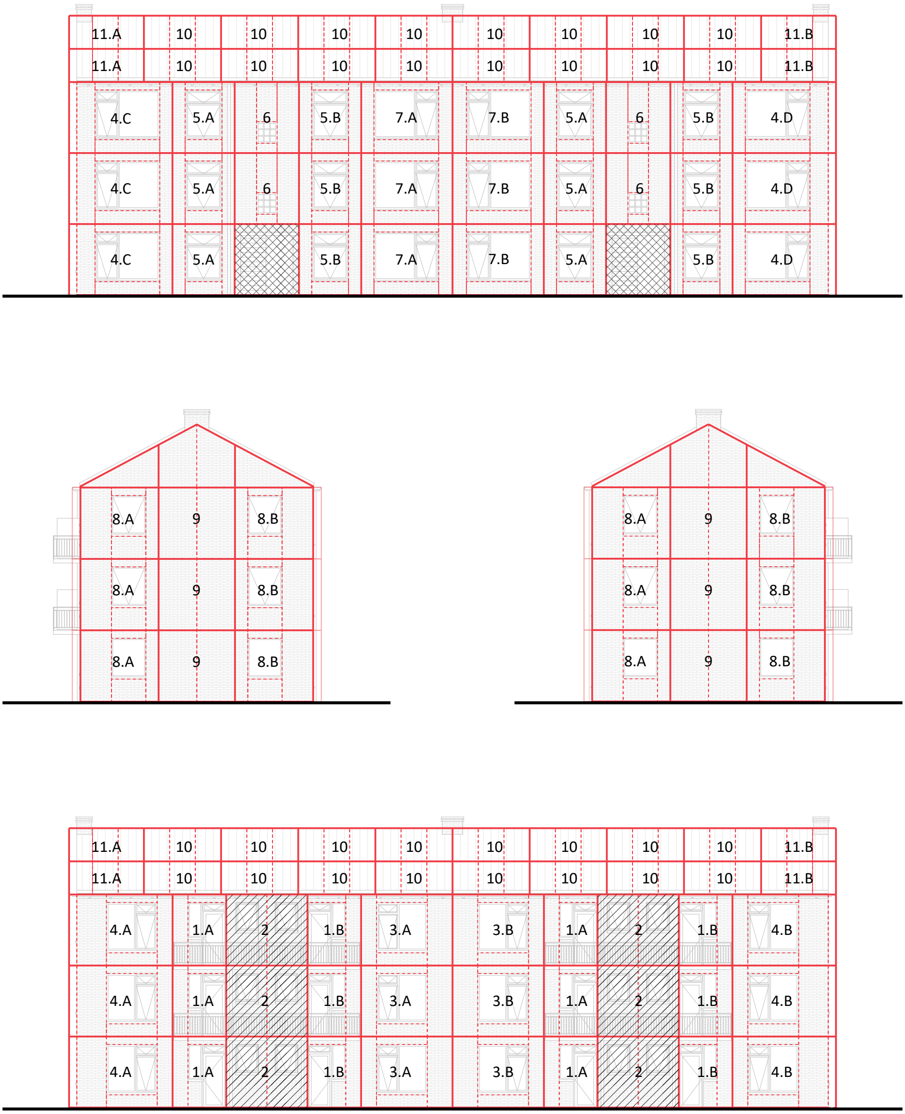


Fig. 9.1.1: *Grid Strategy for the case study application, the full lines depict the modules and the dotted lines the boxes (own illustration).*

§ 9.1.2 *Infill Strategy*

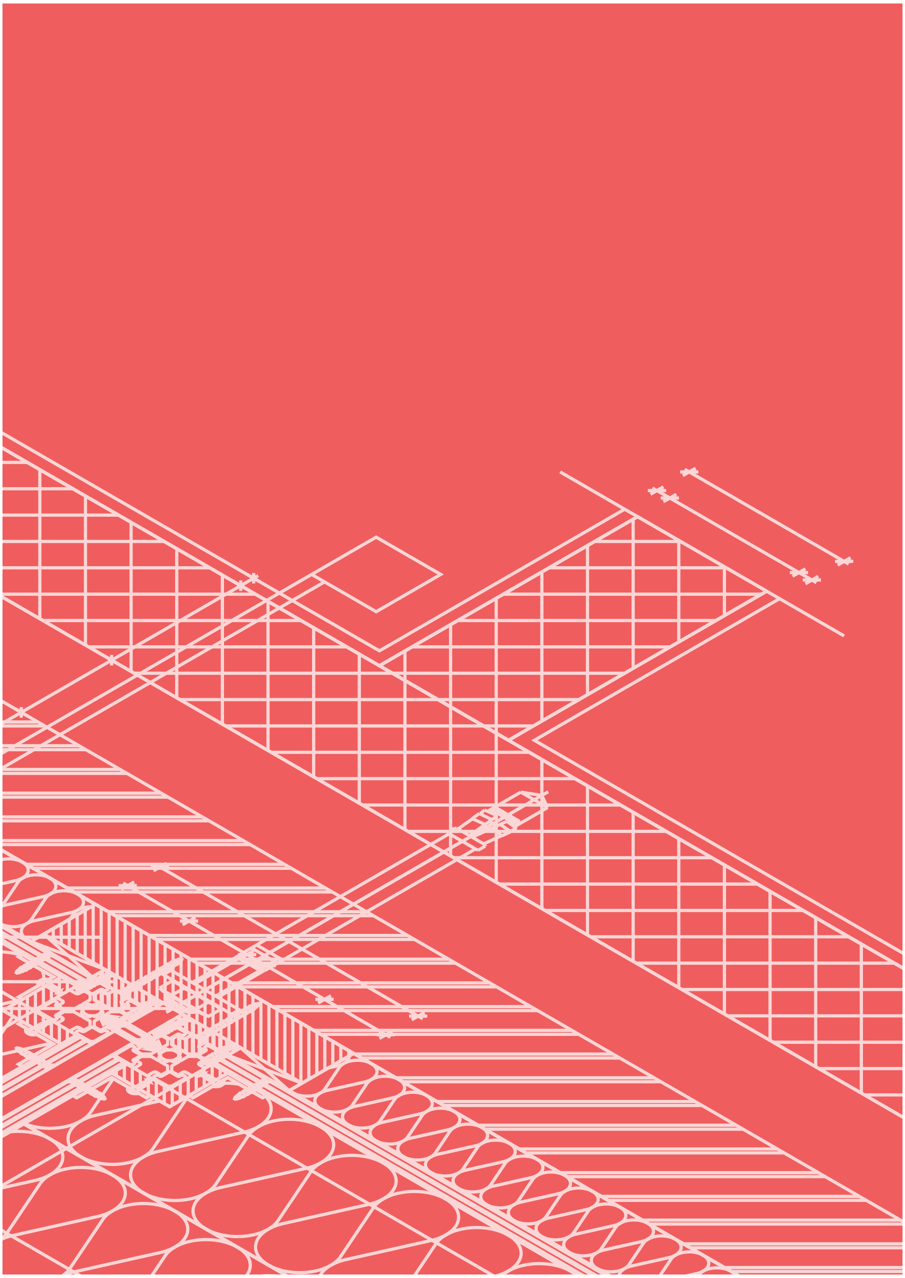
The infill of all the modules boxes, excluding the building installations boxes, consists of 226 mm of insulation and two MDF panels totalling to a depth of 250 mm. The system is finished with the clamp profiles with aluminium finishing snap profiles. The spandrel panels consist of watertight bamboo composite panels.

The roof utilises the same insulation boxes, but the bamboo composite panels are replaced with photovoltaic panels on both the north and south façade. The snap profiles utilised on the roof are shaped with chamfered corners to ensure water can be transported to the gutters.

The building insulation module consists of two module boxes placed in succession. The first box consists of an ordinary insulation box. The second box consists of a hollow module box with sandwich panel sides and finished with an integrated aluminium door. The module box is protected on the sides with a watertight sandwich panel. Penetrations in the existing walls are made to connect the interior to the heat exchanger and the heat pump.

Module		Size		Vertical Boxes				Horizontal Boxes			
				1		2		1		2	
		w	h	w	h	w	h	w	h	w	h
1	A,B	2100	2760	600			300	1500			
2	A,B	3150	2760	1575	2760	1575	2760				
3		3550	2760	600	2760	1000	2760	1950	300	1950	500
4	A,B,C,D	4000	2760	1150	2760	600	2760	1950	300	1950	500
5	A,B	2400	2760	500	2760	500	2760	1400	300	1400	500
6		2500	2760	850	2760	850	2760	800	400	800	1525
7	A,B	3550	2760	500	2760	500	2760	2550	300	2550	500
8	A,B	3000	2760	1200	2760	500	2760	1300	300	1300	500
9		3000	2760	1500	2760	1500	2760				
10		3000	2500	1000	2500						
11	A,B	3000	2500	1000	2500	900	2500				

Tab. 9.1.1: *Module sizes and box sizes (own illustration).*



§ 9.2 Final Drawings

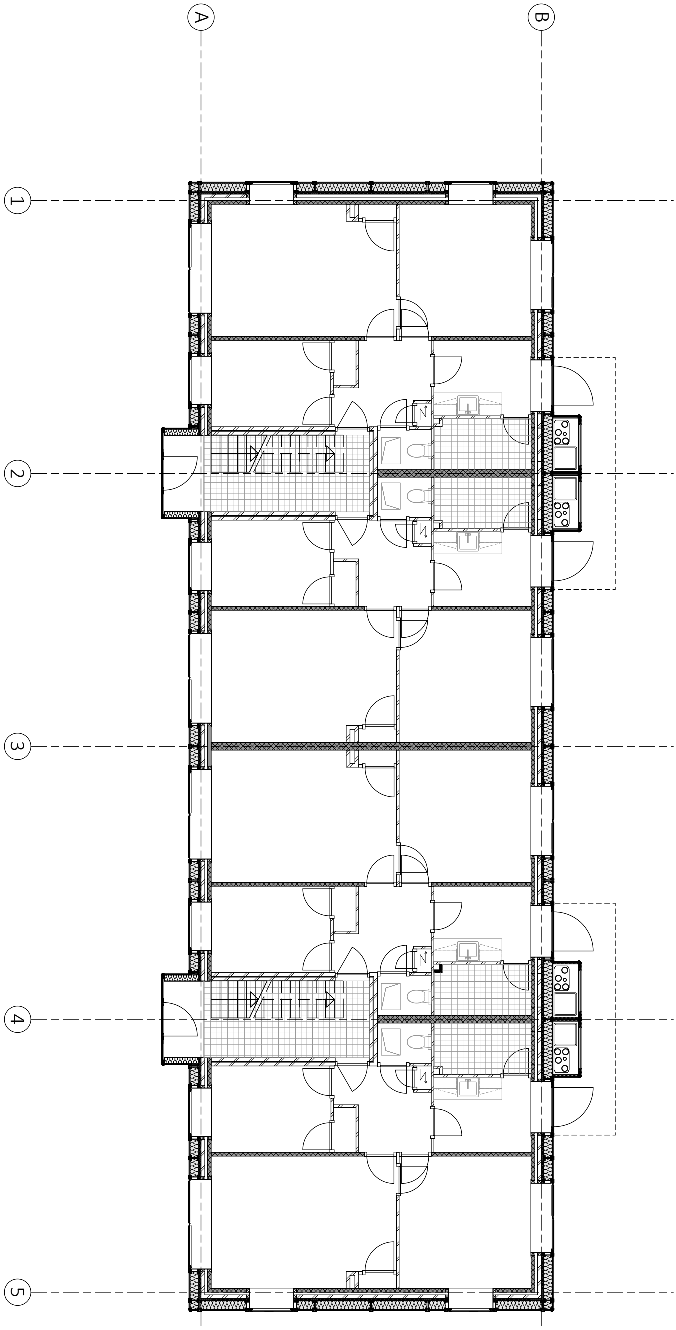


Fig. 9.2.1: *Plan | 1:200 | Ground Floor (own illustration)*

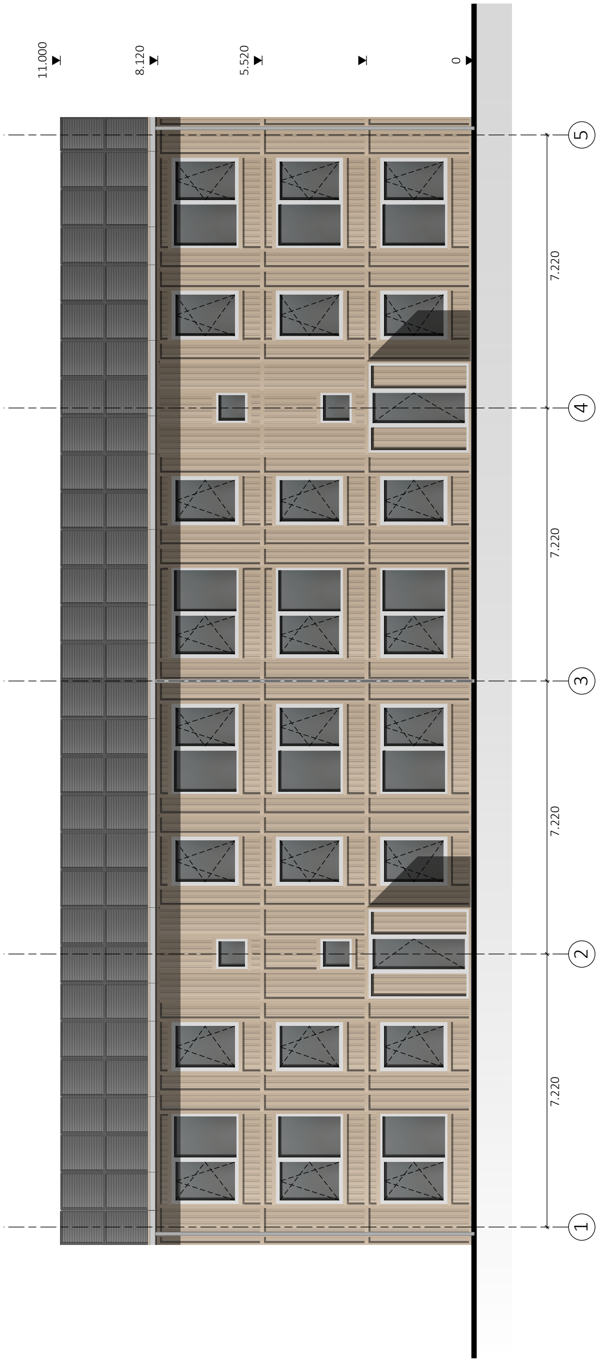


Fig. 9.2.2: *Elevation | 1:200 | South (own illustration)*

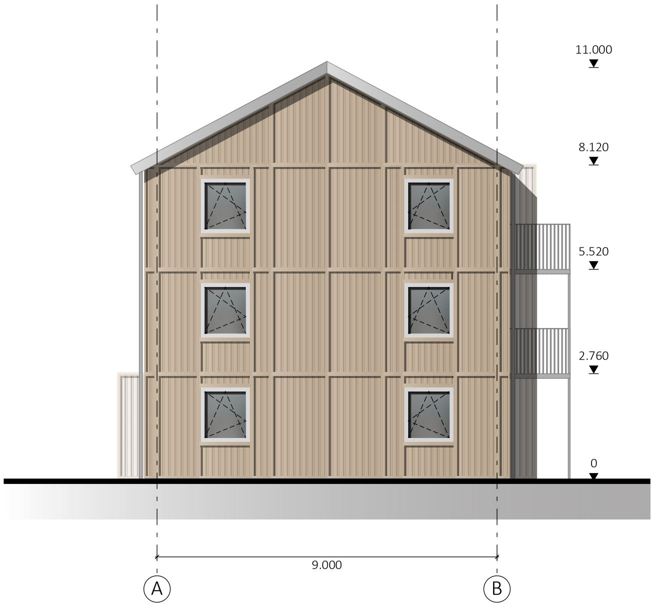


Fig. 9.2.3: *Elevation | 1:200 | East (own illustration)*

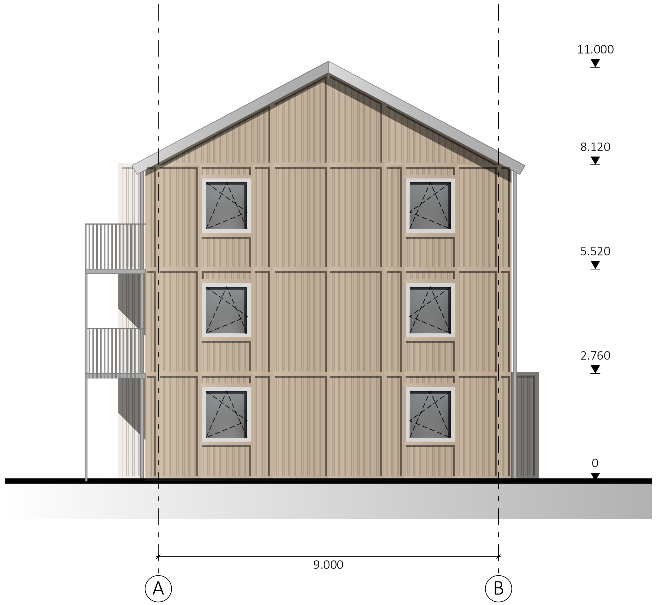


Fig. 9.2.4: *Elevation | 1:200 | West (own illustration)*

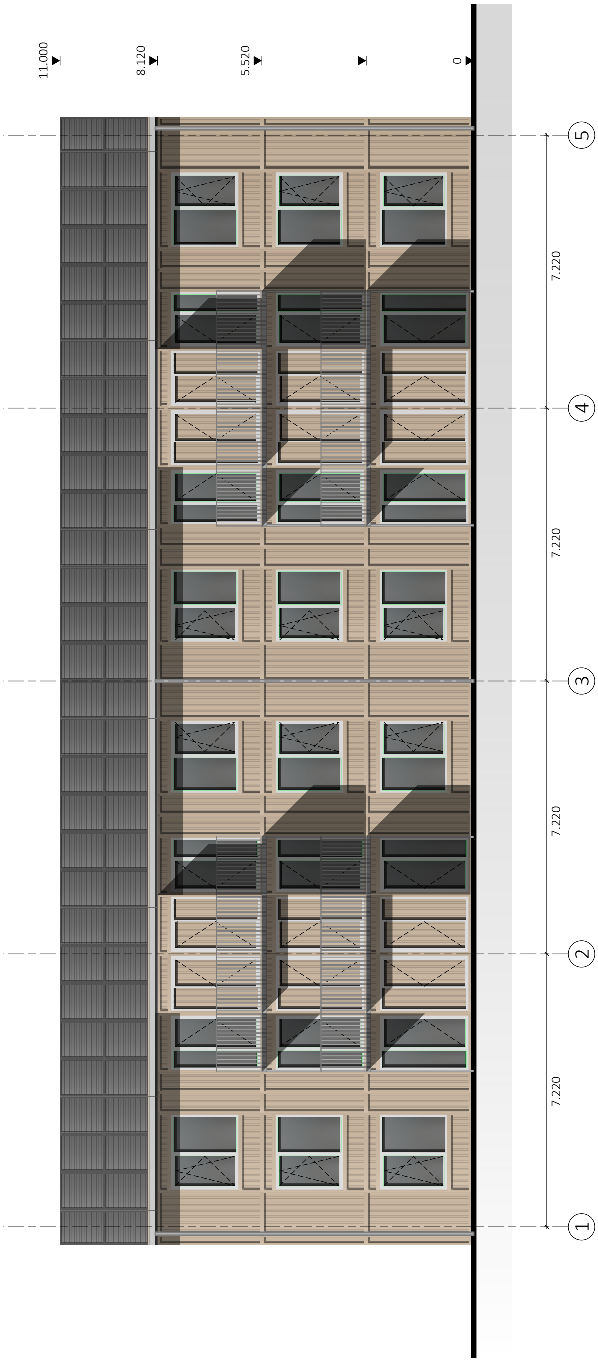


Fig. 9.2.5: Elevation | 1:200 | South (own illustration)

Fig. 9.2.6: *Fragment | 1:40 | South Facade (own illustration).*

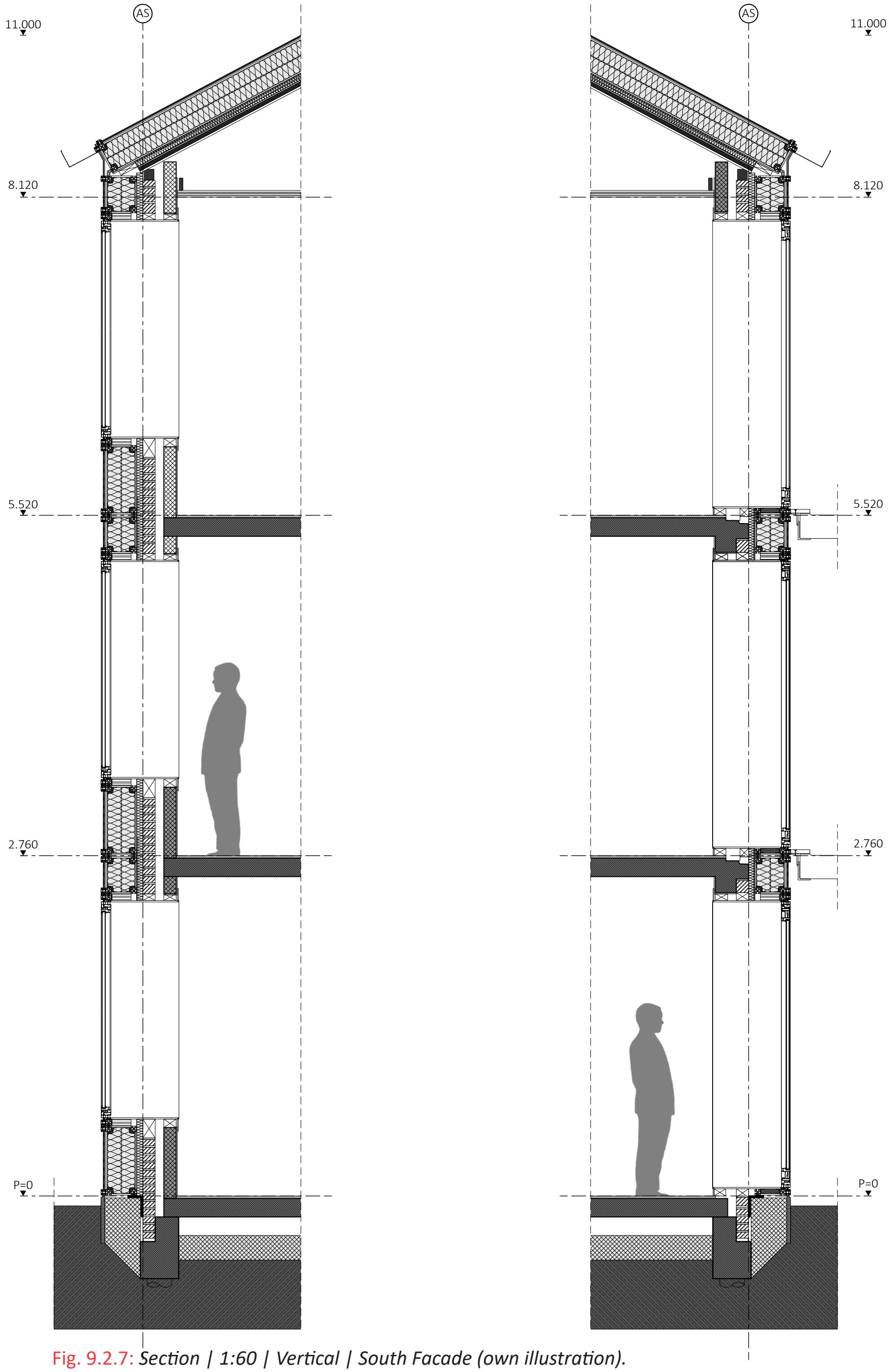


Fig. 9.2.7: *Section | 1:60 | Vertical | South Facade (own illustration).*

Fig. 9.2.8: *Section | 1:60 | Vertical | North Facade (own illustration).*

Fig. 9.2.9: *Detail | 1:10 | Vertical | Foundation (own illustration).*

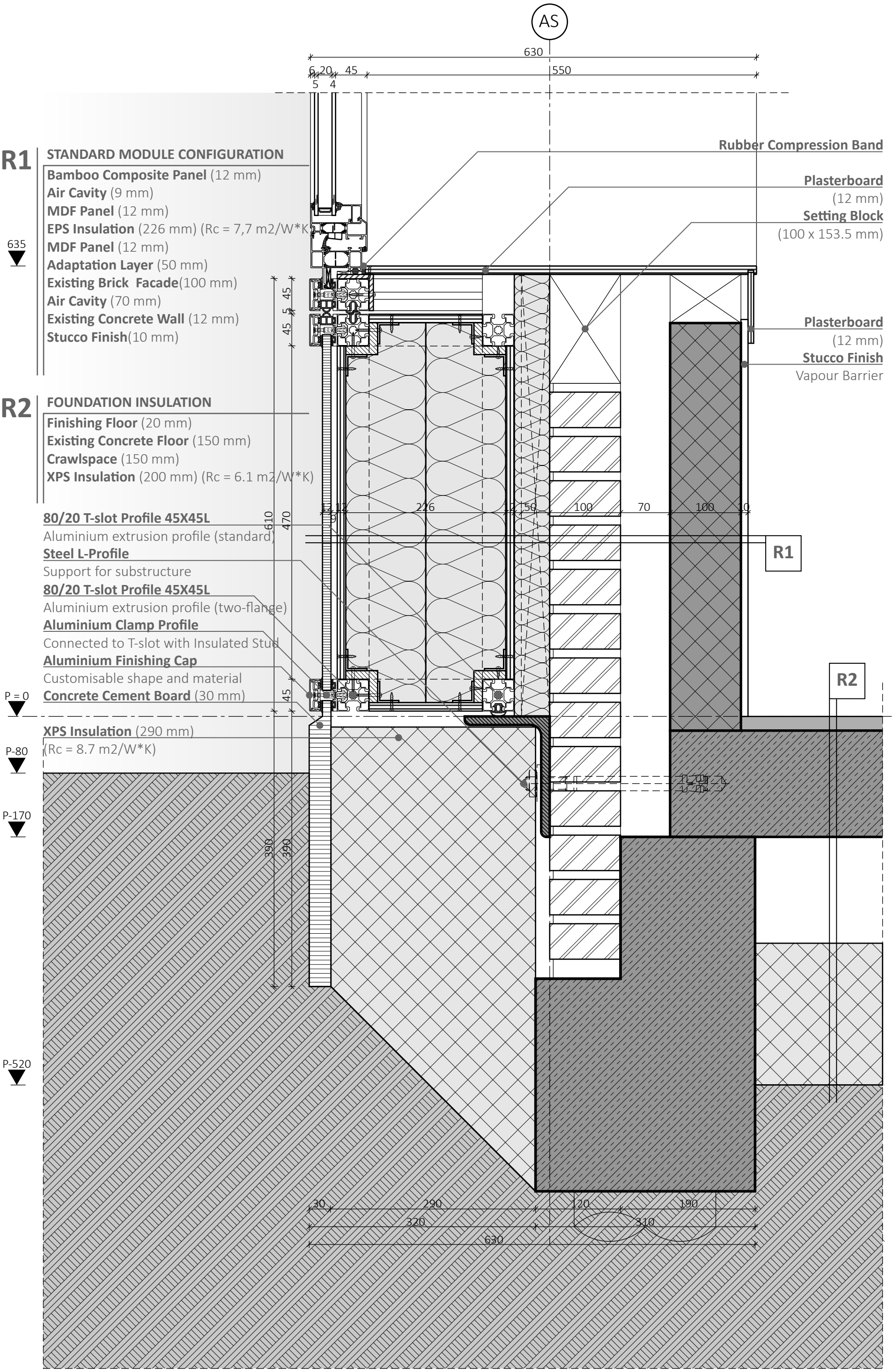


Fig. 9.2.10: *Detail | 1:10 | Vertical | Floor Connection (own illustration).*

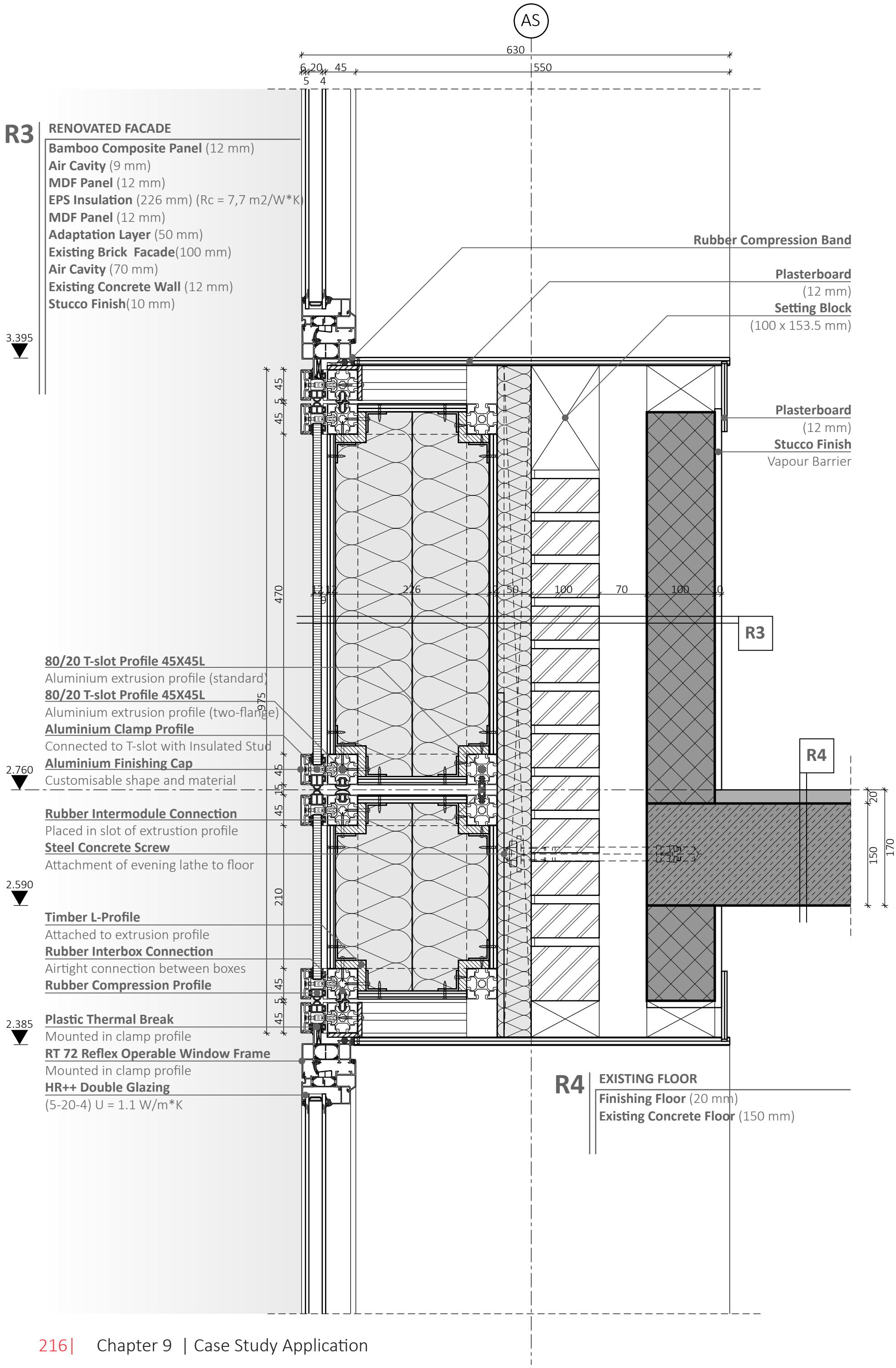
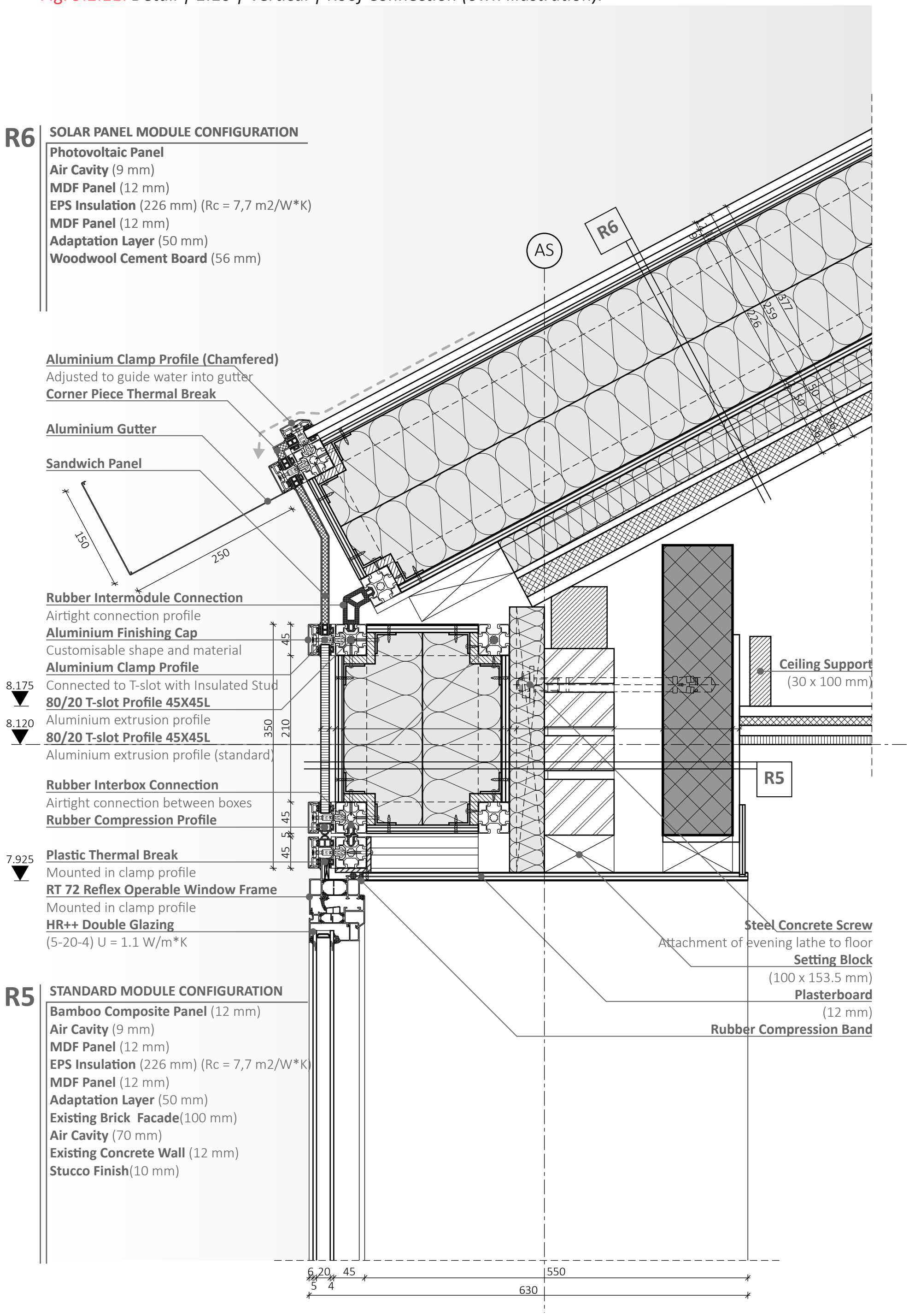


Fig. 9.2.11: *Detail | 1:10 | Vertical | Roof Connection (own illustration).*



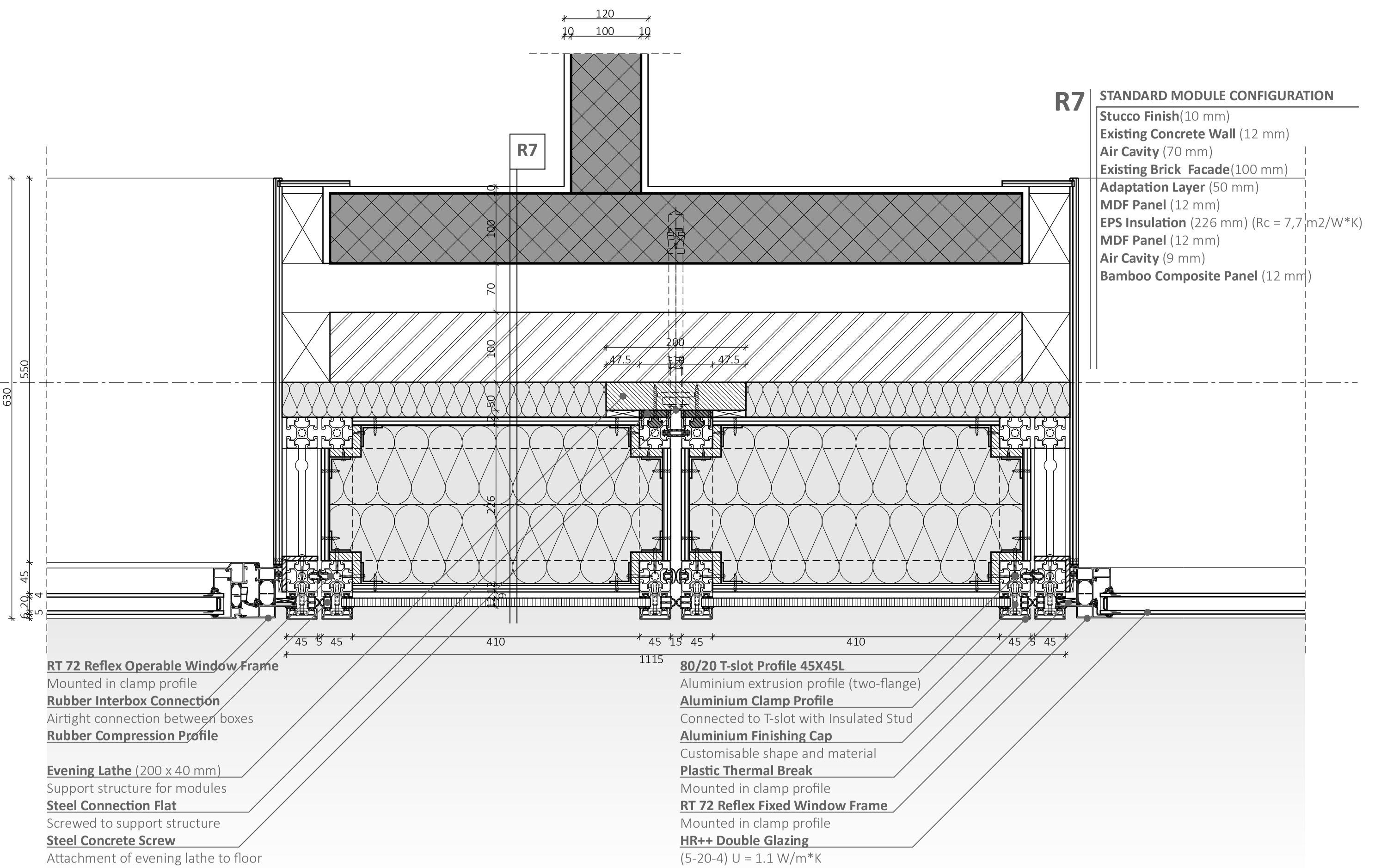


Fig. 9.2.12: *Detail | 1:10 | Horizontal | Module Connection (own illustration).*

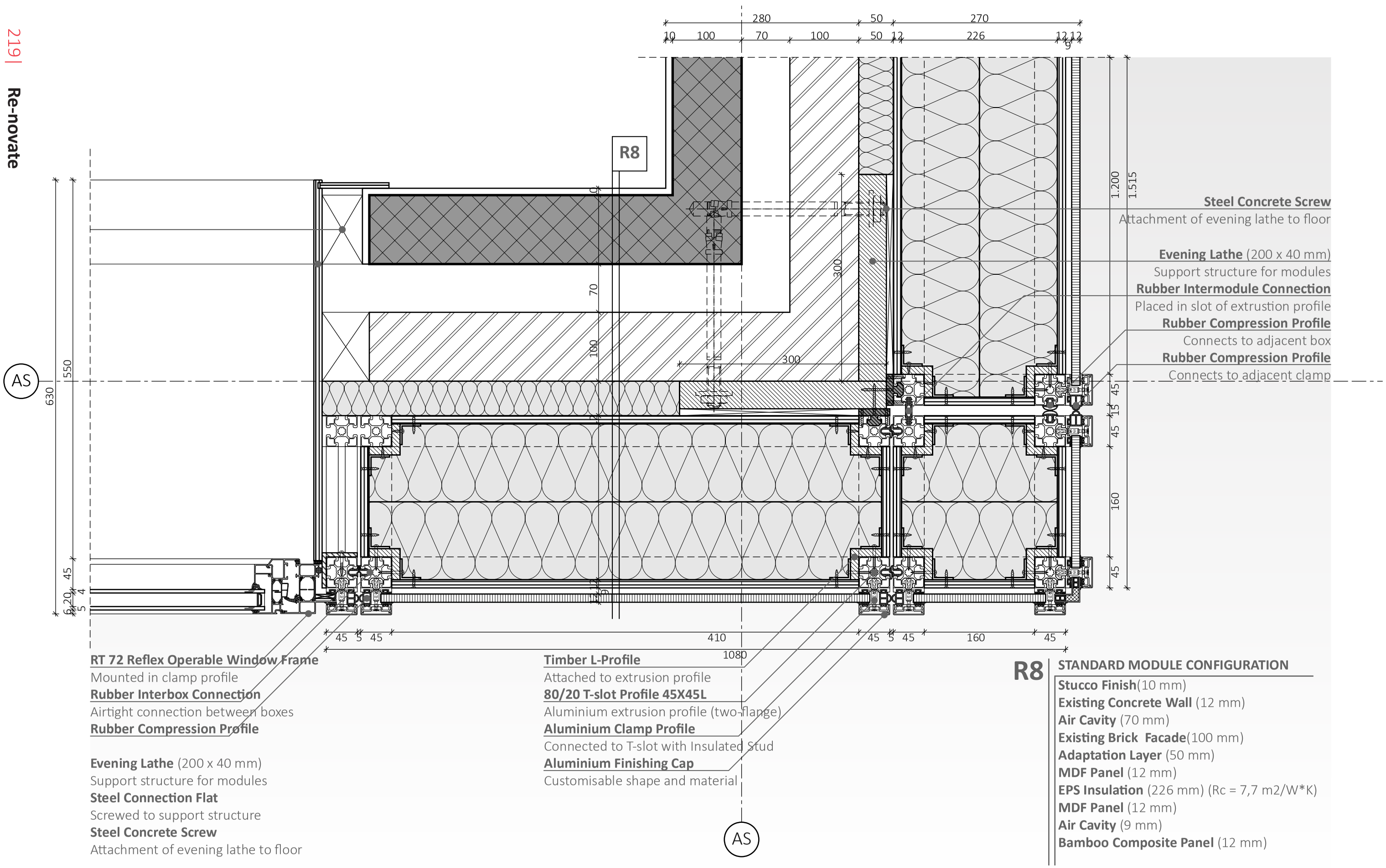
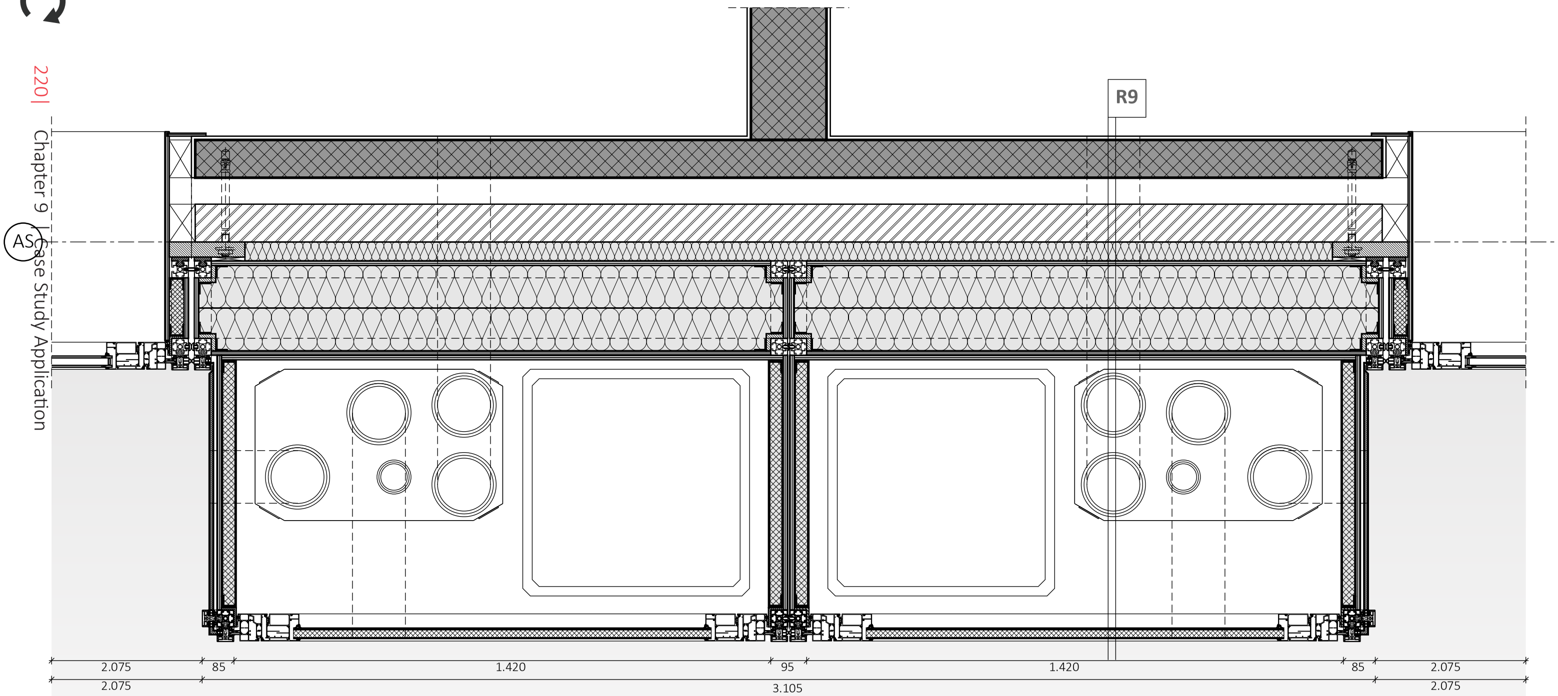


Fig. 9.2.13: *Detail | 1:10 | Horizontal | Corner Connection (own illus9tration).*



R9 **INSTALLATIONS MODULE CONFIGURATION**

Stucco Finish(10 mm)
Existing Concrete Wall (12 mm)
Air Cavity (70 mm)
Existing Brick Facade(100 mm)
Adaptation Layer (50 mm)
MDF Panel (12 mm)
EPS Insulation (226 mm) (Rc = 7,7 m2/W*K)
MDF Panel (12 mm)
MDF Panel (12 mm)
Installation Space (710 mm)
Integrated RT 72 Reflex Door (29 mm)

Fig. 9.2.14: *Detail | 1:20 | Horizontal | Installation Boxes (own illustration).*

§ 9.3 Starting Scenarios

In order to evaluate the designed façade system's resilience through the years, two scenarios are constructed which require specific adjustments to the building envelope system. Every scenario requires a specific reason, which are described in paragraph 7.2.3, which leads to an action and potential component change, which are described in paragraph 8.1. Two starting points for the series of scenarios are constructed which are based on the 2ndSkin project, as well as the preferred renovation path according to the BPIE, described in paragraph 4.8, which utilises the 'learning curve'. The main scenarios follow a timeline from construction around 2020 until 2060, when the building envelope is dismantled or a new cycle of renovations is introduced.

The specific scenarios are based on scenarios that are most likely to happen in a specific timespan, such as exceeding of service life of a material, as well as on possible incidental scenarios, such as severe damage to individual components. The goal of the exercise is not to predict the exact lifecycle of the scenarios, but to prepare for what might transpire.

§ 9.3.1 *2ndSkin Starting Scenario*

The first scenario copies the set of measures utilised in the 2ndskin demonstrator project and portrayed in the case study application to achieve a nZEB level of renovation from the start of the life cycle. The utilised measures consist of adding insulation, replacing the windows, installing the centralised heat pump, installing a decentralised heat exchanger for every apartment, solar control integrated in the windows, adding photovoltaic panels on the roof and removing thermal bridges. The steps applied to this starting scenario are steps that maintain the level of energy reduction through repair and replacement, keeping the functioning principles of the building installations the same through its life cycle.

In the top of figure 9.3.1 the suggested timeline is portrayed. The timeline is divided into three timeslots, excluding the first time slot which indicates the construction period, in which measures can take place. During the first time slot it is likely that the heat pump will be required to be replaced the first, due to its relatively low service life of 15 years (Itho Daalderop, 2018) and potential technologic upgrades. The heat exchanger is expected to last longer due to the easy replacement of filters, stalling the replacement till the second timeslot. The third slot will require the most actions, with the cladding, insulation and PV panel all exceeding their service life, as well as updating the aesthetic of the building to modern standards. It is beneficial to combine actions which require the most labour at the same time to reduce costs allocated to preparing the building site and labour.

§ 9.3.2 ***BPIE Starting Scenario***

The BPIE's preferred starting scenario utilises the 'learning curve' to gradually update renovation projects to nZEB or even ZEB levels, to keep the total investments costs at the lowest possible level while still attaining the goals set by the European Union for 2050. The scenario starts off the essential basic measures to mimimise the initial investment costs. The measures consist of adding insulation, replacing the windows and removing thermal bridges. In later stages the façade system will be upgraded with solar control, photovoltaics on the roof, a ventilation concept and optional experimental solutions, such as solar combs. The scenario mostly involves replacement of components with new components and changing the functioning principles of the building installations through its life cycle.

In the bottom of figure 9.3.1 the suggested timeline for the BPIE starting scenario is portrayed. In the first time slot installing the solar control would be one of the first actions to complete. Furthermore, a ventilation concept can be chosen to further reduce the energy consumption, the timeline suggests three different approaches that are based on the considered ventilation concepts for the 2ndSkin demonstrator project: Decentralised mechanical ventilation, centralised mechanical ventilation, decentralised mechanical outlet and natural ventilation inlet, and a options for full natural ventilation.

During the second time slot the roof cladding and the exterior façade cladding are replaced with PV panels and solar comb boxes to further reduce the energy consumption and establish energy production. This combination of actions should bring the buildings energy consumption to ZEB or even energy positive levels. During the third timeslot maintenance actions should take place potentially replacing windows and insulation if necessary.

Number	Affected Areas	Described in	Reason(s)
1	Systems, Infill, Aesthetic	§ 9.2	Package of measures utilised in the 2ndSkin project.
2	Infill	§ 9.4.1	Option to be upgraded in the future.
3	Systems	§ 9.4.2	Exceeded service life, technology upgrade.
4	Systems, Infill	§ 9.4.3	Exceeded service life, technology upgrade.
5	Systems, Infill	§ 9.4.4	Different user, stricter regulations.
6	Systems, Infill	§ 9.4.5	Different user, stricter regulations.
7	Systems	§ 9.4.6	Different user, stricter regulations.
8	Aesthetic	§ 9.4.7	Technology upgrade, different user, stricter regulations.
9	Aesthetic	§ 9.4.8	Exceeded service life, technology upgrade, appearance update.
10	Infill, Aestethic	§ 9.4.9	Technology upgrade, appearance update, stricter regulations, differ-ent use.
11	Aesthetic	§ 9.5	Appearance update, exceeded service life, fashion.

Fig. 9.3.1: *Affected area for every step of the scenario and the reasons for change.*

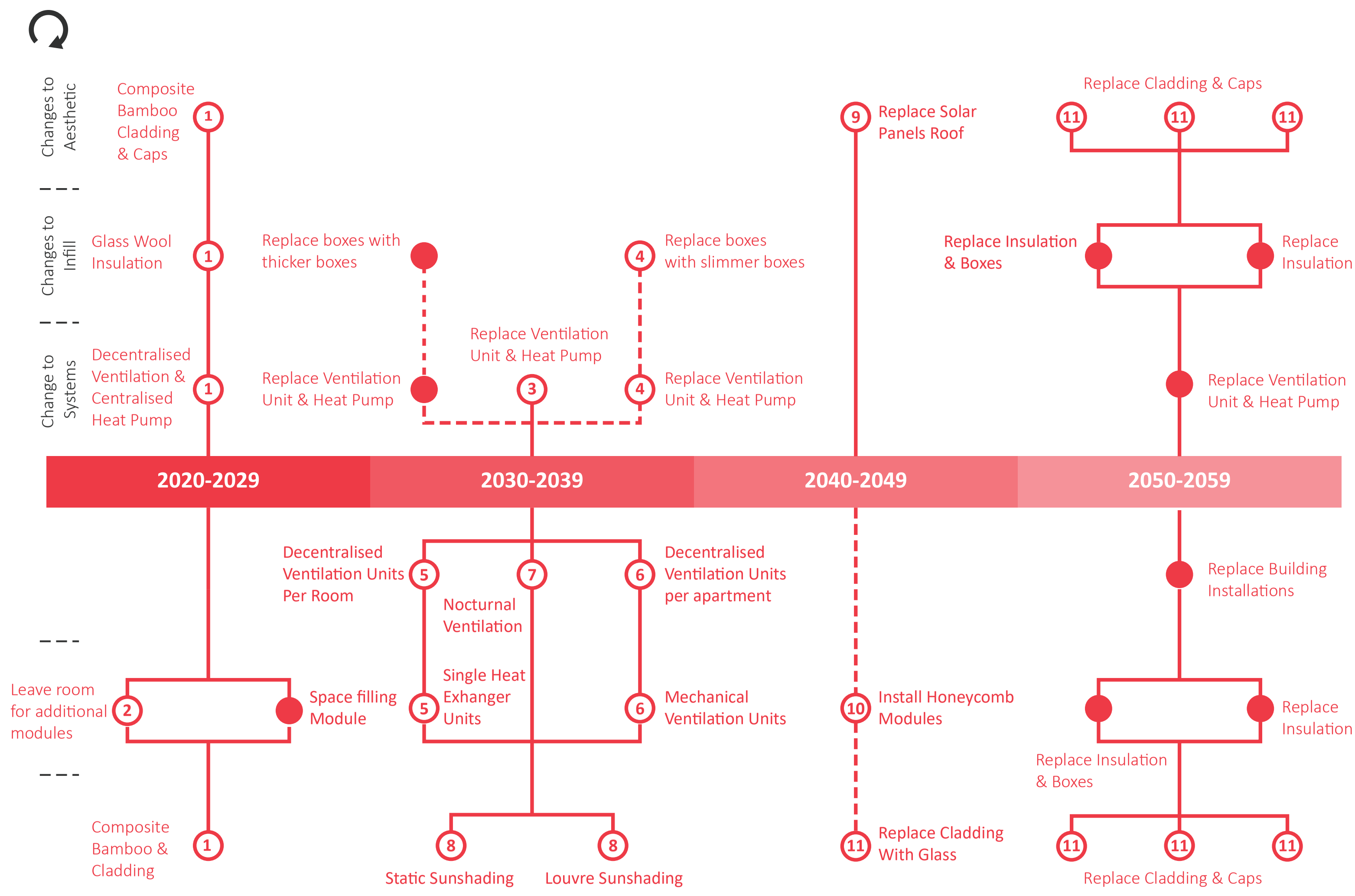


Fig. 9.3.2: *Timeline constructed according to the described scenarios, in the top the 2ndSkin scenerio, in the bottom the BPIE scenario (own illustration).*

§ 9.4.1 *Placeholder Frame*

As an alternate starting point for the life cycle of the BPIE scenario it is possible to use slimmer boxes in combination with an additional empty frame. The empty frame function as a stiffener of the façade construction, connection point for the clamp profiles, as well as a placeholder for boxes implemented at a later stage. When it is required the clamp profile can be demounted and the placeholder frame replaced with a box with additional functionality or additional thermal insulation.

The installation of the insulating box as well as the placeholder frame follows the same procedure. First the insulating box is slid into the main frame and fastened and subsequently the placeholder frame is slid in and fastened, the construction is finalised with the clamp profile.

In the included detail appendix on page 13, the described variant is illustrated. In figure 9.4.1 the components are illustrated.

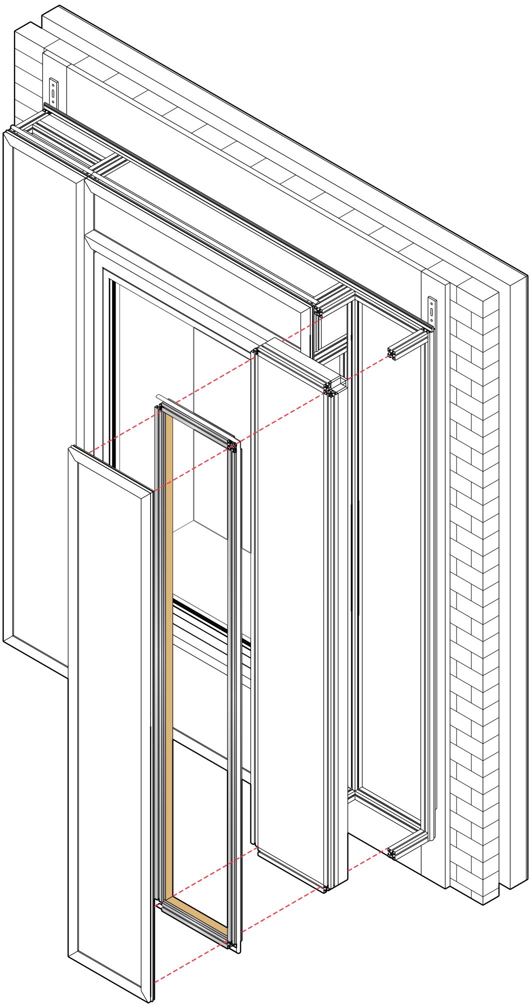


Fig. 9.4.1.1: *One insulation box is slid in and fastened first, the placeholder frame is then placed to fill the remaining space (own illustration).*

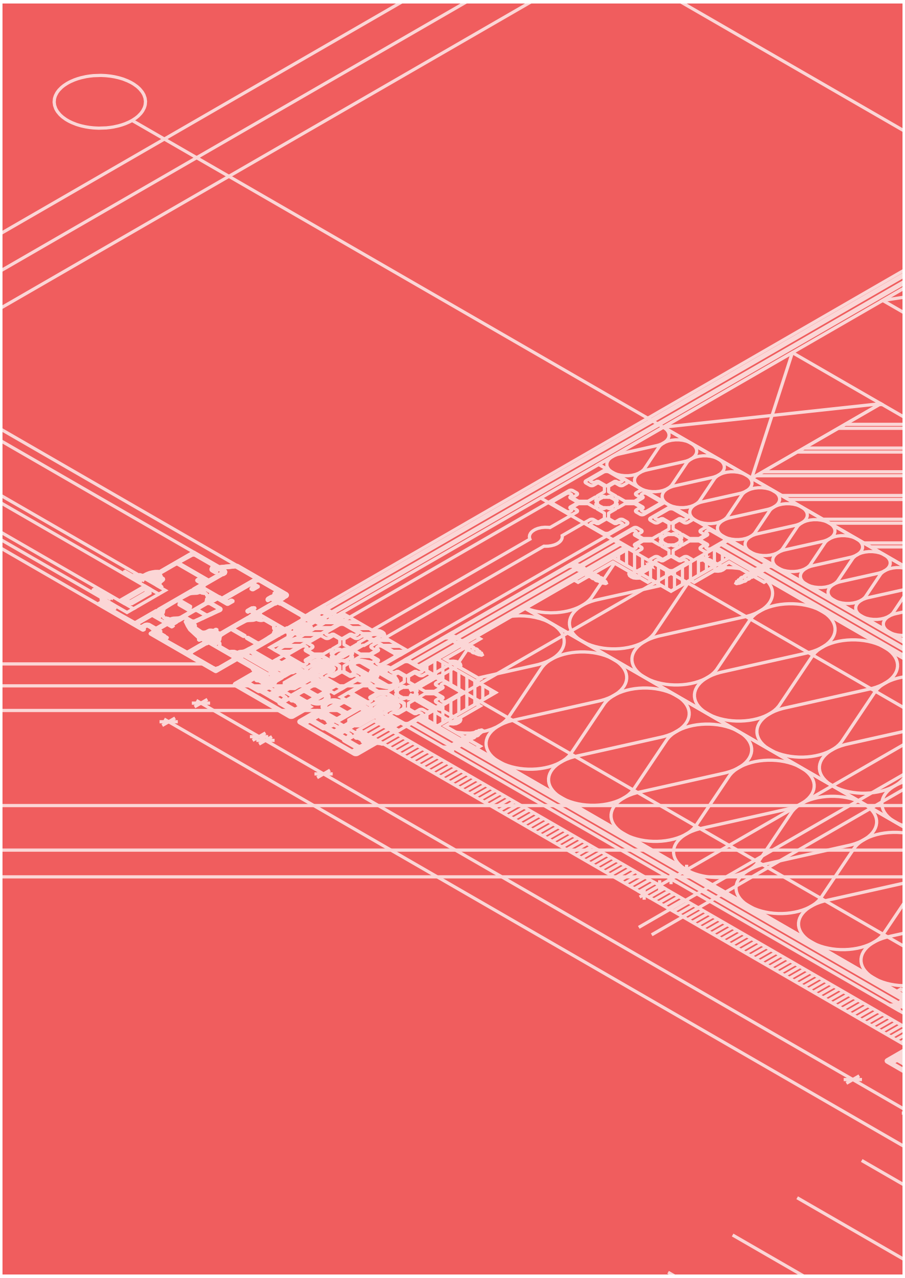
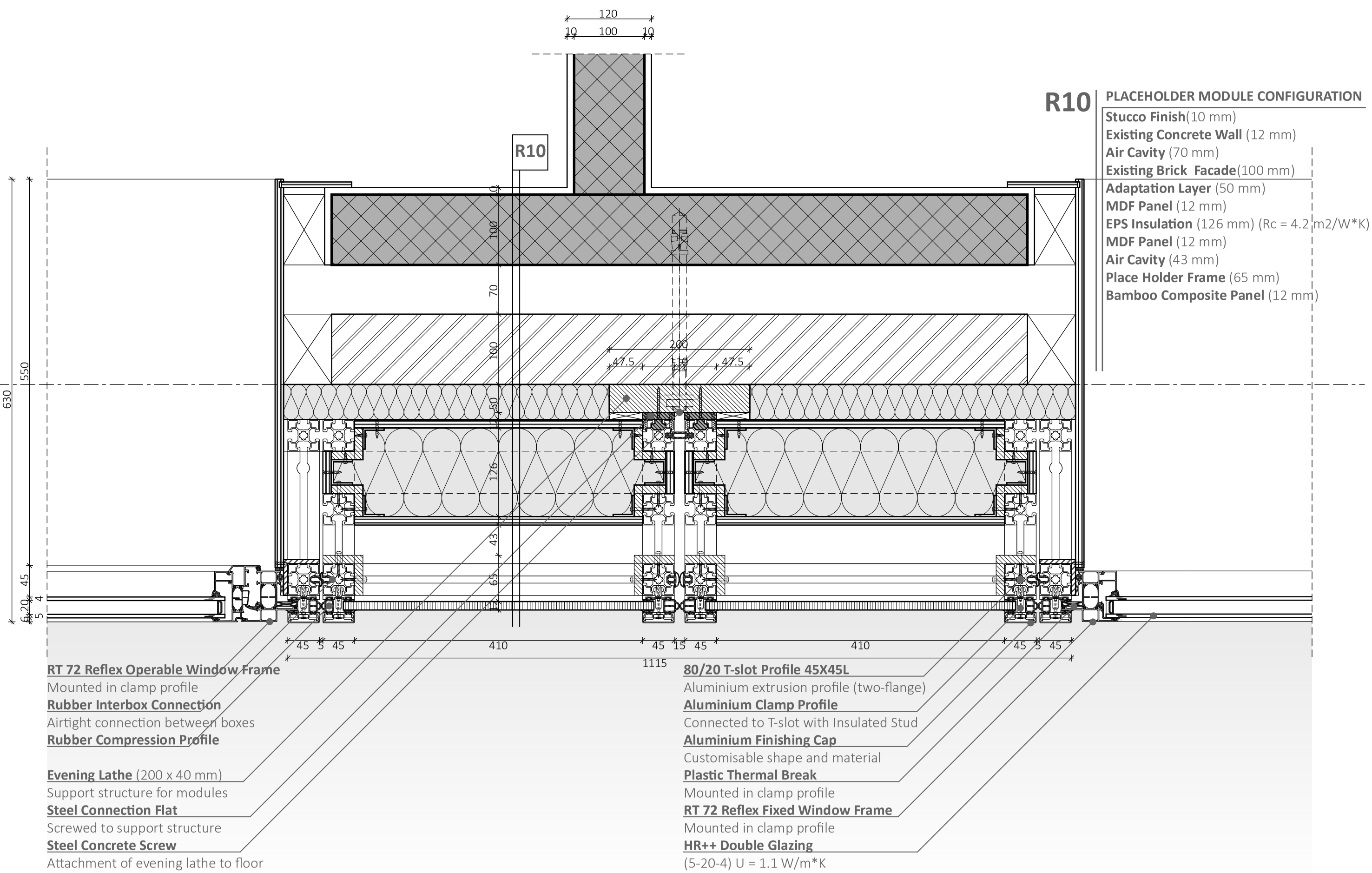


Fig. 9.4.1.2: *(Right) Detail | 1:10 | Horizontal | Placeholder Frame (own illustration).*


R10
PLACEHOLDER MODULE CONFIGURATION
Stucco Finish(10 mm)
Existing Concrete Wall (12 mm)
Air Cavity (70 mm)
Existing Brick Facade(100 mm)
Adaptation Layer (50 mm)
MDF Panel (12 mm)
EPS Insulation (126 mm) (Rc = 4.2 m2/W*K)
MDF Panel (12 mm)
Air Cavity (43 mm)
Place Holder Frame (65 mm)
Bamboo Composite Panel (12 mm)
RT 72 Reflex Operable Window Frame
Mounted in clamp profile
Rubber Interbox Connection
Airtight connection between boxes
Rubber Compression Profile
Evening Lathe (200 x 40 mm)
Support structure for modules
Steel Connection Flat
Screwed to support structure
Steel Concrete Screw
Attachment of evening lathe to floor
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (two-flange)
Aluminium Clamp Profile
Connected to T-slot with Insulated Stud
Aluminium Finishing Cap
Customisable shape and material
Plastic Thermal Break
Mounted in clamp profile
RT 72 Reflex Fixed Window Frame
Mounted in clamp profile
HR++ Double Glazing
(5-20-4) U = 1.1 W/m*K
120
10 100 10
200
47.5 110 47.5
45 5 45 410 45 15 45 410 45 5 45
1115
630
550
AS

§ 9.4.2 *Centralised Heat Pump and Decentralised Heat Exchanger*

This heating and ventilation concept is based on the principles utilised in the 2ndSkin demonstrator project and described in paragraph 6.8. The installation box is located in the same location but rotated 90 degrees. The installation box is accessible via the balconies. Due to the sizing and weight of the installation box, the box requires a separate foundation to support it. Installation of the box involves a similar process as other module boxes, by sliding it in the main frame and fastening it. The box is finished with a clamping profile and an integrated door. Holes for the piping have to be predrilled before the installation in the existing facade. The heat pump and the heat exchanger inside the box can be separately replaced if necessary or the complete box can be removed if smaller alternatives arise in the future. The box is removed and the beams of the main frame can be demounted and replaced with shorter T-slots to accompany the new required depth. The panels located in the interior of the box are outfitted with sandwich panels to ensure the box is properly insulated. Furthermore, the exterior of the of the box is outfitted with a sandwich panel to ensure an airtight connection with the adjacent slimmer module.

On page 14 a horizontal section of the installation box is portrayed on scale 1 to 10 and 1 to 5. The location of the installation boxes is portrayed in figure 9.4.2.3. In the appendix on page 299 further elaboration on sound insulation is given.

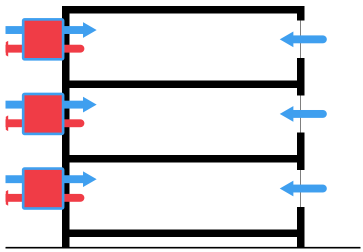


Fig. 9.4.2.1: *Decentralised Heat Recovery in installation box (Boess, et al., 2017).*

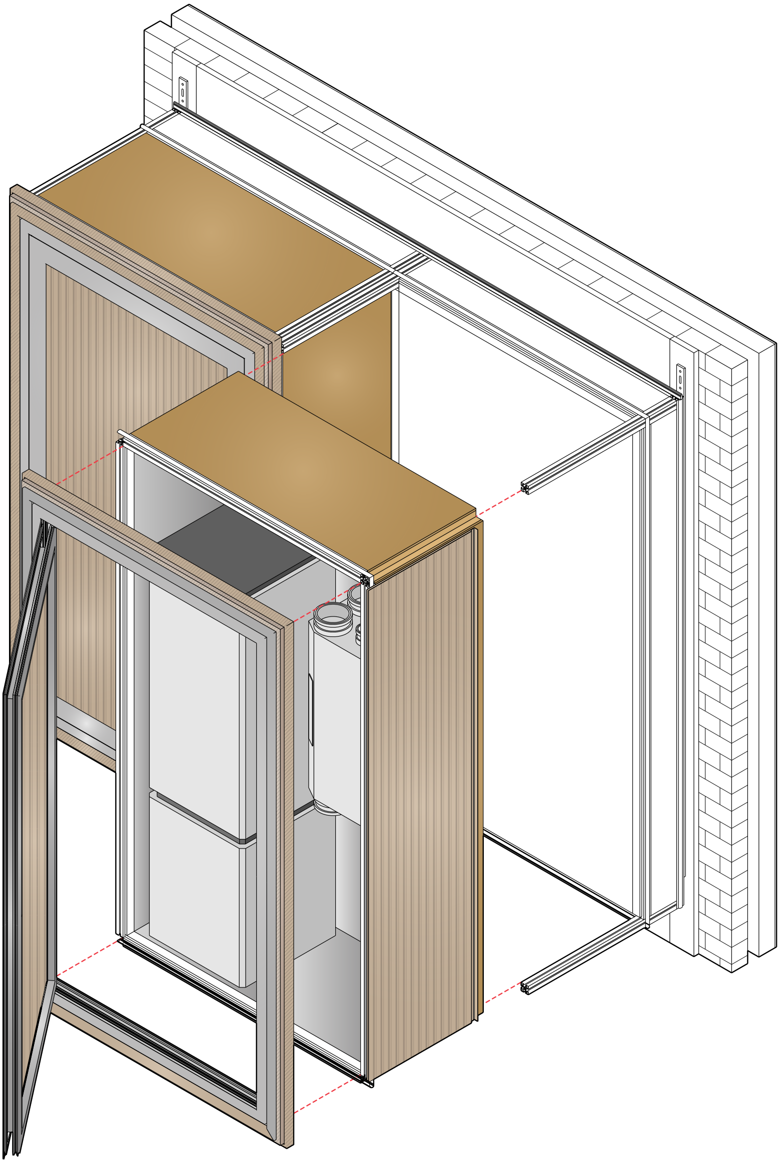
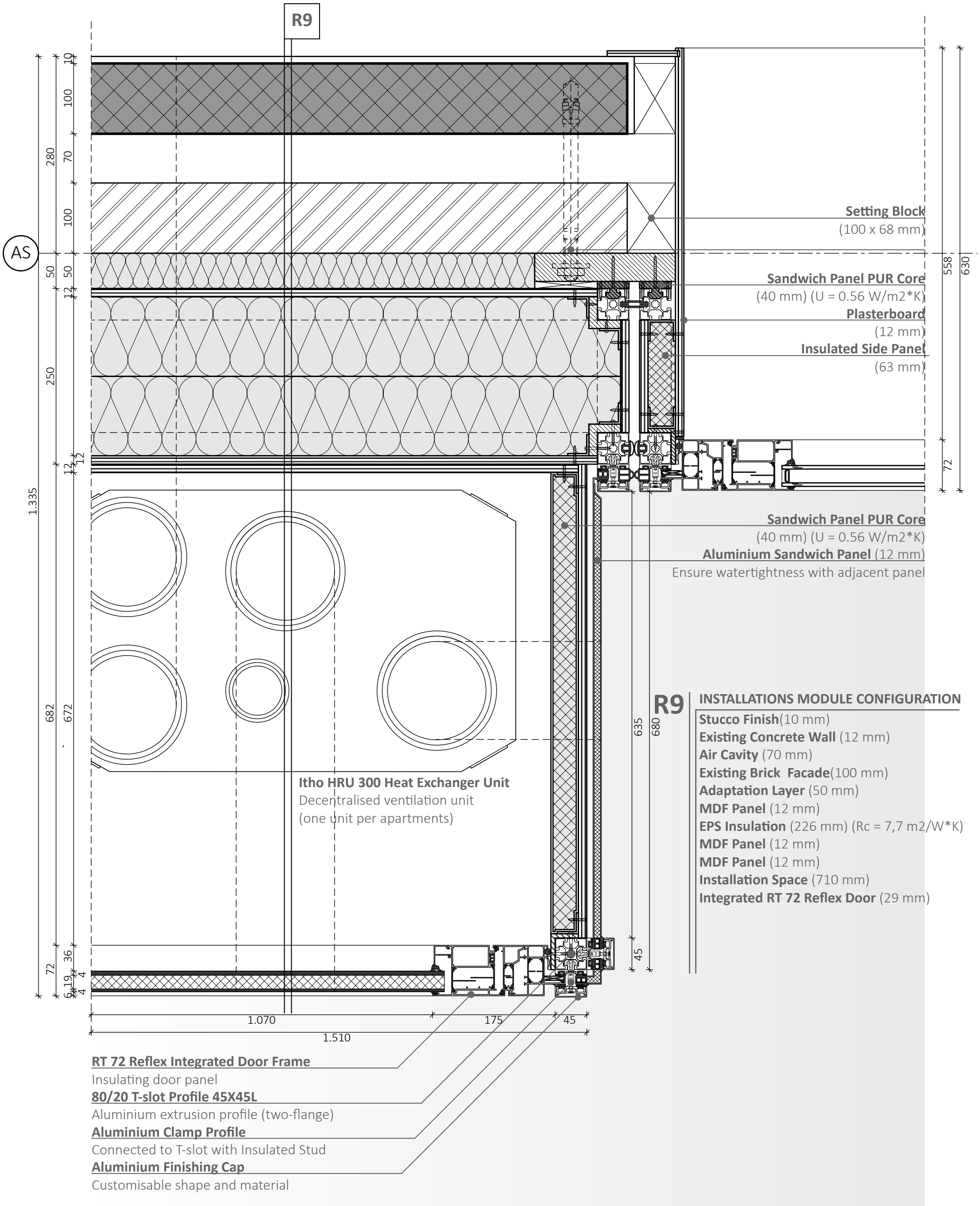


Fig. 9.4.2.2: *The installation box utilises the same principles for application as conventional boxes, an additional sandwich panel is utilised to ensure the airtightness between adjacent modules (own illustration).*

Fig. 9.4.2.3: *(Top) The south and west facade could be used as potential alternative location for the installation box (own illustration).*
Fig. 9.4.2.4: *(Right) Detail | 1:10 | Horizontal | Installation Box (own illustration).*


R9
AS
Setting Block
(100 x 68 mm)
Sandwich Panel PUR Core
(40 mm) (U = 0.56 W/m2*K)
Plasterboard
(12 mm)
Insulated Side Panel
(63 mm)
Sandwich Panel PUR Core
(40 mm) (U = 0.56 W/m2*K)
Aluminium Sandwich Panel (12 mm)
Ensure watertightness with adjacent panel
Itho HRU 300 Heat Exchanger Unit
Decentralised ventilation unit
(one unit per apartments)
R9
INSTALLATIONS MODULE CONFIGURATION
Stucco Finish(10 mm)
Existing Concrete Wall (12 mm)
Air Cavity (70 mm)
Existing Brick Facade(100 mm)
Adaptation Layer (50 mm)
MDF Panel (12 mm)
EPS Insulation (226 mm) (Rc = 7,7 m2/W*K)
MDF Panel (12 mm)
MDF Panel (12 mm)
Installation Space (710 mm)
Integrated RT 72 Reflex Door (29 mm)
1.070
175
45
1.510
RT 72 Reflex Integrated Door Frame
Insulating door panel
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (two-flange)
Aluminium Clamp Profile
Connected to T-slot with Insulated Stud
Aluminium Finishing Cap
Customisable shape and material

§ 9.4.3 *Centralised Ventilation Unit*

The second ventilation concept based on the ventilation concepts considered for the 2ndSkin demonstrator project utilises a single ventilation unit per three apartments located in the attic. Exhaust air is suctioned from the interior to the exterior via the roof. Inlet air is suctioned from the roof and distributed via piping integrated in the building envelope and enters the rooms via ventilation inlets. This ventilation concept requires extensive interior work due to the construction of piping networks, which could discourage its implementation at a later stage. The implementation could be combined with additional measures to justify the work required.

The implementation of boxes with piping follows a similar procedure as other boxes. The clamp is demounted and the insulating box is removed to be replaced with a box with integrated piping. If the individual pipes are small in diameter and placed in a thinner module the piping box could potentially replace the placeholder frame, which would results in the original insulating box being left intact. It is dependent on the original frame depth and required ventilation rate if this option is viable. Also, pipes smaller in diameter could potentially lead to disturbing sound due to draft. The piping is connected to the interior via the interior lining. It is however also possible to connect the piping to the interior by drilling a hole through the existing wall, if drilling in the internal lining is not an option.

In the included detail appendix on page 15 a possible integration of the piping in the box is demonstrated. Three pipes are vertically integrated into one module, one for every floor. The piping diameter is a standard 80 mm utilised in the 2ndSkin mock-up, as well as conventional renovation projects (Dubois, et al., 2016).

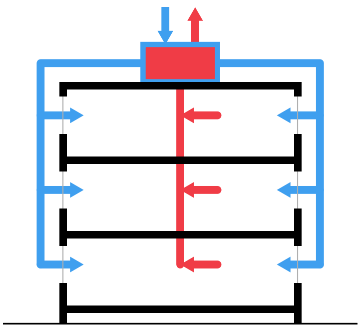


Fig. 9.4.3.1: *Centralised Heat Recovery, inlet air is provided through the ducts integrated in the facade panel (Boess, et al., 2017).*

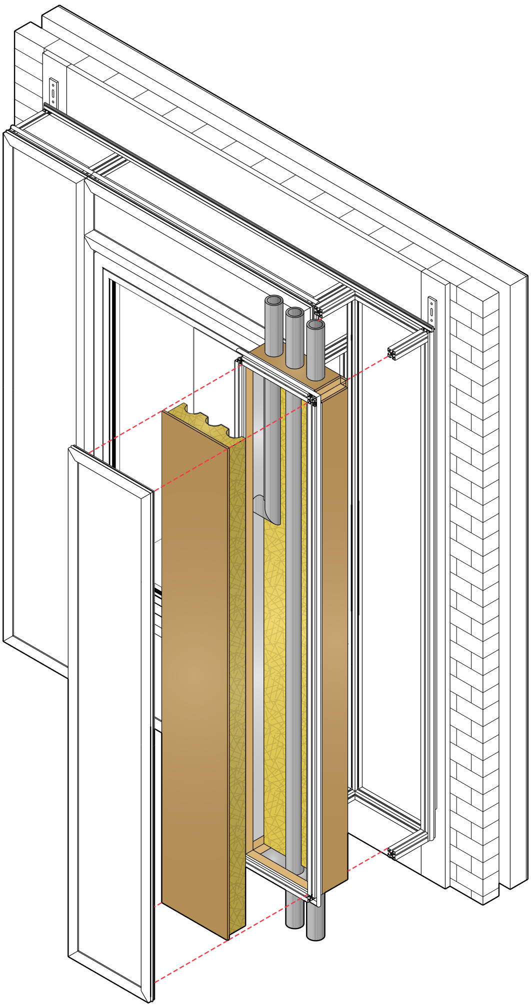
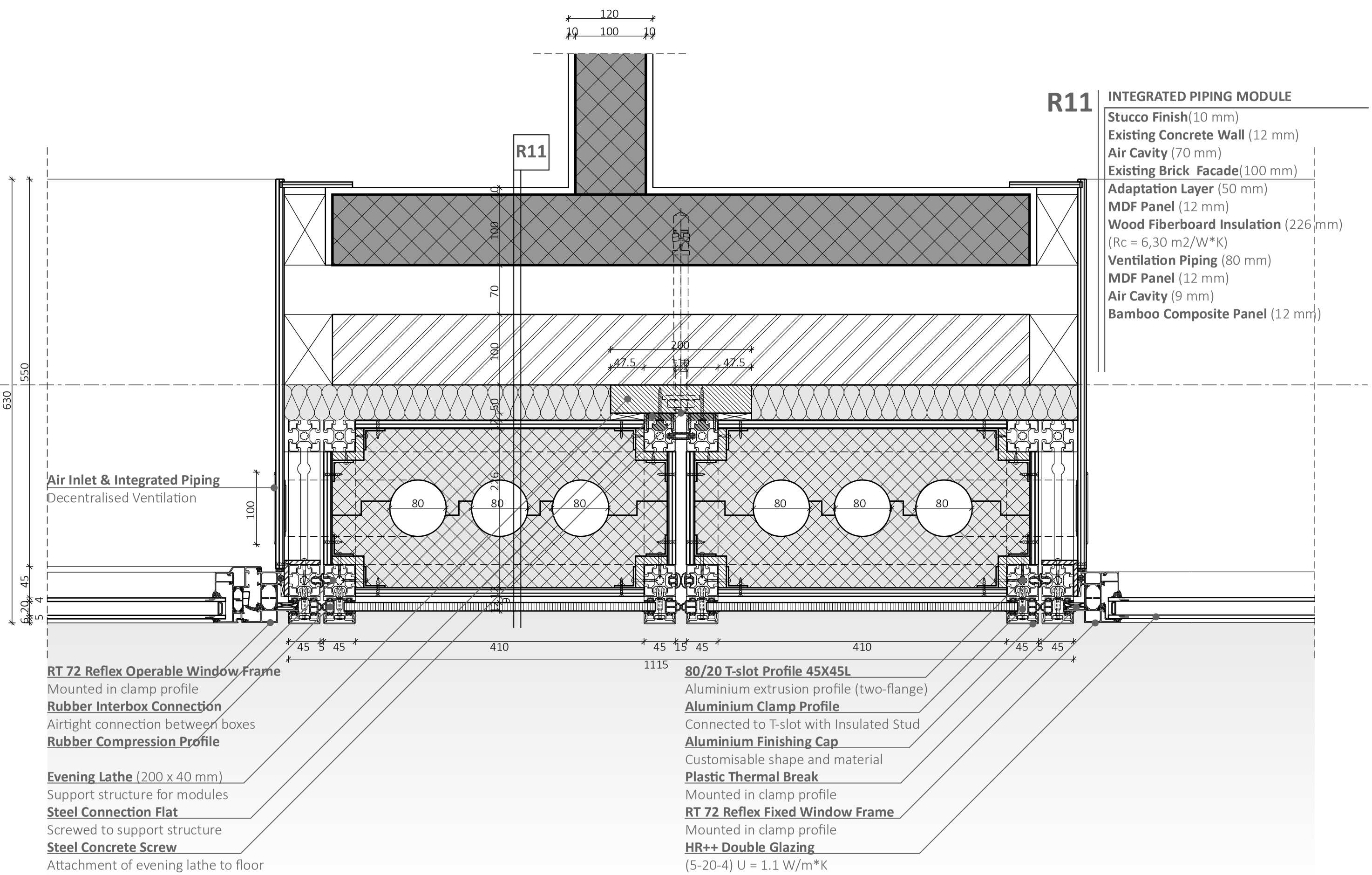


Fig. 9.4.3.2: *Piping is integrated in the box and encapsuled in insulation, the piping enters the dwelling through a hole in the internal lining (own illustration).*

Fig. 9.4.3.3: *(Top) Possible location boxes with integrated piping (own illustration).*
Fig. 9.4.3.4: *(Right) Detail | 1-10 | Horizontal | Integrated Piping (own illustration).*


R11
INTEGRATED PIPING MODULE
Stucco Finish(10 mm)
Existing Concrete Wall (12 mm)
Air Cavity (70 mm)
Existing Brick Facade(100 mm)
Adaptation Layer (50 mm)
MDF Panel (12 mm)
Wood Fiberboard Insulation (226 mm)
(Rc = 6,30 m2/W*K)
Ventilation Piping (80 mm)
MDF Panel (12 mm)
Air Cavity (9 mm)
Bamboo Composite Panel (12 mm)
Air Inlet & Integrated Piping
Decentralised Ventilation
RT 72 Reflex Operable Window Frame
Mounted in clamp profile
Rubber Interbox Connection
Airtight connection between boxes
Rubber Compression Profile
Evening Lathe (200 x 40 mm)
Support structure for modules
Steel Connection Flat
Screwed to support structure
Steel Concrete Screw
Attachment of evening lathe to floor
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (two-flange)
Aluminium Clamp Profile
Connected to T-slot with Insulated Stud
Aluminium Finishing Cap
Customisable shape and material
Plastic Thermal Break
Mounted in clamp profile
RT 72 Reflex Fixed Window Frame
Mounted in clamp profile
HR++ Double Glazing
(5-20-4) U = 1.1 W/m*K

§ 9.4.4 *Decentralised Ventilation Units per Room*

The third ventilation concept based on the ventilation concept considered for the 2ndSkin demonstrator project utilises decentralised ventilation units per separate room. The concept was not chosen for the chosen for the demonstrator project due to limited proof for its effectiveness in zero-energy dwellings. Due to this fact it can be preferred to install it a later stage when more proven products have been produced.

To implement this ventilation concept at a later stage is relatively easily compared to other ventilation strategies. In figure 9.4.4.2, the components necessary are illustrated. The horizontal boxes above windows can be removed and replaced with prefabricated boxes with smaller heat exchanger units. In order to finish the upgrade, the cladding panels can be replaced with panels with pre-cut holes for the ventilation outlet and a manual cut hole on the interior in the internal lining for the inlet. Alternatively, the original cladding panel can be outfitted with a manual cut hole on-site. Furthermore, it also possible to cut a hole directly through the existing wall to guide the incoming air along the ceiling to eliminate draft problems. The downside is that it increases the required labour.

In the included detail appendix on page 16, the described variant is illustrated in more detail. In figure 9.4.4.3 the possible boxes to be replaced are illustrated. The suggested panels are possible locations and number of heat exchanger units can be changed according to the ventilation requirement.

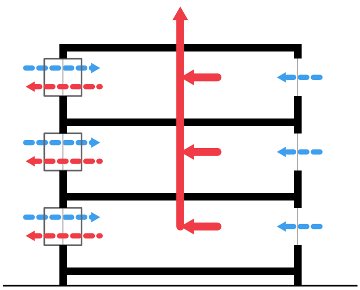


Fig. 9.4.4.1: *Decentralised Ventilation units per room (Boess, et al., 2017).*

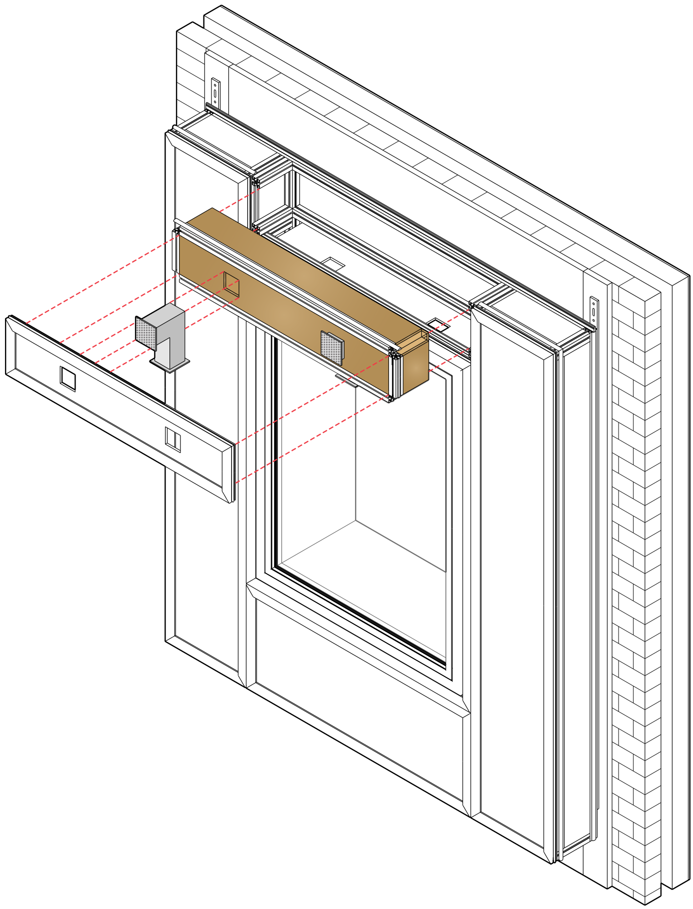
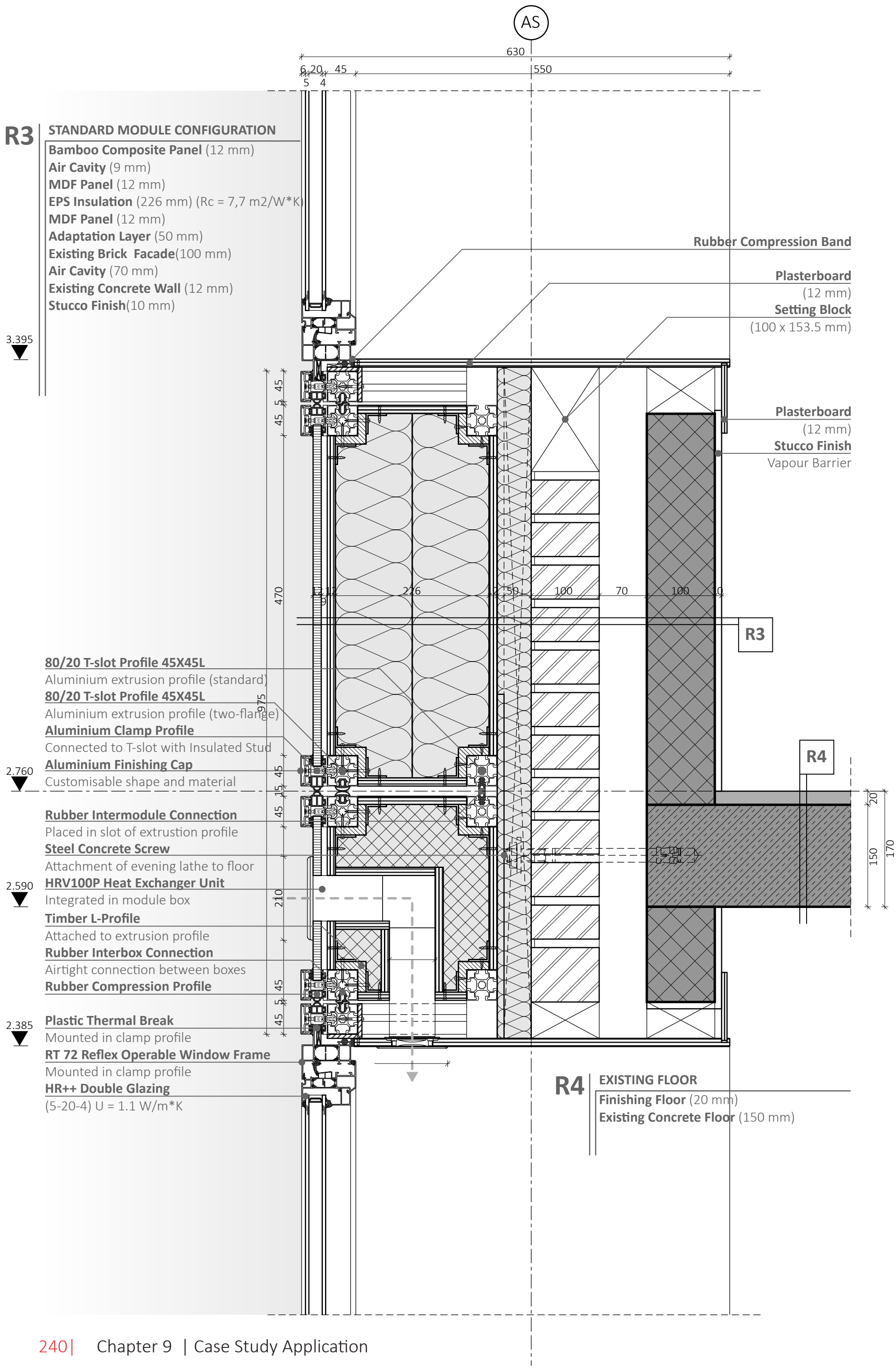


Fig. 9.4.4.2: *The single heat exhanger unit are integrated in the box and are connected to the interior via a hole in the internal lining, amount of units depends on required ventilation rate (own illustration).*

Fig. 9.4.4.3: *(Top) Possible location single heat exchanger units (own illustration).*
Fig. 9.4.4.4: *(Right) Detail | 1-10 | Vertical | Integrated Single Heat Exchanger Unit (own illustration).*


AS
630
6 20 45
5 4
550
R3
STANDARD MODULE CONFIGURATION
Bamboo Composite Panel (12 mm)
Air Cavity (9 mm)
MDF Panel (12 mm)
EPS Insulation (226 mm) (Rc = 7,7 m2/W*K)
MDF Panel (12 mm)
Adaptation Layer (50 mm)
Existing Brick Facade(100 mm)
Air Cavity (70 mm)
Existing Concrete Wall (12 mm)
Stucco Finish(10 mm)
3.395
Rubber Compression Band
Plasterboard
(12 mm)
Setting Block
(100 x 153.5 mm)
Plasterboard
(12 mm)
Stucco Finish
Vapour Barrier
226
50
100
70
100
470
975
R3
R4
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (standard)
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (two-flange)
Aluminium Clamp Profile
Connected to T-slot with Insulated Stud
Aluminium Finishing Cap
Customisable shape and material
2.760
Rubber Intermodule Connection
Placed in slot of extrusion profile
Steel Concrete Screw
Attachment of evening lathe to floor
2.590
HRV100P Heat Exchanger Unit
Integrated in module box
Timber L-Profile
Attached to extrusion profile
Rubber Interbox Connection
Airtight connection between boxes
Rubber Compression Profile
2.385
Plastic Thermal Break
Mounted in clamp profile
RT 72 Reflex Operable Window Frame
Mounted in clamp profile
HR++ Double Glazing
(5-20-4) U = 1.1 W/m*K
20
150
170
210
R4
EXISTING FLOOR
Finishing Floor (20 mm)
Existing Concrete Floor (150 mm)

§ 9.4.5 ***Mechanical Ventilation Unit per Apartment***

A single mechanical ventilation unit per apartment for the exhaust air in combination with manual natural ventilation is also a viable option for ventilation. The single mechanical unit requires a thicker module or a single thicker box, just as the installation box for the heat pump and heat exchanger described in paragraph 9.4.1. The box walls are outfitted with vacuum insulated sandwich panels to achieve the required thermal resistance. Furthermore, the clamping profile can be outfitted with an ordinary cladding panel with a hole for the exhaust or a door for easier access.

In the detail appendix on page 14 the principle of the installation box described earlier can be used as a reference for the solution of the single ventilation unit. In figure 9.4.5.3 a suggestion for the placement of the box is portrayed.

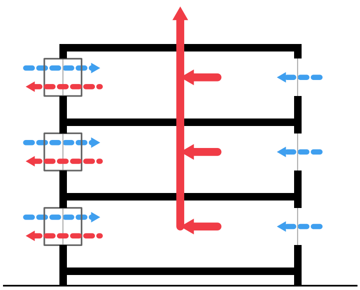


Fig. 9.4.4.1: *Mechanical Exhaust unit to combine with natural ventilation or decentralised heat recovery (Boess, et al., 2017).*

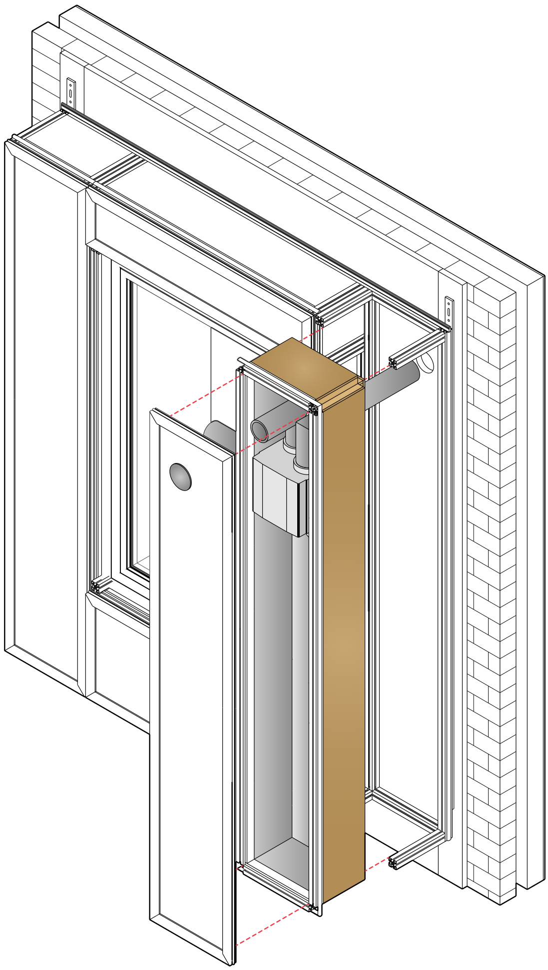
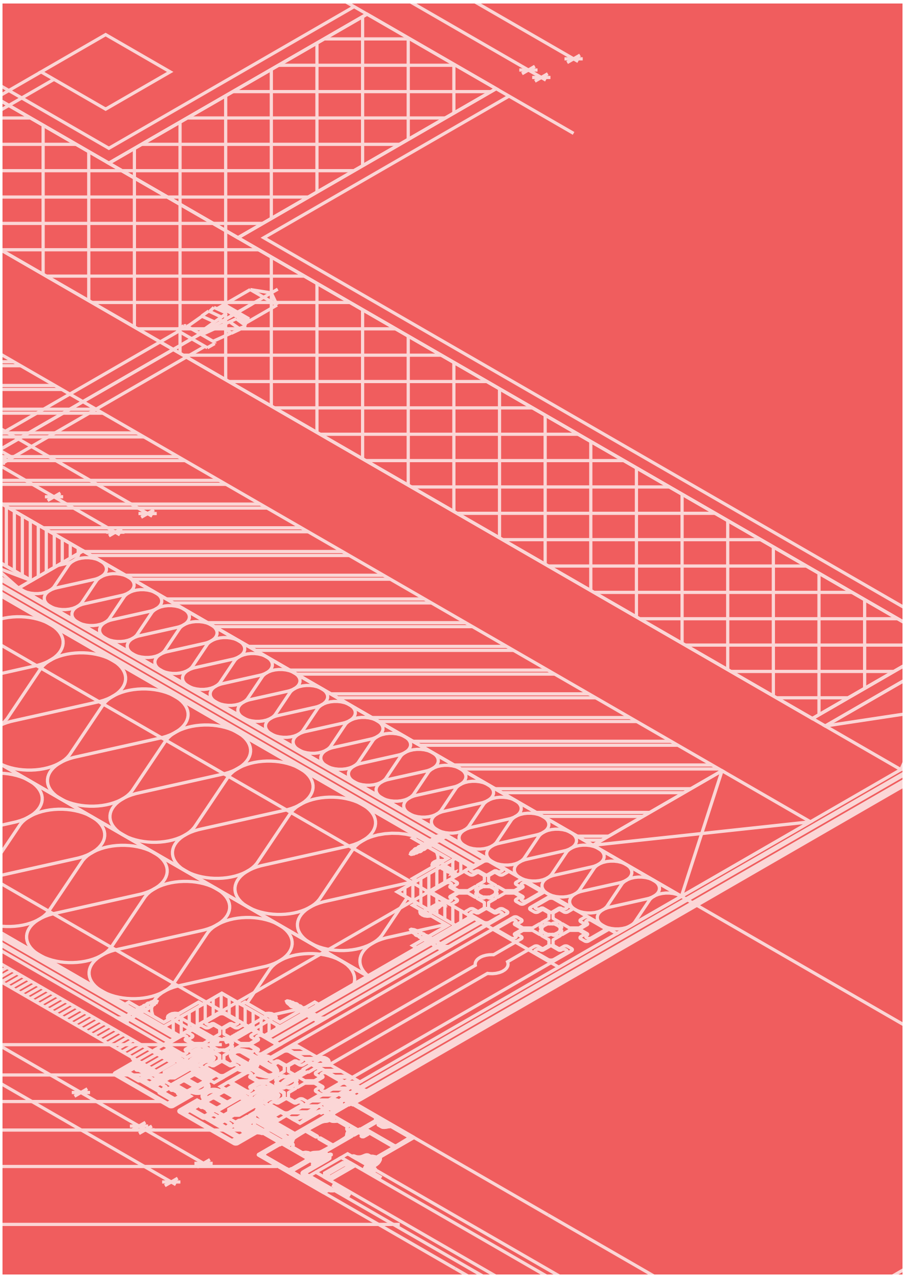


Fig. 9.4.5.2: *The ventilation unit penetrates the existing wall and internal lining to transport internal air to the exterior via the exhaust cap (own illustration).*

Fig. 9.4.5.3: *(Top) Possible locations for the mechanical ventilation unit (own illustration).*



§ 9.4.6 ***Nocturnal Ventilation***

Nocturnal ventilation or night time cooling can be utilised to cool down the building for the next day. The technique can be utilised in conjunction with comfort ventilation in order to minimise the necessity for mechanical ventilation. The ventilation hatch can be prefabricated in a box and installed in a similar fashion as the single ventilation units, utilising the vertical boxes instead of the horizontal. The cladding panel can be replaced with a panel with a slid for the hatch or the original panel can be outfitted manually with a slid on-site. Furthermore, a slid in the internal lining has to be made to connect the hatch with the interior. The connection to the interior can also be made straight through the existing wall.

On page 17 of the detail appendix the integration of nocturnal ventilation is portrayed. Possible location is next to the windows, as portrayed in figure 9.4.6.3.

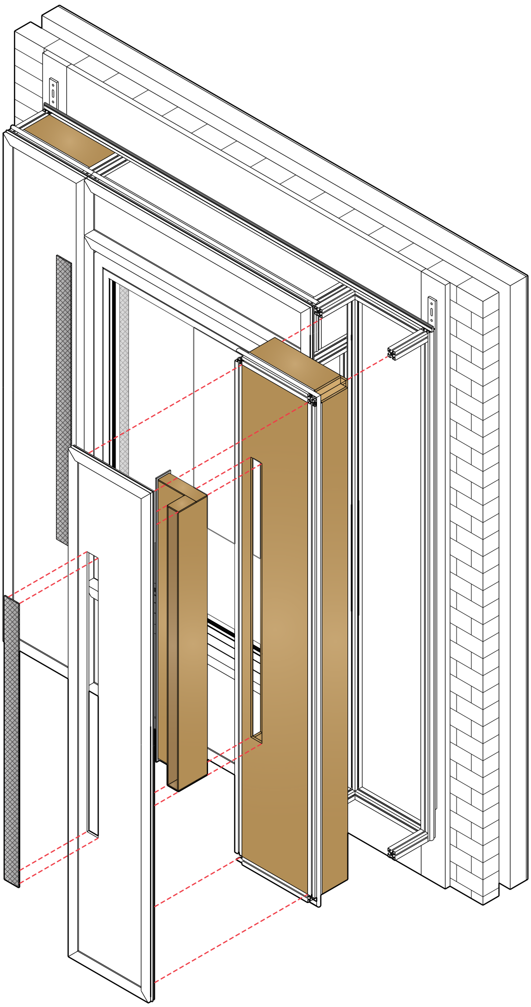
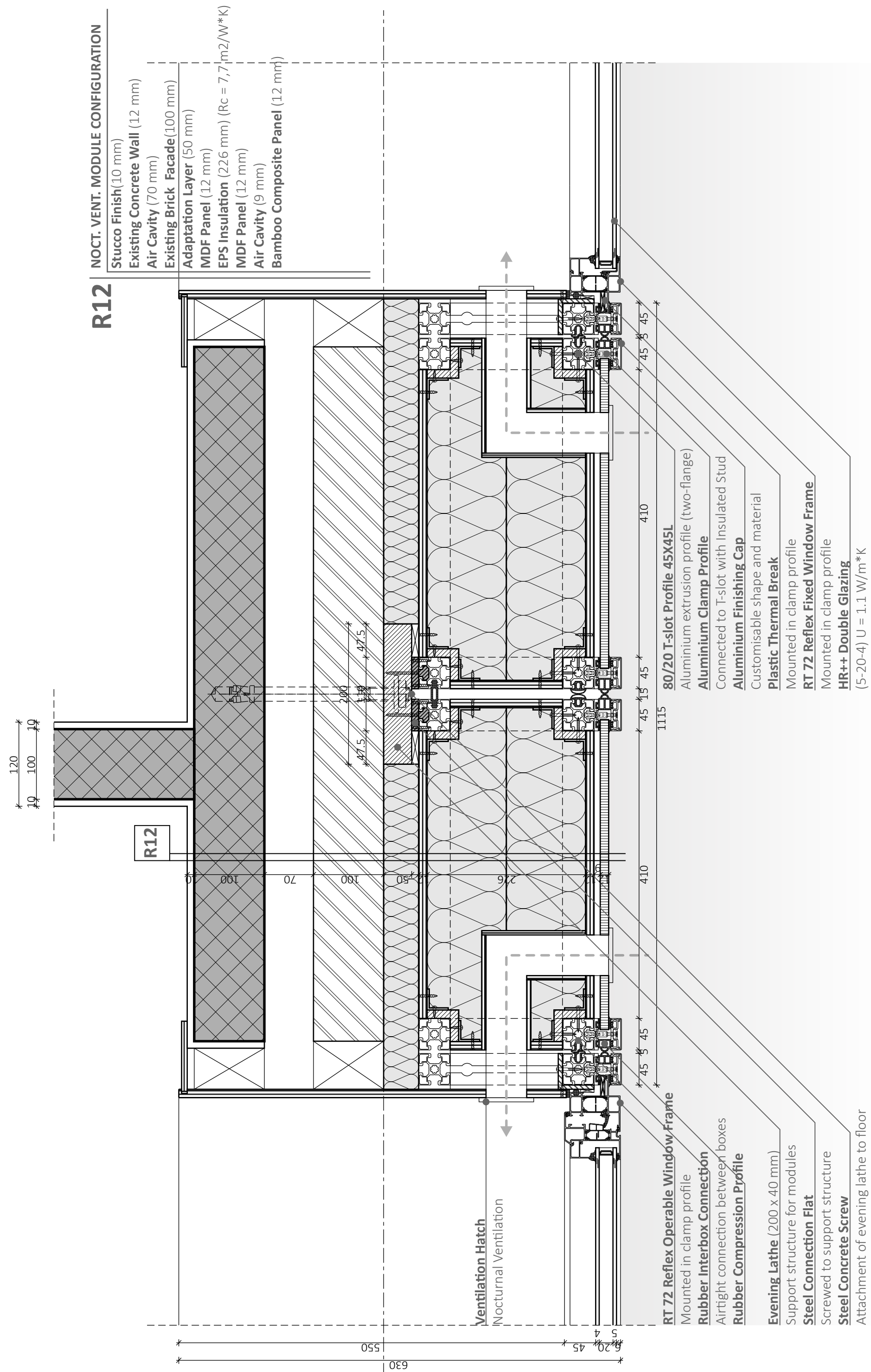


Fig. 9.4.6.2: *The shaft can be prefabricated into the module, air enters through the grill in the cladding panel and enters the dwelling through a grill in the internal lining (own illustration).*

Fig. 9.4.6.3: *(Top) Possible location nocturnal ventilation boxes (own illustration).*

Fig. 9.4.6.4: *(Right) Detail | 1:10 | Nocturnal Ventilation (own illustration).*


R12
NOCT. VENT. MODULE CONFIGURATION
Stucco Finish(10 mm)
Existing Concrete Wall (12 mm)
Air Cavity (70 mm)
Existing Brick Facade(100 mm)
Adaptation Layer (50 mm)
MDF Panel (12 mm)
EPS Insulation (226 mm) (Rc = 7,7 m2/W*K)
MDF Panel (12 mm)
Air Cavity (9 mm)
Bamboo Composite Panel (12 mm)
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (two-flange)
Aluminium Clamp Profile
Connected to T-slot with Insulated Stud
Aluminium Finishing Cap
Customisable shape and material
Plastic Thermal Break
Mounted in clamp profile
RT 72 Reflex Fixed Window Frame
Mounted in clamp profile
HR++ Double Glazing
(5-20-4) U = 1.1 W/m*K
Ventilation Hatch
Nocturnal Ventilation
RT 72 Reflex Operable Window Frame
Mounted in clamp profile
Rubber Interbox Connection
Airtight connection between boxes
Rubber Compression Profile
Evening Lathe (200 x 40 mm)
Support structure for modules
Steel Connection Flat
Screwed to support structure
Steel Concrete Screw
Attachment of evening lathe to floor
120
10
100
10
10
100
70
100
50
12
226
12 9 12
410
410
45 5 45
45 15 45
1115
200
47.5
47.5
15
550
45
20
4
5
6
630

AS

§ 9.4.7 *Static Solar Control*

One possible option to add solar shading which is low in maintenance at a later stage is by replacing the façade caps with deeper extruded caps to function as static solar shading. This option is relatively easy to implement as it is only required to snap off the caps and snap on the new caps. Furthermore, the new caps could be a low budget adjustment contributing to an updated aesthetical look for the building. Alternatively, it is possible to just adjust the cap above the window on the south side of the building or only the side caps on the west and east side of the building.

In figure 9.4.8.1 the components necessary for the upgradation are illustrated, in figure 9.4.8.2 possible location for the upgrade are listed. On page 18 of the detail appendix a variant with louvres integrated in the window is portrayed.

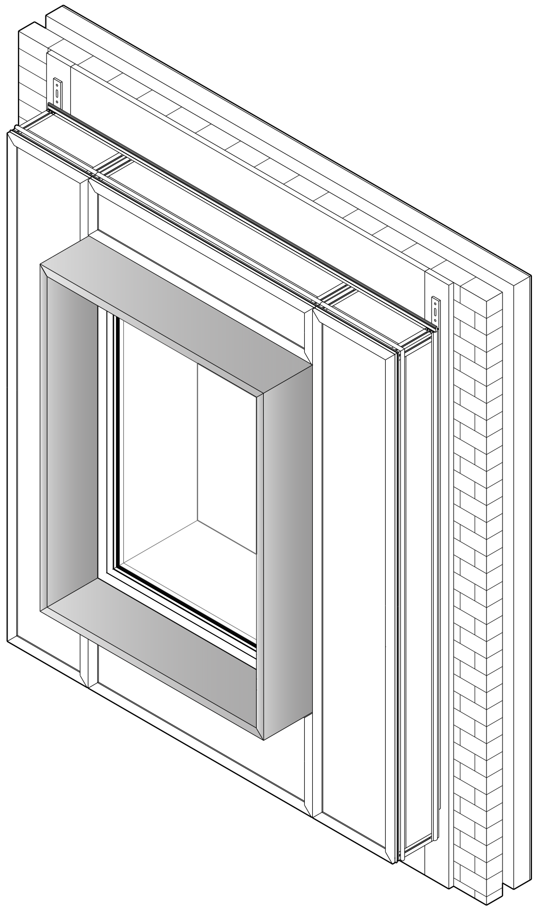
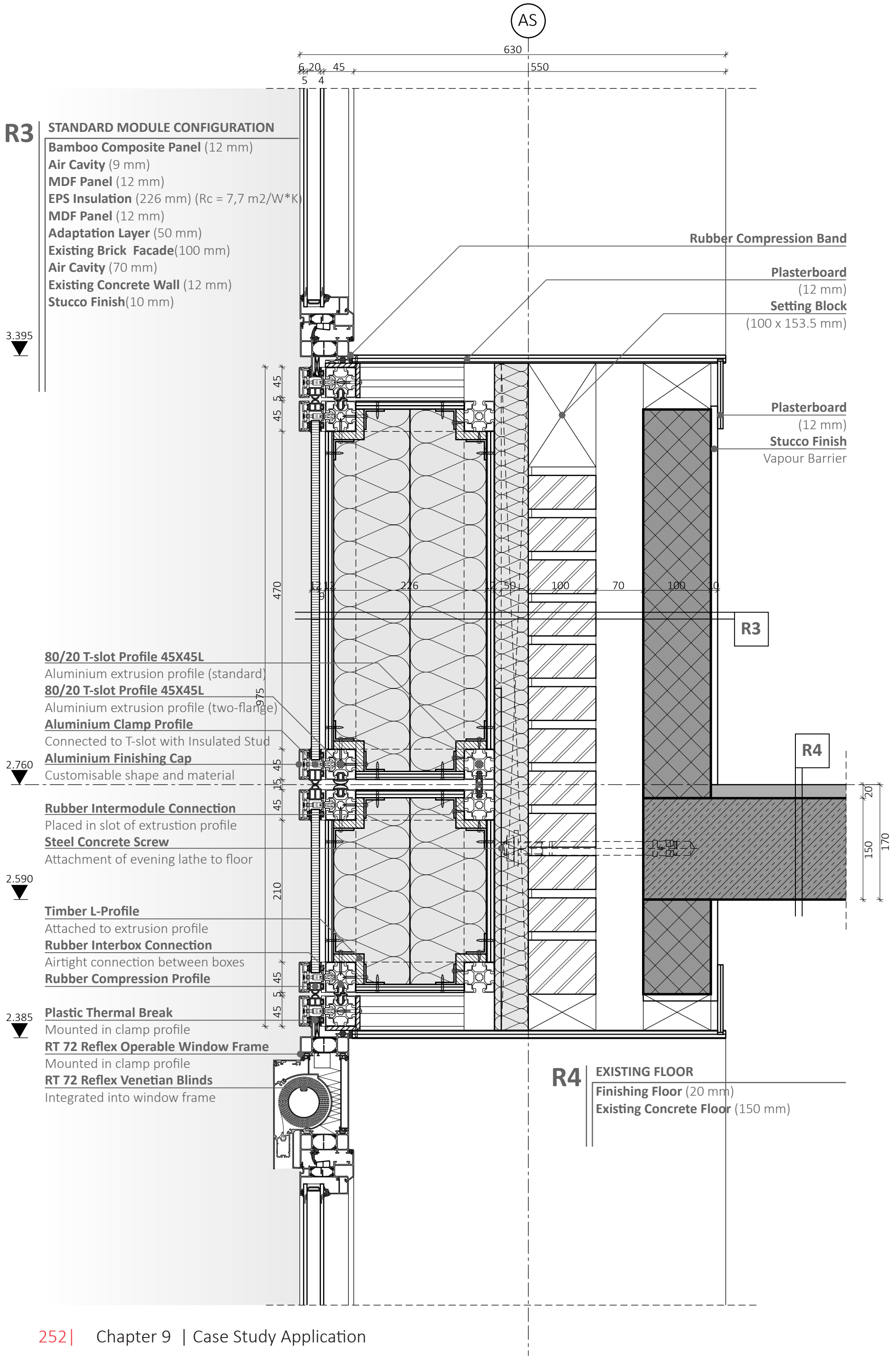


Fig. 9.4.8.1: *Static solar shading cap replaces the orginal cap (own illustration).*

Fig. 9.4.8.2: *(Top) Static solar shading located on the west, east and south facade (own illustration).*
Fig. 9.4.8.3: *(Right) Detail | 1:10 | Vertical | Integrated Solar Shading Window (own illustration).*


AS
630
6 20 45
5 4
550
R3
STANDARD MODULE CONFIGURATION
Bamboo Composite Panel (12 mm)
Air Cavity (9 mm)
MDF Panel (12 mm)
EPS Insulation (226 mm) (Rc = 7,7 m2/W*K)
MDF Panel (12 mm)
Adaptation Layer (50 mm)
Existing Brick Facade(100 mm)
Air Cavity (70 mm)
Existing Concrete Wall (12 mm)
Stucco Finish(10 mm)
3.395
Rubber Compression Band
Plasterboard
(12 mm)
Setting Block
(100 x 153.5 mm)
Plasterboard
(12 mm)
Stucco Finish
Vapour Barrier
226
50
100
70
100
R3
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (standard)
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (two-flange)
Aluminium Clamp Profile
Connected to T-slot with Insulated Stud
Aluminium Finishing Cap
Customisable shape and material
2.760
R4
Rubber Intermodule Connection
Placed in slot of extrusion profile
Steel Concrete Screw
Attachment of evening lathe to floor
2.590
Timber L-Profile
Attached to extrusion profile
Rubber Interbox Connection
Airtight connection between boxes
Rubber Compression Profile
2.385
Plastic Thermal Break
Mounted in clamp profile
RT 72 Reflex Operable Window Frame
Mounted in clamp profile
RT 72 Reflex Venetian Blinds
Integrated into window frame
R4
EXISTING FLOOR
Finishing Floor (20 mm)
Existing Concrete Floor (150 mm)
975
470
210
45
5
15
20
150
170

§ 9.4.8 ***Solar Panels***

Solar panels can be integrated in the façade by removing the façade panels and mounting the solar panels in the clamp. The solar panels function as the new watertight barrier. The same mounting process is utilised for the façades and the roof, simplifying the upgrading process if both are outfitted with solar panels at the same time.

On page number 9 of the detail appendix the integration of the solar panels in the roof are demonstrated. Figure 9.4.10.2 illustrates the possible location for solar panels. Naturally, the vertical placed panels achieve output than slanted panels on the roof, but the additional functioning as watertight barrier eliminates the necessity for façade cladding, which is beneficial.

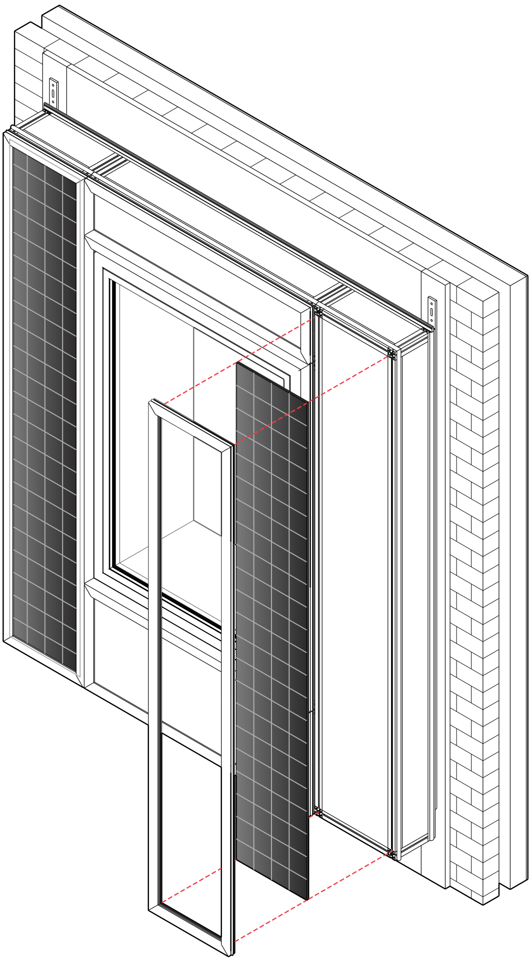
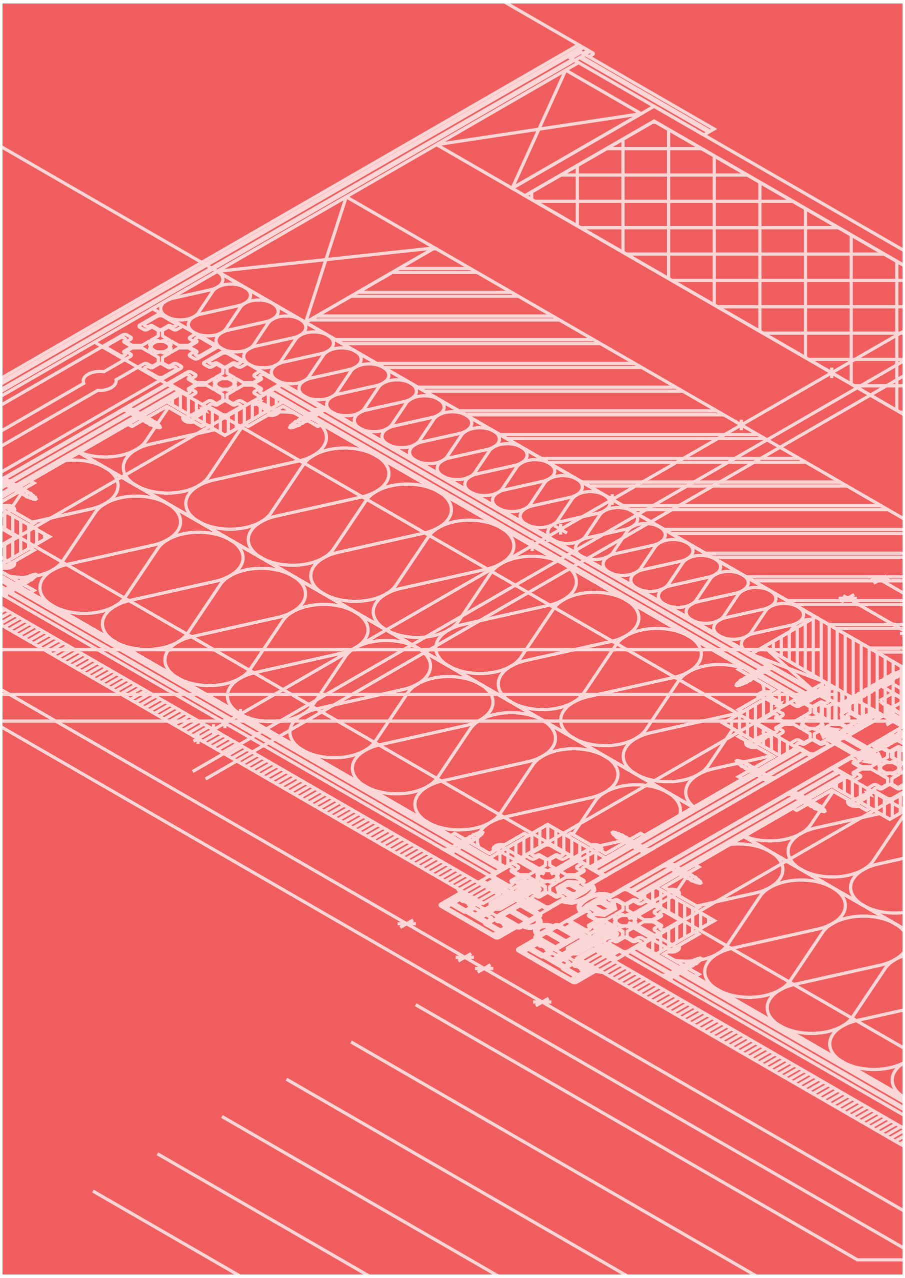


Fig. 9.4.9.1: *The clamp is demounted and the original cladding panel is replaced with a PV panel, the PV panel takes over the role of watertight barrier (own illustration).*

Fig. 9.4.10.2: *(Top) The darker red squares indicate areas with the highest possible output. (own illustration)*



§ 9.4.9 *Solar Comb Box*

The building envelope system can also be combined with more experimental solutions, such as a solar comb, which utilises indirect heat gain during the day and stores it inside the solar comb cavities, and subsequently releases it during the night (Dubois, et al., 2016). The sunlight enters the cavities through the glass façade panel. Besides the energy reductive benefits, the solution also leads to an aesthetical upgrade. The solar comb box requires minimal depth and can therefore replace the placeholder frame. The solar comb box can be installed by demounting the clamp profile and removing the placeholder frame, the comb box is then installed and the clamp is remounted with a glass panel instead of a façade panel.

Page 19 of the detail appendix shows the integration of the solar comb box with a slim insulation box. The solar comb is best utilised on facades with enough sun exposure as illustrated in figure 9.4.10.3.

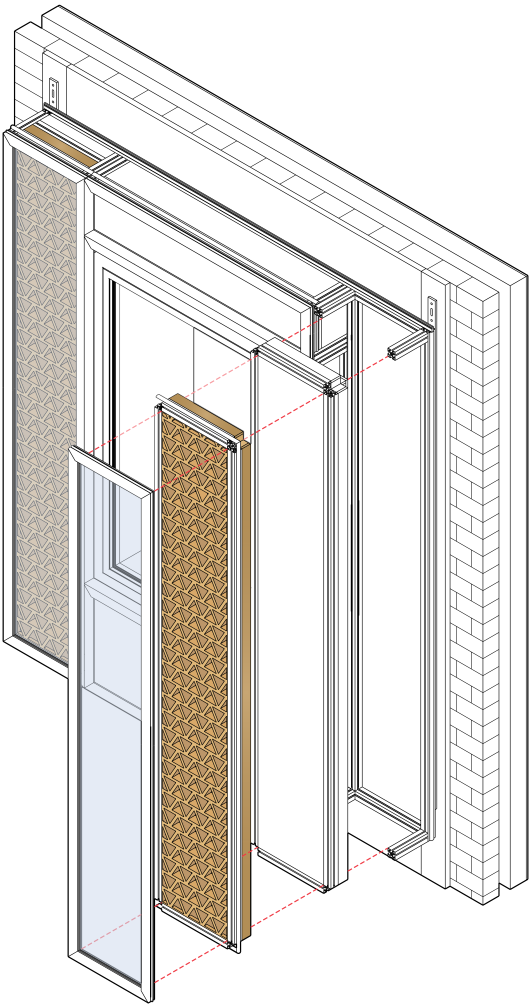
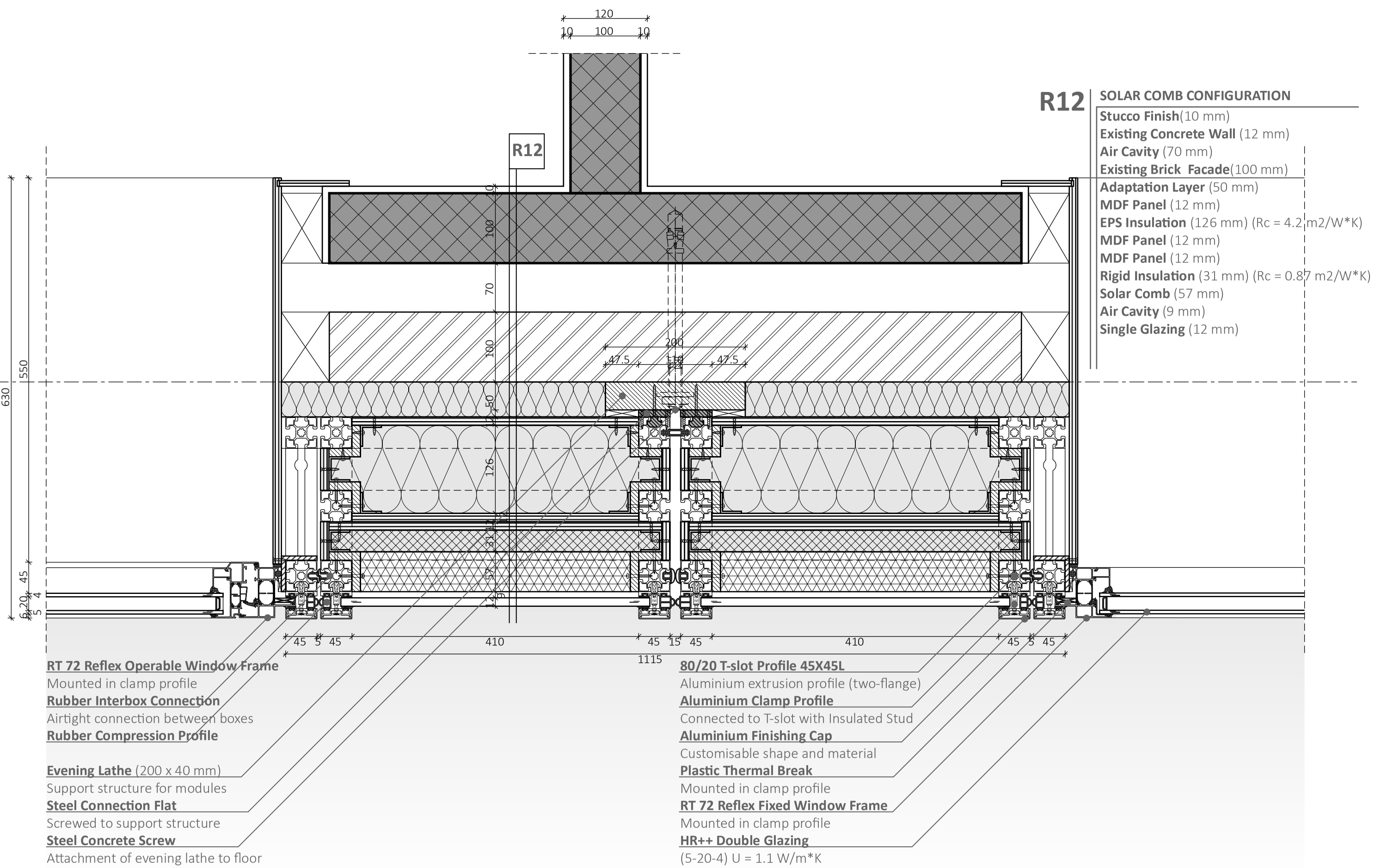


Fig. 9.4.9.1: *The solar comb box is installed in the same fashion as conventional boxes, the panel is replaced with a glazing layer to allow sunlight to enter the solar comb (own illustration).*

Fig. 9.4.9.2: *(Top) The solar comb offers the best results on the south facade, alternatively the east and west facade could be utilised (own illustration).*
Fig. 9.4.9.3: *(Right) Detail | 1:5 | Horizontal | Solar Comb (own illustration).*


R12
SOLAR COMB CONFIGURATION
Stucco Finish(10 mm)
Existing Concrete Wall (12 mm)
Air Cavity (70 mm)
Existing Brick Facade(100 mm)
Adaptation Layer (50 mm)
MDF Panel (12 mm)
EPS Insulation (126 mm) (Rc = 4.2 m2/W*K)
MDF Panel (12 mm)
MDF Panel (12 mm)
Rigid Insulation (31 mm) (Rc = 0.87 m2/W*K)
Solar Comb (57 mm)
Air Cavity (9 mm)
Single Glazing (12 mm)
R12
120
10 100 10
200
47.5 47.5
45 5 45 410 45 15 45 410 45 5 45
1115
550
630
RT 72 Reflex Operable Window Frame
Mounted in clamp profile
Rubber Interbox Connection
Airtight connection between boxes
Rubber Compression Profile
Evening Lathe (200 x 40 mm)
Support structure for modules
Steel Connection Flat
Screwed to support structure
Steel Concrete Screw
Attachment of evening lathe to floor
80/20 T-slot Profile 45X45L
Aluminium extrusion profile (two-flange)
Aluminium Clamp Profile
Connected to T-slot with Insulated Stud
Aluminium Finishing Cap
Customisable shape and material
Plastic Thermal Break
Mounted in clamp profile
RT 72 Reflex Fixed Window Frame
Mounted in clamp profile
HR++ Double Glazing
(5-20-4) U = 1.1 W/m*K

AS

§ 9.5 Customisation

Other than functional flexibility the building envelope systems also provides flexibility in aesthetical quality. A wide variety of material finishes and depth profiles can be incorporated in the design and changes between aesthetical looks can be achieved relatively easily by replacing the cap and the panel. The panels mounted in the clamp profiles do have the requirement that they have to be able to prevent water from traversing through the panel and potentially damage the interior boxes.

The final set of drawings showcase the aesthetical flexibility in more detail. The different variants are based on the customisation options presented in paragraph 8.4.5, the scenarios steps as well as the finishes available for the prefabricated variant of the 2ndSkin project.

Fig. 9.5.1: *Fragment different facade finishes (1:60) (own illustration).*

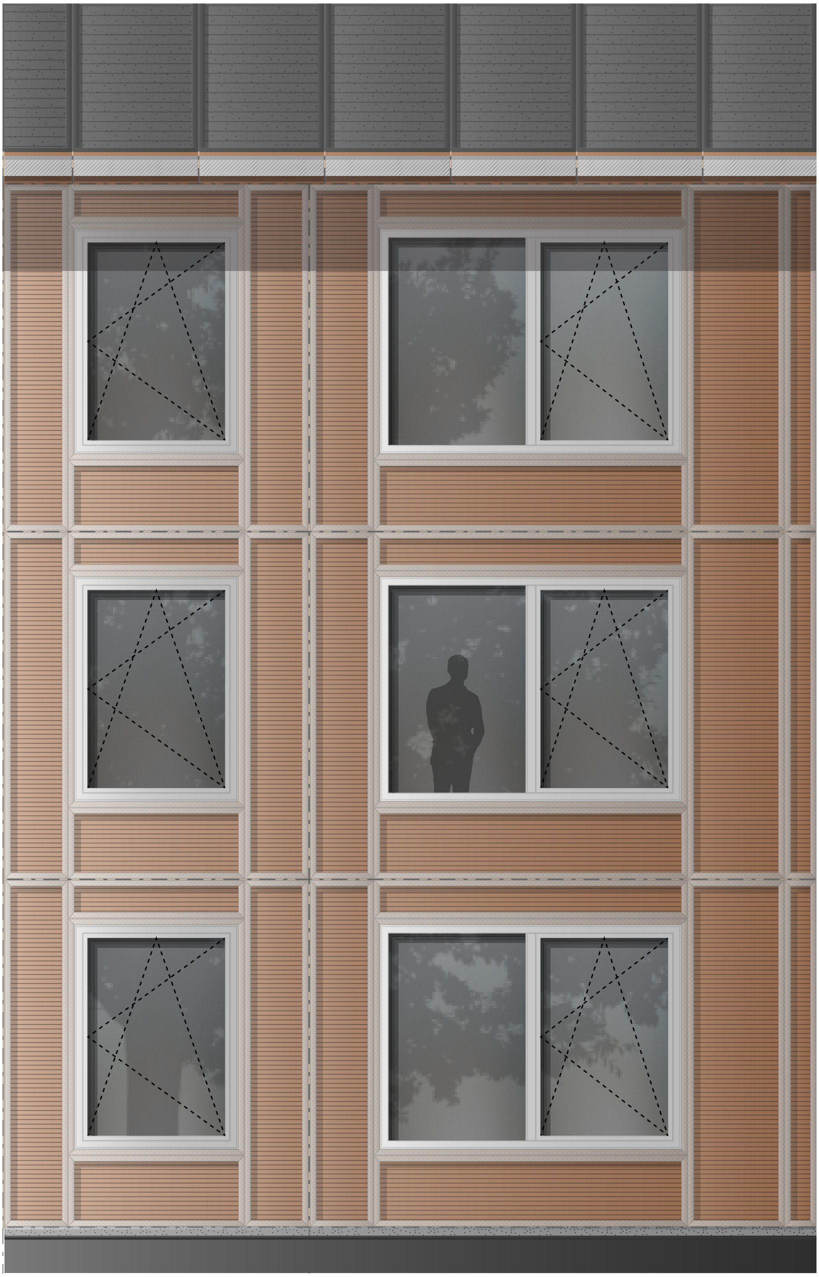


Fig. 9.5.2: *Differing cap and panel color (1:60) (own illustration).*

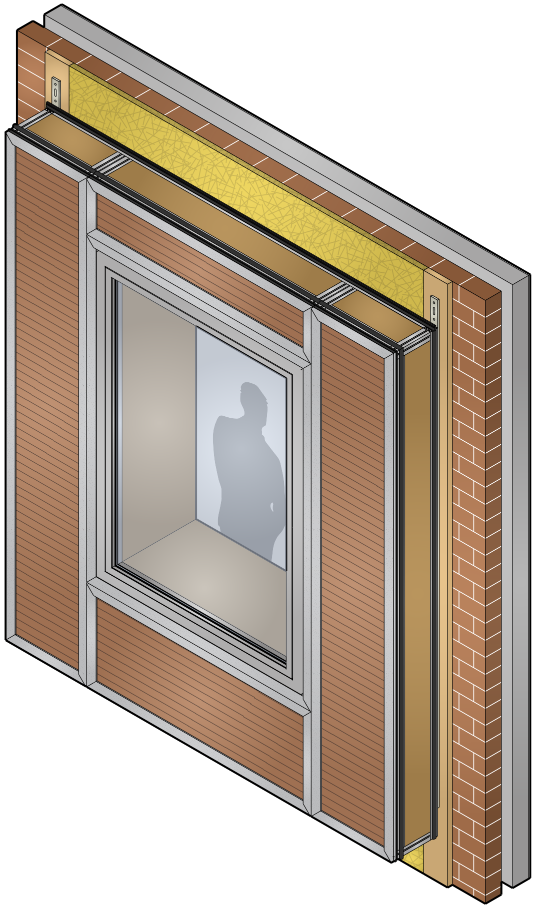


Fig. 9.5.3: *Isometric view of variant (own illustration).*

Fig. 9.5.4: *Deeper extruded caps in combination with panel color variation (1:60) (own illustration)*

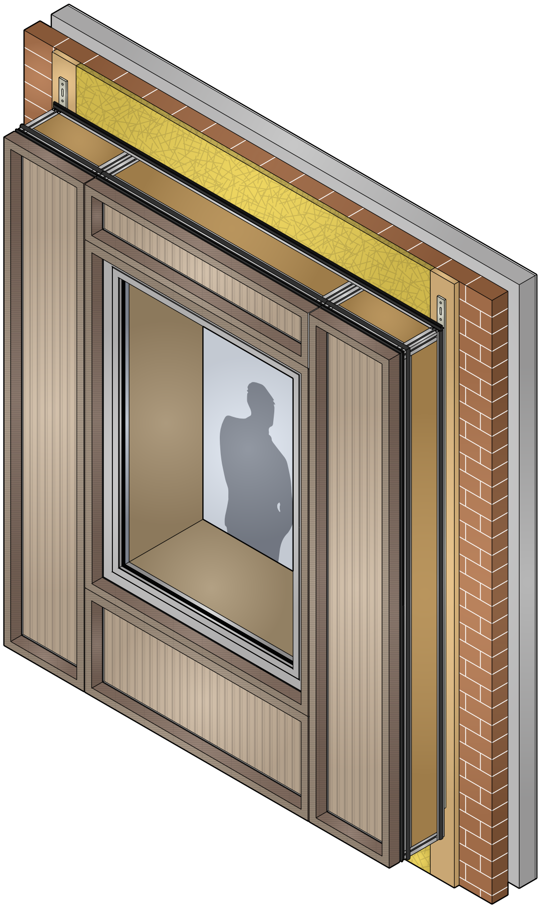


Fig. 9.5.5: *Isometric view of deeper cap extrusion variant (own illustration).*

Fig. 9.5.6: *Extruded static solar shading in combination with a steel finish (1:60) (own illustration)*

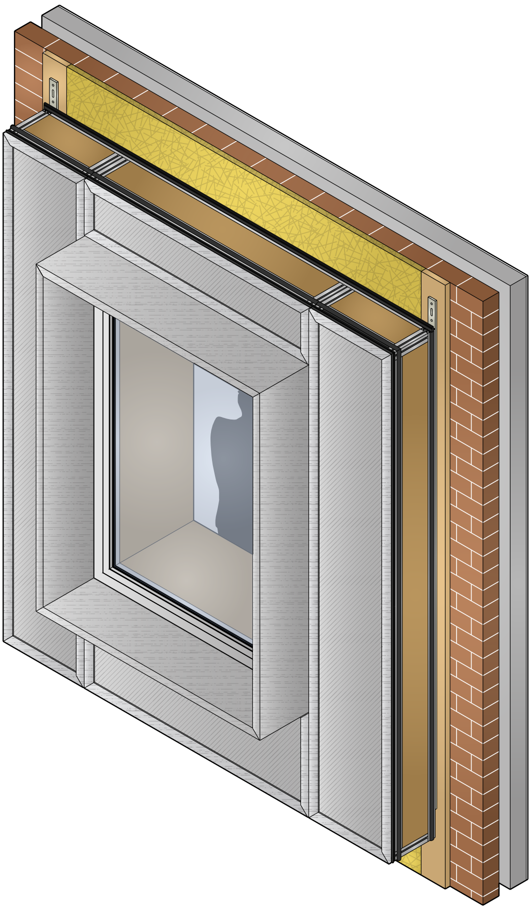


Fig. 9.5.7: *Isometric view of static solar shade variant (own illustration).*

Fig. 9.5.8: *Solar comb with glazing in front (1:60) (own illustration).*

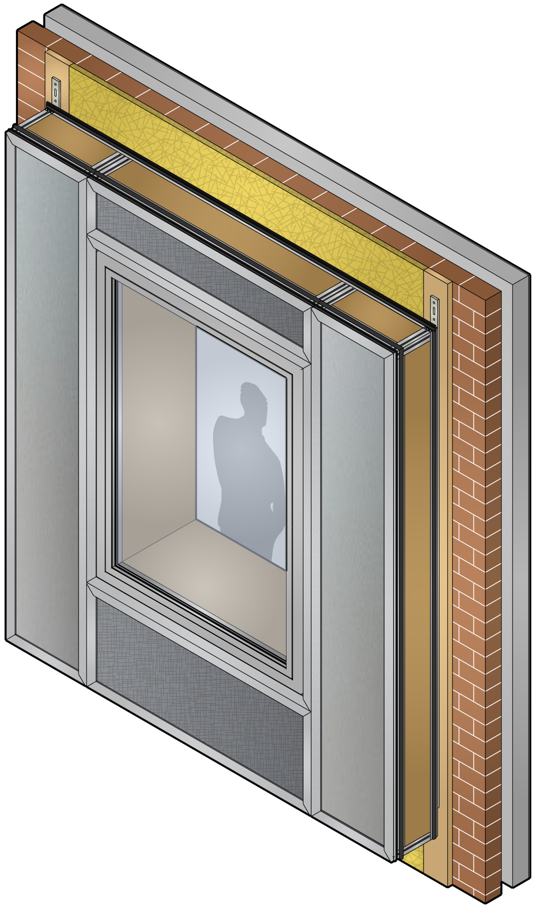
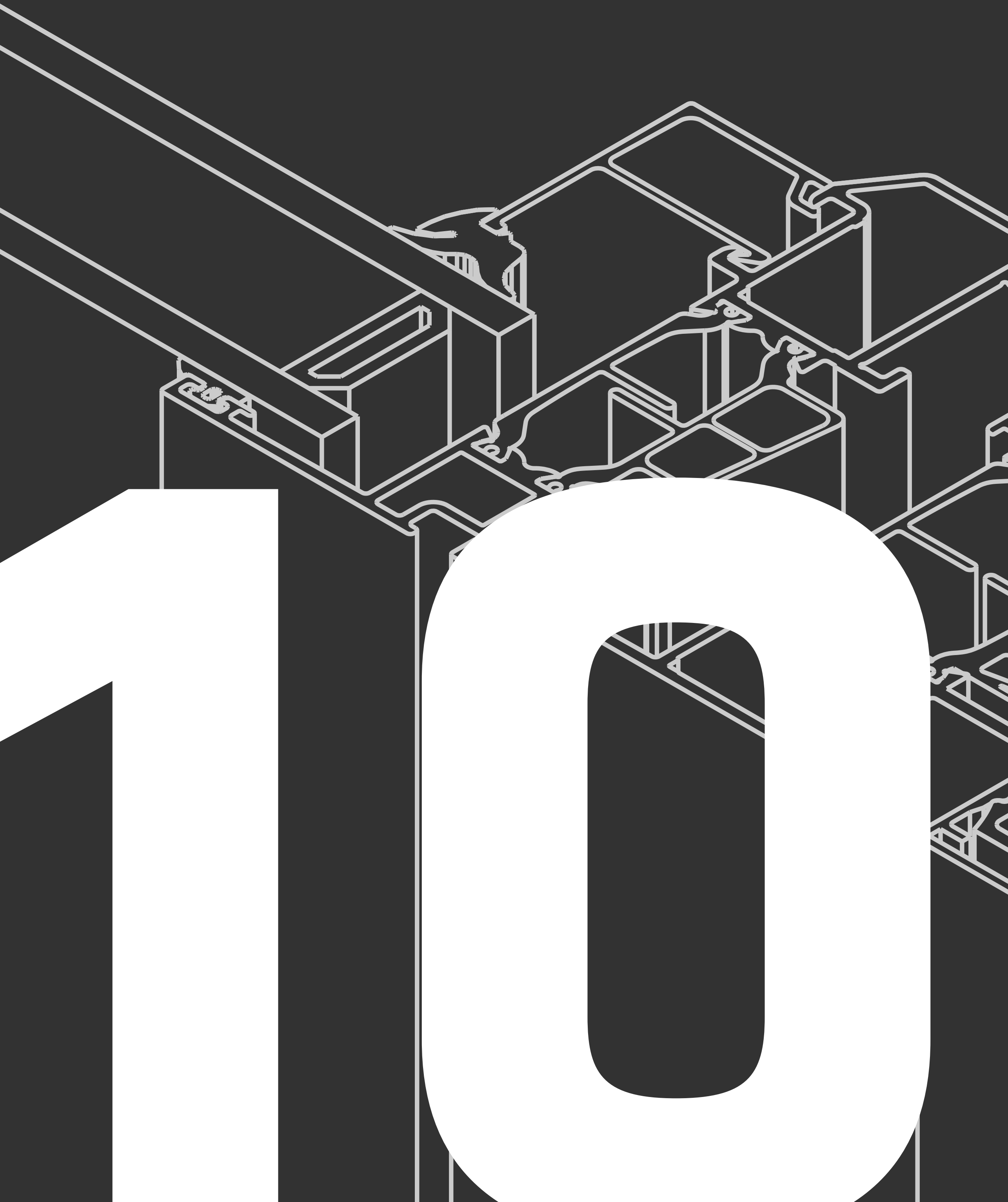
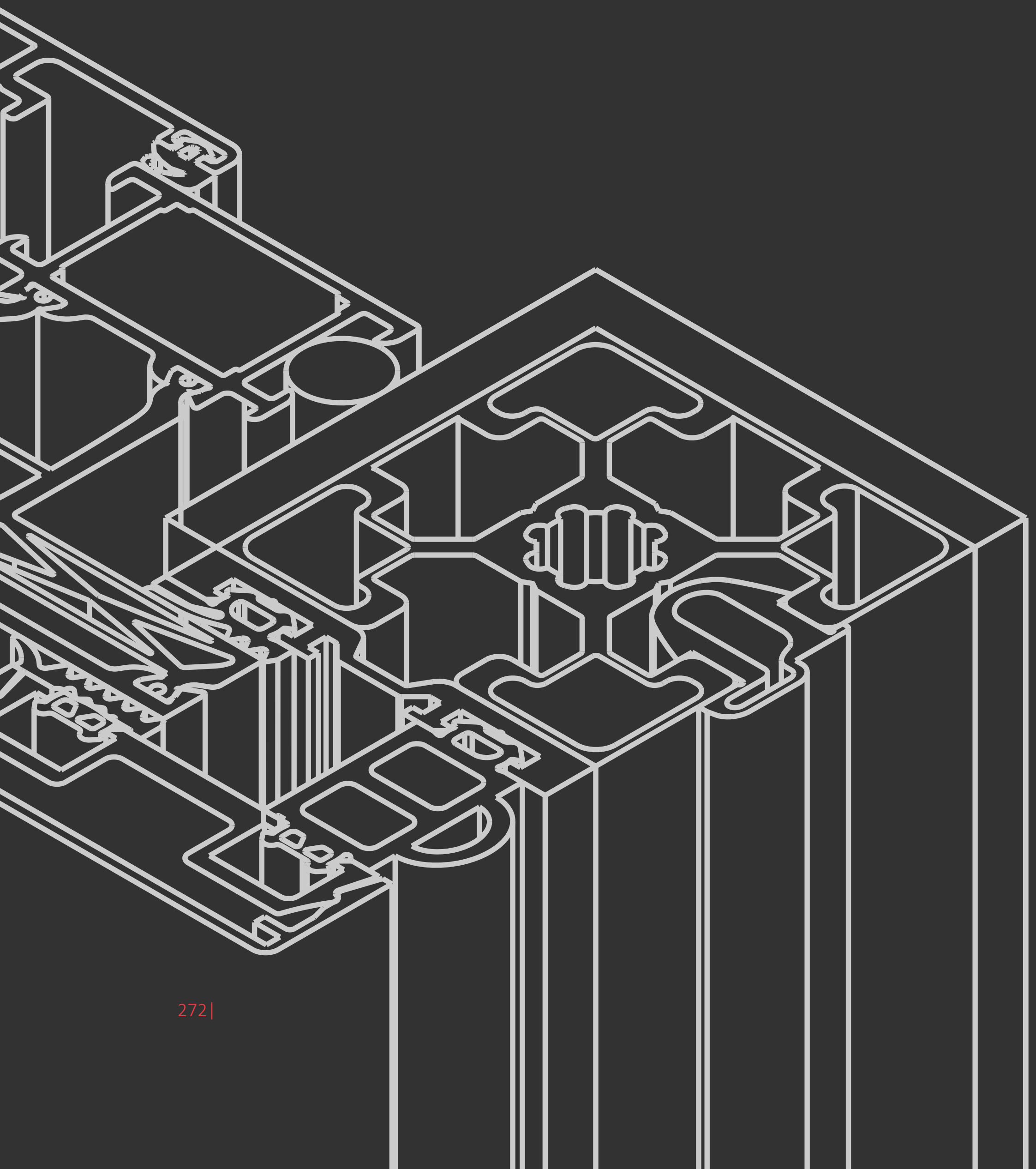


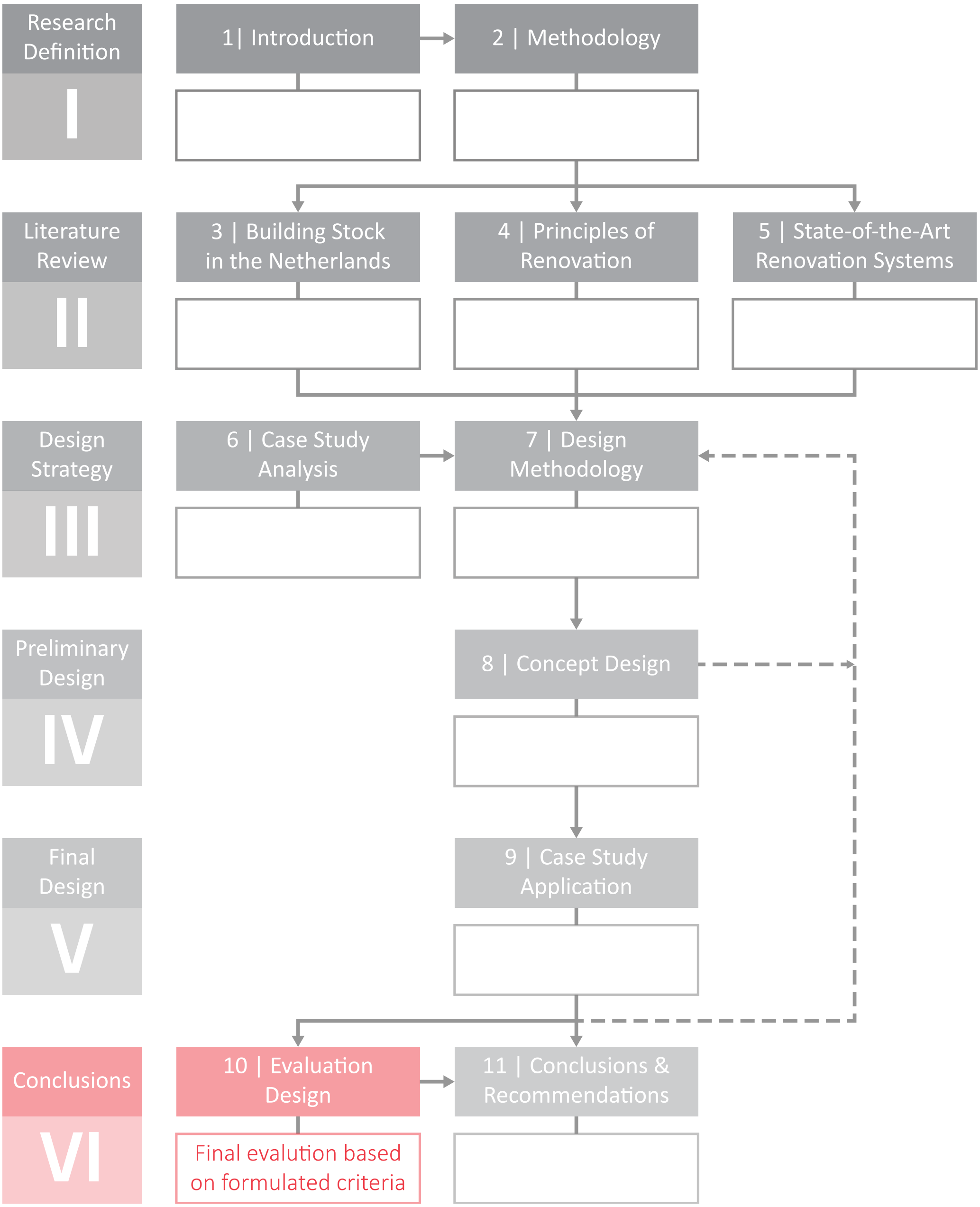
Fig. 9.5.9: *Isometric view of solar comb variant (own illustration).*



10

CHAPTER 10
EVALUATION DESIGN




Research Definition
I
1| Introduction
2 | Methodology
Literature Review
II
3 | Building Stock in the Netherlands
4 | Principles of Renovation
5 | State-of-the-Art Renovation Systems
Design Strategy
III
6 | Case Study Analysis
7 | Design Methodology
Preliminary Design
IV
8 | Concept Design
Final Design
V
9 | Case Study Application
Conclusions
VI
10 | Evaluation Design
Final evalution based on formulated criteria
11 | Conclusions & Recommendations

10 Evaluation Design

In chapter 10 the final design will be evaluated on three separate aspects: the design methodology, the design concept and the design elaboration. The evaluation will function as a basis from which a final answer is formulated on the research question in chapter 11.

In paragraph 10.1 the design elaboration will be evaluated on the individual criteria formulated in chapter 7. A final comparison is made to the analysed building envelope systems in chapter 5. In paragraph 10.2 the process of producing a satisfactory concept and the subsequent elaboration is discussed. Paragraph 10.3 will discuss the possible impact of the design in the current renovation market. Finally, in paragraph 10.4 the limitations of the system are elaborated in more detail.

§ 10.1 Design Elaboration

The final design will be assessed per category and on every individual criterion. Both the concept and the elaboration of the concept are utilised as references in order to formulate an accurate assessment. Every criterion will at first be assessed in an isolated fashion. Afterwards, the individual assessments are combined to formulate a final assessment of the complete solution.

§ 10.1.1 *Energy*

Energy Production

The integration of photovoltaic panels is considered in an early stage as the main component for production of energy. Integrating the option in the clamp profiles on the roof for the panels to be replaced with photovoltaic panels ensures a relatively easy way of upgrading the roof. The main disadvantage is that the panels have to also function as a watertight layer and are constricted to fixed sizes. By doing the number of applicable panels are restricted.

Energy Reduction

All the measures utilised in the 2ndSkin project have been integrated into the design of the façade system, showcasing that the system has the same energy reduction potential as the 2ndSkin project. However, additional passive measures portrayed in the energy tools could not be integrated into the design, such as exterior sunspaces or Trombe walls, without severely compromising other criteria and were therefore left out of the design. Adding the ability to incorporate these energy reductive measures, without compromising other aspects, could further enhance the energy reduction potential of the system.

§ 10.1.2 ***Architecture***

Customisation

The façade system can be altered in a number of ways via the windows, caps of the clamp profiles and the panels. The windows are outfitted with a thermal break piece in order to be fixed in the clamp profiles. Most window types can be outfitted with such a piece, as it is a commonly used piece to attach windows in curtain walls. Certain windows that aren't combinable with the connection piece are excluded from the design. The caps of the clamp profiles can be altered relatively easy, leading to many different configurations and façade variations. The main disadvantage is that the cap will always have a dominant effect on the overall appearance of the building, something that can be minimised, if unwanted, but never nullified. The panels are required to be watertight. While a wide variety of finishes are still available, it does limit the options. The overall assessment is that customisation options were sacrificed to improve the upgradability of the system.

Off-site Production Ability

The whole module can be prefabricated off-site. Furthermore, the main elements, such as the frames, connections and clamps, can be stored in the factory and cut to size when necessary. Most components of the boxes can be also be stored, but the side panels and the L-profiles have to be custom made to be adjusted to the right dimensions of the target building. A calculated compromise that benefits the adaptability of the system. Furthermore, the façade systems also have the option to be mounted in parts to the building, which is beneficial when applicating the system to buildings where heavy construction apparatus cannot be utilised.

Integration

The building installations used in the 2ndSkin project are integrated into the façade systems as boxes and the module can be transported in completed form to the construction site. However, due to the depth and subsequent weight of the modules, heavy construction apparatus is necessary to adequately install the module. If the necessary apparatus cannot be provided, there is the option to install the installation module in components. Smaller building installations offer less issues and are easier to integrate in the façade module. The wide variety of box sizes ensure that any system can be placed in a dimensionally suitable box, as is demonstrated in chapter 9.

Sustainable Materials

The materials used for the boxes and the infill of the boxes can be altered to any material that a project requires, ensuring sustainable materials with low embodied energy can be used for these components. The material for the clamps and the main frame is the only components that are not subject to change and are made of aluminium to ensure their longevity. Aluminium has a relatively high embodied energy, but can be almost completely recycled to counteract this disadvantage. A compromise that was necessary for the functioning of the system.

Structural Adjustments
The system is made out of lightweight materials and can be suspended from the existing structure. Furthermore, the existing foundation is left intact and doesn't require additional work to strengthen it. It is assumed the existing structure has enough structural capacity to bear the façade system. The building installations module box due to its large thickness does require the addition of a separate foundation to support it. Although this is disadvantageous, it is a compromise that cannot be avoided due to the sizing and weight of the installations.

Adaptability
The frame of the system is designed in a way that it can be easily adapted to different module sizes, as well as sizes of the module boxes can be adapted easily. The downside is that the boxes cannot be stored before the start of a project, as they have to be custom-made for every project. However, most components of the boxes, such as the framing and connections, can be stored to ensure a swift production process. Furthermore, the system is designed to be adaptable to different parameters, such as window sizing to accompany different building blocks. The design area dimensions can be easily adapted by sliding the aluminium extrusion profiles horizontally or vertically along the slots of connected profiles. A potential issue occurs when a building is not capable of bearing the suspended weight of the façade modules. This can be resolved with more slender modules, which the systems can adapt easily too, as well as strengthening the existing foundation, which requires more intensive labour on-site.

Disturbance
Due to the modules being fully prefabricated labour time on-site is minimised, which subsequently minimises the disturbance to occupants. However, preparatory labour, such as installation of the adaptation layers and evening lathes, is necessary to ensure the adequate mounting of the system. In general, this type of labour is required for every system available on the renovation market and is seen as acceptable disturbance.

Construction Time
Although the exact construction time is difficult to predict, it can be assumed that the system has a similar construction time as similar approaches. The goal of the system is to be competitive in this criterion, which can be assumed to be true.

§ 10.1.3 ***Future Proof***

Upgradability

The upgradability of the façade system is achieved in many different ways. Everything in the system can be adapted to different functional requirements in the present, as well as the future. The boxes can be replaced by removing the clamps, unscrewing the anchor connections between the main frame and the frame of the boxes and sliding the boxes out of the frame. It is also possible to change the arrangement of boxes by sliding the frame to different positions. Furthermore, it is possible to add or remove frame pieces to be able to house more or less box modules. The infill of the boxes can be replaced with similar actions. One could argue that the removal of the clamps is an unwanted step to remove the boxes, but it was deemed necessary to ensure the water and airtightness of the system. Furthermore, combining the water-tight layer with the boxes would mean that replacing one would also mean replacing the other, which would be against the concept of separating functional layers so that upgradation of individual components can be achieved.

Upgradability of the appearance of the building is also generally easily achieved by removing the panels from the clamps, as well as the caps of the clamp profiles, which can be snapped off and replaced with new caps without intensive labour.

Lastly, modules can also made thicker by extending the main frame with additional pieces and connecting them with butt fasteners described in paragraph 8.4.2, as long as the existing structure can bear the additional weight. The elongated modules have to be protected from weather damage by applying an additional clamp profile with watertight sandwich panels. This upgrade requires some additional steps and could be deemed to extensive. The goal in this aspect was to ensure that it was possible if absolutely necessary.

Maintenance

Maintenance to components is ensured in the same way as the upgradation of the systems occurs. Components can be easily reached and replaced if necessary. The inclusion of doors in the system further ensure building installations can be reached without removing the façade elements. Via the balconies. the door of the building installations can be reached. When integrating building installations in boxes that are not reachable via the balconies, maintenance becomes more difficult. The façade system also does not allow for the installations to be reached from the interior.

§ 10.1.4 *Final Assessment*

Based on the assessments of the individual criteria, an overall assessment can be made for the completed system. The system is compared with existing building envelope systems utilised for renovation. The performance is expressed by stating if the final design performs better, worse or neutral on the criteria in comparison with the average grade given to these systems in chapter 5. The results can be found in figure 10.1.

Assessment Final Design

Category	Sub-category	Criteria	Average grade existing systems	Improved
Architecture	Appearance	Customisation	● ● ● ● ◐	-
	Construction	Off-site Production Ability	● ● ● ◐ ○	=
		Integration	● ● ● ○ ○	+
		Sustainable Materials	● ● ◐ ○ ○	+
	Application	Structural Adjustments	● ● ● ● ○	=
		Adaptability	● ● ◐ ○ ○	+
		Disturbance	● ● ● ● ○	=
		Construction Time	● ● ○ ○ ○	+
Future Proof		Upgradability	● ○ ○ ○ ○	++
		Maintenance	● ● ○ ○ ○	++

Fig. 10.1: *Assessment final design in comparison with analysed systems in chapter 5 (own illustration).*

§ 10.2 Design Process

The design process followed a design methodology customised for this thesis. Although the method is based on a conventional design methodology, the vast amount of literature in different fields required a defined structure in order to accurately apply this knowledge into the design phase. The first step was to distil the information gathered in the literature review and abstract it into design tools which could be used for the following steps. Step two was to combine the design tools to start off a divergent design process leading to ten concepts. Step three consists of chosen one design concept, a converging process, and then start a new divergent design process for every individual component of the design. The last step was to materialise the design on a case study and validate the systems resilience through the utilisation of constructed scenarios. In the next paragraphs the design process per step is elaborated further.

§ 10.2.1 *Design Tools*

The overview of available options the design tools provided was utilised as a preparatory tool for the design process. By assessing the tools on their value in providing the right elements for the building envelope design, a more analytical basis could be provided to the design process. Conventional design methods often fail to materialise gained knowledge into an adequate design, which needs to be avoided. In combination with the list of formulated criteria, the design process could be structured precisely and could be evaluated on its effectiveness. The pitfalls are that the general preferences of the designer are too entangled in the design tools, disregarding other tools beforehand, as well as forgetting tools that could potentially also be useful. By assessing all design tools individually, the chance of disregarding design tools was avoided to some degree. As the personal preference of a designer can still be an influence on the assessment. The second pitfall is impossible to avoid, as more design tools can always be found if more knowledge is gained. The negative effects are however avoided by using abstract design tools that don't formulate a completed design, so the designer still has to further investigate alternatives. Lastly, there is a potential that the design tools are disregarded completely during the design process. During the design process the chosen design tools were also used as an evaluation tool to reassess the design to ensure they are entangled in the design.

§ 10.2.2 *Concept Production*

The concept production phase, where a divergent design process was utilised, lead to ten different concepts with multiple different variations. The design tools gave the scope in which concepts could be produced. With the aid of the tools is became relatively easy and quick to produce different concepts that satisfy the general direction of the thesis. However, the design tools could potentially also be limiting by disregarding potential design options completely, that would be possible if they were not used. This hypothetical problem is difficult to solve in a design process, as the same problem could potentially also occur in a process without the aid of design tools.

§ 10.2.3 *Components Design*

After defining the final concept, the components design also utilised a divergent design process. Several options per component were investigated and evaluated on their intended individual functioning, as well as their functioning in the system as a whole. In general, this approach functioned adequately. The main pitfall in this phase of the design process was that, by separating the different components in separate to be designed elements, potentially combined solutions were disregarded. The approach was utilised to achieve a structured design process, but could potentially limit the creative ability of the designer.

§ 10.2.4 *Application Case Study*

The application of the façade system on the case study was a convergent process. A clear idea of how every component should function was already established in the previous step, so only minor adaptations were required to make in order for the system to be effectively applied. In general, the process was linear, focussing on establishing the detail required to verify the systems functioning.

§ 10.2.5 *Scenarios*

Two separate scenarios were constructed to test the façade systems resilience to future changes. The scenarios were constructed based on the literature and the 2ndSkin project. When predicting future changes, it is highly likely that some steps of scenarios will never occur, which is a problem that cannot be avoided. The goal of the scenarios was therefore not to predict the future accurately, but to verify if the changes could be easily performed. To counteract the uncertainty of future changes, the scenarios were constructed to show a wide diversity of required actions, predicting that disregarded scenarios would require approximately similar actions.

§ 10.3 Impact of the Design

Besides the performance of the final design on the formulated criteria, there are other advantages and possibilities associated with the design. In the following section we will shortly discuss them.

Although the building envelope system is catered to the renovation industry, the upgradability and flexibility of the system could potentially also be useful for new façade constructions. In general, the building industry is a slow market that responds slowly to new developments. Building envelope systems, such as the designed one, could potentially improve the reaction speed of the building industry towards new technology.

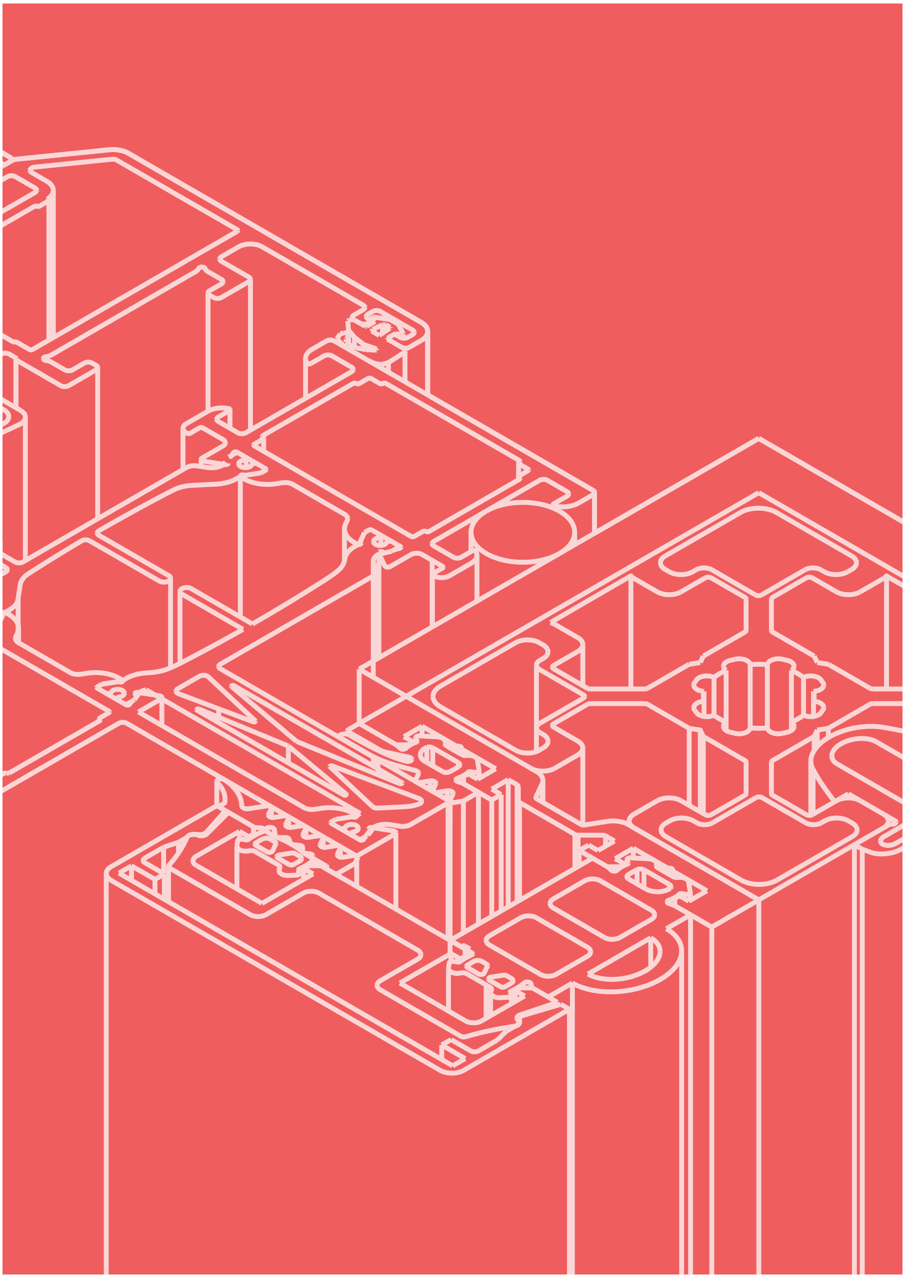
The current costs of a renovation project are a point of discussion in the Netherlands. The projected cost of a full energy positive renovation of a similarly sized apartment block as the case study can reach up to 65.000 euro (Azcarate Aguerre, et al., 2017). While the renovation could prove to be profitable in the long-run, the high investment costs have a high deterrent effect on homeowners. The proposed system intends to spread those investment costs, while also being combinable with cheaper building installations and a longer overall service life.

§ 10.4 Limitations of the Design

Besides the advantages there also some disadvantages. The most important ones are described in the following section.

While the intention of the system to be upgradable and flexible can be proven to be successfully integrated, the financial benefits of the upgradability are under discussion. In general, prefabricated systems have higher initial investment costs over, for example, an exterior insulation finishing system. This due to the costs of setting up a production line to produce the modules. Prefabricated systems are only profitable if they are applicated on a large number of dwellings.

The system was designed to be a simple as possible, utilising components and techniques that were already available and altering them to requirements of the design concept. In practice, the system could prove to be too complex for it to work as intended, either through inadequate design or through inexperience of construction workers with such systems.



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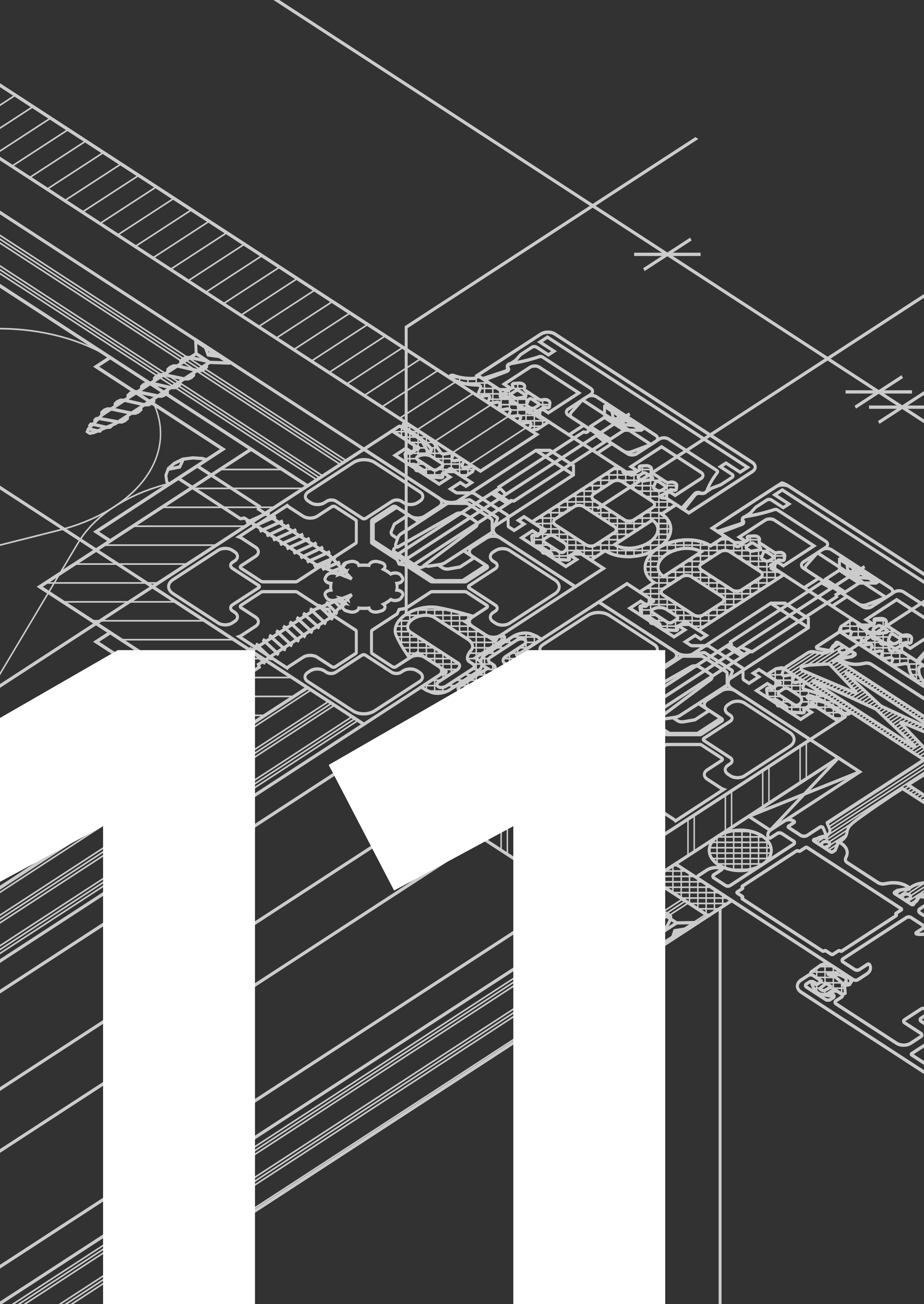
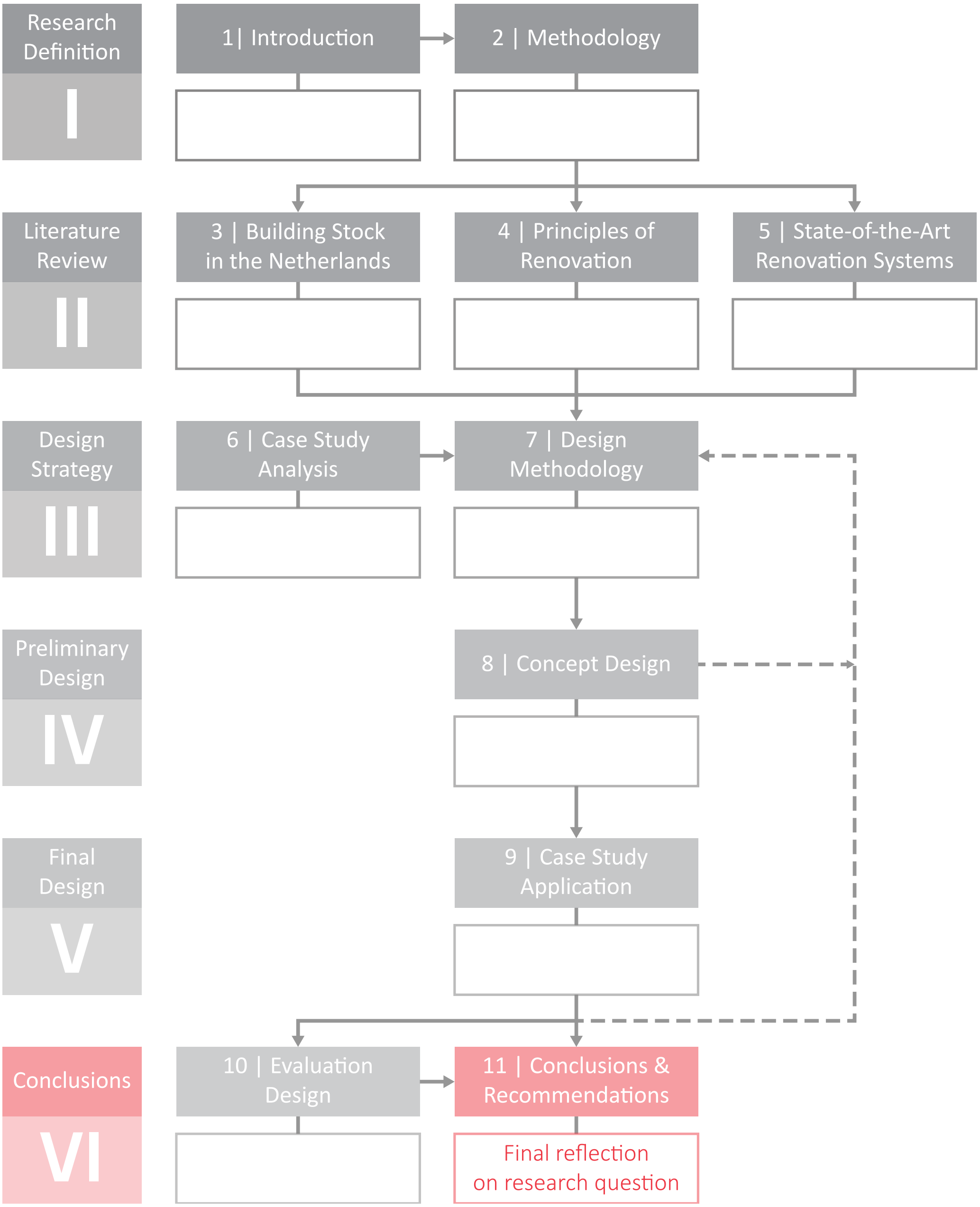


VI

CHAPTER 11
CONCLUSIONS & RECOMMENDATIONS


Research Definition
I
1| Introduction
2 | Methodology
Literature Review
II
3 | Building Stock in the Netherlands
4 | Principles of Renovation
5 | State-of-the-Art Renovation Systems
Design Strategy
III
6 | Case Study Analysis
7 | Design Methodology
Preliminary Design
IV
8 | Concept Design
Final Design
V
9 | Case Study Application
Conclusions
VI
10 | Evaluation Design
11 | Conclusions & Recommendations
Final reflection on research question

11 Conclusions & Recommendations

§ 11.1 Summary

The first objective of creating an overview of the current situation of the Dutch building stock eligible for renovation. In chapter 3 it became evident that the post-war apartment blocks are very suited for large scale as well as deep renovation. The apartments blocks use very similar construction methods, which broadens the range on which the final design for the façade system can be applied, amplifying the impact of the renovation.

The energy consumption in the apartment blocks can be mainly attributed to space heating, making up 57% of the energy consumption. The main goal of the renovation should therefore to increase the thermal resistance value of the buildings. Heating of water is second biggest consumer at 25%, which can be solved with improving or expanding on the building installations.

The second objective is to gather knowledge on all parameters and principles that are necessary for adequate renovation. In chapter 4 firstly described the approach to reducing energy consumption in buildings. The New Stepped Approach, based on the Trias Energetica, described the necessary strategy to achieve a nullified energy consumption: Reduce energy demand, provide remaining demand through renewable resources and reusing waste streams. Several passive and active measures can be utilised to implement the strategy successfully. The main passive measures that are necessary to implement are: Adding insulation, replacement of low insulating windows, achieving an airtight building envelope and adequate solar control. The main active measure that can be implemented is energy production through solar panels.

Furthermore, chapter 4 delved deeper into the definition of a future proof renovation. The principles of the circular economy prescribe several measures that can achieve a renovation that is prepared for the future: Design out waste, build resilience through diversity, rely on renewable resources, thinking in systems and using the waste for new life cycles. Furthermore, the design of the facade system should focus on reducing the operational energy first and lowering the embodied energy lastly, as the operational energy is the dominant factor in assessing the long-term energy consumption.

The third objective is to assess current state-of-the-art project on their effectiveness in achieving an adequate prefabricated renovation. Main criteria for an adequate renovation are to give options for customisation, in terms of appearance as well as building installations, minimisation of disturbance to occupants is important in order to motivate occupants to agree with the renovation process, allow for flexible maintenance and achieve high quality modular components in order to minimise construction time and subsequently costs.

The main issue is the project-to project approach of current renovation systems, which is not adopted to a larger scale, and the lack of flexibility to allow follow up measures. Current systems are design as closed systems that don't allow for easy replacement of maintenance of internal components other than the building installations.

The fourth objective is to condensate the gather knowledge in a methodology to be utilised to achieve an adequate façade system achieving a satisfactory answer to the main research question. The literature was converted to a list of criteria divided in three fields of study: Energy, Architecture, further divided in appearance, construction and application and Future Proof. Furthermore, design tools were formulated to function as an aid for the design phase. The tools were subdivided in three categories: Typology tools, energy tools and buildability tools.

The fifth objective was to utilise the methodology to formulate a design for a façade system that satisfied the formulated criteria. The design methodology formulated in chapter 6 formed the basis for a structured design process that led to a singular solution. The final design for the façade system utilises a T-slot frame with adaptable modular boxes in sizing and infill to achieve an upgradable and flexible design able to incorporate current as well as future required functionalities.

The sixth and last object was to implement the façade system on a case and complement it with two separate scenarios with different timeline and corresponding steps. In chapter 9 the evaluation led to the design finalised in detail and an action plan to fulfil the actions required to successfully complete the constructed scenario.

§ 11.2 Answer Research Question

"In what way can a prefabricated building envelope system for energy reduction renovation of building envelopes of Dutch post-war apartment blocks be designed to be future proof by taking into account service life and changing standards?"

The research question contains a number of segments: prefabricated, energy reduction renovation, Dutch post-war apartment dwelling and future proof by taking into account service life and changing standards. We will discuss the research question per segment.

The system prefabricated nature is established by using components that can be easily stored and manufactured to project requirements in factory settings. The system incorporates elements for connecting modules to each other, connecting modules on-site to the existing façade and being lightweight and utilising small modules to be relatively easy to transport and applicate on-site.

Energy reduction is achieved by the system by being able to incorporate the energy reduction measures utilised by the 2ndSkin project, as well as incorporating additional passive and active measures. The system is customizable in terms of energy reduction percentage to any projects requirements.

The system is catered to Dutch post-war apartments blocks by incorporating the ability to adjust to different parameters, either in dimensions or functionality, so adaptability to other apartment blocks within the same typology is assured.

Finally, the main objective of the thesis, achieving a future proof renovation by taking into account service life and changing standards. Future proof by taking into account service life in this thesis was formulated as being able to replace components or materials which exceeded their service life individually. The system established this by separating functionalities in separate boxes and functional layers into detachable layers, that can be individually replaced or repaired. By separating them, it can be avoided that the materials with the lowest service life dictates the service life of the complete system, leading to materials being disposed of before they reached the end of their potential service life.

Future proof by taking into account changing standards in this thesis was formulated as being able to adapt to changes in functionality, technology and regulations, either foreseen or unforeseen. The system is designed to be adaptable to these aspect by being able to rearrange boxes, increase or decrease the number of design areas, as well as being able to accompany different thicknesses. The system is designed to allow for replacing the infill of boxes, replacing complete boxes, replacing finishing layers, building installations, as well as the main frame. Every aspect is adaptable to assure the long-term functionality of the system.

§ 11.3 Recommendations

Realisation of the upgradable building envelope system will depend on follow-up research in various domains. Recommendations for potential future researches are described below:

Financial Feasibility: Additional research is required on viability of the design solution with regard to financial aspects. Finance is one of the main determining factors of the implementation of a new system.

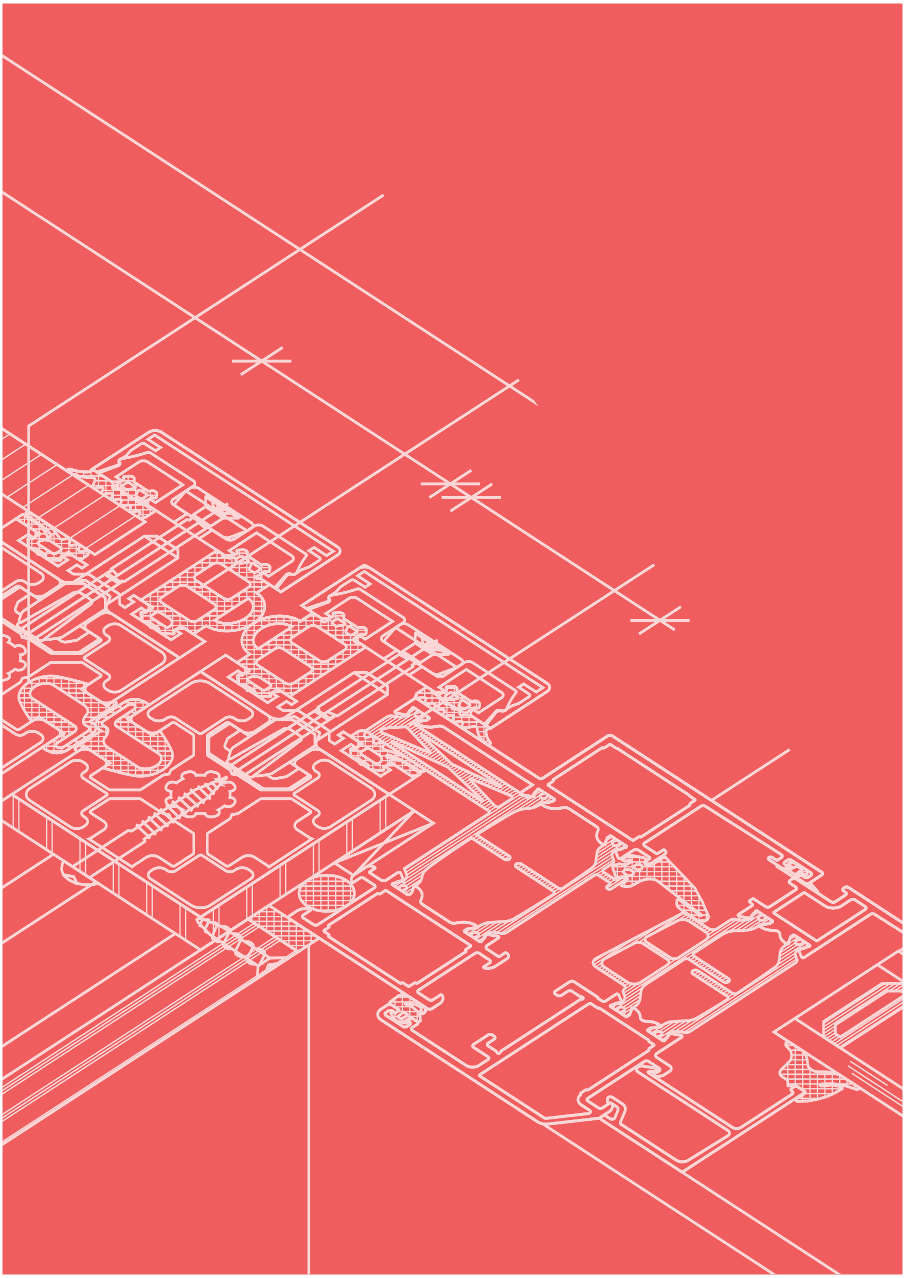
Circularity: More research on the circularity in terms of embodied energy and recycling potential of upgradable systems is necessary to further confirm the usefulness of such systems in regard to the circular economy.

Production: The production of prefabricated renovation system is a crucial part in determining the success of a solution. Further improving the production line in terms of time and costs would benefit the incentive to use such systems.

Adaptability: This thesis focusses on one typology, the adaptation of the system to different typologies would further increase the usefulness of the system.

Customisation: More customisation options would potentially increase the motivation for stakeholders to utilise the system and acceptance by occupants.

Disturbance: Further improving the application of the system on-site by decreasing the necessary labour and construction time required would benefit the incentive to use prefabricated systems.



Bibliography

80/20 Incorporated. (2018, November 11). *Catalog 22.* Retrieved from catalogs.8020.net: http://catalogs.8020.net/80-20-Inc-Catalog-22/Cover/

Awenta. (2018, Novemver 11). *WTW Unit HRV100P.* Retrieved from Awenta.eu: http://www.awenta.eu/index.php/products/plastic-products/ventilation-systems#

Azcarate Aguerre, J., Konstantinou, T., Klein, T., Steensma, S., Guerra Santin, O., & Silvester, S. (2017). Investigating the business case for a zero-energy refurbishment of residential by applying a pre-fabricated façade module. *ECEEE 2017 Summer Study on Energy Efficiency*.

BBSR. (2018). *Nutzungsdauern von Bauteilen für Lebenszyklsanalysen nach Bewertungssystem Nachhaltiges Bauen (BNB).* BBSR. Retrieved from nachhaltigesbauen.de: https://www.nachhaltigesbauen.de/fileadmin/pdf/baustoff_gebauededaten/BNB_Nutzungsdauern_von_Bauteilen__2011-11-03.pdf

Boess, S., Konstantinou, T., Klein, T., Azcarate Aguerre, J., Silvester, S., Auer, T., . . . Henry, Q. (2017). *2ndSKIN Demonstrator Climate KIC: Performance Report 2017.* EIT-Climate-KIC.

Bouwhulp Groep . (2013). *Documentatie Systeemwoningen '50 -'75.* Eindhoven: Platform31.

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

BRIS. (2018, August 29). *Afdeling 3.2. Bescherming tegen geluid van installaties*. Retrieved from Bouwbesluitonline.nl: https://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012_nvt/hfd4/afd3-2

BRIS. (2018, August 29). *Afdeling 4.6. Buitenruimte, nieuwbouw*. Retrieved from Bouwbesluitonline.nl: https://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012/hfd4/afd4-6

Cronhjort, Y., Nuikka, M., Hirsi, H., & Lylykangas, K. (2009). *TES Energy Facade Timberbased element systems for improving the energy efficiency of the building envelope.* Researchgate.

Department for Communities and Local Government. (2009). *Multi-criteria Analysis: a Manual.* London: Communities and Local Government Publications.

Dubois, S., Remy, O., & De Bouw, M. (2016). *Retrofitting with AIM-ES.* BBRI-CSTC-WTCB.

Ellen MacArthur Foundation. (2013). *Towards the Circular Economy.* Ellen MacArthur Foundation.

EN 15804. (2012). *Life cycle stages and modules used in LCA.* Retrieved from greenspec.com: http://www.greenspec.co.uk/building-design/embodied-energy/

ENDIS. (2018). *ENDIS Portiekflat Renovatie.* Retrieved from endis.nl: http://endis.nl/downloads/

European Union. (2010). *A Strategy for Competitive, Sustainable and Secure Energy.* Luxembourg: European Union.

F and L Industrial Solutions, Inc. (2018, November 11). *Extrusion Builder News the Fastener Issue: An Introductory Guide to T-Slot Fastening Options.* Retrieved from Fandl8020.com: http://fandl8020.com/wp-content/uploads/2015/01/EBN-Spring15.pdf

Geier, S. (2010). *10 Steps to a Pref-fab Module: IEA ECBCS Annex 50 – Prefabricated Systems for Low Energy Renovation of Residential Buildings.* Gleisdorf: AEE – Institute for Sustainable Technologies.

Guerra, S., Bosch, H., Budde, P., Konstantinou, T., Boess, S., Klein, T., & Silvester, S. (2018). Considering user profiles and occupants' behaviour on a zero energy renovation strategy for multi-family housing in the Netherlands. *Energy Efficiency*.

Hadzimuratovic, A., & Swedmark, M. (2016). *Study of active technologies for prefabricated multi-active facade elements for energy renovation of multi-family buildings.* Mälmo: Lund University.

Hermelink, A., Schimschar, S., Boermans, T., Pagliano, L., Zangheri, P., Armani, R., . . . Musall, E. (2013). *Towards Nearly Zero-energy Buildings: Definition of common principles nder the EPBD.* Cologne: ECOFYS Germany GmbH.

Israëls, E., & Stofberg, F. (2017). *Energie Vademecum: Energiebewust Ontwerpen van Nieuwbouwwoningen.* Klimapedia.

Itard, L., & Klunder, G. (2007). Comparing environmental impacts of renovated housing stock with new construction. *Building Research and Information*.

Itard, L., & Meijer, F. (2008). *Towards a sustainable Northern European housing stock (Vol.22).* Amsterdam: IOS.

Itho Daalderop. (11, November 2018). *Itho Smartboiler 150L.* Retrieved from Ithodaalderop.nl: https://www.ithodaalderop.nl/producten/boilers/smartboilers/smartboiler-150

Itho Daalderop. (2018, November 11). *De 10 meest gestelde vragen over warmtepompen*. Retrieved from Ithodaalderop.nl: https://newsroom.ithodaalderop.nl/blog/de-10-meest-gestelde-vragen-over-warmtepompen

Itho Daalderop. (2018, November 11). *Itho WTW HRU ECO 300.* Retrieved from Ithodaalderop.nl: https://www.ithodaalderop.nl/producten/ventilatie-hele-huis/ventilatie-met-wtw/hru-eco-300

Itho Warmtepomp WPU 55. (2018, November 11). Retrieved from Itho Daalderop: https://www.ithodaalderop.nl/producten/warmtepompen/waterwater/wpu-55co-eteck

Jansen Steel Systems. (2018, December 7). *VISS Vliesgevel.* Retrieved from ods-geveltechniek.nl: http://www.ods-geveltechniek.nl/nl/home/gevels-en-daken/gevAels/viss-vliesgevel/

Kawneer. (2018, December 5). *RT 72 Reflex.* Retrieved from Kawneer.com: https://www.kawneer.com/bcs/architectuursystemen/nl/product.asp?prod_id=4466

Kayll, D. (2014). CSA S478 Guideline on Durability in Buildings. Ottawa: Morrison Hershfield.

Kleiven, T., Woods, R., & Risholt, B. (2014). *Retrofitting multifamily buildings with prefabricated modules - RETROKIT.* Oslo: SINTEF Academic Press.

Knaack, U., Klein, T., Bilow, M., & Auer, T. (2007). *Facades: Principles of Construction.* Basel: Birkhäuser Verlag AG.

Konstantinou, T. (2014). *Facade Refurbishment Toolbox.* Delft: Delft University of Technology, Faculty of Architecture and The Built Environment.

Konstantinou, T., Ignjatović, N. Ć., & Zbašnik-Senegačnik, M. (2018). *Energy Resources and Building Performance.* Delft: TU Delft Open.

Kuijpers-Van Gaalen, I. M., Zeegers, A., Erdtsieck, P., & Van der Linden, A. C. (2011). *Bouwfysica.* Amersfoort: ThiemeMeulenhoff.

Langston, C. (2011). Estimating the useful life of buildings. *36th Australasian University Building Educators.* Bond University .

Loussos , P., Konstantinou, T., Van den Dobbelsteen, A., & Bokel, R. (2015). Integrating Life Cycle Energy into the Design of Façade Refurbishment for a Post-War Residential Building in The Netherlands. *Buildings 2015*.

Maes, A. (2015). *Analysis of Dry Connections for Precase Concrete Low-rise Buildings.* Gent: University of Gent.

MeeFS Retrofitting. (n.d.). *Retrofitting Facade Concept*. Retrieved from meefs-retrofitting.eu: http://www.meefs-retrofitting.eu/project/retrofitting-facade-concept.html

Ministry of National Affairs and Kingdom Relations. (2012). *Artikel 5.2. Energieprestatiecoëfficiënt*. Retrieved from rijksoverheid.bouwbesluit.co: https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012

Ministry of National Affairs and Kingdom Relations. (2013). *Cijfers over Bouwen en Wonen.* Ministry of National Affairs and Kingdom Relations.

Ministry of National Affairs and Kingdom Relations. (2015). *Infoblad Trias Energetica en energieneutraal bouwen.* Utrecht: Rijksdienst voor Ondernemend Nederland.

Netherlands Enterprise Agency. (2018). *Bepalingsmethode EPC*. Retrieved from rvo.nl: https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels-gebouwen/nieuwbouw/energieprestatie-epc/bepalingsmethode-epc

Rozanska, M. (2016). *Multifunctional Energy Efficient Façade System for Building Retrofitting: Project Final Report.* European Union.

Samuel, D. G., Nagendra, S. M., & Maiya, M. P. (2013). Passive alternatives to mechanical air conditioning of building: A review. *Building and Environment 66*, 54-64.

Sartori, I., & Hestnes, A. (2006). Energy use in the life cycle of conventional and low-energy buildings: A review article. Trondheim: Elsevier Ltd.

Stroomversnelling. (2015). *Stroomversnelling Nederland: 4,5 miljoen woningen naar nul-op-de-meter.* Taskforce Vergunningen.

TKI/Energo. (2016). *2ndSkin: zero energy apartment renovation via an integrated facade approach.* TKI/Energo.

Van den Dobbelsteen, A., & Tillie, N. (2011). Energetic Urban Planning – A novel approach to carbon-neutral cities. *World Sustainable Building Conference (SB11).* Helsinki: TU Delft.

Vollebregt, R. (2011, March). Gemiddeld gasverbruik niet onder de 1000 kubieke meter. *epg netwerk business magazine*, pp. 50-51.

	System Typology			Module Orientation		Module Size		Component Combination			Functionality Organisation		Connection Typology		Technical Integration	
	Principle System	Base System	Fixed System	Horizontal Orientation	Vertical Orientation	Small Modules	Large Modules	Closed System	Layered System	Modular System	Component Facade	Element Facade	Wet Connections	Dry Connections	Separated Installation	Integrated Installation
Accumulated Future Proof	-2	0	2	-2	2	2	-2	-2	0	2	2	-2	-2	-2	2	-1
Accumulated Architecture	-1	-1	1	2	6	2	2	-2	0	4	-3	4	-4	5	-4	4
Accumulated Energy																
Maintenance	-	o	+	-	+	+	-	-	o	+	+	-	-	+	+	-
Upgradability	-	o	+	-	+	+	-	-	o	+	+	-	-	+	+	o
Construction Time	-	o	+	o	+	-	+	+	o	o	-	+	o	+	-	+
Disturbance				+	+	+	-	+	o	o	-	+	-	+	-	+
Adaptability	+	o	-	o	+	+	o	-	o	+	o	+	-	+	-	+
Sustainable Materials													-	+		
Structural Adjustments															+	-
Integration	-	-	+	-	+	-	+	-	o	+	-	+			-	+
Off-site Production Ability	-	o	+	+	+	+	+	-	o	+	-	+	-	+	-	+
Customisation	+	o	-	+	+	+	o	-	o	+	+	-				
Energy Generation																
Energy Reduction																

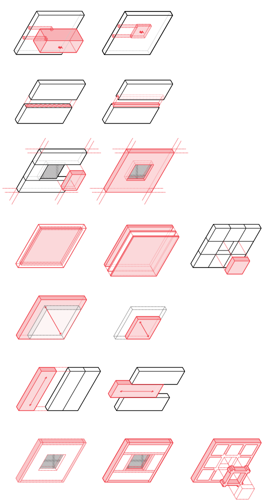


Fig. A.1: *Assessment Typology Tools paragraph 8.2 (own illsutration).*

	Shading Typology				Insulation Improvement		Double Facades		Heat Gain Mass	RES	
	Horizontal Shading	Vertical Shading	Adaptable Shading	Cantilever Shading	Apply Insulation	Replace Windows	Box Window	Attached Sunspace	Trombe Wall	Building Applied PV	Building Integrated PV
Accumulated Future Proof	2	2	0	0	0	0	2	-2	-2	2	-2
Accumulated Architecture	7	7	6	-7	7	-5	5	-7	-6	-3	5
Accumulated Energy	1	1	1	2	1	1	1	1	1	1	2
Maintenance	+	+	-	+	-	+	+	-	-	+	-
Upgradability	+	+	+	-	+	-	+	-	-	+	-
Construction Time	+	+	+	-	+	-	+	-	-	-	+
Disturbance	+	+	+	-	+	-	+	-	-	-	+
Adaptability	+	+	+	-	+	-	-	-	-	+	-
Structural Adjustments	+	+	+	-	+	+	+	-	-	+	+
Sustainable Materials	+	+	0	-	+	+	+	-	-		
Integration	+	+	+	-	+	-	+	-	-	-	+
Off-site Production Ability	+	+	+	-	+	-	+	-	-	-	+
Customisation	+	+	+	-	+	-	+	-		-	+
Energy Generation	0	0	0	+						+	+
Energy Reduction	+	+	+	+	+	+	+	+	+	0	+

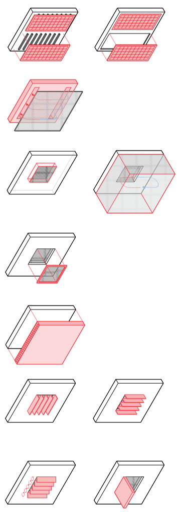
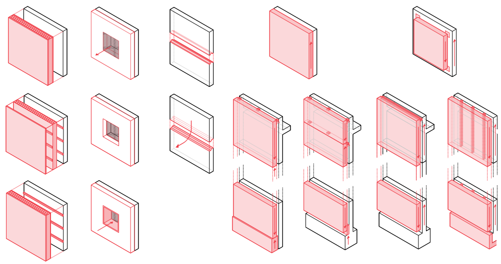


Fig. A.2: Assessment Energy Tools paragraph 8.2 (own illsutration).



		Energy Reduction	Energy Generation	Customisation	Off-site Production Ability	Integration	Sustainable Materials	Structural Adjustments	Adaptability	Disturbance	Construction Time	Upgradability	Maintenance	Accumulated Energy	Accumulated Architecture	Accumulated Future Proof
Level of Prefabrication	Composite Insulation System			-	-	-	-	+	+	-	o	-	-		-3	-2
	Semi-prefabricated System			+	o	+	+	o	+	-	-	+	+		2	2
	Prefabricated System			+	+	+	+	o	+	+	+	+	+		7	2
Placement Window	Exterior Flush-mounted			-	+	-	+	o	+	+	+	+	+		3	2
	Centre in Reveal			+	o	+	o	o	o	+	+	o	o		4	0
	Interior Flush-mounted			o	-	o	-	+	-	-	-	-	-		-4	-2
Connection Modules	Fixed Module System	+			+	+		+	o	+	+	-	-	1	5	-2
	Single Fixed Modules	o			+	o		-	-	+	-	+	+	0	-1	2
New Foundation	Area Covering Module				+	+	-	+	+	-	+	-	-		3	-2
	New Foundation				-	-	-	-	+	-	-	+	+		-5	2
Loaded Plinth	Segmented Module				+	+	+	-	+	-	-	-	-		1	-2
	Load Application Plinth				+	+	+	+	-	+	+	-	-		5	-2
Eave Suspended	Suspended from Eave				+	o	+	-	-	+	+	-	-		2	-2
	Existing Foundation				+	+	+	+	-	+	+	-	-		5	-2
Reinforced Foundation	Substructure Loaded				-	-	-	-	+	-	-	+	+		-5	2
	Reinforced Foundation				-	-	-	-	+	-	-	+	+		-5	2

Fig. A.3: *Assessment Buildability Tools paragraph 8.2 (own illsutration).*

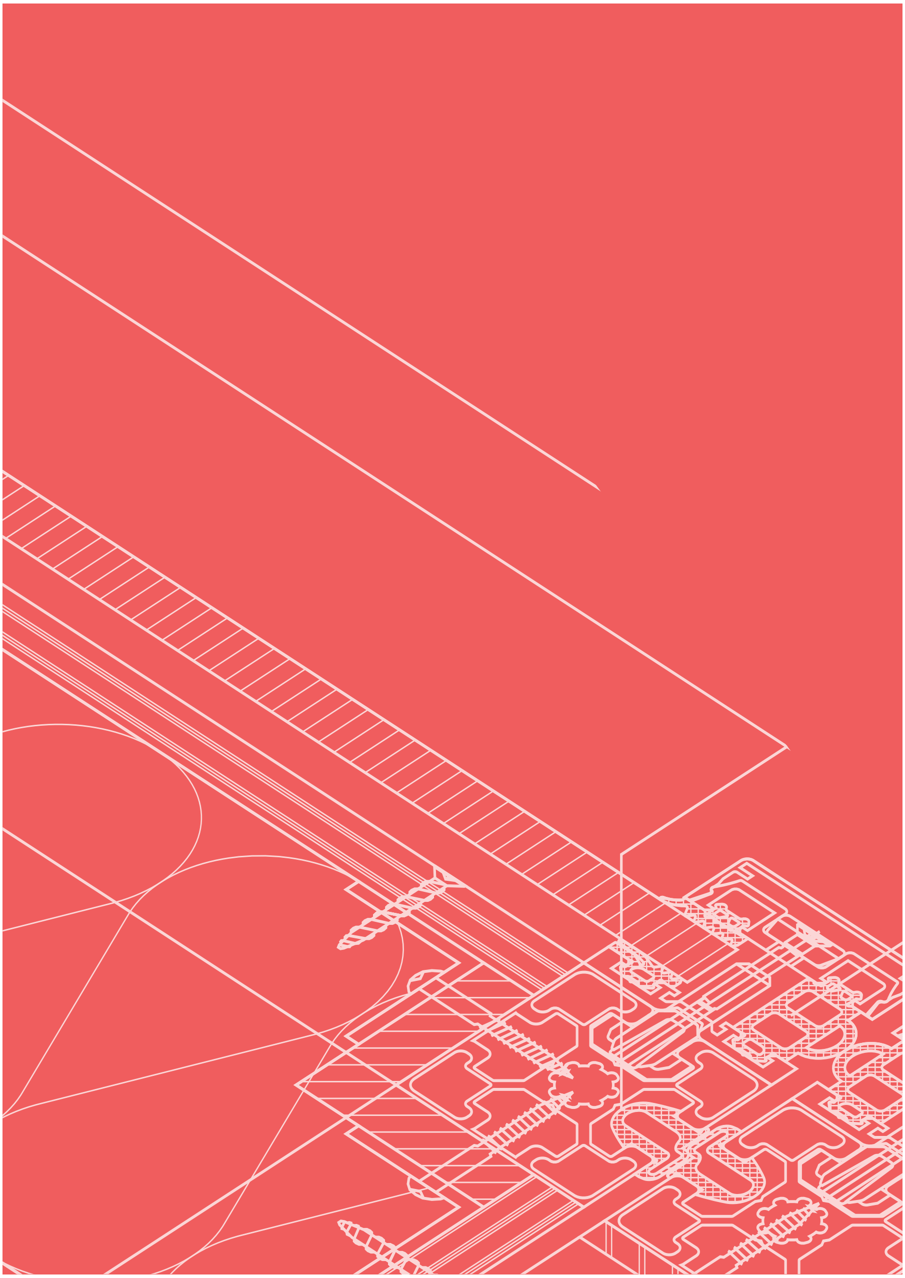
	Vertical Frame	Horizontal Frame	Drawer	Surrounding Frame	Self-supporting Modules	Slot System	Add-in System	Open Frame System	Pin System	Closed Modules
Accumulated Future Proof	1	1	2	1	0	0	-2	1	2	-1
Accumulated Architecture	-4	-6	2	1	-2	1	1	7	3	3
Accumulated Energy										
Maintenance	+	+	+	+	0	+	-	0	+	-
Upgradability	0	0	+	0	0	-	-	+	+	0
Construction Time	-	-	+	0	-	+	+	+	0	+
Disturbance	-	-	+	0	-	+	+	+	+	+
Adaptability	-	-	-	-	+	-	-	+	+	-
Sustainable Materials										
Structural Adjustments	+	-	+	0	+	-	-	+	-	0
Integration	-	-	-	+	0	+	+	+	+	+
Off-site Production Ability	-	-	+	+	-	+	+	+	0	+
Customisation	0	0	-	0	-	-	-	+	+	0
Energy Generation										
Energy Reduction										

Fig. A.4: *Assessment Concepts paragraph 8.3 (own illsutration).*

Sound Insulation

In terms of sound insulation, the largest standard Itho heat pump, the WPU 5G, produces 43.5 dB maximum at a distance of one meter, smaller versions produce slightly less (Itho Daalderop, 2018). Itho Daalderop also produces heat pumps with sound insulating casing to further decrease the sound production. The Dutch building code (2018) indicates that, when renovating buildings, a maximum of 40 dB is allowed to be produced by installations. The described heat pump is slightly above the maximum, but as the heat pump is located on the exterior the sound is dampened by the insulation provided in the new façade, as well as the existing façade. The existing façade, consisting of 100 mm of concrete, 70 mm of air cavity and 100 mm of brick, has a high mass and therefore high sound insulation. Furthermore, there is also the possibility to utilise insulation in the new façade system with high mass, if sound problems consist.

This sound production excludes possible vibration sound produced by the installations. Vibration sounds could potentially travel through the aluminium framing to the existing façade. There are a number of options available to counteract potential vibration disturbance: The use of rubber anti-vibration dampers that are attached to the feet of the installation is possible, that limit the possibility of the installations to pass on the vibration to other components of the system. Furthermore, it is possible to decouple the façade renovation connection to the existing façade through the use of dampening rubber (Geier, 2010).



Calculatie Statisch Gewicht Installaties			
Installatie	**Gewicht**	**Aantal**	**Totaal**
Itho Boiler 150L	201	3	603
Itho Warmtepomp	121,5	1	121,5
Itho Booster	38	1	38
Itho WTW	35	3	105
Totaal Zwaarste Verdieping			194,5
Gewicht per m2			78,30113
Totaal Alles			867,5
Gewicht per m2			61,62972

Fig. A.5: *Calculations static weight of building installations paragraph 8.4.1 (own illsutration).*

Scenario 1 - Small Thickness - Cantilevered

			Profile			Scenario								
Company	Material	Name	Ix, Iy cm4	E GPA	Weight kg/m	B mm	H mm	System kg	Weight kg/m2	L-Prof mm	W mm	Max W mm	Sigma N/mm2	Max Sigma N/mm2
Coomach	6063-T66	45 x 45L-0	11,5	68,3	1,6	500	2760	0	40	300	0,062217	0,833333	4,249436	190
Coomach	6063-T66	45 X 45Z	14	68,3	2	500	2760	0	40	300	0,051938	0,833333	3,547366	190
80/20	6105-T5	45-4545-Lite	9,2029	70,3265	1,394707	500	2760	0	40	300	0,074877	0,833333	5,265807	241,1
80/20	6105-T5	45-4545	13,9604	70,3265	2,041166	500	2760	0	40	300	0,050668	0,833333	3,563286	241,1
Vention	6063-T5	45 x 45	15,4	68,3	2,06	500	2760	0	40	300	0,04733	0,833333	3,232618	145
Minitec	6060-T66	45 x 45 F	14,172	70	2,005	500	2760	0	40	300	0,050072	0,833333	3,505014	240
Minitec	6060-T66	45 X 45	15,934	70	2,205	500	2760	0	40	300	0,044891	0,833333	3,14236	240
Minitec	6060-T66	45 x 45 UL	9,953	70	1,445	500	2760	0	40	300	0,0697	0,833333	4,878992	240
Minitec	Steel 1.4301	45 x 45 SST	6,47	200	2,712	500	2760	0	40	300	0,039473	0,833333	7,894518	500
Mcmaster Carr	6360-T6	45 x 45, Wide, Hollow	10,778	68	1,52	500	2760	0	40	300	0,066461	0,833333	4,519354	501
Rexroth	6063-t5	45 x 45 Light	10,9635	68,3	1,543	500	2760	0	40	300	0,065111	0,833333	4,447055	145

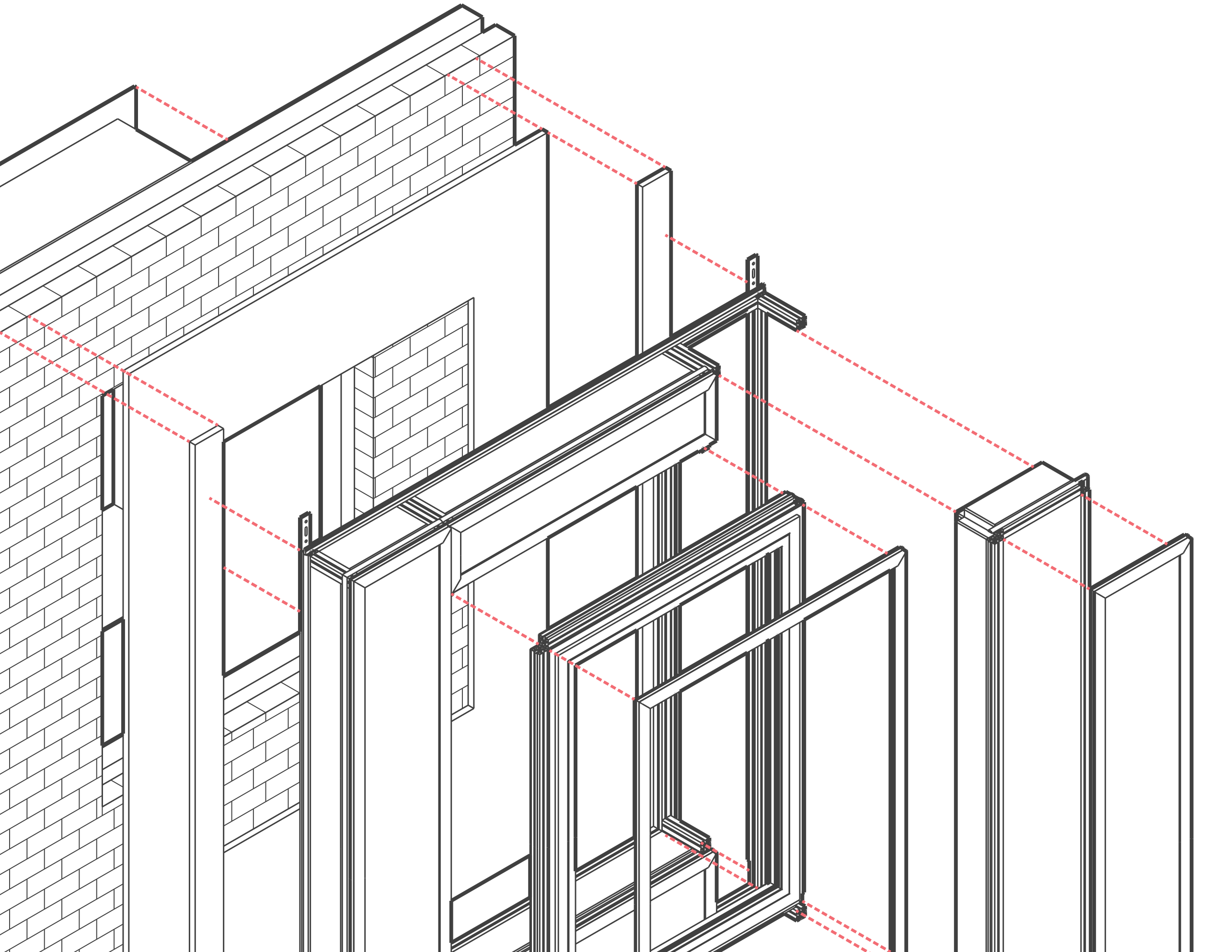
Fig. A.6: *Calculations Scenario 1 for paragraph 8.4.1 (own illsutration).*

Scenario 2 - Building Installations - Cantilevered														
			Profile			Scenario								
Company	Material	Name	Ix, Iy cm4	E GPA	Weight kg/m	B mm	H mm	System kg	Weight kg/m2	L-Prof mm	W mm	Max W mm	Sigma N/mm2	Max Sigma N/mm2
Coomach	6063-T66	45 x 45L-0	11,5	68,3	1,6	900	2760	194,5	40	900	8,688976	2,5	65,93967	190
Coomach	6063-T66	45 X 45Z	14	68,3	2	900	2760	194,5	40	900	7,204685	2,5	54,67555	190
80/20	6105-T5	45-4545-Lite	9,2029	70,3265	1,394707	900	2760	194,5	40	900	10,49388	2,5	81,99979	241,1
80/20	6105-T5	45-4545	13,9604	70,3265	2,041166	900	2760	194,5	40	900	7,023672	2,5	54,88337	241,1
Vention	6063-T5	45 x 45	15,4	68,3	2,06	900	2760	194,5	40	900	6,558892	2,5	49,77471	145
Minitec	6060-T66	45 x 45 F	14,172	70	2,005	900	2760	194,5	40	900	6,945208	2,5	54,01829	240
Minitec	6060-T66	45 X 45	15,934	70	2,205	900	2760	194,5	40	900	6,206052	2,5	48,26929	240
Minitec	6060-T66	45 x 45 UL	9,953	70	1,445	900	2760	194,5	40	900	9,759894	2,5	75,91028	240
Minitec	Steel 1.4301	45 x 45 SST	6,47	200	2,712	900	2760	194,5	40	900	5,412432	2,5	120,2763	500
Mcmaster Carr	6360-T6	45 x 45, Wide, Hollow	10,778	68	1,52	900	2760	194,5	40	900	9,294374	2,5	70,22416	501
Rexroth	6063-t5	45 x 45 Light	10,9635	68,3	1,543	900	2760	194,5	40	900	9,101924	2,5	69,07349	145

Fig. A.7: *Calculations Scenario 2 for paragraph 8.4.1 (own illsutration).*

Scenario 3 - Building Installations - Supported														
			Profile			Scenario								
Company	Material	Name	Ix, Iy cm4	E GPA	Weight kg/m	B mm	H mm	System kg	Weight kg/m2	L-Prof mm	W mm	Max W mm	Sigma N/mm2	Max Sigma N/mm2
Coomach	6063-T66	45 x 45L-0	11,5	68,3	1,6	1700	8280	867,5	40	900	0,578979	2,7	26,36284	190
Coomach	6063-T66	45 X 45Z	14	68,3	2	1700	8280	867,5	40	900	0,478395	2,7	21,7829	190
80/20	6105-T5	45-4545-Lite	9,2029	70,3265	1,394707	1700	8280	867,5	40	900	0,700521	2,7	32,84346	241,1
80/20	6105-T5	45-4545	13,9604	70,3265	2,041166	1700	8280	867,5	40	900	0,466208	2,7	21,85787	241,1
Vention	6063-T5	45 x 45	15,4	68,3	2,06	1700	8280	867,5	40	900	0,435287	2,7	19,82005	145
Minitec	6060-T66	45 x 45 F	14,172	70	2,005	1700	8280	867,5	40	900	0,461145	2,7	21,5201	240
Minitec	6060-T66	45 X 45	15,934	70	2,205	1700	8280	867,5	40	900	0,411353	2,7	19,19649	240
Minitec	6060-T66	45 x 45 UL	9,953	70	1,445	1700	8280	867,5	40	900	0,651232	2,7	30,39083	240
Minitec	Steel 1.4301	45 x 45 SST	6,47	200	2,712	1700	8280	867,5	40	900	0,357198	2,7	47,62643	500
Mcmaster Carr	6360-T6	45 x 45, Wide, Hollow	10,778	68	1,52	1700	8280	867,5	40	900	0,619757	2,7	28,09567	501
Rexroth	6063-t5	45 x 45 Light	10,9635	68,3	1,543	1700	8280	867,5	40	900	0,606801	2,7	27,62967	145

Fig. A.8: *Calculations Scenario 3 for paragraph 8.4.1 (own illsutration).*



Problem Definition and main objective: Current prefabricated building envelope systems utilised for energy reduction renovations are expected to be a long-lasting solution. In practice, the building envelope systems are not adapted to facilitate future updates due to changing regulations or changing standards. Furthermore, in most renovation systems the material or component with the lowest service life dictates the service life of the complete system, leading to materials being disposed of before they reached the end of their potential service life. The goal of the thesis is to design a system that is adapted to these issues by being a flexible system that separates functionalities in separate boxes and layers, and therefore is able to upgrade or replace individual components when necessary to ensure the system's long-term functionality.

Study Design: Literature review, followed by the formulation of a strategy and a design. Design effectiveness is confirmed through application on a case study. Long-term functionality is confirmed through transformation of the case study application based on formulated scenarios.

Setting: The thesis is part of a series of ongoing research projects associated with the 2ndSkin project. The case study is an apartment block located at the Soendalaan in Vlaardingen.

Results: A design concept for an external building envelope system for energy reduction renovation for Dutch post-war apartments elaborated in a 1 to 5 detail scale. The final design incorporates an adaptable aluminium frame system with module boxes containing different functionalities which can be slid into the main frame. The system is finished with a clamp system with cladding, functioning as the protecting layer for the system.

Keywords: Prefabricated, building envelope system, energy reduction renovation, Dutch post-war apartments, future proof, service life, changing standards.